ALKALINE LAMPROPHYRES FROM THE SOKLI COMPLEX, NORTHERN FINLAND

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Alkaline lamprophyric dykes in the Sokli carbonatite complex closely resemble kimberlites in mineralogical and chemical composition. Mineralogically, they differ from kimberlites by the presence of high-manganese ilmenite and richterite, and the absence of high-pressure minerals and cognate inclusions. They most likely represent altered kimberlites with a high degree of crustal contamination and carbonatite admixture.

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Introduction

The geology of the Sokli carbonatite complex in northern Finland has been briefly discussed by Paarma (1970), and Vartiainen and Woolley (1974). Lamprophyric dykes occur both within the complex and in the wall-rock. Diamond drill cores are the main source of observations owing to the absence of outcrops.

The width of the dykes varies from a few millimetres to some metres. The average thickness of 246 dykes studied is 52 centimetres. The length of the dykes could not be estimated. In drill sections from the carbonatite body, lamprophyric dykes constitute between 0.6 and 8.7 % by volume; corresponding figures for the wall-rock are 1.1. to 5.8 % (Fig. 1). They commonly form dyke swarms (Fig. 2A), with dips ranging from near horizontal to almost vertical. All observations indicate a random pattern of intrusions, rather than a regular one as proposed by von Eckermann (1948, 1958) for the Alnö dykes.

Dyke emplacement is obviously one of the latest events at Sokli. Within the carbonatite, dykes are assimilated and brecciated by late sövite; all dykes show veinlets of calcite and dolomite.

Petrography

The Sokli dykes are divided into four petrographic groups (Table 1) with different
Table 1. Characteristics of Sokli dykes.

| Type          | Colour                          | Flow textures | Chilled margins |
|---------------|---------------------------------|---------------|-----------------|
| Porphyritic   | green, grayish and dark green    | common        | common          |
| Xenolithic    | gray, grayish green             | common        | common          |
| Massive       | green, grayish green            | rare          | rare            |
| Micaceous     | green, reddish brown            | rare          | rare            |

Fig. 1. Geological sketch map of the Sokli complex, showing the relative distribution of dyke rocks.

Colour and texture vary considerably within one dyke, giving the rock a very heterogeneous appearance (Fig. 2C). Dyke swarms are usually made up of dykes of the same petrographic group. The mineralogical characteristics of the various groups are given in Table 2.
Fig. 2. A. Micaceous dyke swarm cutting sövite. DH 368/259.5. B. Xenolithic dyke with phoscorite and olivinite fragments, surrounded by calcite reaction rims. DH 366/59.5. C. Semi-banded structure in composite dyke. DH 366/89.0.

Table 2. Mineralogical compositions of Sokli dykes (in vol.-%).

| Sample | —0001 | —0003 | —0004 | —0005 | —0007 | —0002 | Rm 852 |
|--------|-------|-------|-------|-------|-------|-------|--------|
| Phenocrysts                                   |       |       |       |       |       |       |        |
| Olivine, fresh                                | 26.0  |       |       |       |       |       | 4.5    |
| Olivine, altered:                            |       |       |       |       |       |       |        |
| serpentine                                   | 3.0   | 3.5   | 8.5   | 13.5  | 7.5   | 6.0   | 2.5    |
| bowlingite                                   | 0.5   |       | 8.5   | 6.0   |       |       |        |
| iddingsite                                   |       |       | 11.0  |       | 2.5   |       |        |
| carbonate                                    | 0.5   | 19.0  | 0.5   | 2.0   |       |       |        |
| phlogopite                                    | 0.5   | 2.5   | 0.5   | 0.5   |       |       |        |
| clinohumite                                  | 3.0   |       |       |       |       |       |        |
| opaques                                      | 0.5   | 1.0   | 0.5   |       | 0.5   |       |        |
| Phlogopite                                   | 0.5   | 13.0  | 2.0   | 3.5   |       |       |        |
| Richterite                                    | 1.5   |       | 1.0   |       |       |       |        |
| Calcite                                      |       |       | 2.0   |       |       |       |        |
| Opaques                                      |       |       |       | 4.5   | 9.5   |       |        |
| Xenoliths                                    |       |       |       |       |       | 23.0  |        |
| Matrix                                        |       |       |       |       |       |       |        |
| Phlogopite                                    | 16.0  | 21.0  | 13.0  | 22.0  | 15.0  | 27.0  | 68.2   |
| Calcite                                       | 20.0  | 21.0  | 24.5  | 27.0  | 15.5  | 24.0  | 21.3   |
| Serpentine                                    |       | 2.5   | 3.5   | 6.0   | 6.5   | 3.0   |        |
| iddingsite                                   | 7.5   | 6.0   |       | 6.5   | 3.0   |       |        |
| Richterite                                    | 7.5   |       | 8.5   | 5.5   | 25.0  |       |        |
| Apatite                                       | 4.0   |       |       | 3.0   | 0.5   |       |        |
| Opaques                                       | 9.0   | 13.5  | 23.0  | 9.5   | 11.5  | 10.0  | 10.5   |

