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Petrography and geochemistry of the Devonian ultramafic lamprophyre at Sokli in the northeastern Baltic Shield (Finland)

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북동 Baltic Shield (핀란드) Sokli 지역의 데본기 초염기성 lamprophyre의 암석학 및 지구화학

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Abstract: The Sokli complex in the northeastern Baltic Shield (Finland) forms a part of the extensive Devonian Kola Alkaline Province. The complex contains ultramafic lamprophyres occurring as dikes of millimetric to metric thickness. The Sokli ultramafic lamprophyres have petrographical and geochemical affinities with aillikite. High concentrations of Cr and Ni with low Al_2O_3 content of the Sokli aillikites indicate a strongly depleted harzburgitic source. However, compared to the kimberlites, the lower Cr and Ni contents and *mg*-number with weaker HREE depletion of the Sokli aillilkites imply a smaller proportion of garnet in the source and thus suggest a shallower melting depth of the source. In order to account for high concentrations of all incompatible elements and LREEs, with high volatile content (especially CO_2), an additional enriched material is thought to have been incorporated into the Sokli aillikite source. An anomalous enrichment of K in the Sokli aillikites, compared to nearby ultrapotassic rocks and world-wide ultramafic lamprophyres, indicate a presence of K-rich phase (probably phlogopite) in the source mantle.

Key words: ultramafic lamprophyre, aillikite, Sokli, Kola Alkaline Province

요 약: 북동 발틱 순상지의 데본기 콜라 알칼리 암석구의 일부에 해당하는 속리복합체는 암맥상으로 산출되는 다양한 규모의 초염기성 럼프로파이어를 동반한다. 속리 초염기성 럼프로파이어(lamprophyre)는 암석학적 그리고 지구화학적 특성에 의해 아이리카이트(aillikite)로 분류된다. 속리 아아리카이트가 갖는 높은 Cr과 Ni 함량 그리고 낮은 Al_2O_3 함량은 이 암석이 결핍된 맨틀의 하쯔버자이트(harzburgite)로부터 유래되었음을 지시한다. 그러나 킴벌라이트(kimberlite)와 비교하면 Cr, Ni의 함량과 *mg*-number가 낮고 중희토류원소의 결핍정도가 약한 특징을 보이는데, 이는 기원맨틀의 석류석 함량이 적었고 따라서 용융심도도 킴벌라이트보다 얕았다는 것을 지시한다. 속리 아이리카이트에 함유된 매우 높은 불호정성원소들과 휘발성 성분(주로 CO_2)은 근본적으로 결핍된 기원맨틀에 부화된 물질이 첨가되어야 함을 지시한다. 또한 속리 아이리카이트의 특징적으로 높은 K함량으로부터 기원맨틀에 금운모 같은K함량이 높은 광물이 존재하였을 것이라고 추정할 수 있다.

핵심어: 초염기성 럼프로파이어, 아이리카이트, 속리, 콜라 알칼리 암석구

Introduction

Ultramafic lamprophyres, as reviewed by Rock (1991), are low-Si (29-36 wt% SiO_2) and high-Ca (12-20 wt% CaO) hypabyssal rocks, rich in Mg, Cr, Ni, Sr, Ba, REE, K and volatiles. They commonly carry phenocrysts of Mg-olivine, Ti-phlogopite, Ti- augite and rarely richterite. The groundmass may include dolomite, melilite, feldspathoids,

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*Corresponding author: Tel. 82-31-400-6444, E-mail. mjlee@kordi.re.kr monticellite, ilmenite, perovskite, Cr-spinel, Ti-magnetite and glass. The most common types of ultramafic lamprophyres are alnöite (melilite-rich, clinopyroxene-bearing) and aillikite (melilite-free, carbonate-rich). Rare types are polcenite (melilite + feldspathoids, clinopyroxene-poor or -free), ouachitite (feldspathoids + carbonates) and damkjernite (feldspathoids + carbonates + rare alkali feldspars). Unlike other varieties of a lamprophyre family, ultramafic lamprophyres are thought to be generated in the upper mantle and compositionally to be close to primary melt (Foley, 1990).

In the Kola Alkaline Province, ultramafic lamprophyres, melilitites and kimberlites represent the products of most primitive silicate magmas. They are characterized by high incompatible element contents and a pronounced enrichment in LREEs. Recent geochemical and mineralogical studies indicate that all of these rocks were products of small degree partial melts of an enriched upper mantle, although formed under different pressure and temperature conditions and probably from different mantle mineral assemblages (e.g., Rogers *et al.*, 1992; Wilson *et al.*, 1995; Beard *et al.*, 1998, 2000). These ultramafic rocks occur in proximity to many alkaline and carbonatite complexes of the Kola Alkaline Province and yield Rb-Sr ages of 360-380 Ma, which are related to the Devonian continental rifting (Kramm *et al.*, 1993).

Here we present the geochemical data of ultramafic lamprophyres of the Sokli complex and compare them with those of nearby contemporaneous Terskii Coast kimberlites and melilitites as well as world-wide ultrapotassic rocks in an attempt to understand their petrogenesis.

Regional Geology

The Kola Alkaline Province (KAP) comprises more than 24 ultramafic and alkaline complexes together with numerous dikes and pipes, which were formed by intraplate alkaline magmatism, related to continental rifting during Hercynian time. (Kramm *et al.*, 1993; Kogarko *et al.*, 1995). The KAP covers in an area of more than 100,000 km^2 between the northeastern Finland and the eastern part of the Kola Peninsula (Fig. 1). The KAP includes two giant, differentiated agpaitic nepheline syenite massifs: Khibina (1,300 km^2) and Lovozero (650 km^2). The Khibina massif, the largest agpaitic body in the world, contains the largest accumulation of apatite ores yet found in the world and a number of mafic dikes. Besides of them, the KAP includes numerous smaller massifs, less than 60 km^2 in size, and several of them (Kovdor, Sokli, Vuorijarvi, Turiy Mys and Seblyavr) contain significant volumes of carbonatites and locally dike swarms of carbonatites and alkaline rocks (melilitites, ultramafic lamprophyres). The emplacement of some alkaline complexes (e.g., Khibina, Lovozero, Ozernaya Varaka and Afrikanda) was controlled by preexisting rift structures perpendicular to and along the NW-SE trending Proterozoic structures associated with the Kontozero Graben (Ziegler, 1988). While the alkaline complexes of Sokli, Kovdor, Kandagubskii and Turiy Mys form an E-W trending belt related to the Kandalaksha deep fracture zone (Vartianian and Paarma, 1979). Numerous carbonatite and lamprophyre and alkaline dikes and pipes including melilitites and kimberlites occur in the coast and islands of the Kandalaksha Gulf, the northwestern end of the White Sea, and along the southern coast of the Kola Peninsula (Kalinkin *et al.*, 1993; Arzamastsev and Dahlgren, 1994; Kapustin, 1994; Beard *et al.*, 1996). These dikes and pipes do not belong to any particular alkaline complex and are considered to be related to the Kandalaksha-Onezh rift (Kukharenko *et al.*, 1965).

