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The petrography, mineralogy and chemistry
of the fenites of the Sokli carbonatite intrusion,
Finland

by Heikki Vartiainen and Alan R. Woolley



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THE PETROGRAPHY, MINERALOGY AND CHEMISTRY
OF THE FENITES OF THE SOKLI CARBONATITE
INTRUSION, FINLAND

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HEIKKI VARTIAINEN AND ALAN R. WOOLLEY

WITH 55 FIGURES AND 16 TABLES IN THE TEXT

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The Sokli carbonatite intrusion lies in north eastern Finland, and is part of the extensive province of carbonatites and alkaline igneous complexes which extends across the Kola Peninsula. The carbonatite forms an oval shaped, downward tapering plug of some 20 km² in surface area, surrounded by an extensive fenite envelope. Numerous sheets of carbonatite cut the fenites, and kimberlite dykes are also common. A broad range of carbonatite types are present ranging from pure sövites to dolomite-rich types, and including varieties rich in phlogopite, amphibole, serpentine and opaque minerals. Phoscorites occur within the carbonatites. Chemical analyses and modes of 7 carbonatites and phoscorites are given.

The country rocks comprise granite gneisses, amphibolites and hornblende schists. Close to Sokli there is an intrusion of syenite, and several ultramafic intrusions. Analyses are given of four gneisses and of four amphibolites and hornblende schists. Fenites extend up to 3 km from the carbonatite and descriptions are based principally on cores from seven drill holes, one of which goes through the fenite-carbonatite contact. Fenitization involves the development of alkali feldspars, pyroxenes, alkali amphiboles and phlogopite, and the Sokli fenites are characterised by the exceptional abundance and variety of the amphiboles. A sodic and a later potassic series of fenites can be distinguished. Extensive phlogopitization has taken place close to the carbonatite producing pure phlogopite and phlogopite-alkaline amphibole rocks, and the same phenomenon, on varying scales, can be seen along carbonatite veins and veinlets. Analyses for major and trace elements of 38 fenites are given including five rock — potassic metasomatic vein pairs, and the addition and subtraction of elements to and from the aureole is discussed using these data.

Analyses of eleven magnesio-arfvedsonites and eckermannites, one ferrotschermakitic hornblende five aegirines and aegirine-augites and five phlogopites are given. The classification of the arfvedsonite — eckermannite series is discussed and suggestion made that the series should be sub-divided at mg ratios of 25, 50 and 75. Feldspar compositions in some fifty fenites have been investigated by diffractometry. The chemical variations of coexisting amphibole-phlogopite and amphibole-pyroxene pairs suggest that some chemical equilibrium was attained between minerals in the aureole, and there is a strong correlation between rock and mineral compositions such that chemical compositions producing the assemblages pyroxene, pyroxene + amphibole, amphibole, or amphibole + phlogopite can be defined.

Using the Sokli data and that in the literature, a suggested five fold classification of fenites is given, based principally on the ratio of sodium to potassium. The method of element transport in fenites is discussed and the suggestion made that much of the alkali, particularly in the inner zones, moves as carbonates, but that considerable mobility is achieved by 'chemical transport reactions' involving migration of gaseous complexes, in which fluorine plays an important role.

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INTRODUCTION

The Sokli carbonatite intrusion (Figs. 1 and 2) was discovered in 1967 by an airborne geophysical survey (Paarma, 1970) carried out by the steel company Rautaruukki Oy, as part of an extensive project to search for alkaline rocks in northeastern Finland. Since the discovery, the weathered cap of the carbonatite has been the main object of a detailed prospecting programme. However, various geochemical and geophysical anomalies encountered in the fenite aureole have also necessitated sampling the fenites. The fenites are covered by glacial deposits ranging between 0.5 and 10 metres thick, so that sampling for this investigation has been possible only from trenches, of which some 500 metres have been excavated, and from drilling, some 1 900 metres of diamond drill core having been recovered. The sites of the principal trenches and the positions of the drill holes, and their attitudes if not vertical, are indicated on Fig. 2.

The rocks of the Sokli intrusion comprise a central carbonatite plug with an enveloping metasomatic aureole of fenites. Within the plug and aureole occur numerous dykes having kimberlitic affinities. Alkaline igneous rocks of the types commonly associated with carbonatites do not occur at Sokli, although the Marjavaara syenite crops out some 5 km to the west (Fig. 2). This syenite, however, gives a very much older age than the Sokli carbonatite and cannot be considered to be consanguineous with it.

An account of the age of the Sokli intrusion and its place in the extensive carbonatite — alkaline igneous province of the Kola Peninsula and northwestern Europe (Fig. 1) has been discussed by Vartiainen and Woolley (1974). Dates from the carbonatite range from 334 to 378 m. y. (*op. cit.* Table 1). The Marjavaara syenite gives $1\,740 \pm 35$ m. y., while a biotite from a gneissose granite in the immediate vicinity of the Sokli intrusion gives $1\,695 \pm 29$ m. y. The fenites give a spectrum of dates between those of the carbonatite and the country rocks.

Earlier published papers on the intrusion include a brief general account by Paarma (1970); an interpretation of falsecolour air photographs (Paarma *et al.*, 1968), and an account of geochemical surveys of the Sokli complex (Nuutilainen, 1973). The only other described occurrences of fenites in Finland are at Iivaara (Lehijärvi, 1960) and Siilinjärvi (Puustinen, 1971). The Iivaara Complex differs from the Sokli intrusion in comprising essentially varieties of nepheline syenite and ijolite, not carbonatite. The Siilinjärvi Complex, however, consists principally of carbonatite and syenite. From the

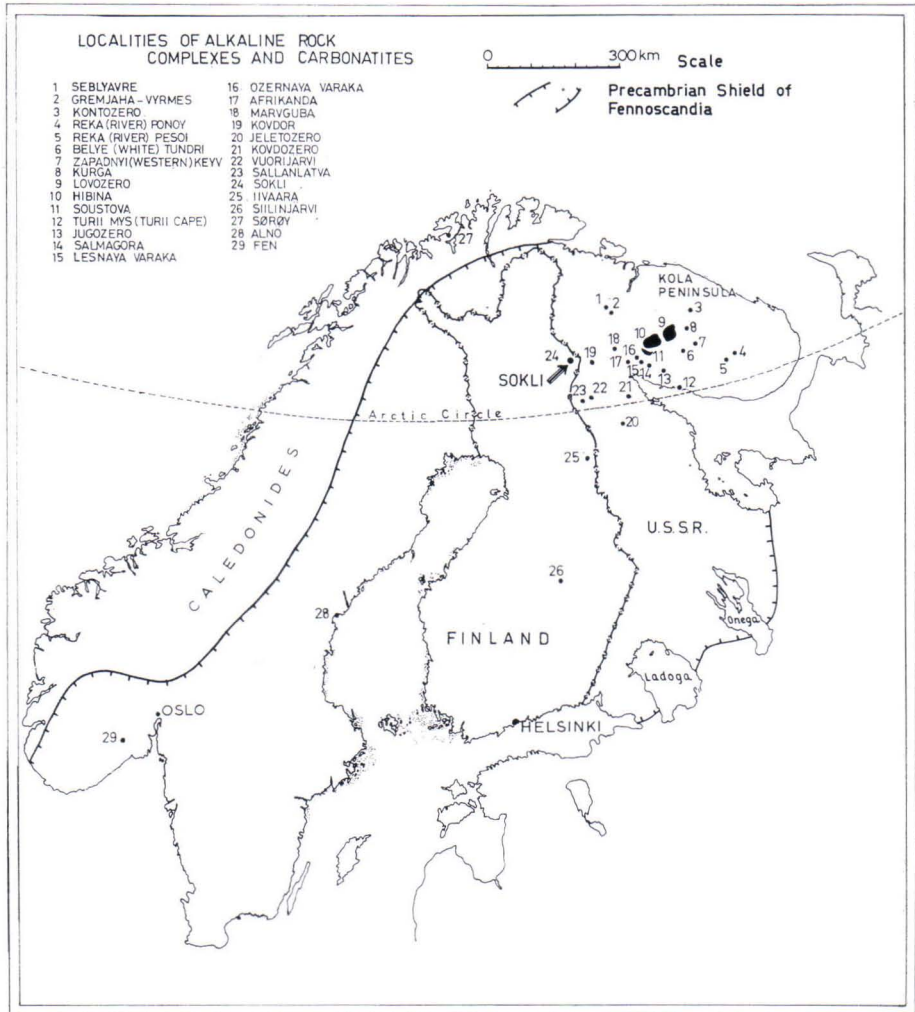


FIG. 1. Map of northwestern Europe showing the location of the Sokli carbonatite intrusion and the other carbonatites of the area.

description of the rocks and their chemistry (Puustinen, 1971), and from study of a few thin sections, and observations made during one day walking over the ground in the company of Dr. Puustinen, it appears probable that the syenites are in fact high grade fenites, which have possibly been mobilized. If this should indeed prove to be the case, then the Sokli and Siilinjärvi intrusions are lithologically very similar.

The purpose of this paper is to give a petrographic, mineralogical and petrochemical description of the fenites, and to present less detailed accounts of the country rocks and carbonatites. It is hoped to publish a full account of the carbonatites in the

future. The field work on which this paper is based has been done by H. Vartiainen who is responsible for the geological map, and the accounts of the country rocks and the carbonatite. The second author is responsible for the part of the paper devoted to the fenites. All the rock and mineral analyses and mineral separations were done in the British Museum (Natural History). The analyses were made by V.K. Din (rocks) and A. J. Easton (minerals), with much of the preparative work and some of the individual determinations by G. C. Jones. The mineral separations were done by Miss V. Jones.

