Geochemistry, mineralogy and tectonic setting of the Kvaløya lamproite

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Introduction

The Kvaløya lamproite can from its chemical composition and content of rare minerals, such as yangzhumingite, baotite, fluoro-potassic-magnesio-arfvedsonite and oxo-amphibole, be considered to be a unique rock. The geochemistry and mineralogy of the rock have during the last 5 years been documented in a series of articles (Zozulya *et al.* 2010; Kullerud *et al.* 2011, 2012, 2013; Schingaro *et al.* 2014). The highlights from these articles will be presented in this paper.

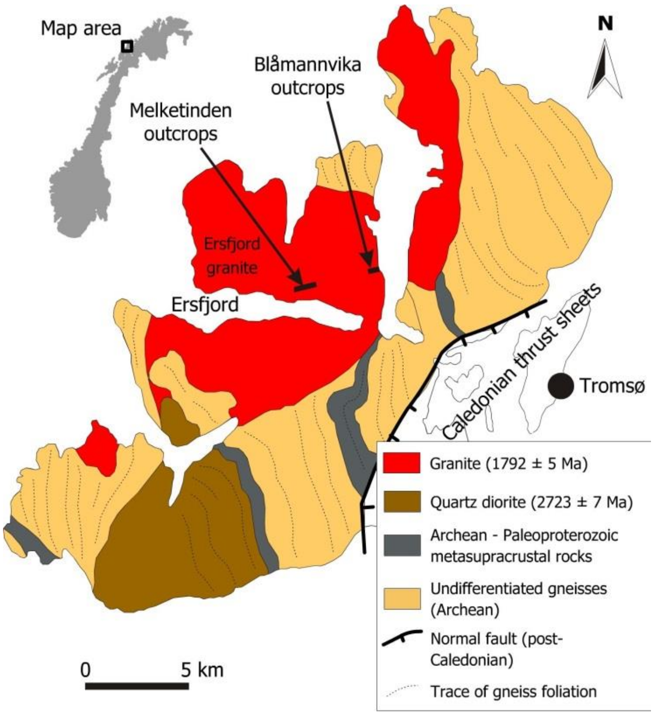

Fig. 1. Geological map of the Kvaløya island showing the occurrences of the Kvaløya lamproite. See inset map for location. Modified from Bergh *et al*. (2010).

Field occurrence of the lamproite

The Kvaløya lamproite outcrops near Melketinden and in Blåmannvika at the island Kvaløya, west of Tromsø, North Norway (Fig. 1). The lamproite, which is inferred to be of Carboniferous age, occurs as a <30 cm wide (Fig. 2a) steeply dipping dyke having a uniform ENE-WSW strike, in the 1792±5 Ma Ersfjord granite (Zozulya *et al.* 2010; Kullerud *et al.* 2011). Field observations suggest that the lamproite intruded during brittle deformation of the host granite. The dyke commonly shows 0.5 - 1 cm thick chilled margins (Fig. 2a, b). Along the contact to the lamproite, the host granite commonly shows a dark, several cm thick zone of alteration (Fig. 2b). Furthermore, the dyke rock commonly shows a heterogeneous colouring, with pale orange spots and bands in an elsewhere grey rock. These observations suggest that the fluids derived from the lamproite magma caused fenitization of the granite and autometasomatism of the dyke rock (Kullerud *et al.* 2011).

Fig. 2. a) Contact relationships between the approximately 25 cm thick lamproite dyke (grey) and granite from the Melketinden outcrops. The lamproite shows a thin chilled margin. **b)** Scanned thin-section showing contact between lamproite and granite. Note the colourless phenocrysts of K-feldspar (Kfs) and apatite (Ap), and the light brown phlogopite phenocrysts (Phl). Grey spots represent aggregates of amphibole (Amph).

Mineral contents of the lamproite

The lamproite is characterized by phenocrysts of light brown phlogopite, occasionally with a dark brown rim, together with apatite in a fine-grained matrix of K-feldspar, quartz and alkali amphibole (Fig. 2b, 3, 6). Occasionally, euhedral phenocrysts of K-feldspar containing inclusions of phlogopite and apatite are observed. Accessory minerals include rutile, barite, zircon, monazite, baotite, yangzhumingite and Ti-aegirine (Figs. 4, 5). Furthermore, an unknown Na-Mg-Ba phosphate and an unknown hydrophosphate have been observed.