The Sokli massif is located in the eastern Finnish Lapland, at 67° 48' N, 29° 27' E, near the border to Russia (Fig. 1). It is the only member of the KAP located outside Russia and situated at 60 km NNW from the Kovdor complex, which is one of the well-known complexes in the KAP as outcrops are common and mining operations (for magnetite, apatite, baddeleyite, phlogopite and vermiculite) have excavated huge quarries. The Sokli massif is covered by glacial drift and thus geological map of this complex is exclusively based on geophysical survey and petrochemical examinations for drill core materials (Fig. 2). It was emplaced at about 360 Ma (Kramm *et al.*, 1993) into Archean Belomorian group rocks that comprise gneisses (mainly gneissose granites and associated pegmatites), syenites, amphibolites, hornblende schists and ultramafic rocks. The massif has concentrically zoned structure, largely being divided into two zones, and is surrounded by fenite aureole of 1-2 km in width (Fig. 2). The overall outline of the massif is a vertical pipe, of about 6.4 km in diameter, with walls steeply dipping

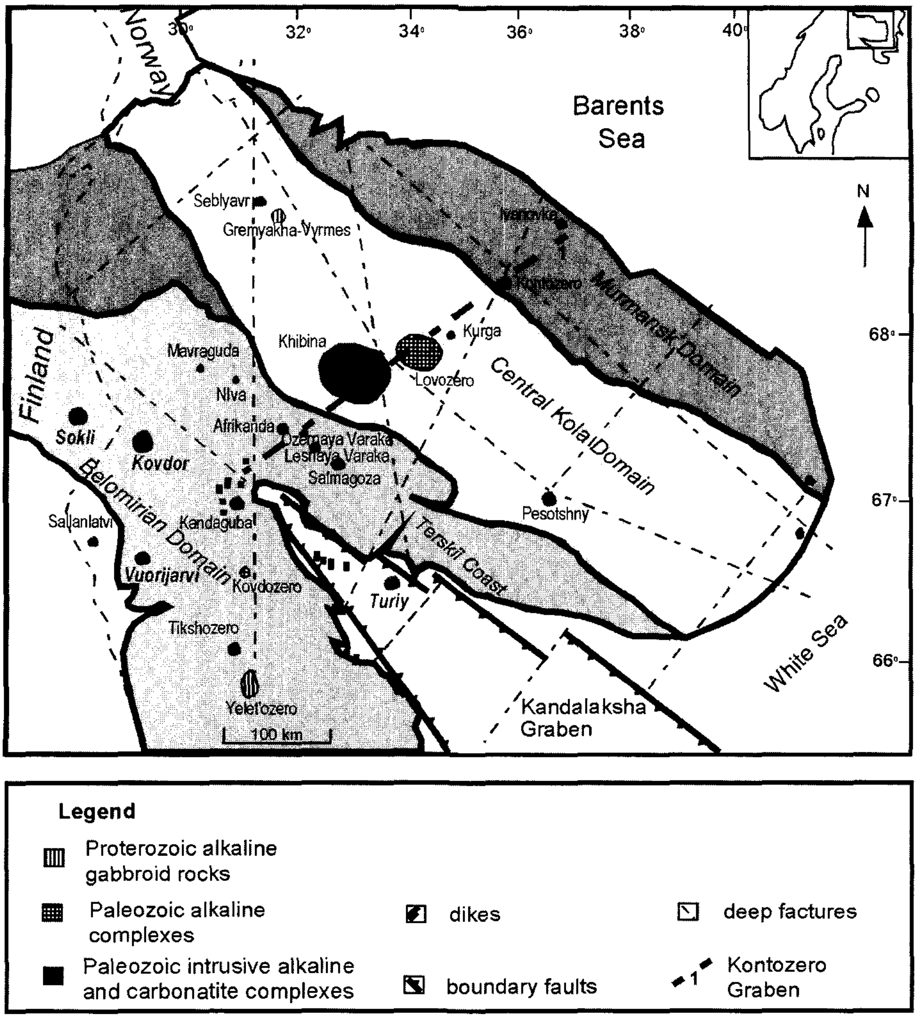

Fig. 1. Map of the Kola Alkaline Province showing the location of the Proterozoic and Paleozoic alkaline intrusions (modified from Bell *et al.*, 1996).

inward. The outer zone is composed of "metacarbonatite" and "metaphoscorite" (terminology by Vartiainen, 1980). However, they are not metamorphic carbonatites and phoscorites. Vartiainen (1980) interpreted that they are metasomatic carbonatites and phoscorites produced by replacement of preexisting ultramafic rocks. The inner zone, called "magmatic core", consists of multiple intrusions of carbonatites and phoscorites.

Ultramafic lamprophyres (UMLs) of the Sokli complex occur as dikes of millimetric to metric thickness. The Sokli ultramafic lamprophyres present all the typical features, in chemistry and in mineralogy of aillikite as defined by Rock (1991). They cut most types of rocks, but some lamprophyric dikes are assimilated and brecciated by later carbonatitic rocks. It seems thus that a part of UMLs intruded quite early in the history of the complex formation. All the observations indicate a random distribution, rather than a regular one like that reported for the Alno dikes. According to Vartiainen *et al.* (1978), they constitute from 0.6 to 8.7 vol. % in each drill section.