Chemical procedures

Standard gravimetric procedures were used for the determination of H₂O and CO₂ in all 54 rock specimens. Ferrous iron was determined by titration with standardised KMnO₄ solution after dissolution of the sample as described by French and Adams (1972), and fluorine was determined colorimetrically using alizarin fluorine blue (Analytical Methods Committee 1971) following pyrohydrolysis of the sample (Clements *et al.* 1971).

The fenite specimens were analysed by X-ray fluorescence methods for Si, Al, Mg, Ca, Fe, Ti, K, S and P using the method of Norrish and Hutton (1969): Na and Mn were determined by atomic absorption spectrophotometry (A.A.S.) of solutions prepared according to the method of Langmyhr and Pans (1968). The same solutions were used for the estimation by A.A.S. of Cr, Li, Ni, Cu, Zn, V, Sr, Ba and Rb. The three trace elements, Nb, Zr and Y were estimated spectrographically by visual comparison of the sample spectra with the spectra of a range of synthetic standards.

The carbonatites and phoscorites were analysed for R₂O₃, MgO and CaO using classical gravimetric techniques after the expulsion of Si from the sample by treatment with HF/HClO₄ mixture. SiO₂ was determined colorimetrically, on a separate sample, using the heteropoly blue method, after fusion with sodium hydroxide and dissolution of the solidified melt in HCl. P, Ti and total Fe were determined colorimetrically as their molybdovanadate, tiron and sulphosalicylic acid complexes respectively. The Al₂O₃ values were calculated by correcting the R₂O₃ as determined for the amounts of P₂O₅, TiO₂ and total Fe₂O₃ found. The procedures for the determination of trace element concentration were those used in the analysis of the other specimens and were extended to include K, Cs and Co with the A.A.S. determinations and Pb and Ga with the spectrographic estimations. The S content was found by igniting the sample mixed with vanadium pentoxide flux in a stream of nitrogen and collecting the effluent SO₂ in a solution of H₂O₂ which was then titrated with standardised borax solution.

In the minerals, the Fe³⁺/Fe²⁺ ratio was determined by dissolution of a few mg of sample under an atmosphere of nitrogen using the 2,2-dipyridyl complex (Riley and Williams, 1959). The major constituents, with the exception of iron, were determined by A.A.S. on a lithium metaborate fusion followed by dissolution of the fusion cake in dilute nitric acid (Sühr and Ingammells, 1966) using mixed standards as suggested

by Abbey (1968) in a lithium metaborate matrix; total iron was determined on an aliquot of the solution using 2,2-dipyridyl. Water was determined by a standard gravimetric procedure after combustion with sodium tungstate flux; fluorine was determined by the same method as the rock samples. Trace elements were determined by the same spectrographic method as used for the rocks, with the exception that Rb, Ba, Sr and Cr were determined by A.A.S. methods.

FIELD RELATIONS

Satellite pictures of central Lapland indicate that the Sokli intrusion lies on a major fault which also intersects the Kovdor carbonatite in the Kola Peninsula. Some 400 km² of the basement of the Sokli district has been remapped as part of the present prospecting programme and this, together with airborne geophysics, has allowed the construction of a more accurate and detailed geological map (Fig. 2) than that of Mikkola (1936). The dominant rocks of the area are gneissose granites and associated pegmatites, but there are also extensive areas of amphibolite and hornblende schist occurring in a broad zone extending north eastwards across the eastern part of the mapped area, and ultramafic rocks and syenite. To the west of Sokli an oval-shaped area of amphibolite has a core of olivinite, and other smaller ultramafic masses have also been mapped (Fig. 2). The geological relationship of the gneissose granites and the amphibolites is not known. Mikkola (1941, p. 160) has stated with regard to the amphibolites and ultramafic rocks of the area: »One would rather consider them as being early manifestations of magmatic activity — already prior to the intrusions of gneissose granites». However, it is possible that the amphibolites are the younger rocks.

The Marjavaara syenite may represent the youngest rocks within the basement. Although it gives a K/Ar date (on amphibole) of $1\ 740 \pm 35$ m. y., and the gneissose granite gives a K/Ar date of $1\ 695 \pm 29$ m. y., the latter was done on biotite which probably relates to a later metamorphic event (Vartiainen and Woolley, 1974).

The oval-shaped mass of ultramafic rocks to the west of Sokli, known as the Tulppio complex, probably represents a large igneous intrusion of olivinite. The central parts of this complex are relatively unaltered olivine-rich rocks, but the envelope comprises metaolivinites and other ultramafic variants. Four similar, but smaller, masses of ultramafic rocks with or without an amphibolite envelope occur within the Sokli district. The contact relationships between these ultramafic masses and the surrounding rocks are everywhere obscured by glacial deposits.

The carbonatite forms a composite plug which has a brecciated contact against the surrounding fenites (Fig. 2). The plug occupies an oval area covering some 20 km², and thus is one of the largest carbonatites known. Gravity surveys indicate a downward tapering, cone-like form. There are no 'high level' volcanic features evident so the intrusion as now exposed represents either a relatively deep section through a volcanic plug, or an essentially plutonic intrusion, perhaps of diatreme-type, as

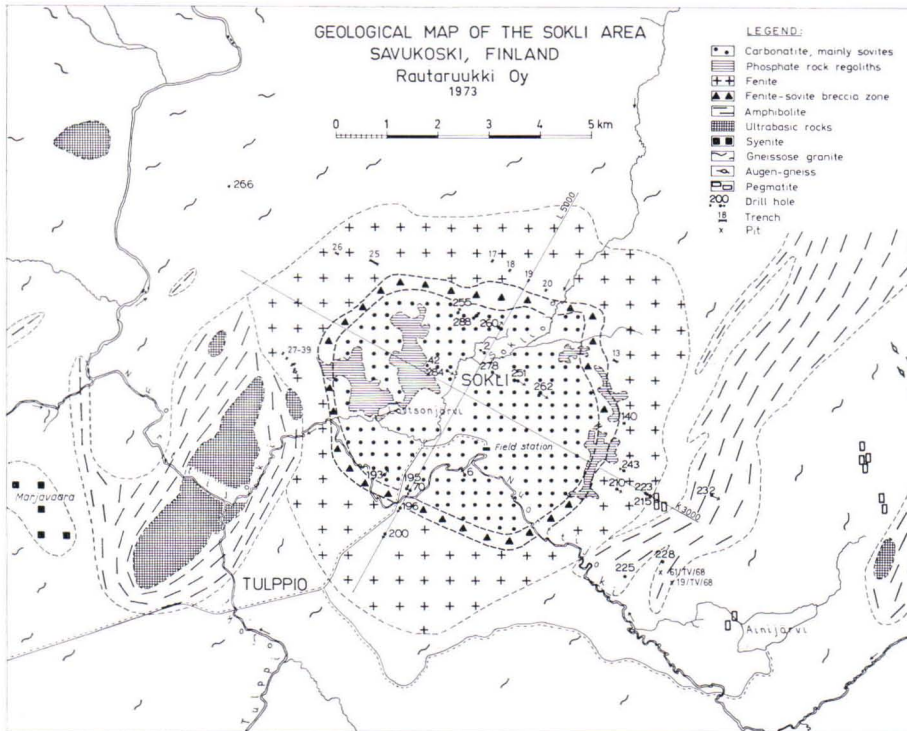


FIG. 2. Geological map of the Sokli carbonatite intrusion and its immediate vicinity. The positions of trenches, drill holes and sites from which specimens referred to in the text were collected are indicated.

envisaged at Alnö by von Eckermann (1948). The carbonatite has a vertical banding but it has not proved possible to demonstrate whether this is concentric to the contacts. Several types of carbonatite are present most of them calcite-rich variants. Overlying part of the western and eastern side of the carbonatite and the innermost fenites is a phosphate-rich regolith which is probably a product of complex weathering processes of the carbonatite (Fig. 2).

Carbonatite also forms dykes, veins and veinlets which penetrate the fenites up to 1.3 km from the contact, and some indication of their abundance in the fenites may be gained from the drill hole logs in Fig. 3. It has not proved possible to determine the attitude of these carbonatite dykes, but their abundance suggests that they probably form tangential sheets, probably similar to the system of cone-sheets described from Alnö (von Eckermann, 1948). Kimberlitic dykes also occur within the fenites and it is probable that these form a similar though less extensive system to the carbonatite dykes.

The fenite aureole extends up to three km from the carbonatite contact. The innermost part of the aureole is a fenite-sövite contact breccia zone from 200 to 700

metres in width discovered by a power augering programme based on a 100×100 metres grid. There is also one incomplete diamond drill core through the contact zone. Within the breccia zone there is every gradation from brecciated and comminuted fenites through to isolated fenite fragments set in a sövite matrix. Fenite fragments are also encountered within the main carbonatite intrusion.

The outer margins of the fenite aureole are gradational, as is usual in such aureoles, and the gradual disappearance of the fenitization effects is well illustrated in drill holes 215 and 223 (Figs. 2 and 3). The outer margins of the aureole have been interpreted by the former photogeologist of Rautaruukki Oy, Dr. J. Talvitie, using aero false colour and anaglyph colour pictures. The narrowness of the fenite aureole in the vicinity of the Tulppio ultramafic body is apparent. This may suggest that the Tulppio rocks effectively resisted penetration by the fenitizing fluids at the time of the emplacement of the carbonatite. However, detailed work on this part of the aureole remains to be done.