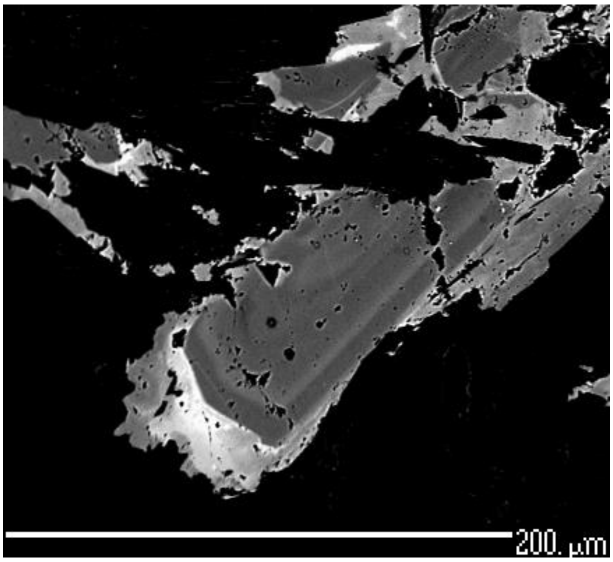

Fig. 3. Backscattered electron image of apatite (various shades of grey) in a matrix of K-feldspar and quartz (black). Note the oscillatory zoned euhedral core of the large apatite grain in the centre, and the anhedral, bright rim.

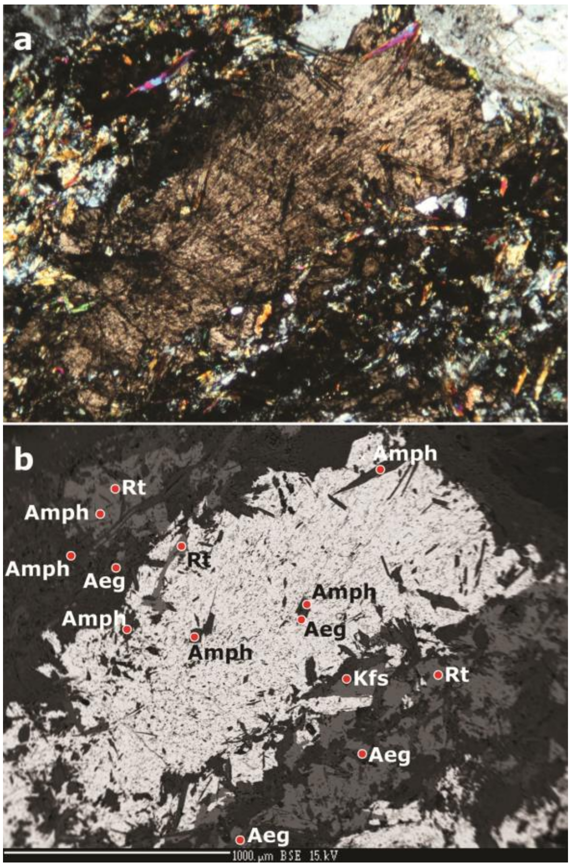

Fig. 4. Photomicrograph with crossed polarizers (a) and back scattered electron image (b) of the same area showing baotite (bright grains in b) and associated mineral phases. Mineral abbreviations: Amph = amphibole, Aeg = aegirine, Kfs = K-feldspar, Rt = rutile. Note that in the optical microscope, baotite resembles titanite.