Petrography

The Sokli UMLs show highly variable color and texture. Two varieties of lamprophyres have been observed: one is a fine-to medium-grained, mica-rich

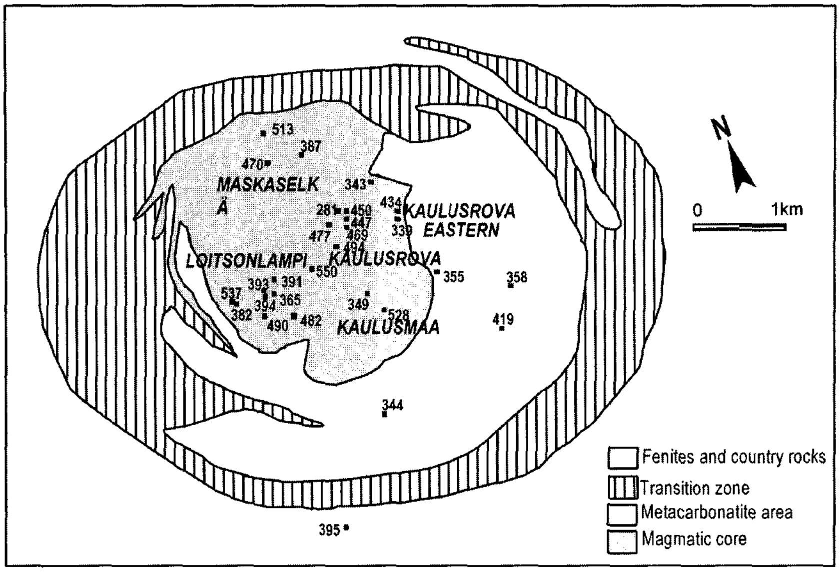

Fig. 2. Geological map of the Sokli complex and locations of the sampling drill holes (after Vartiainen, 1980). The map was originally drawn from many drill core data.

variety (Fig. 3a), and the other is a porphyritic, olivine-rich one (Fig. 3b). The large compositional and textural variations observed even within the same variety are not considered to be a result of derivations from different parental magmas, but reflect highly variable proportions of olivine and phlogopite xenocrysts.

Mica-rich lamprophyre is distinguished by high modal proportion of phlogopite (up to 60%) and the rarity of olivine phenocryst. It is generally a reddish brown or green in color and mainly composed of phlogopite, magnetite and richterite. Olivine has been replaced by serpentine and clinohumite. The grounmass contains subhedral calcite and dolomite. Phlogopite occurs as both macrocryst and microphenocryst. Following the usage in studies on kimberlites or alkaline lamprophyres (Nixon *et al.*, 1984), the non-genetic term 'macrocryst' is used here to describe merely rounded to anhedral large crystals (0.5-10 mm), that may be either phenocrysts or xenocrysts. These rounded macrocrysts are frequently zoned, with a complex distribution of pleochroism. The deep brown core (TiO_2 rich) is occasionally mantled by a pale yellow intermediate zone (Fig. 3c), which is itself occasionally embayed by dark orange rim. Small dark orange tetraferriphlogopite occurs as secondary products. Magnetite is euhedral to subhedral. Prismatic or acicular richterite is ubiquitous. Olivine crystals are almost completely altered, with only faint outlines, and their inner parts are frequently replaced by fine aggregates of anhedral magnetite, tetraferriphlogopite, richterite and calcite (Fig. 3d).

Porphyritic lamprophyre is characterized by an inequigranular texture in which macrocrysts of olivine and phlogopite are set in a fine grained magnetite and calcite matrix. It is generally massive and dark green to gray in color, but occasionally bears a reddish appearance because of secondary orange tetraferriphlogopites. Acicular richterite and small euhedral tetraferriphlogopite occur as secondary minerals developed on or from olivine. Olivine, usually more abundant than phlogopite, varies from 0.5 to 5 mm in size and is rounded. Both fresh and altered crystals are observed. Altered olivine is commonly filled with acicular richterite and enclosed by small tetraferriphlogopite of lath-shaped habit (Fig. 3e). In sample 387R171, an olivine xenocryst with anhedral inclusions of chromite has been found; it is interpreted as a xenocryst of mantle origin. Phlogopite is zoned from pleochroic pale yellowish to greenish core to strongly reddish orange iron-rich rim.

Carbonate is generally found as a constituent of the groundmass, but, in some samples, spherical or ellipsoidal