Logs of seven drill holes in the fenites are shown as Fig. 3, plotted against distance from the fenite-sövite contact. This diagram is somewhat simplified in that all seven were inclined holes. Drill hole 70, for example, was drilled outwards from the carbonatite in to the fenite and shows that the contact is not, in fact, a clear cut one. Drill hole 215 is sited on the outer edge of the fenite aureole and was drilled outwards at an

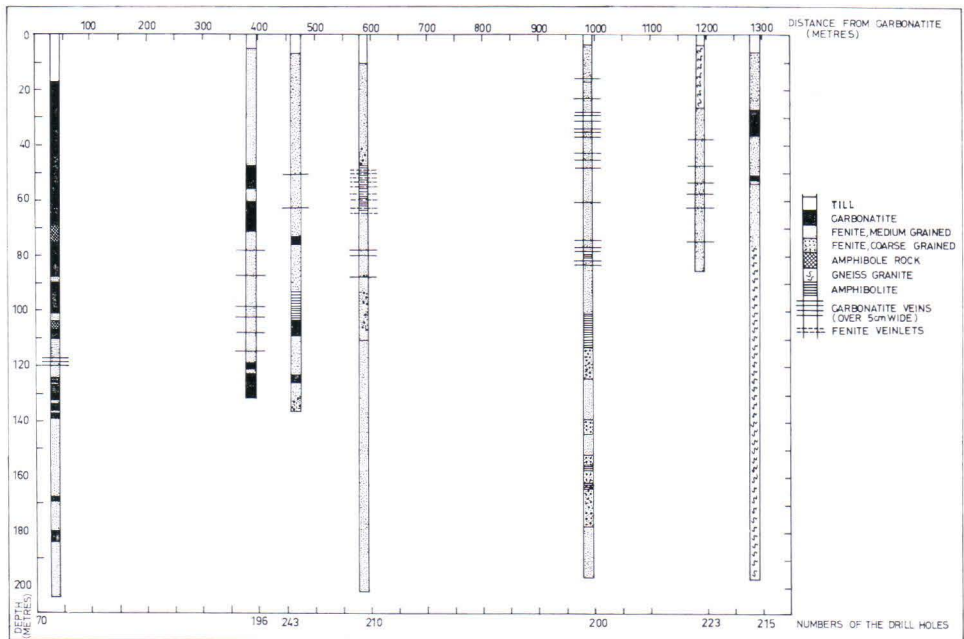


FIG. 3. Logs of seven drill holes in the Sokli fenite aureole plotted against distance from the carbonatite-fenite contact. All the holes were drilled at an angle, but this is not indicated on the diagram.

angle of about 45°. The upper 80 metres of core comprise distinctly fenitized rocks interspersed with carbonatite sheets, but below this the effects of fenitization rapidly diminish and no carbonatite dykes are encountered. The general heterogeneity of the fenites is also well illustrated by Fig. 3 with rapid variations between coarse and medium grained fenites and with occasional intercalations of amphibolite.

COUNTRY ROCKS

Petrography

According to Mikkola (1941, pp. 18—22) the granitic basement rocks of the Sokli area comprise gneissose granites and granodioritic gneissose granites. Augen gneisses occur to the east of the Sokli intrusion (Fig. 2) and contain reddish microcline augen from 0.5 to 2 cm in diameter in a medium grained, faintly foliated granitic matrix. The gneissose granites vary from grey to red, may be fine or medium grained and may be massive, foliated or banded. Texturally they often display cataclastic features such as mortar textures. Microcline and plagioclase (An_{10-20}) occur in variable proportions and, together with quartz, are the principal mineral constituents. Biotite is the only important mafic mineral and when abundant gives the rock a strong schistosity, and chlorite, sphene, iron ore, apatite and zircon have been found as accessories. In the immediate vicinity of the Sokli fenite aureole the gneissose granites tend to be grey and fairly homogeneous.

The granodioritic gneissose granite occurs to the northeast of the Sokli intrusion. It is predominantly grey, medium grained and does not have particularly well developed gneissose texture. It differs from the gneissose granite in the higher anorthite content of the plagioclase (An_{30}) and the presence of hornblende, while microcline is less abundant. Biotite may also be plentiful.

Pegmatites are simple types the main constituents being microcline, muscovite and quartz. They form irregular veins between 1 and 20 metres in width.

No primary textural or structural features have been preserved in the amphibolites and hornblende schists. These rocks are petrographically somewhat variable; they are greyish to blackish green, fine to medium grained and may be either foliated or massive. The foliated texture is due to the orientation of hornblende crystals and the segregation of dark and light minerals into distinct layers gives to some rocks a striped appearance. The colour index varies from about 50 to 100. Hornblende occurs mainly as bladed crystals whereas diopside, which when present tends to be concentrated into distinct layers, forms stubby prisms. The amphibole has been separated from one specimen and chemically analyzed (Tables 4 and 5, No. 27); it proves to be ferro-tschermakitic hornblende, according to the classification of Leake (1968). Epidote may be abundant in some diopside-rich layers while garnet, when present, tends to be evenly distributed throughout the rock. Plagioclase is usually zoned and of andesine composition. Accessory minerals include iron ores, sphene, biotite, chlorite and calcite.

Geological mapping of the Tulppio ultramafic complex indicates that the following rocks occupy the following surface areas: metaolivinite, 90 %; olivinite, 6 %; tremolite schist, 3 %; and anthophyllite rock, 1 %. All these rocks grade into each other. The olivinite is the least altered rock of the complex and is a medium to dark green, medium grained, granular rock. On sawn surfaces hypidiomorphic olivine grains between 0.2 and 1.0 cm in diameter can be distinguished in a finer grained and lighter coloured matrix of olivine and serpentine. The olivine is forsteritic ($Fe_{0.0} \pm 2$) in composition and comprises between 85 % and 95 % of the rocks. Serpentine, magnetite, carbonate, talc and tremolite are accessory minerals.

The metaolivinites are a group of rather variable rocks which may be massive, foliated or brecciated and have a range of mineralogical compositions. The olivine content varies between 25 and 85 %, serpentine between 10 and 40 %, carbonate and tremolite between 0 and 30 % and talc and magnetite 0 to 10 %. The most strongly

TABLE 1
Chemical analyses of granite gneisses, schists and amphibolite

	1	2	3	4	5	6	7	8
SiO ₂	66.93	69.03	69.69	75.59	50.21	48.60	48.09	46.64
TiO ₂	0.40	0.34	0.27	0.04	1.20	0.92	1.05	0.96
Al ₂ O ₃	16.05	15.47	16.00	13.93	13.91	15.35	14.77	12.91
Fe ₂ O ₃	1.04	0.59	0.31	0.09	1.73	0.91	1.24	1.71
FeO	2.37	1.90	1.16	0.31	11.22	8.70	8.10	13.34
MnO	0.06	0.05	0.02	0.01	0.22	0.22	0.26	0.62
MgO	1.80	1.19	1.01	0.05	7.61	6.41	7.05	5.13
CaO	4.16	3.09	2.53	1.33	10.16	14.49	10.12	15.28
Na ₂ O	4.83	5.10	6.15	4.16	2.00	2.28	3.43	1.18
K ₂ O	1.37	1.33	1.53	3.59	0.27	0.13	0.65	0.33
H ₂ O ⁺	0.69	0.58	0.52	0.23	1.32	0.58	1.23	0.72
H ₂ O ⁻	0.09	0.12	0.08	0.11	0.11	0.08	0.21	0.08
P ₂ O ₅	0.10	0.05	0.09	0.03	0.12	0.10	0.03	0.13
CO ₂	0.53	0.53	0.32	0.14	0.28	0.77	3.55	0.36
F	0.03	0.05	0.03	0.01	0.03	<0.01	0.02	0.01
S	nil	0.01	nil	nil	nil	0.38	0.11	0.50
others	0.117	0.175	0.221	0.116	0.164	0.159	0.182	0.173
	100.57	99.60	99.93	99.74	100.55	100.09	100.09	100.07
O ≡ F, S	0.012	0.026	0.013	0.004	0.013	0.194	0.063	0.254
	100.55	99.58	99.92	99.73	100.54	99.90	100.03	99.82
trace elements in p.p.m								
Cr	25	40	15	25	165	250	260	215
Li	25	145	25	25	15	15	45	50
Nb	nil	nil	nil	nil	nil	nil	100	nil
Ni	75	70	70	60	140	155	155	150
Cu	30	70	10	15	110	35	20	15
Zn	75	85	60	10	130	110	130	130
V	80	20	20	20	325	290	360	250
Zr	150	150	200	150	50	50	100	100
Y	nil	nil	nil	nil	nil	10	25	25
Sr	330	370	750	170	85	140	90	60
Ba	90	220	600	275	75	tr	tr	150
Rb	45	135	25	200	5	nil	20	5

altered rocks are tremolite schists and anthophyllite rocks which can be nearly monomineralic or have up to 10 % of accessory minerals. In general the smaller ultramafic masses to the east of the Sokli intrusion resemble the Tulppio metaolivinites, whereas those to the west are fairly pure serpentinites.

The Marjavaara syenites are typically red massive rocks with a medium grained granular texture. The felsic minerals form a panxenomorphic fabric and microcline is predominant usually comprising some 60 % of the rock with plagioclase and quartz 10 % or less. Hornblende, which forms ragged lath-shaped crystals, forms up to 20 % of the rock. There is some alteration of hornblende to biotite and a little sericitization of the microcline. Apatite, biotite, sphene and opaques form accessories. Towards the contact with the gneissose granites, which is, unfortunately, obscured by moraine, there is an increase in the content of quartz, biotite and plagioclase.