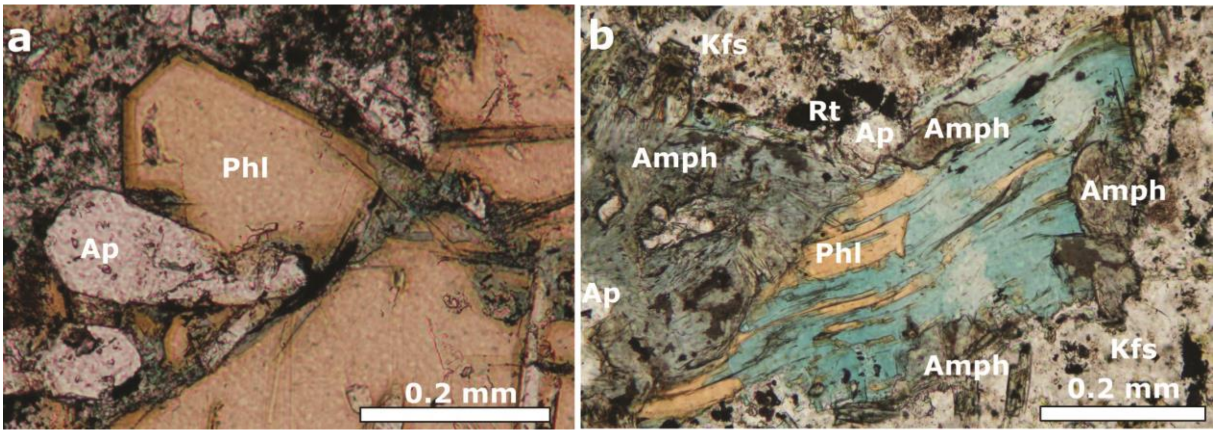

Fig. 5. Photomicrographs of micas from the lamproite in parallel light. **a)** In the central part of the image: euhedral light brown phenocryst of phlogopite with a thin rim of dark brown phlogopite, in contact with a euhedral crystal of apatite. **b)** Yangzhumingite (bright green mineral) overgrowing light brown phlogopite. Mineral abbreviations as in Fig. 4.

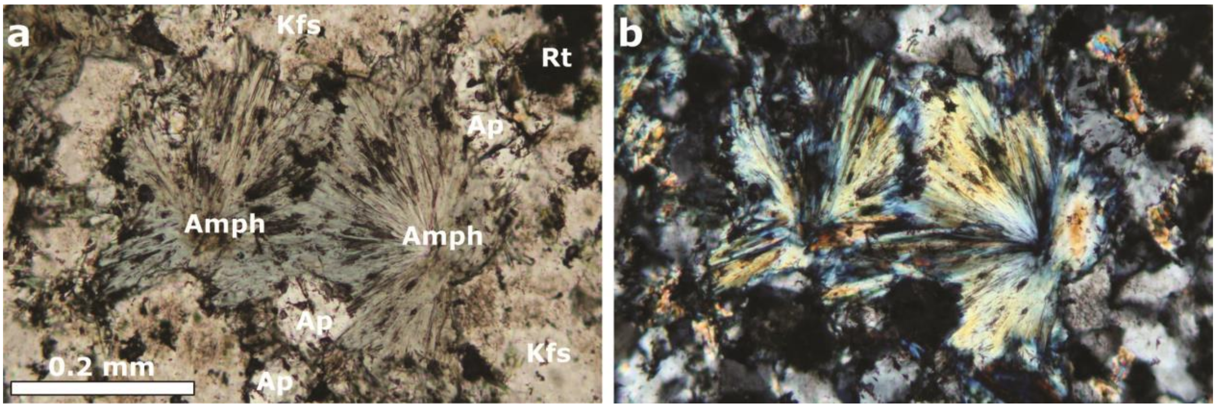

Fig. 6. Photomicrographs in parallel light **(a)** and with crossed polarizers **(b)** of rosettes of amphibole in a matrix of K-feldspar together with apatite and rutile. Mineral abbreviations as in Fig. 4.

Mineral compositions

Mineral analyses were performed at the Geological Survey of Slovakia with a Cameca SX100 electron microprobe, and on a similar instrument at the Department of Geosciences at the University of Oslo (see Kullerud *et al.* 2012, 2013, 2014 for details of the analytical procedures). Chemical compositions of biotite, micas (phlogopite and yangzhumingite) and amphibole are given in Table 1.

Apatite

Apatite contains up to 4.5 wt % F, but only traces of Cl, and classifies as fluorapatite. Fluorapatite commonly shows oscillatory zoned euhedral cores with bands of dark and intermediate shades of grey on back scattered electron images (Fig. 3). The euhedral cores are commonly overgrown by anhedral fluorapatite, which shows bright shades of grey in back scattered electron images. The brightness of fluorapatite in back scattered electron images is primarily controlled by the REE contents. The darkest domains of fluorapatite cores contain only traces of REE, while the brightest rims contain more than 7 wt% of $(La, Ce, Pr, Nd)_2O_3$.