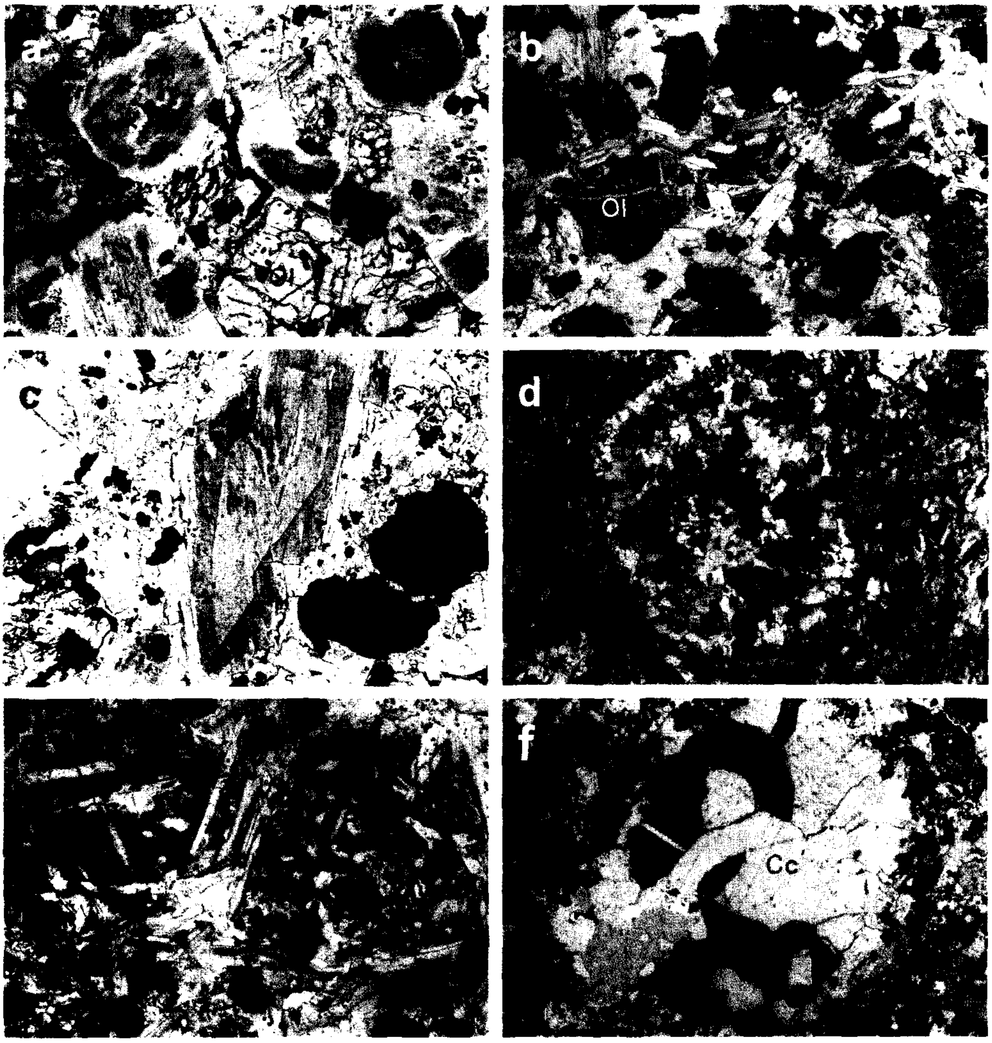

Fig. 3. Photomicrographs of Ultramafic lamprophyres. (a) Fine- to medium-grained mica-rich lamprophyre (open, width=2.5 mm). (b) Porphyritic olivine-rich lamprophyre (open, width=2.5 mm). (c) The 'macrocrysts' are frequently zoned, with complex pleochroism (open, width=1.3 mm). (d) Olivine pseudomorph completely replaced by fine aggregates of anhedral magnetite, tetraferriphlogopite, richterite and calcite (open, width=2.5 mm). (e) Altered olivine grains commonly filled with acicular richterite (open, width=2.5 mm). (f) An ellipsoidal leucocratic patch consisting of anhedral, coarse-grained calcite (open, width=2.5 mm). Abbreviations: Ph, phlogopite; Ol, olivine; Rit, richterite; Cc, calcite.

leucocratic patches, or ocelli, 1 to 5 mm in size, are observed (Fig. 3f). Ocelli consist of calcite, which is of coarser grain than the surrounding matrix phases and apatite.

Whole Rock Geochemistry

Analytical procedure

The major, trace and some rare earth elements were analyzed by an X-Ray Fluorescence (XRF) spectrometer and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) at Ecole des mines de Saint Etienne, France. Measurements by XRF were performed on a Phillips PW 1404 spectrometer (with a wavelength dispersive system) with a rhodium target X-Ray tube. For ICP-AES analysis, a simultaneous spectrometer (Jobin Yvon JY32) was used to determine the concentrations of 32 elements, including major elements (except Si) and Sc,

Table 1. Representative major and trace element compositions of the Sokli ultramafic lamprophyres.

	Sokli Aillikites													Terskii Coast Rocks				Aillikite	Average UML
Sample	365R 258	387R 56	387R 88	393R 156	393R 198	419R 87	434R 185	450R 133	450R 196	469R 182	470R 211	482R 79	537R 156	Kimberlites		Melilitites			
Site	LOITS	MSKS	MSKS	LOITS	LOITS	META	KRVE	KRVA	KRVA	KRVA	MSKS	LOITS	LOITS						
SiO_2	23.83	25.45	26.76	24.57	28.02	17.69	26.18	26.53	28.36	27.76	24.85	24.90	22.37	27.87	35.13	34.61	35.1	22.30-26.50	32.2
TiO_2	3.43	4.05	2.49	2.50	2.99	2.47	4.86	3.07	2.53	1.40	2.97	2.18	2.63	1.17	0.97	1.28	1.97	2.86-3.49	2.2
Al_2O_3	2.78	2.99	3.13	2.13	3.89	2.36	2.56	3.12	1.90	2.30	2.66	2.81	1.56	4.67	4.48	7.49	10.41	2.63-6.00	9.2
Fe_2O_3*	16.70	18.51	17.53	15.18	16.89	16.29	16.48	17.07	14.99	16.83	15.66	17.01	14.35	8.91	6.83	11.71	13.04	11.31-14.70	12.69
MnO	0.34	0.73	0.45	0.45	0.36	0.28	0.23	0.34	0.38	0.59	0.29	0.39	0.37	0.2	0.19	0.21	0.21	0.22-0.31	0.24
MgO	15.93	28.80	22.87	22.91	16.06	12.76	20.23	19.91	26.15	29.68	21.95	18.59	19.22	23.95	23.99	16.93	12.23	13.18-20.25	15.3
CaO	16.11	8.01	13.21	16.77	14.87	23.33	11.83	11.03	9.32	9.17	10.45	13.95	19.50	12.59	9.97	17.56	18.8	7.25-17.8	16
Na_2O	0.53	0.15	0.24	0.48	1.36	0.21	1.08	0.51	0.79	0.29	0.60	0.20	0.94	0.22	0.32	1.36	4.18	0.12-1.22	2.1
K_2O	4.48	2.02	2.71	2.31	3.94	1.68	2.73	4.69	2.14	1.74	1.49	5.21	1.84	2.11	2.75	0.44	1.42	1.48-2.89	2.1
P_2O_5	1.08	0.30	0.92	2.41	1.72	2.56	0.93	0.97	0.76	2.55	0.46	1.12	1.63	3.33	0.65	0.29	0.21	1.78-2.35	1.5
LOI	14.20	7.52	8.99	10.57	10.36	19.26	11.77	12.25	11.86	6.88	17.86	12.54	15.43	13.24	13.78	7.47	2.02	11.86-18.74	
Total	99.41	98.52	99.30	100.28	100.46	98.89	98.88	99.48	99.18	99.19	99.24	98.90	99.84	98.26	99.06	99.35	99.59		

Table 1. Continued.