Samples: —0001 porphyritic                     Samples: —0007 xenolithic
—0003 »                                       —0002 massive
—0004 »                                       Rm 852 micaceous
—0005 »
Fig. 3. A. Porphyritic dyke with fresh olivine phenocrysts, rimmed and fracture-filled by magnetite. DH 2/192.2.

Fig. 3. B. Porphyritic dyke, with olivine phenocrysts completely altered into serpentine, bowlingite and carbonate. DH 343/207.5 (Nr —0003).
Table 3. Microprobe analyses.

| No. | 1      | 2      | 3      | 4      | 5      | 6      | 7      |
|-----|--------|--------|--------|--------|--------|--------|--------|
| SiO₂ | 40.9   | 42.1   | 41.5   | 53.3   | —      | —      | —      |
| TiO₂ | 0.05   | 0.05   | 0.06   | 0.63   | 52.0   | 52.7   | 51.3   |
| ZrO₂ | 0.05   | 0.05   | 0.05   | —      | —      | —      | —      |
| Nb₂O₅ | 0.07   | 0.05   | 0.05   | —      | —      | —      | —      |
| Al₂O₃ | 0.05   | 0.05   | 0.05   | 1.65   | 0.06   | 0.08   | 0.08   |
| Cr₂O₃ | 0.05   | 0.05   | 0.05   | —      | 0.02   | 0.01   | 0.07   |
| FeO (tot.) | 8.5 | 8.0   | 5.4   | 2.6   | 38.3   | 35.0   | 40.5   |
| NiO  | 0.38   | 0.46   | 0.05   | —      | —      | —      | —      |
| MnO  | 0.10   | 0.11   | 0.85   | 0.11   | 3.74   | 3.97   | 4.45   |
| MgO  | 49.3   | 48.3   | 53.2   | 22.4   | 5.9    | 7.7    | 5.1    |
| CaO  | 0.19   | 0.13   | 0.13   | 8.4    | —      | —      | —      |
| Na₂O | 0.05   | 0.05   | 0.05   | 5.5    | —      | —      | —      |
| K₂O  | 0.05   | 0.05   | 0.05   | 0.8    | —      | —      | —      |
| Total | 99.74  | 99.45  | 101.48 | 95.39  | 100.42 | 99.46  | 101.50 |

1. Olivine phenocryst, porphyritic dyke (—0001), DH 347/403.0
2. Olivine, olivinite of Tulppio, trench 2 (960—2145)
3. Olivine, phoscorite, DH 260/77.0
4. Richterite phenocryst, porphyritic dyke (—0001), DH 347/403.0
5. Ilmenite, average of 8, porphyritic dyke (—0001), DH 347/403.0
6. Ilmenite, average of 8, porphyritic dyke (Rm 107), DH 2/192.2
7. Ilmenite, average of 8, massive dyke (—0002), DH 343/145.7

Olivine occurs as phenocrystal phase, constituting between 20 and 40 % by volume of the rock (Table 2). The size of the phenocrysts varies from 0.5 to 4 mm. The phenocrysts are usually rounded (Fig. 3), rarely subhedral. Euhedral grains are very exceptional. Secondary alteration into a variety of minerals is common (Table 1, Fig. 3B); fresh olivines occur only in porphyritic and xenolithic dykes (Fig. 3A). Alteration has been most intense in micaceous dykes, which preserve only faint outlines of the original phenocrysts.