Chemistry

Four specimens of gneissose granites and four of amphibolites and hornblende schists considered to be representative of the basement rocks of the Sokli vicinity, and therefore the antecedents of the Sokli fenites, have been chemically analyzed. The analyses, including major and trace elements, together with CIPW norms are given in Table 1 and the localities are indicated on Fig. 2.

Table 1 continued

C.I.P.W. norms

	1	2	3	4	5	6	7	8
Qz	22.38	26.31	21.60	34.99	1.76	—	—	—
C	0.53	1.37	0.59	1.18	—	—	—	—
Or	8.10	7.86	9.04	21.22	1.60	0.77	3.84	1.95
Ab	40.87	43.15	52.03	35.20	16.92	19.29	29.02	9.98
An	16.64	11.65	9.94	5.52	28.18	31.27	22.99	28.96
Di	—	—	—	—	16.23	28.92	3.75	36.88
Hy	7.43	5.50	3.98	0.57	28.53	7.42	22.70	11.26
Ol	—	—	—	—	—	6.16	4.11	4.13
Mt	1.51	0.86	0.45	0.13	2.51	1.32	1.80	2.48
Il	0.76	0.65	0.51	0.08	2.28	1.75	1.99	1.82
Ap	0.24	0.12	0.21	0.07	0.28	0.24	0.07	0.31
CC	1.21	1.21	0.73	0.32	0.64	1.75	8.07	0.82
H ₂ O ⁺	0.69	0.58	0.52	0.23	1.31	0.58	1.23	0.71
H ₂ O ⁻	0.09	0.12	0.02	0.11	0.11	0.08	0.21	0.08
Others	0.16	0.26	0.24	0.12	0.18	0.36	0.25	0.43

1. Biotite hornblende granite gneiss. Drill hole 266 at 41.0 metres (B. M. 1973, P15(7)).
2. Biotite granite gneiss. Drill hole 228 at 86.5 metres (B. M. 1973, P15(9)).
3. Biotite granite gneiss. Drill hole 215 at 89 metres (B. M. 1973, P15(10)).
4. Biotite granite gneiss. 3 Km. SE. of Sokli (R. O. 19/TV/68; B. M. 1973, P15(5)).
5. Hornblende schist. 2.5 Km. SE. of Sokli (R. O. 61/TV/68; B. M. 1973, P15(4)).
6. Hornblende-pyroxene schist. 1 Km. W. of Sokli (R. O. Trench 27; B. M. 1973, P15(2)).
7. Hornblende schist. Drill hole 232 at 83.4 metres (B. M. 1973, P15(8)).
8. Pyroxene-garnet amphibolite. Drill hole 232 at 16.5 metres (B. M. 1973, P15(6)).

Localities and sites of boreholes are indicated on Fig. 2.

Analyst: V. K. Din.

FeO, H₂O and CO₂ determined by G. C. Jones. F determined by A. J. Easton.

The gneisses are all typically granitic in composition with high normative Qz values. In all four rocks is $\text{Na}_2\text{O} > \text{K}_2\text{O}$ and in numbers 1 and 3 markedly so, which is reflected in very high normative Ab values and comparatively low Or values. These data suggest that rocks 1 to 3 should, if treated as igneous rocks, be assigned to the tonalites. Specimen 4 with its higher Or value is a granodiorite, although the An value is rather lower than is usual. All four gneisses when plotted in the normative system Qz — Ab — Or, lie outside the area shown by Tuttle and Bowen (1958) to be occupied by igneous granites, suggesting that although these rocks may have had an igneous origin they have since undergone considerable chemical changes.

Inspection of the analyses and norms of amphibolite and hornblende schist suggests that they are metamorphosed basic to intermediate igneous rocks. Comparison with the average rock compositions of Nockolds (1954) shows that rocks 5, 6 and 8 are very close to gabbros, two of them having olivine and one a little quartz in the norm. Specimen 7 has normative Ab $>$ An indicating a dioritic composition. Rocks 7 and 8 come from the same borehole and yet represent the extremes of the compositional range of the four analyses, and this indicates the heterogeneity of the extensive mass of amphibolites lying to the east of Sokli. The heterogeneity may be because this mass originally comprised a number of distinct intrusive units, because it was layered, or because of the possibility that metamorphic segregation took place within the amphibolite units.

Rock 6 is taken from the amphibolite envelope of the Tulppio ultramafic body. If, therefore, the amphibolites are metamorphosed basic igneous rocks, then the Tulppio intrusion must have had both ultra-basic and basic members.

There appears to be no particular features amongst the trace element data which could be unequivocally used for differentiating between an igneous and a sedimentary origin for these rocks.

CARBONATITE

Only such petrographic and mineralogical work as would help in understanding the fenites has so far been done on the carbonatites.

The carbonatite intrusion comprises essentially two groups of rock types: sövites and phoscorites. A range of these types occurs within the intrusion and some internal intrusive contacts have been recognised between them, although observations are confined to drill cores, pits and trenches. The rock variants are extremely heterogeneous having streaks and bands of varying mineralogy and texture. These structures are nearly vertical but whether or not the foliation is concentric with the intrusive contact cannot be determined from the drill cores. The heterogeneity of the carbonatites is illustrated by the modes of the analyzed samples given in Table 2. The following principal variants have been distinguished:

TABLE 2

Mineral compositions (volume per cent) of analyzed carbonatite and phoscorite samples

	9. Sövite				10. Tremolite-phlogopite sövite				11. Phlogopite-magnetite sövite				12. Tremolite sövite			
	DH 2	DH 260	DH 262	Aver- age	DH 193	DH 260	DH 262	Aver- age	DH 193	DH 262	DH 278	Aver- age	DH 193	DH 6	DH 251	Aver- age
	14.0	93.0	61.0		110.0	60.0	116.0		112.0	99.5	102.0		85.5	120.8	37.0	
Carbonate	84.3	86.9	84.4	85.2	70.0	69.7	84.2	74.6	35.2	69.1	77.2	60.5	77.0	45.9	73.6	65.5
Apatite	5.0	7.6	10.6	7.7	4.7	16.2	6.8	9.2	28.0	5.5	9.1	14.2	5.5	20.2	10.4	12.0
Phlogopite	5.5	3.3	0.7	3.1	2.5	9.7	2.4	4.9	21.4	8.7	8.1	12.7	3.3	4.2	8.7	5.4
Amphibole	—	—	1.7	0.6	14.0	—	2.7	5.6	2.1	1.0	1.7	1.6	11.4	21.9	1.2	11.5
Serpentine	—	—	—	—	6.3	2.3	2.2	3.6	0.3	—	—	0.1	—	0.3	—	0.1
Pyrochlore	—	0.3	0.8	0.4	—	0.2	—	0.1	0.3	—	—	0.1	—	—	—	—
Zircon	—	—	—	—	0.3	—	—	0.1	0.1	—	—	—	—	1.0	—	0.3
Opaques	5.5	1.9	1.8	3.0	2.2	1.9	1.7	1.9	12.9	15.7	3.9	10.8	2.8	6.5	6.1	5.2
	13. Phoscorite				14. Sulphide phoscorite				15. Rauhaugite							
	DH 2	DH 278	DH 288	Aver- age	DH 2	DH 260	DH 278	Aver- age	DH 92	DH 284	DH 262	Aver- age				
	53.5	73.0	71.5		67.0	85.0	51.0		16.5	13.0	45.0					
Carbonate	10.4	7.7	18.2	12.1	39.8	4.2	9.0	17.7	85.8	94.7	95.0	91.9				
Apatite	25.5	2.1	3.1	10.1	4.0	33.5	6.1	14.5	12.0	0.4	—	4.2				
Phlogopite	28.6	2.8	13.5	15.0	7.6	14.8	16.7	13.0	1.3	0.7	1.9	1.3				
Amphibole	—	—	—	—	—	—	0.1	—	—	—	—	—				
Serpentine	9.1	51.3	—	20.1	—	5.7	6.0	3.9	—	—	0.1	—				
Olivine	—	0.7	—	0.2	—	—	—	—	—	—	—	—				
Clinohumite	—	8.5	—	2.8	—	7.3	—	2.4	—	—	—	—				
Pyrochlore	1.4	0.1	0.1	0.6	0.2	0.8	1.0	0.7	0.3	0.1	0.1	0.2				
Zircon	1.0	—	—	0.3	—	0.2	—	0.1	—	—	—	—				
Opaques	24.0	26.8	65.0	38.6	48.4	33.5	61.1	47.7	0.6	4.1	2.5	2.4				

For each sample 1,000 points were counted at 0.5 mm intervals. For details and method of sampling see text. Drill hole numbers and depths are shown at the top of each column.

sövite	— calcite over	80 %	(by volume)
silicosövite	— calcite	40—80	» »
rauhaugite	— dolomite over	80	» »
silicorauhaugite	— dolomite	40—80	» »

The silicosövites and silicorauhaugites are named according to their principal non-carbonate minerals, except that apatite which is ubiquitous and abundant, is ignored. The principal non-carbonate minerals (Table 2) are mica (mainly phlogopite), amphibole (variously tremolite or a blue alkaline type), serpentine and opaque minerals.

Texturally the sövites and rauhaugites are generally fine to medium grained, massive rocks, whereas the silicosövites and silicorauhaugites are medium grained and streaked and banded. Dyke rocks tend to be fine to medium grained and relatively massive.

The phoscorites seem to occur as fragmental rocks within sövites and they tend to be concentrated in the central parts of the intrusion as irregular breccia zones. They are characteristically coarse grained massive rocks of variable composition. The principal minerals are magnetite, green and red brown phlogopite, apatite, calcite and dolomite. Where the sulphides exceed 10 %, the rocks are distinguished as sulphide phoscorites. Towards the margin of the intrusion fragments of amphibole rock occur and these show noticeable alteration towards compositions which are comparable to those of the phoscorites.