	Sokli Aillikites													Terskii Coast Rocks				Aillikite	Average UML
Sample	365R 258	387R 56	387R 88	393R 156	393R 198	419R 87	434R 185	450R 133	450R 196	469R 182	470R 211	482R 79	537R 156	Kimberlites		Melilitites			
Site	LOITS	MSKS	MSKS	LOITS	LOITS	META	KRVE	KRVA	KRVA	KRVA	MSKS	LOITS	LOITS						
Sc	61	54	25	28	89	18	31	36	23	27	14	26	18						25
V	254	154	183	167	212	226	286	173	153	178	189	157	282	116	38	170	158	168-209	180
Cr	409	1710	807	646	286	269	967	579	1394	1049	759	459	540	1518	1316	520	300	331-628	541
Co	80	0	89	0	0	0	0	0	0	0	104	50	0						
Ni	349	725	589	847	248	293	542	407	941	825	861	406	554	802	1180	592	272	161-516	435
Cu	150	0	145	0	0	0	0	0	0	0	112	167	0	18	28	196	251		
Zn	143	338	141	150	149	118	104	172	98	219	105	142	144	65	48	99	128		
Ga	13	19	14	12	19	12	16	17	10	19	9	15	11						
Rb	117	90	69	60	96	50	84	139	58	71	52	142	47	119	95	19	37	46-85	69
Sr	1395	1270	1239	1461	1375	2010	839	1335	986	1068	901	1717	2102	2446	859	1480	1767	2031-3905	1342
Y	19	15	17	40	35	33	29	15	20	20	41	17	29	14	16	14	17	46-259	62
Zr	381	336	171	513	941	631	438	283	236	362	357	87	394	216	123	132	131	321-688	328
Nb	222	419	160	316	396	161	178	362	146	321	301	556	198	136	237	76	124	232-323	121
Ba	743	718	690	508	1149	1084	923	1161	1601	625	938	781	450	6826	1571	473	405	919-3104	1387
La	72	176	81	178	139	158	185	69	75	94	116	87	123	120	201	67	107	217-609	150
Ce	148	253	157	390	375	303	407	151	127	211	195	158	309	203	246	139	223	518-837	256
Eu	3	5	3	10	10	6	7	3	3	4	4	3	6	2	3	2	3		4.7
Yb	2	2	2	3	2	2	2	1	2	1	5	1	2	1	1	1	1		2.8
Ta	0	33	0	6	6	7	7	0	0	0	0	7	0						7
Pb	5	5	0	0	0	3	0	0	6	0	0	0	0	22	11	12	68		
Th	13	92	7	44	59	10	13	17	9	20	16	20	9	12	16	9	13	1-39	22
U	0	18	0	0	0	0	0	0	0	0	0	0	0					7-15	8
mg-no.	0.65	0.76	0.72	0.75	0.65	0.61	0.71	0.70	0.78	0.78	0.74	0.68	0.72	0.84	0.88	0.75	0.66		0.78

Fe_2O_3* = total iron as Fe_2O_3, LOI = loss on ignition, mg-no = MgO/(MgO+Fe_2O_3) (mol %).
KRVA, Kaulusrova; KRVE, Eastern Kaulusrova; LOITS, Loitsonlampi; MSKS, Maskkaselka; META, Metamorphic area.
The data for comparison are the ranges of aillikites (Malpas *et al.*, 1986), average ultramafic lamprophyres (Rock, 1991) and Terskii Coast kimberlites and melilitites (Beard *et al.*, 1998).

Table 2. Whole rock trace and rare earth element compositions of the Sokli ultramafic lamprophyres analyzed by ICPMS.

	Sokli Aillikites				Terskii Coast Rocks			
Sample	393R156	393R198	419R87	434R185	Kimberlites	Melilitites		
Site	LOITS	LOITS	META	KRVE				
Ba	524	1118	1124	920	6826	1571	473	405
Co	70	47	65	83				
Cr	707	289	312	959	1518	1316	520	300
Cs	1	1	0	0				
Cu	88	188	185	198	18	28	196	251
Ga	12	19	15	15				
Hf	14	31	15	12				
Nb	363	376	187	161	136	237	76	124
Ni	638	226	302	493	802	1180	592	272
Pb	2	2	6	5	21.8	10.7	12.1	67.6
Rb	63	90	50	83	119	94.8	18.9	37.2
Sn	4	5	4	5				
Sr	1539	1591	1957	855	2446	859	1480	1767
Ta	19	14	13	12				
Th	34	58	16	18	12	16.3	8.6	13.4
U	8	3	5	4				
V	139	201	212	262	116	38	170	158
W	0	0	1	0				
Y	40	37	37	28	13.8	16.4	14	16.7
Zn	203	186	145	132	65	48	99	128
Zr	675	1218	608	442	216	123	132	131
La	164	155	171	188	119.79	201.29	66.93	107.12
Ce	377	376	344	373	202.74	246.19	139.02	223.18
Pr	48.2	48.8	38.6	42.2				
Nd	190	201	150	160	56.7	89.1	42.9	69.4
Sm	30	33.5	22.5	23.3	7.51	10.96	5.88	9.59
Eu	8.47	9.26	6.56	6.47	2.05	2.91	1.66	2.56
Gd	21.6	21.6	17.7	15.9	5.33	6.77	4.33	6.58
Tb	2.72	2.8	2.05	1.84				
Dy	12.4	12.9	9.63	8.68	2.91	3.49	2.72	3.64
Ho	1.83	1.77	1.41	1.19				
Er	4.03	4.06	3.36	2.56	1.07	1.15	1.16	1.28
Tm	0.423	0.391	0.421	0.284				
Yb	2.17	1.86	2.44	1.34	0.89	1.04	1.05	1.04
Lu	0.247	0.24	0.328	0.21	0.14	0.16	0.16	0.15

KRVE, Eastern Kaulusrova; LOITS, Loitsonlampi; META, Metamorphic area.
The data of Terskii Coast kimberlites and melilitites are from Beard *et al.* (1998).

V, Cr, Co, Ni, Cu, Zn, Sr, Ba, Nb, Y and REEs. A sequential spectrometer with higher optical resolution (Jobin Yvon JY138 Ultrace) was used to analyze Ta, U and Th and to check Nb, Y and several REEs on different peaks.