Baotite

Baotite is a rare Ti-Ba-Nb-Cl silicate mineral in which Cl is incorporated in large cavities between pairs of Si_4O_{12} rings in the structure (Nekrasov *et al.* 1969). The major compositional variations of baotite occur between a Nb-free end member $Ba_4Ti_8Si_4O_{28}Cl$ and a Nb-rich end member $Ba_4Ti_2Fe^{2+}{}_2Nb_4Si_4O_{28}Cl$. Most of the analyses of baotite from the Kvaløya lamproite show compositions close to the Nb-free endmember. However, a few grains of Pb-bearing baotite with approximately 3 Ba per formula, and significant concentrations of Pb, Ca, Sr and K were identified. Baotite was for the first time described from Bayan Obo, Inner Mongolia, China, and it has later been described from about 15 other localities (see references in Kullerud *et al.* 2012).

Phlogopite

Two different types of phlogopite occur in the rock. The most common type is represented by light brown phlogopite phenocrysts that crystallized from the magma (Schingaro *et al.* 2014). These phenocrysts occasionally show 15 µm thick overgrowths of dark brown phlogopite (Fig. 5a). Both types of phlogopite show high TiO_2-content (2-4 wt%). The light variety shows high MgO (23.2-25.4 wt%) and low FeO (2.5-5.3 wt%), while the dark variety shows lower MgO (19-21 wt%) and higher FeO (3.3-11.2 wt%).

Yangzhumingite

Yangzhumingite was for the first time described from Bayan Obo in Inner Mongolia, China by Miyawaki *et al.* (2011). The occurrence of yangzhumingite in the Kvaløya lamproite, which is described in detail in Schingaro *et al.* (2014), is the second, and so far the only other occurrence of the mineral. Yangzhumingite belongs to the rare group of tetrasilicic micas, i.e. micas with the tetrahedral sites fully occupied by Si. The ideal formula of the mineral is $KMg_{2.5}Si_4O_{10}F_2$. The yangzhumingite reported by Miyawaki *et al.* (2011) is colourless and shows a composition close to the ideal formula. Yangzumingite from the Kvaløya lamproite shows a bright green colour, which can be related to its high Fe-content, and low Ti-content.

Potassic alkali amphibole

Potassic alkali amphibole of rare compositions occurs as a rock-forming mineral in the Kvaløya. Amphibole typically occurs as small grains forming irregular and rosette-shaped aggregates in a matrix together with K-feldspar and quartz (Fig. 6). Amphibole grains are chemically zoned, showing gradual chemical changes from core to rim. Kullerud *et al.* (2013) formulated three limiting compositions for the chemical variations of amphibole (Amph A, Amph B, and Amph C in Table 1). Amph A and Amph B represent core compositions, while Amph C represents rim compositions. Amph A is a Fe^{2+}, Fe^{3+} and ^{C}Na rich variety of potassic-obertiite (an oxo-amphibole), while Amph B is characterized by an exceptional high value of vacancies on the C-sites. Such high values of ^{c}Na and C-site vacancies, as reported for Amph A and Amph B, respectively, have not been described from any other occurrences. The real existence of such rare amphibole compositions needs to be documented by other methods. Amph C shows significant content of fluoro-potassic-magnesio-arfvedsonite. Fluoro-potassic-magnesio-arfvedsonite is a rare mineral that was identified for the first time by Hogarth & Lapointe (1984) from fenitized metasediments in Cantley, Quebec, Canada. The second occurrence of the mineral was reported from a lamproite in Mozambique by Robinson *et al.* (2008).

Table 1. Electron microprobe analyses of selected minerals from the Kvaløya lamproite.