As a result of recent work on carbonatites in the U.S.S.R., a phase doctrine has been developed which, in its fullest development, involves several successive and distinct stages of carbonatite evolution (Ternovoi *et. al.*, 1969; Potzaritskaja and Samoilov 1972). At Sokli, although work on the carbonatite is in the beginning, five stages have been distinguished. Magmatic and metasomatic processes have affected the evolution of the carbonatite complex.

Chemistry

Five samples of carbonatite and two phoscorites have been analyzed (Table 3). The material analyzed was chosen so as to give averages of the principal rock types and each sample consisted of three 30 cm long drill cores obtained from different parts of the intrusion. The limits of such a procedure are apparent, but for the purposes of this work, which is directed principally towards the fenites, average compositions are probably of more utility than extreme carbonatite compositions. The modal variations within and between samples are illustrated by Table 2.

There is a good correlation of the modal and normative carbonate contents of the carbonatites ranging from the 95 % carbonate in the rauhaugite to 58 % in the magnetite-phlogopite sövite. The magnesian nature of the carbonate in the rauhaugite

TABLE 3
Chemical analyses of carbonatites and phoscorites

	9	10	11	12	13	14	15
SiO ₂	1.36	5.82	6.29	6.92	12.12	10.15	0.46
TiO ₂	0.04	0.33	0.52	0.48	1.19	1.10	0.016
Al ₂ O ₃	0.83	1.45	1.99	1.81	0.91	1.05	0.15
Fe ₂ O ₃	2.31	4.87	9.67	6.63	30.18	25.14	0.77
FeO	1.79	3.76	5.48	4.61	16.67	22.16	0.54
MnO	0.29	0.26	0.38	0.30	0.63	0.52	0.33
MgO	3.09	5.01	4.87	7.73	11.54	10.61	9.49
CaO	48.08	40.96	36.86	34.84	9.95	10.65	43.11
Na ₂ O	0.08	0.32	0.40	1.12	0.36	0.13	0.13
K ₂ O	0.21	0.91	0.83	0.84	1.99	1.18	0.04
H ₂ O ⁺	0.27	0.62	0.74	0.59	1.92	1.41	0.27
H ₂ O ⁻	0.09	0.13	0.10	0.05	0.22	0.25	0.05
P ₂ O ₅	2.54	3.76	5.32	5.14	2.66	4.46	0.62
CO ₂	37.67	30.31	25.70	28.12	8.15	5.00	43.39
F	0.10	0.24	0.30	0.31	0.42	0.33	0.03
S	0.83	0.69	0.36	0.59	1.49	9.31	0.18
others	0.89	0.67	0.85	0.74	1.00	1.22	0.67
	100.47	100.11	100.66	100.82	101.40	104.67	100.25
O ≡ F, S	0.46	0.46	0.31	0.43	0.93	4.80	0.10
Total	100.01	99.65	100.35	100.39	100.47	99.87	100.15

trace elements in p.p.m.

Cr	nil	nil	nil	13	nil	nil	nil
Li	5	8	7	13	40	11	5
Nb	500	200	300	300	2 000	2 000	100
Ni	75	75	100	90	50	60	70
Cu	80	35	30	60	280	3 125	10
Zn	55	80	130	170	540	380	18
V	60	125	240	150	415	355	60
Zr	350	1 000	2 000	1 200	2 500	1 750	120
Y	100	100	75	50	nil	nil	25
Sr	5 200	3 200	3 200	3 100	1 030	970	4 900
Ba	1 110	590	660	960	515	330	465
Rb	6	14	17	17	40	25	1
Cs	125	140	155	50	nil	nil	75
Co	nil	nil	nil	nil	nil	340	nil
Pb	10	10	10	25	40	nil	tr
Ga	nil	25	50	25	100	30	nil

9. Söвите. (B. M. 1973, P14(1)).
10. Tremolite-phlogopite söвите. (B. M. 1973, P14(2)).
11. Phlogopite-magnetite söвите. (B. M. 1973, P14(3)).
12. Tremolite söвите. (B. M. 1973, P14(4)).
13. Phoscorite. (B. M. 1973, P14(5)).
14. Sulphide phoscorite. (B. M. 1973, P14(6)).
15. Rauhaugite. (B. M. 1973, P14(8)).

For details of localities and method of sampling see text.
Modal compositions of these rocks are given in TABLE 2.

Analyst: V. K. Din.

FeO; H₂O; CO₂; S and F determined by G. C. Jones.

is confirmed by the high MgO value of the rock. The tenor of trace element concentrations in the carbonatites is typical for such rocks, with high Sr and Ba and Sr:Ba ratios between 3 and 10. Nb is somewhat below the average for carbonatites, while Cu is relatively high. The phoscorites are characterized by enrichment in Fe and S (the latter reaching 9.3 % in the sulphide phoscorite), Ti, Nb, Cu, Zn, and Zr; they are depleted by comparison with the carbonatites in Y, Sr, Cs and in CaO and CO₂.

FENITES

Some of the specimens used in this study were collected from trenches and pits on the W, NW, and E sides of the aureole but most were cut from the cores from seven boreholes drilled in the southern and southeastern parts of the aureole (Fig. 2). The trench and pit specimens are usually somewhat weathered and so the chemical and mineralogical work has been done on the borehole material.

Petrography

Fenite nomenclature is imprecise because of the diverse mineral assemblages which result from the partial fenitization of a wide range of host rocks. However, many carbonatite intrusions have been emplaced in basement complexes which are composed dominantly of granites and granite gneisses and the gradual replacement of the quartz in the country rocks during the fenitization process allows the convenient subdivision into 'quartz fenites' and 'syenitic fenites', the latter being rocks in which all the quartz has been replaced. This nomenclature can be applied at Sokli with reference to fenitized granite gneisses but not to fenitized amphibolites which contain little or no quartz. It is convenient, therefore, to refer instead to the fenites as low to medium grade fenites and syenitic fenites. Low and medium grade fenites contain either quartz or identifiable 'primary' minerals, that is minerals which are derived from the country rocks. Low to medium grade fenites derived from amphibolite, for instance, contain hornblende. The term syenitic fenite is applied when the whole mineralogy comprises the alkali-rich minerals diagnostic of fenites. There is a perfect gradation through the series from country rocks to syenitic fenites.

Because their antecedents are known the low to medium grade fenites are subdivided here into those derived from granite gneiss and those derived from amphibolite and hornblende schist.

The majority of fenites at Sokli are 'normal' fenites, in that the secondary minerals they contain are characteristically sodic. However, another type of fenitization which is characteristically potassic has also been recognised and these fenites are described separately.

Low to medium grade fenites

Granite gneiss

The first sign of fenitization apparent in hand specimen is the development of a reticulate pattern of veinlets of iron oxides. With increasing fenitization these become a little more abundant and they become green or blue depending on whether they contain aegirine or alkaline amphibole. The rocks gradually assume an overall greenish or bluish hue, caused by the growth of aegirine and alkaline amphibole in knots and patches as well as along the veinlets.

The first sign of fenitization as seen in thin section is the development of turbidity in the feldspar. The turbidity progresses from the margin of grains towards the interior along cracks, cleavages and twin planes (Fig. 4), so that in some rocks the turbidity has a reticulate pattern while in others rounded 'cores' of fresh feldspar remain in a turbid matrix. A system of more substantial criss-crossing, continuous and discontinuous veinlets develops along, and in the vicinity of which, turbidity is more pronounced and iron oxides are concentrated (Fig. 5). The nature of the turbidity has not been determined; it may be due to partial hydration of the feldspar, for in a few sections tiny sericite flakes can be identified, or possibly it may result from a change in the ratio of the alkalis in the feldspar. Similar turbid feldspars in fenites around the Kangankunde carbonatite, Malawi have been shown to involve an increase in the potassium to sodium ratio (Woolley 1969, Plate 9A). Commonly at this stage microcline, if present, remains fresh and only the sodic plagioclase is turbid (Fig. 6); but with increasing fenitization the microcline becomes turbid also.

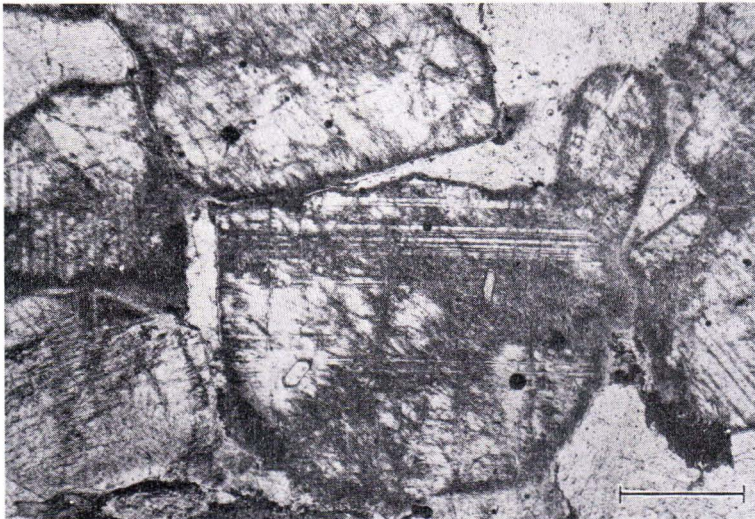


FIG. 4. 'Turbidity' developing in feldspar in an early stage of fenitization; quartz (paler grey) is unaffected. Plane polarised light. Drill hole 200 at 61 metres. B. M. 1973, P20(49). Scale line, 0.5 mm.