For major elements, the results of XRF and ICP-AES were checked for consistency and then combined together. ICP-AES results are used for elements of lower concentrations and XRF for those of greater abundances, using the following cut-off values: $TiO_2 = 0.3\%$; MnO =

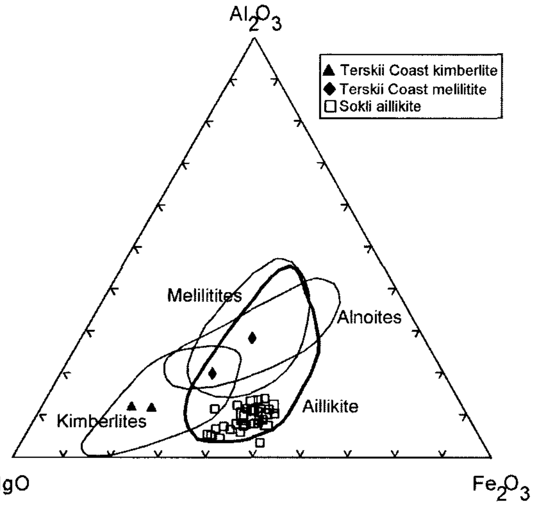

Fig. 4. Whole rock compositional fields for ultramafic lamprophyres, kimberlites and melilitic rocks (after Rock, 1987). Terskii Coast kimberlites and melilitites are plotted together for comparison (Beard *et al.*, 1998).

2%; MgO = 2%; K_2O = 0.3%; Nb_2O_5 = 0.4% and SrO = 0.6%. For Si, Al, Fe, Ca and P, the selected value is given by XRF while for Na, the ICP-AES value is retained in all cases. Among trace elements, Ni, Zn, Sr, Ba, La, Ce, Ta, Y, Th, U and Nb were determined by both methods; the ICP-AES results were used for Sc, V, Cr, Co, Ni, Cu, Zn, Sr, Ba, La, Ce, Eu and Yb, whereas the XRF results using pressed pellets were used for Zr, Rb, Ga, Sn, Pb, Th, U and Ta.

For the four representative samples, a more complete series of elements, including complete rare earth elements spectra, was obtained by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the SARM (Service d'Analyses des Roches et des Mineraux) of CRPG (Centre de Recherches Petrographiques et Geochimiques), Nancy.

Geochemical Results

A large number of samples have been analyzed in order to explain high variability observed in texture and modal composition. Representative chemical compositions of the Sokli aillikites are given in Table 1. The results of trace elements by ICP-MS analysis are given in Table 2.

The major element compositions of the Sokli UMLs are highly dispersive, indicating geochemical heterogeneity. The ranges of major oxide concentrations are lager than those of the type-locality aillikite from Aillik Bay, Labrador (Table 1). The Sokli UMLs have either olivine or phlogopite as dominant phenocrysts. They contain no Ca-bearing silicate phase or Ca-bearing oxide, except some rare perovskite. Calcium is essentially contained in calcite as confirmed by the strong correlation between Ca content and amount of loss on ignition values. Calcite is commonly present in the groundmass, but several samples present peculiar textures, commonly described in aillikites (Rock, 1991), where carbonate, in the form of calcite + apatite ocelli, is clearly segregated from the matrix of olivine + phlogopite + magnetite. Such textural features are in favor of a primary origin of carbonate enrichment of the lamprophyres.

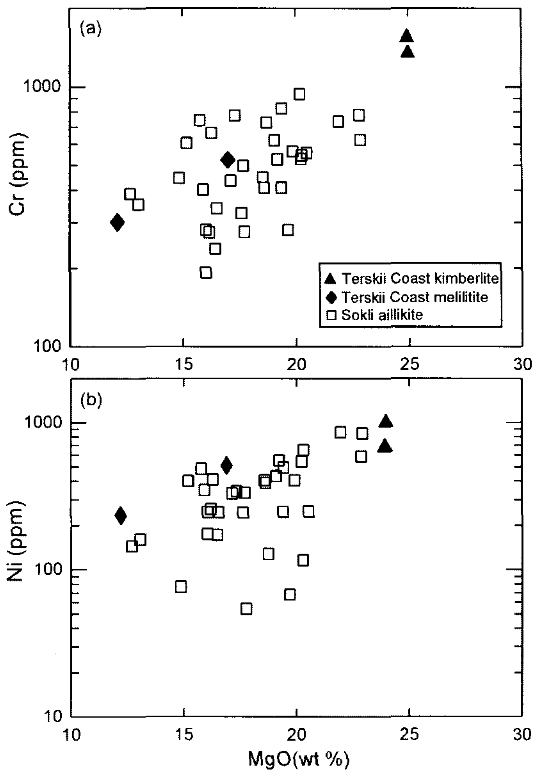

Fig. 5. (a) Cr vs. MgO and (b) Ni vs. MgO relatios for the Sokli aillikites, Terskii Coast kimberlites and melilitites.

The Sokil UMLs are all strongly silica undersaturated (18-34 wt% SiO_2) with high MgO (12.7-30.9 wt%), low Al_2O_3 (1.3-6.0 wt%) and highly variable TiO_2 (1.4-4.9 wt%) contents. They are also strongly potassic with high K_2O/Na_2O ratios. Figure 4 shows that the Sokli UMLs all

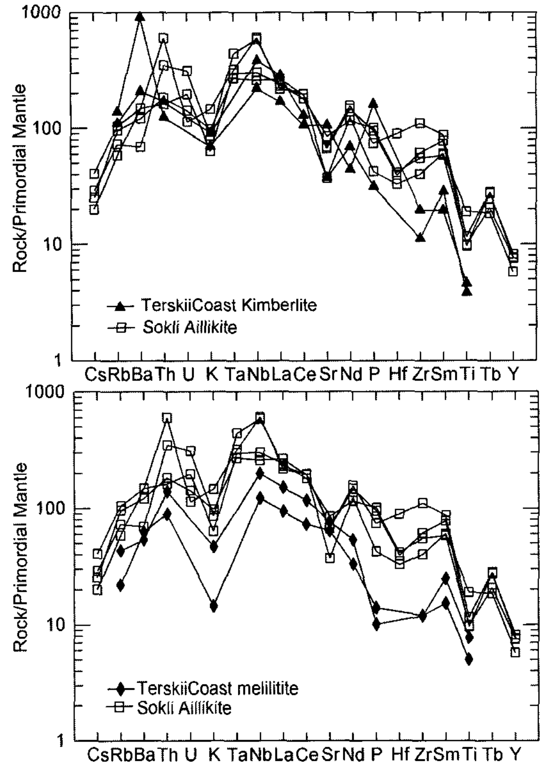

Fig. 6. Comparisons of trace element abundances (a) between the Sokli aillikites and Terskii Coast kimberlites and (b) between the Sokli aillikites and Terskii Coast melilitites. The normalization values for primordial mantle are from Wood *et al.* (1979). The whole rock data of Terskii coast kimberlites and melilitites are from Beard *et al.* (1998).

plot in the aillikite field. They generally have a lower range of Mg-number (0.62-0.83) than that of the Kola Terskii Coast kimberlites (0.80-0.88), and similar or slightly higher than that of the Terskii Coast melilitites (0.63-0.75). High losses on ignition (5-18%) indicate high volatile contents. Variable contents in K_2O (1.5-6.2 wt%) and Fe_2O_3 (11.1-35.9 wt%) are another important factor of variability, but extremely high K (>5 wt%) and Fe (>25 wt%) contents, which are anomalous for common ultramafic lamprophyres, are not a general feature; they are specific in dikes located near late phoscorites, and are considered as a secondary enrichment in tetraferriphlogopite or magnetite.