The chemical composition of the olivines resembles that of olivine from the Tulppio ultramafic massif close to the complex (Table 3). Both have higher NiO, slightly higher FeO, and lower MnO contents than olivine from phoscorite (Table 3). At present, the number of analyses is still insufficient to allow a more detailed discussion.

Phlogopite occurs as both phenocrystal phase (size 0.5—5 mm), and matrix constituent. Pleochroism is normal (Z = yellowish or greenish brown, Y = X = pale yellow to colourless). Phenocrysts exhibit slight compositional zoning, and are sometimes rimmed by late-stage phlogopite showing reverse pleochroism (X = bright orange, Y = Z = pale yellow to colourless).

Calcite if found as corroded subhedral phenocrysts, or aggregations of two or more grains. This might indicate that calcite is not primary magmatic but a xenolithic constituent derived from sövite.

Richterite occurs as colourless phenocrysts, 0.5 to 1.5 mm long, which are often ragged and replaced by calcite. Chemical analysis (Table 3) yields the following formula: (Na₉₁K₄₄) (Na₆₁Ca₁₈₂Fe₁₆₂) (Mg₄₇₆Mn₉₁Fe₂₁) (Si₇₆₂Al₈₂Ti₇₈) O₂₂(OH)₂, with A = 1.05, X = 2.00, Y = 5.00, Z = 7.97.

X-ray powder diffraction of sample —0002 (Table 2) proved the mineral to be richterite, with the following strongest reflections (Å):

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Magnetite phenocrysts are rounded, and measure up to 15 mm in diameter.

Xenoliths are rounded to subrounded (Fig. 2B), measuring 1 to 5 cm across. Xenolithic dykes within the carbonatite contain fragments of phoscorite, sövite and olivinite; those from the wall-rock mainly sövite and fenite. A more detailed study of the xenoliths is lacking.

The matrix generally constitutes 60 to 75 % by volume of the dykes; for massive and micaceous dykes up to 100 %. Its principal constituents are fairly similar for all petrographic groups (Table 2). The average grain size of matrix minerals is below 0.1 mm.

The sequence of crystallization is opaques — phlogopite and calcite — richterite. Flow textures of the rocks are outlined by preferred orientation of phlogopite and richterite.

Calcite is found in anhedral grains; richterite is commonly euhedral. Opaques occur as small grains: disseminated magnetite may exceptionally comprise more than 50 % of the matrix.

Ilmenite occurs in minor amounts only; it is most common in porphyritic and some micaceous dykes. The chemical composition of ilmenite is characterized by fairly high contents of MnO and moderate contents of MgO (Table 3). Compared with ilmenites from related rocks, the Sokli ilmenites constitute a group of their own (Fig. 4). Ilmenites from kimberlites are characterized by low MnO contents and high MgO contents. The literature gives only two analyses of ilmenites deviating from this pattern: a high MnO — low MgO ilmenite from Monastery Mine (Mitchell et al. 1973), and an ilmenite from Premier Mine (Frick 1970), which is very similar in composition to the Sokli ilmenites (Fig. 4). An ilmenite from alnöite at Alnö (von Eckermann 1974) is very similar to kimberlite ilmenites; ilmenites from damkjernites at Fen (Griffin and Taylor 1975) have very low MgO contents, similar to the Monastery Mine sample (Fig. 4).

Ilmenites from kimberlites, alnöites and related rocks can thus be divided into three groups (Fig. 4):

1) low manganese: most kimberlites, alnöite (Alnö)
2) high manganese, low magnesium: damkjernite (Fen), Monastery Mine
3) high manganese, moderate magnesium: Sokli dykes, Premier Mine

More data are needed for a detailed discussion of the possible petrogenetic implications of this pattern. A more shallow, low-pressure origin of the high-manganese ilmenites seems plausible.