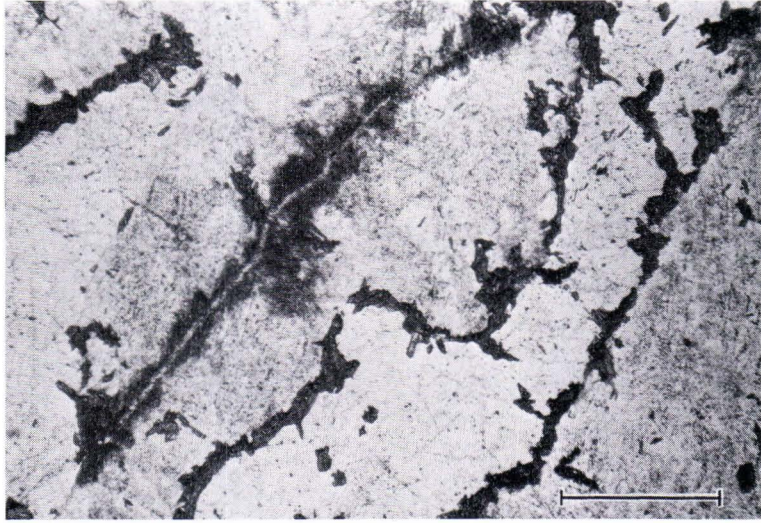


FIG. 5. Slight turbidity in feldspar, enhanced along a veinlet, and aegirine (dark grey) developing along quartz-feldspar contacts in a quartz fenite. Plane polarised light. Drill hole 210 at 44 metres. B. M. 1973, P20(30). Scale line, 0.5 mm.

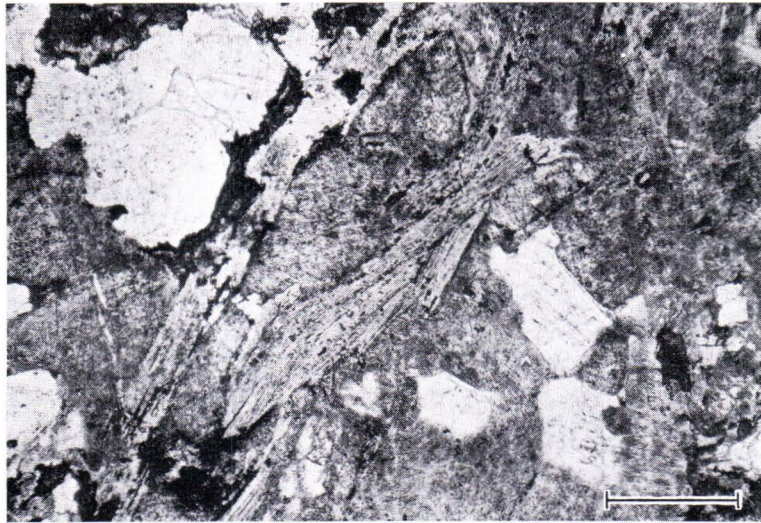


FIG. 6. Primary plagioclase is densely turbid but primary microcline (pale grey, upper left) is still relatively fresh in a quartz fenite. Biotite is pseudomorphed by fine grained alkali feldspar (running bottom left to top right); the light grey mineral at bottom right is quartz. Plane polarised light. Drill hole 215 at 60.5 metres. B. M. 1973, P20(10). Scale line, 0.5 mm.

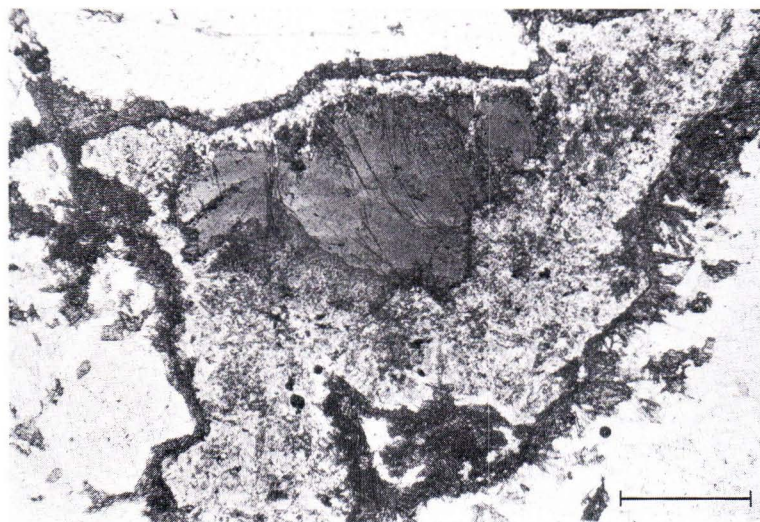


FIG. 7. A primary biotite crystal (dark grey) is partly replaced by fine grained alkali feldspar. Aegirine (also dark grey) forms a narrow rim around, and forms prisms penetrating into, quartz crystals (pale grey to white). Plane polarised light. Drill hole 200 at 150 metres. B.M. 1973, P20(57). Scale line, 0.5 mm.

Biotite which is present in many of the gneisses and abundant in some of them, in the very earliest stages of fenitization is replaced by a fine grained granular aggregate of what appears to be potassic feldspar (Figs. 6 & 7). Some fine grained ore, usually defining the original cleavages, is also present in the pseudomorphs after biotite. Muscovite is replaced in a similar way and the mica pseudomorphs persist into relatively high grade fenites. A little aegirine and or alkaline amphibole soon develops and tends to be restricted to the network of veinlets but may be concentrated in rare patches or along the contacts between quartz and feldspar grains (Fig. 5). The amphibole is a deep blue to bluish-green very fine grained variety, giving anomalous blue interference colours, and is usually a magnesio-arfvedsonite.

The medium stage of fenitization is characterised by the widespread development of aegirine and/or alkaline amphibole. There is every gradation from rocks in which aegirine is the only secondary mafic mineral to those in which alkaline amphibole is the sole secondary mafic mineral. Both minerals are strikingly developed along veinlets but also occur as isolated grains and aggregates, as rims to and penetrating quartz grains (Figs. 5 and 7), which are gradually replaced inwards, and occasionally they replace primary biotite. Aegirine is deeply coloured in shades of yellow or green, and at this stage of fenitization is usually fine grained and fibrous, and occurs mainly as radiating zoned aggregates (Figs. 8 & 9), but may form isolated acicular prisms or clusters of prisms. Alkaline amphibole varies from deep-blue to bluish green, and is characteristically very fine grained and fibrous, and has anomalous blue interference colours. There is a considerable amount of carbonate, which may be concentrated



FIG. 8. Clusters of radiating aegirine needles amongst variably turbid alkali feldspar. Plane polarised light. Drill hole 200 at 30 metres. B. M. 1973, P20(48). Scale line, 0.5 mm.

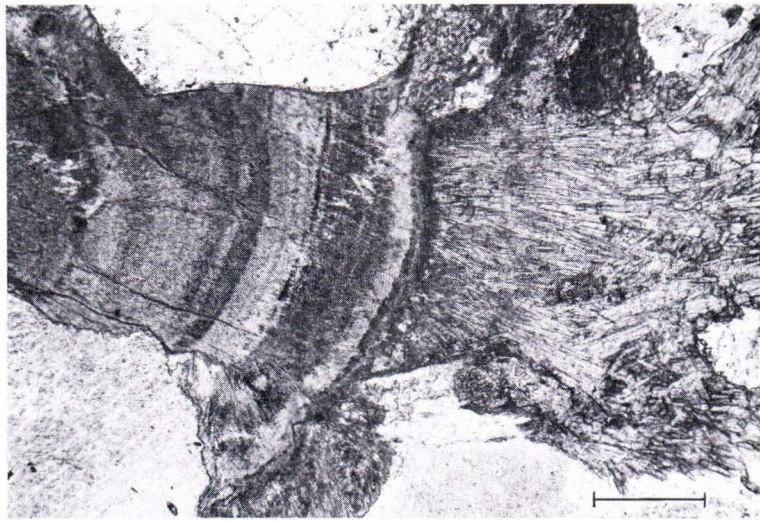


FIG. 9. A cluster of sub-radiating aegirine needles showing colour zoning perpendicular to direction of growth, and coarsening of later crystals. Plane polarised light. Drill hole 200 at 159 metres. B. M. 1973, P20(59). Scale line, 0.25 mm.

along the centres of veins, at feldspar boundaries, or scattered throughout feldspar crystals. Ore minerals are generally scarce, though what appears to be hydrated iron oxides (limonite?, goethite?) are rather plentiful, particularly within the system of veinlets.

The development of turbidity in the feldspars continues into the cores of grains and 'new' fresh feldspar starts to form at the rims. Even the microcline, which tends to resist alteration in the early stages, is now turbid. Sometimes primary plagioclase is still distinguishable from primary alkali feldspar, but commonly the feldspar takes on a 'flamy' appearance or appears to be vaguely perthitic. The new feldspar rims have complex sutured margins and patches of fresh, fine grained feldspar sometimes develops between the larger grains. The fine grained feldspar may or may not be finely twinned. The rocks often show the effects of strain, usually in the form of bent, broken and displaced twin lamellae in plagioclase, and bent cleavages in biotite. That general shattering of the rock facilitated penetration by fenitizing fluids is shown by the association of turbid feldspars and mechanical deformation features. More severe deformation is shown by occasional zones of comminuted minerals, and by mortar textures.