Besides these variations, the remarkable heterogeneity of bulk rock compositions reflects mainly, on one hand, variable degrees of enrichment in phenocrysts and xenocrysts, on the other hand, variable carbonate contents, rather than a diversity of parental magma compositions.

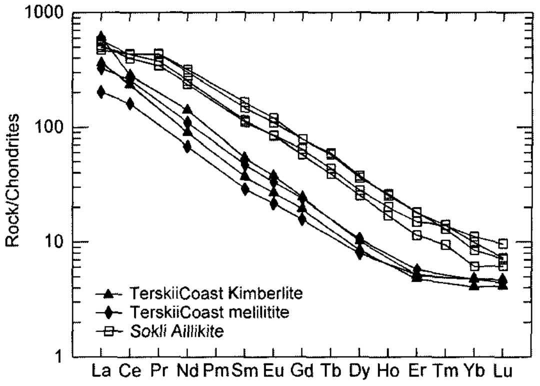

Fig. 7. Chondrite-normalized REE abundances of the Sokli aillikites, Terskii Coast kimberlites and melilitites (Beard *et al.*, 1998). Chondrite normalization values from Nakamura (1974).

Concentrations of Cr and Ni from the Sokli aillikites are slightly lower than those from the Kola Terskii Coast kimberlites and similar to those from the Terskii Coast melilitites (Fig. 5). These high Cr and Ni concentrations indicate that the aillikites are basically mantle-derived rocks. Plots of Cr or Ni against MgO give roughly linear trends that are better explained by mixing, rather than by crystal fractionation. The presences of abundant olivine macrocrysts and Cr-rich magnetites, presumably derived from disaggregated mantle xenoliths, and of Cr-bearing phlogopite macrocrysts with complex zoning suggest that elevated Cr and Ni contents are mostly due to a variable charge in mantle-derived xenocrysts.

The trace and REE compositions of the Sokli aillikites are compared with those of the Terskii Coast kimberlites and melilitites (Figs. 6 and 7). The incompatible trace element abundances show a significant enrichment in most elements, particularly Nb and LREEs, and pronounced troughs at K, Sr and Ti. When compared to the trace element abundances in the Terskii Coast kimberlites and melilitites, the patterns are very similar, but the Sokli aillikites show slightly higher degree of enrichment in all incompatible elements.

The Sokli aillikites have higher overall REE abundances than those of the Terskii Coast kimberlites and melilitites, but their degrees of LREE enrichment (La/Yb = 70-140) are lower than those of the Terskii Coast kimberlites (La/

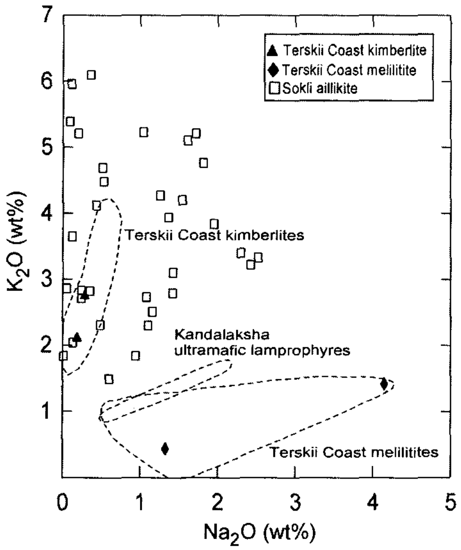

Fig. 8. K_2O vs. Na_2O variation diagram. Shown for comparison are: Kandalaksha ultramafic lamprophyres (Beard *et al.*, 1996), Terskii Coast kimberlites and melilitites (Beard *et al.*, 1998).

Yb = 135-194) and overlap to some degree with those of the Terskii Coast melilitites (La/Yb = 63-104).

Discussion

Characteristics of the mantle source

Aillikite is a porphyritic ultramafic rock rich in olivine and mica with a groundmass dominated by carbonates. The Sokli aillikites have wide compositional ranges of many elements (i.e., Cr, Ni, Mg, Ca and Fe), significantly low SiO_2 and Na_2O contents, and high K_2O and volatile contents. As a consequence of high K_2O coupled with low Al_2O_3 and Na_2O contents, the majority of the rocks are peralkaline [molar $(K_2O + Na_2O)/Al_2O_3 > 1$], ultrapotassic [molar $(K_2O/Na_2O) > 3$] and perpotassic [molar $(K_2O/Al_2O_3) > 1$].

Figure 8 discriminates between the Terskii Coast kimberlites and melilitites, clearly demonstrating the strongly potassic nature of the kimberlites and sodic nature of the melilitites. The Sokli aillikites plot close to the kimberlite field or more enriched K_2O field and have considerably high K_2O content compared to those of nearby Kandalaksha UMLs. Beard *et al.* (1998) explained that the strongly potassic nature of the kimberlites may be due to the presence of phlogopite or K-Ba phosphate in the kimberlite source. The Sokli aillikites, besides of anomalous K enrichment, are significantly enriched in Ti compared to average world-wide UMLs and aillikites from Aillik Bay, Labrador (Table 1). This can be interpreted as either that the source was significantly enriched in these elements or that phases hosting these elements in the mantle source melted completely. However, the complete melting of mineral phases hosting K and Ti is not realistic, as the UMLs are considered to be a product of small degree partial melts, so K- and Ti-rich phases are more likely to remain as residuals in the source. A possible source that contributes K and Ti enrichments to the aillikites could be metasomatic veins composed of K-richterite and phlogopite, existing as a stockwork within a depleted harzburgitic mantle (Foley, 1992; Beard *et al.*, 1998). However, extremely undersaturated character of the Sokli aillikites is not well explained by the incorporation of K-richterite which can make a more silica-rich melt than phlogopite. Moreover, the dominant xenolith phases in the Kola kimberlites or ultramafic rocks are phlogopite-bearing lherzolite and wehrlite (Sablukov, 1995; Beard *et al.*, 2000). Therefore, the role of K-richterite for the K-enrichment of the Sokli aillikites is not clear, although K-richterite together with phlogopite occurs as a typical component of the world-wide metasomatized peridotite and MARID-suite xenoliths.