Chemical composition

Six whole-rock analyses of Sokli dykes are given in Table 4. The Sokli dykes show
Table 4. Chemical analyses of Sokli dykes.

| Sample | —0001 | —0003 | —0004 | —0005 | —0007 | —0002 |
|--------|--------|--------|--------|--------|--------|--------|
| SiO₂   | 27.0   | 21.8   | 28.7   | 27.1   | 19.1   | 30.2   |
| TiO₂   | 2.3    | 3.5    | 3.6    | 2.9    | 2.9    | 2.1    |
| Al₂O₃  | 2.0    | 2.4    | 4.1    | 1.9    | 2.2    | 3.9    |
| Fe₂O₃  | 8.2    | 7.0    | 11.8   | 7.4    | 20.5   | 8.2    |
| FeO    | 6.7    | 7.4    | 6.5    | 6.0    | 11.1   | 6.2    |
| MnO    | 0.37   | 0.29   | 0.27   | 0.26   | 0.52   | 0.37   |
| MgO    | 20.7   | 17.6   | 16.6   | 20.3   | 17.0   | 18.4   |
| CaO    | 13.2   | 13.8   | 15.4   | 11.1   | 10.5   | 12.7   |
| Na₂O   | 1.2    | 1.2    | 0.4    | 1.1    | 0.7    | 2.9    |
| K₂O    | 2.2    | 3.6    | 2.5    | 1.5    | 2.3    | 2.0    |
| H₂O+10⁵ | 2.7 | 1.9 | 2.4 | 3.9 | 1.8 | 2.3 |
| H₂O−10⁵ | 0.5 | 0.5 | 0.7 | 1.2 | 0.4 | 0.3 |
| P₂O₅   | 2.5    | 1.06   | 0.99   | 0.18   | 2.5    | 0.80   |
| CO₂    | 9.5    | 17.6   | 4.6    | 14.5   | 4.8    | 9.8    |
| F      | 0.55   | 0.58   | 0.32   | 0.27   | 0.49   | 0.47   |
| S      | 0.66   | 0.12   | 0.11   | 0.13   | 0.18   | 0.09   |
| BaO    | 0.10   | 0.08   | 0.16   | 0.08   | 0.14   | 0.16   |
| Sum    | 100.38 | 100.43 | 99.15  | 99.82  | 100.73 | 100.69 |
| —O=F, S | 0.40  | 0.27   | 0.16   | 0.15   | 0.26   | 0.22   |
| Total  | 99.98  | 100.16 | 98.99  | 99.67  | 100.47 | 100.47 |
| Molec. norm. | | | | | | |
| Or     | 10.93  | 9.82   | —      | 8.99   | 1.14   | 6.98   |
| Ab     | —      | —      | —      | 1.44   | —      | —      |
| An     | —      | —      | 2.04   | —      | —      | —      |
| Lc     | —      | 2.58   | 11.77  | —      | 8.49   | 3.76   |
| Ne     | —      | —      | 1.86   | —      | —      | 4.82   |
| Ac     | 8.96   | 8.95   | —      | 7.04   | 5.20   | 13.70  |
| Ks     | 0.58   | 2.27   | —      | —      | 0.44   | —      |
| Di     | —      | —      | 15.61  | —      | —      | —      |
| Hy     | 0.74   | —      | 18.48  | —      | —      | —      |
| Ol     | 35.12  | 21.06  | 24.36  | 14.58  | 23.35  | 34.88  |
| Cs     | —      | —      | 5.56   | —      | —      | —      |
| Mt     | 7.41   | 5.87   | 11.17  | 7.35   | 27.02  | 4.98   |
| Hm     | —      | —      | 4.28   | —      | —      | —      |
| Il     | 4.37   | 6.65   | 6.94   | 5.58   | 5.49   | 3.97   |
| Ap     | 5.93   | 2.51   | 2.38   | 0.43   | 5.90   | 1.89   |
| Fr     | 0.67   | 1.00   | 0.48   | 0.53   | 0.55   | 0.81   |
| Pr     | 1.24   | 0.22   | 0.21   | 0.25   | 0.33   | 0.17   |
| Cc     | 16.91  | 20.93  | 10.63  | 19.03  | 12.21  | 19.76  |
| Mg     | 3.98   | 16.11  | —      | 12.13  | 5.75   | 1.67   |

Analyses by the Geological Survey of Sweden

Higher contents of TiO₂, FeO (total), MnO, Na₂O and CO₂, but lower contents of SiO₂, MgO and H₂O⁺ than do average kimberlites (Dawson 1967). They differ from the damkjernites at Fen (Griffin and Taylor 1975) by higher contents of FeO (total), MgO and CO₂, and lower contents of SiO₂, TiO₂ and Al₂O₃. The Sokli dykes have higher contents of FeO (total), MnO, Na₂O and CO₂, and lower contents of Al₂O₃ and CaO than the alnöites and kimberlites from Alnö (von Eckermann, unpublished data).