Amphibolite and hornblende schist

There is a complete gradation among the low grade fenites from amphibolites with 50 per cent or more hornblende, to hornblende-biotite schists. The amphibolites are more resistant to fenitization than the granite gneisses and schists, and there appears to be two principal reasons for this. Firstly, the hornblende is relatively stable in the outer fenite zones and resists alteration; and secondly, the system of veinlets which seems to be the principal means of access of the fenitizing fluids do not develop as easily in these rocks as in the gneisses and schists. Where such veins are developed, however, they are very distinctive.

As with the gneisses and schists the onset of fenitization is indicated by the development of turbidity in the feldspar. The feldspars in the amphibolites, however, are less disrupted by veinlets, but instead the turbidity gradually encroaches inwards from grain margins producing concentric patterns of turbidity (Fig. 11). The turbidity is more pronounced in the vicinity of the few fenitization veinlets, and in some specimens the feldspar is so turbid as to be almost opaque (Fig. 10). The alteration of the feldspar can become very intense before any alteration is apparent in the hornblende.

In only a few specimens is the alteration of the mafic minerals evenly spread through the rock as a whole, rather than being confined to the aureoles of veins. In these few rocks the hornblende is altered to a mixture of alkaline amphibole and phlogopite or phlogopite and alkali feldspar (Fig. 10). The alkaline amphibole, which forms ragged or sub-prismatic crystals which are sometimes poikilitic towards feldspar, is a magnesio-arfvedsonite varying from shades of pale blue to deep blue-green. Phlogopite is pale brown and forms subhedral to anhedral flakes which may be intimately intergrown with amphibole, form isolated flakes, or occur as small clusters of flakes. Primary biotite is replaced by a finely granular feldspar mosaic with opaque minerals outlining the cleavages. Carbonate is abundant.

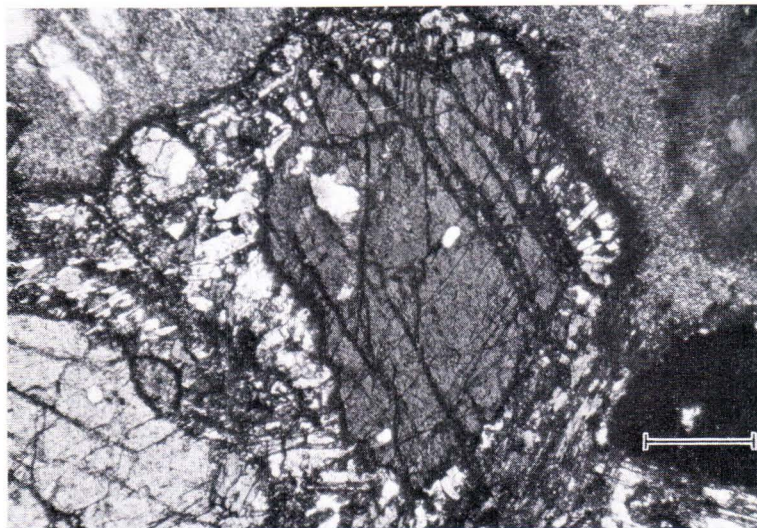


FIG. 10. A primary hornblende crystal (dark grey) being replaced peripherally by an aggregate of phlogopite, alkali feldspar, and carbonate, which is surrounded by very turbid (lightly speckled) feldspar. Plane polarised light. Drill hole 243 at 127 metres. B. M. 1973, P20 (23). Scale line, 0.25 mm.

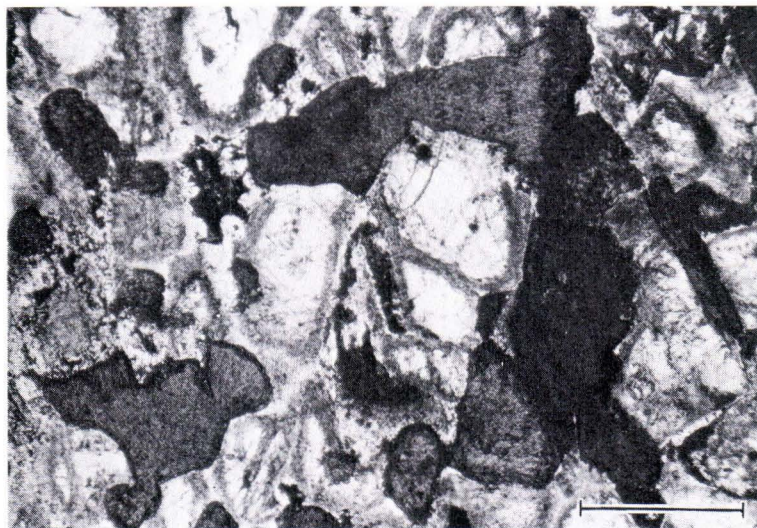


FIG. 11. Hornblende (black) altering to fine grained, rounded patches of aegirine (dark grey); and feldspar showing the peripheral development of turbidity in the vicinity of a fenite veinlet in a fenitized hornblende schist. Plane polarised light. Drill hole 243 at 120 metres. B. M. 1973, P20 (21). Scale line, 0.5 mm.

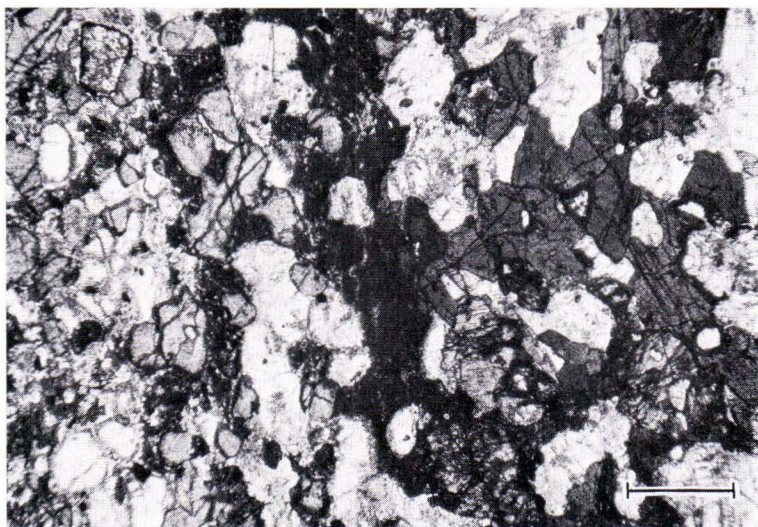


FIG. 12. Near to a veinlet hornblende (dark grey, to the right) is altered to fine grained, rounded patches of aegirine (medium grey, to the left), the transition being relatively sharp, in a fenitized hornblende schist; feldspar, pale grey. Plane polarised light. Drill hole 210 at 57 metres. B. M. 1973, P20(31) Scale line, 0.5 mm.

The fenite veinlets in the amphibolites usually have a central thread of carbonate with an aureole of fenitization up to 3 or 4 cm wide on either side. The vein plus aureole may be white to grey, or a distinctive brick red to pink; the latter type are described with the potassic fenites. The zones of alteration are sharply bounded against the amphibolite (Figs. 11 & 12). Within the altered zone feldspar is turbid, and hornblende is altered to aggregates of aegirine (Figs. 11 & 12), or alkaline amphibole plus pale brown phlogopite, and opaque minerals. The aegirine usually forms sharply bounded, rounded, fine-grained, fibrous aggregates, while the amphibole tends to be restricted to the outer parts of the alteration zones where it often forms rims to the primary hornblende. The style of alteration may be different on either side of a vein, and it is noticeable that the width of the alteration zones is not necessarily related to the size of the central vein of carbonate.

Syenitic fenites

In the syenitic fenites no primary minerals remain, though pseudomorphs after primary minerals, textures, or structures may be recognizable. The syenitic fenites are found in the inner parts of the fenite aureole, the best examples being encountered in boreholes 196, 210 and particularly in borehole 70 which cuts the contact with car-

bonatite. The mineralogy comprises essentially alkali feldspar and aegirine and or alkaline amphibole; phlogopite is abundant in some amphibole-rich fenites, and carbonate is always plentiful; opaque minerals are sometimes present.

Initially feldspar is turbid, as in the low to medium grade fenites, but turbidity becomes less marked until in some of the syenitic fenites from borehole 70 the feldspar is almost clear. In some specimens the granular mosaic of new feldspar, which develops between the large feldspar plates in some of the lower grade fenites, becomes more abundant; in others, however, the feldspar coarsens to form large poikilitic plates a centimetre or more across, which include patches of mafic minerals, sometimes in the form of a complex network of veins. In all textural types the intra-feldspar boundaries are always complexly sutured (Fig. 13). The feldspar is dominantly albite but some of the more turbid feldspar is untwinned and, apart from being alkali feldspar, it is difficult to determine its precise nature. The albite may be simply twinned on the albite law or form a very complex chequer albite, while a vaguely perthitic or 'flamy' pattern is sometimes evident. Deformation is shown by the almost ubiquitous bending and breaking of the twinned feldspars. Other types of twinning are sometimes present and patently produced mechanically, as shown by their spatial relationships to deformation features such as cracks along which there has been displacement.