Petrogenesis of the Sokli aillikites

Any hypotheses responsible for the genesis of the Sokli aillikites have to explain the following observations:

1. The Sokli aillikites are not in textural or chemical equilibrium, and their bulk-rock compositions may represent an amalgamation of materials from several sources.
2. They have very high contents of losses on ignition, probably due to large amounts of CO_2 that cause abundant carbonate crystallization in the groundmass.
3. The chondrite normalized REE patterns and the specific geochemical characteristics, such as strong enrichment in REE, Nb and other incompatible elements, are similar to those of the Kola Terskii Coast kimberlites and melilitites. However, the overall REE abundances and incompatible trace element contents are higher than those of the Kola Terskii Coast kimberlite, but mg-numbers and

a degree of HREE depletion are lower.

4. Aillikites exhibit significant negative K, Sr and Ti anomalies in the primitive mantle-normalized trace element diagram, even though their considerably high contents of these elements.

As noted in petrological features, the highly hybrid Sokli aillikites are not likely to represent the direct crystallization product from a mantle-derived primary magma. The complex zoning and inter-crystal compositional variation found in macrocrystal and phenocrystal mica populations demonstrate that most of these micas have not crystallized in situ. One possible interpretation of these observations is that the micas represent the products of crystallization of several batches of aillikite magma of broadly similar composition. Support for this process is found in the composite occurrence of the Sokli aillikite dikes, each phase being composed of modally different assemblages of similar macrocrysts and phenocrysts. Additionally, the Sokli aillikite magma is considered to have been extremely contaminated by mantle-derived xenocrysts. The olivine crystal containing chromian spinel inclusion and lots of Fe-Ti oxides having high Cr content might be derived from the depleted harzburgitic host.

The geochemical characteristics of the Sokli aillikites suggest that the aillikite magma should be derived from a source which contains CO_2 and H_2O with minerals extracting alkali, alkaline earth, rare earth elements and transition elements. The lower mg-number, Cr and Ni contents, and weaker HREE depletion indicate a lower proportion of garnet in the source and thus imply a shallower melting depth of the Sokli aillikite source, compared to that of the kimberlites. Additionally, the low Al_2O_3 content suggests a strongly depleted harzburgitic source. However, the high concentrations of incompatible elements and CO_2 imply an additional incorporation to the source. The preexisting carbonated metasomatic vein is likely to be most probable as an additional enriched source. Generation of carbonatite melts in mantle at pressure ≥ 2 Gpa and their importance as efficient metasomatic agents acting on the mantle lithosphere have been demonstrated by Green and Wallace (1988) and supported by further experimental work (Lee and Wyllie, 1998). These metasomatism and melt infiltration in the lithospheric mantle by carbonatite melt now are considered to produce a wide variety of veins with or without metasomatic aureoles (Erlank *et al.*, 1987; Menzies *et al.*, 1987; Foley, 1992; Mitchell, 1995). The veins are believed to be formed as a stockwork within the depleted harzburgitic or peridotitic mantle (Menzies *et al.*, 1987; Hogarth, 1989; Foley, 1992) and are considered to play an important role in the formation of the enriched sources for the various potassic rocks (e.g., McCulloch *et al.*, 1983; Mitchell *et al.*, 1987; Mitchell, 1994). The higher abundances of ΣREEs and most incompatible elements compared to those of Terskii Coast kimberlites may be interpreted as a result of either that the Sokli aillikite magma was derived from a lower degree of partial melts than partial melt of kimberlites or that there were differences of degree of enrichment in their mantle source, probably due to the differences of the major minerals, contained in the metasomatic veins.

Primitive mantle-normalized trace element abundances for the aillikites (Fig. 6) indicate a strong enrichment in highly incompatible elements, with some troughs at K, Sr and Ti. The K and Ti depletions may be related to a residual phlogopite phase in the source mantle during partial melting or the result of the aillikite magma ascending through and reacting with the lithospheric mantle and recrystallising phlogopite (Beard *et al.*, 2000). Alternatively, the Ti and Sr depletions which are not common in the other UMLs (Rock, 1991) may be attributed entirely to late stage fractional crystallization, including removal of sphene, apatite, perovskite and ilmenite.

Conclusions

On the basis of the petrography and whole rock geochemistry presented for the Sokli ultramafic lamprophyres, the following conclusions can be drawn.

(1) The Sokli UMLs have various modal proportions of Mg-Olivine and Ti-phlogopite phenocrysts and/or xenocrysts in calcite-rich groundmass, and hence they are not in textural or chemical equilibrium. They have considerably low SiO_2 and Al_2O_3 and high Cr, Ni and MgO contents. These petrographical and geochemical characteristics indicate that they are classified into aillikites.

(2) Considerbly high Cr, Ni and MgO with low Al_2O_3

contents suggest that the Sokli aillikite magma was derived from a depleted harzburgitic source. However, the lower mg-number and weaker HREE depletion, compared to those of Kola Terskii coast kimberlites which are considered to have been derived from asthenospheric harzburgitic mantle, indicate a lower proportion of garnet in the source and thus suggest a shallower melting depth of the Sokli aillikite source. On the other hand, the highly enriched nature in incompatible elements and REEs suggests a possibility of incorporation of an additional enriched metasomatic materials into the source.

(3) The anomalous ultrapotassic character of the Sokli aillikites, compared to those of the Kola Terskill Coast kimberlites and melilitites and world-wide UMLs, implies a presence of K-rich phase in the source.

(4) The K and Ti depletions in the trace element abundance patterns may be related to a residual phlogopite phase in the source mantle during partial melting or the result of the reacting with the lithospheric mantle and recrystallizing phlogopite during ascent of the aillikite magma. The Ti and Sr depletions are considered to be a result of a late stage fractional crystallization, including removal of sphene, apatite, perovskite and ilmenite.

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