	^{1}Yzm	^{1}Phl LB	^{1}Phl DB	^{2}Amph A	^{2}Amph B	^{2}Amph C	^{3}Baotite
SiO_2	52.40	42.16	42.10	52.36	53.16	55.92	15.70
TiO_2	0.32	2.30	2.33	4.06	2.19	0.32	41.91
Al_2O_3	3.93	10.50	9.36	0.03	0	0.03	0.32
Cr_2O_3	0.15	0.21	0.05	0.03	0.02	0.13	
FeO	3.52	3.29	8.22	19.56	21.68	11.01	< d.l.
MnO	0.06	0.02	0.10	0.26	1.75	0.18	
MgO	22.60	24.60	21.07	6.94	4.64	16.59	< d.l.
CaO	0.01	0.01	0.05	0.01	0.06	0.02	0.06
SrO	0.06	0.04	0.04	0.04	0.08	0.05	0.17
BaO	0.01	0.16	0.14	0	0	0	39.20
Na_2O	0.23	0.08	0.16	7.6	6.99	7.71	
K_2O	11.00	10.76	10.53	5.18	5.2	4.92	0.16
NiO	0.10	0.26	0.12	0.02	0	0.06	
Nb_2O_5							0.35
*Li_2O	0.005	0.006					
Cl	0.01	0.01	0.01	0.01	0.03	0.01	2.43
F	6.07	4.55	4.41	2.02	1.44	2.97	

Notes: Chemical compositions given in wt%; *Li_2O from ICP analysis; < d.l. = below detection limit. ^{1}from Schingaro *et al.* (2014); ^{2}from Kullerud *et al.* (2013); ^{3}from Kullerud *et al.* (2012).

Whole rock chemistry and classification of the dyke rock

Fourteen whole-rock samples were analyzed for major and trace elements, and REE; analyses of two samples are given in Table 2. On basis of its mineralogy, whole rock chemistry (e.g., SiO_2=54.4–57.3 wt%, K/Na=2.02–7.03, K/Al=0.86–1.22, Mg#=76–84 and K_{agp}=1.0–1.7), and specific mineral compositions (e.g. tetrahedral coordination of Fe^{3+} in phlogopite, high Fe, but negligible Na in K-feldspar, and high Ti in amphibole and phlogopite) the rock can be classified as a high-Si phlogopite lamproite (Kullerud *et al.* 2011). Concentrations and element ratios of a number of trace elements (e.g. high LILE and HFSE, except from Nb and Ta, high La/Yb_n and low Th/Nb) in addition to isotope data (moderately radiogenic $^{87}Sr/^{86}Sr$ and extremely non-radiogenic $^{143}Nd/^{144}Nd$; εNd(T) varies from −19.9

to −22.4) indicate an anorogenic, i. e., within-plate setting for the Kvaløya lamproite (Kullerud *et al.* 2011).

Formation, transport and crystallization of the lamproite magma

Kullerud *et al.* (2011) suggested that the mantle source of the Kvaløya lamproite underwent several stages of enrichment before formation of the lamproite magma, and that the lamproite was emplaced in a within-plate or anorogenic setting. The lamproite intruded the host granite during Carboniferous time, while the whole region was exposed to extensional forces. From the data presented in Zozulya *et al.* (2010), Kullerud *et al.* (2011, 2012, 2013) and Schingaro *et al.* (2014) it can be inferred that the hot lamproite magma ascended rapidly from its mantle source to higher crustal levels before crystallization started. Phenocrysts of light brown phlogopite, euhedral fluorapatite and K-feldspar crystallized shortly before emplacement of the magma to the present position, at relatively high temperatures. The subsequent crystallization of matrix K-feldspar, quartz and amphibole occurred at constant pressure, but during rapid cooling and changes in fluid chemistry. Subsequent to crystallization of the lamproite, a highly reactive fluid derived from the volatile-rich lamproite magma resulted in fenitization of the surrounding granite, and autometasomatism of the lamproite, i.e. extensive reactions between the already formed magmatic minerals and the fluid phase (Kullerud *et al.* 2011, 2012, 2013; Schingaro *et al.* 2014). The presence of alkali amphibole, Ti-aegirine and baotite both within the lamproite dyke and within the fenitized granite, suggests that these minerals formed during reactions with the fluid phase. Also yangzhumingite, the unknown phosphate and hydrophosphate, and the anhedral overgrowth of REE-rich apatite on euhedral apatite phenocrysts (Fig. 3) might be related to reactions with the late magmatic fluid. The dark brown phlogopite rims formed either late during crystallization of the magma, or during reactions with the late magmatic fluid.

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