The contents of selected trace elements are given in Table 5. The data are consistent with those reported for kimberlites (Dawson 1967, Mitchell and Brunfelt 1975, Fesq et al. 1975, Kable et al. 1975) and Alnö dykes (unpublished data). The rare-earth patterns for
the Sokli dykes (Fig. 5) are linear for porphyritic dykes; a xenolithic dyke shows a slight Eu anomaly. La/Yb ratios range from 66 to 141, indicating a fairly high degree of differentiation, if parental magmas of basaltic or lherzolitic compositions are assumed.

K/Rb ratios are in the range 235—431, average 308, which is higher than for alnöites and kimberlites (Kresten 1977), but within the range reported for damkjernites from Fen (Griffin and Taylor 1975).

In summary, it can be stated that the Sokli dykes represent carbonated alkaline lamprophyres with affinities to both alnöites and kimberlites. The calculated normative compositions (Table 4) indicate a possible dolomitic composition of the carbonate phase. Thermal analyses carried out on the samples
Table 5. Selected trace elements in Sokli dykes (ppm)

| Sample | —0001 | —0003 | —0004 | —0005 | —0007 | —0002 |
|--------|--------|--------|--------|--------|--------|--------|
| Zn     | 165    | 130    | 165    | 110    | 300    | 165    |
| Rb     | 36     | 100    | 75     | 38     | 50     | 43     |
| Sr     | 1300   | 900    | 1200   | 520    | 930    | 1100   |
| Nb     | 95     | 150    | 60     | 15     | 45     | 40     |
| Zr     | 275    | 345    | 150    | 130    | 650    | 300    |
| Cu     | 125    | 100    | 150    | 75     | 130    | 75     |
| Ni     | 400    | 350    | 700    | <100   | 370    | —      |
| La     | 197    | 93     | 87     | 126    | —      | —      |
| Ce     | 334    | 150    | 12.4   | 2.9    | —      | —      |
| Sm     | 25.5   | 14.4   | 0.96   | 0.18   | —      | —      |
| Eu     | 6.4    | 3.5    | 15     | 14     | —      | —      |
| Tb     | 1.4    | 1.4    | 18     | 6      | —      | —      |
| Yb     | 0.45   | 0.37   | 0.45   | 0.45   | —      | —      |
| Lu     | 35     | 21     | 35     | 35     | —      | —      |
| Sc     | 27     | 37     | 27     | 27     | —      | —      |
| Th     | 10     | 8      | 10     | 10     | —      | —      |

Sr.: atomic absorption, Th. Berg (Geological Survey of Sweden); Rb, Nb, Zr, Ni: X-ray fluorescence, Y. Kafkas; Cu: spectrophotometry, P. Kresten; REE, Sc, Th, U: instrum. neutron activation, P. Kresten.

Discussion

The mineralogical compositions of the Sokli dykes compare well with those reported for kimberlites. Amphibole, however, seems to be very rare in kimberlites. Possibly tremolitic amphibole has been reported from two occurrences in Southern Africa (Lipelaneng, Nixon and Kresten 1973, Monastery Mine, Whitelock 1973), and one in Greenland (Emeleus and Andrews 1975). Actinolite has been reported as inclusions in diamond (Prinz et al. 1975), potassic richterite from nodules in kimberlite (Er Hank and Finger 1970) and a possible kimberlite from Barkly West, South Africa (Er Hank 1973).

Nevertheless, the absence of several minerals considered to be »critical« for kimberlite, such as (chrome) pyrope, chrome diopside and diamond, as well as the complete lack of ultramafic nodules in the material examined do not allow the term »kimberlite« to be used for the Sokli dykes. On the other hand, the Sokli dykes do not fit the present definition of the term »alnöite« (von Eckerman 1948); they do not contain melilite, and diopsidic or salitic pyroxene, which is common in alnöites.

It seems likely that the Sokli dykes derive from kimberlitic magma, from which some material (ultramafic nodules) had segregated and some (high-pressure minerals) had been re-equilibrated in a crustal magma pool. Crustal contamination and interaction with carbonatite magma must have played a key role in the petrogenesis of the Sokli dykes.

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