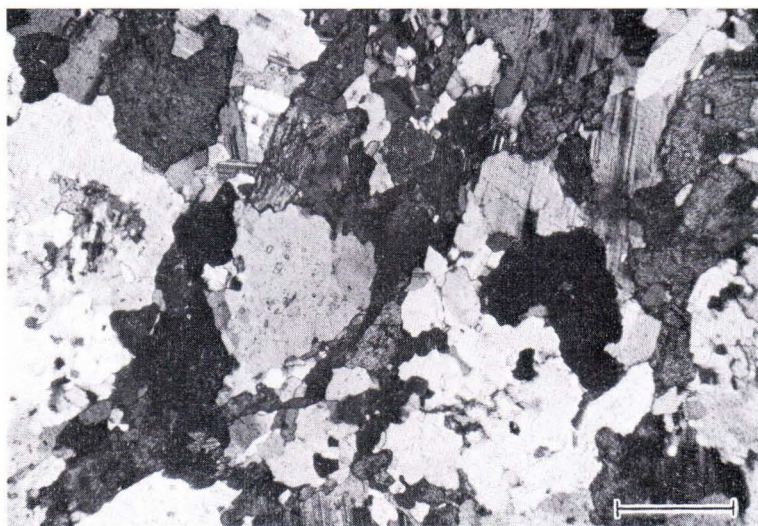


FIG. 13. Syenitic fenite. Alkali feldspar (white to grey, low relief) has lost its turbidity, and has complex sutured margins. Pyroxene has recrystallized to stout crystals. Crossed polarisers. Drill hole 70 at 161 metres. B. M. 1973, P20(73). Scale line, 0.5 mm.

Aegirine continues to crystallize in the syenitic fenites and may comprise as much as 40 per cent of some rocks. It characteristically forms clusters of radiating crystals which may be a centimetre or more across (Fig. 8), and a vague reticulate pattern of

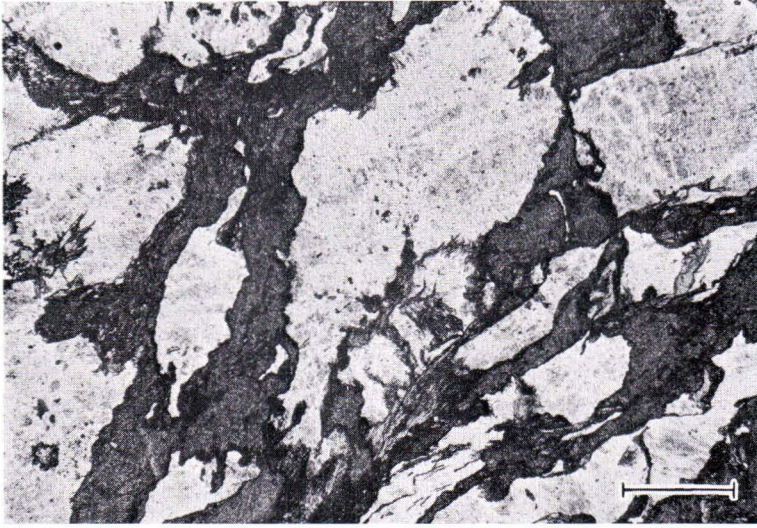


FIG. 14. A sinuous, reticulate vein pattern comprising fibrous aegirine (dark grey). Plane polarised light. Drill hole 200 at 175 metres. *B. M.* 1973, P20(62). Scale line, 0.5 mm.

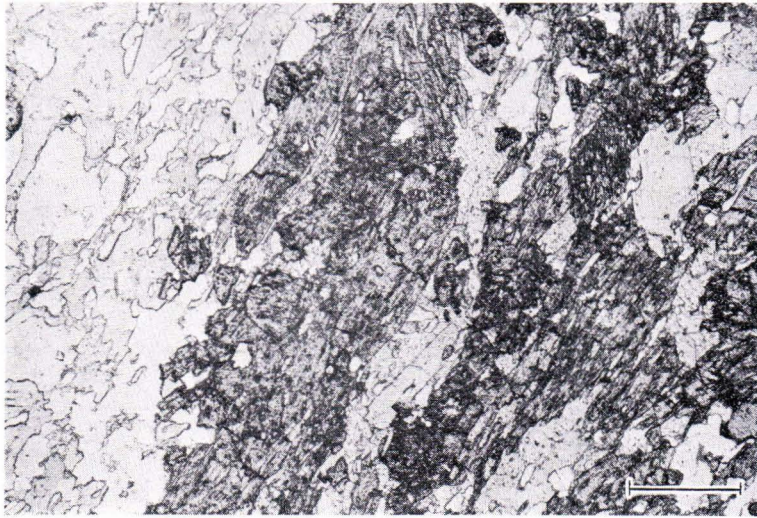


FIG. 15. Syenitic fenite from close to the carbonatite contact showing coarse aegirine-augite crystals (dark grey, centre and to the right), coarse alkaline amphibole (medium relief, to the left) and feldspar (white, low relief). Plane polarised light. Drill hole 70 at 161 metres. *B. M.* 1973, P20(73). Scale line, 0.5 mm.

veins (Fig. 14). The crystals are larger than in the low to medium grade fenites, and increase in size until in the fenites close to the carbonatite contact they are stout subhedral to euhedral prisms. In these rocks there is little sign of the usual fenite veinlet network (Figs. 13 & 15). The aegirine is deeply coloured in shades of buff,

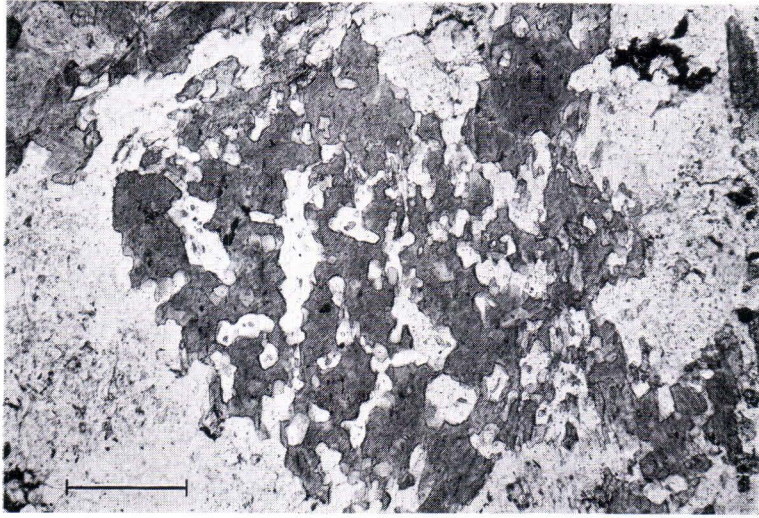


FIG. 16. A poikilitic plate of alkaline amphibole (dark grey) growing around and including alkali feldspar. Plane polarised light. Drill hole 196 at 93.5 metres. B. M. 1973, P20(81). Scale line, 0.25 mm.

yellow and green, and radiating masses may be colour zoned, but there is no appreciable difference in extinction angle across the zones. However, the stout pyroxenes from borehole 70 have a $a : z = 19-20^\circ$ indicating aegirine-augite.

Amphibole is very variable in colour, habit, and texture, and the abundance and variety of the amphiboles in the Sokli fenites appears to be unique. In many of the pyroxene-rich fenites a very pale green or blue amphibole occurs as isolated crystals or patches within pyroxene aggregates, and in some of the pyroxene fenites of borehole 70 a very pale blue-green to colourless amphibole forms occasional veinlets (Fig. 15). In other rocks a more abundant amphibole forms isolated, ragged, poikilitic plates (Fig. 16), while in fenites which are probably derived from amphibolites the amphibole is very abundant, of a deep blue-green colour, and forms patches which may replace the primary hornblende, and with which a brown phlogopite is usually intergrown. Cross-cutting veins composed almost wholly of amphibole are very striking in some rocks from boreholes 196 and 210, and may cut sharply across pyroxene fenite suggesting more than one stage of fenitization (Fig. 17). The veins are up to 0.5 cm across and the stout to acicular pale blue to green amphibole prisms are orientated parallel to the length of the rather sinuous veins, producing a remarkable appearance of flow (Figs. 18, 19 & 20). These veins are probably to be correlated with the zones of blue amphibole-rich fenite, up to three metres wide, which can be seen cutting across green pyroxene fenite in the trenches in the WNW and NNW part of the aureole.

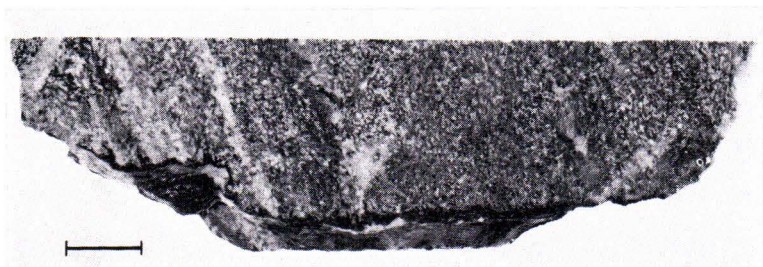


FIG. 17. Hand specimen of drill core showing a late alkaline amphibole-rich vein cutting sharply across a pyroxene fenite. Drill hole 210 at 71.2 metres. B. M. 1973, P20(37). Scale line, 1.0 cm.



FIG. 18. Veins of fibrous alkaline amphibole (darker grey and higher relief); the other mineral is alkali feldspar. Plane polarised light. Drill hole 243 at 72.5 metres. B. M. 1973, P20(14). Scale line, 0.5 mm.

In some parts of the core from borehole 70 there is a striking bluegreen amphibole, which forms stubby, euhedral prisms up to a millimetre long which are associated with phlogopite. In some places these two minerals are the sole constituents of the rock (Fig. 21). This amphibole-phlogopite rock forms lenses and patches within the more normal syenitic fenite but in places occurs as 'aureoles' to carbonate veins.

Phlogopite is invariably pale brown and associated with amphibole. Carbonate is abundant in all the syenitic fenites and may comprise as much as 15 volume per cent of the rock. It forms cross-cutting veins, isolated patches, and small grains within the feldspar. Opaque minerals are usually absent but are plentiful in a few specimens. A

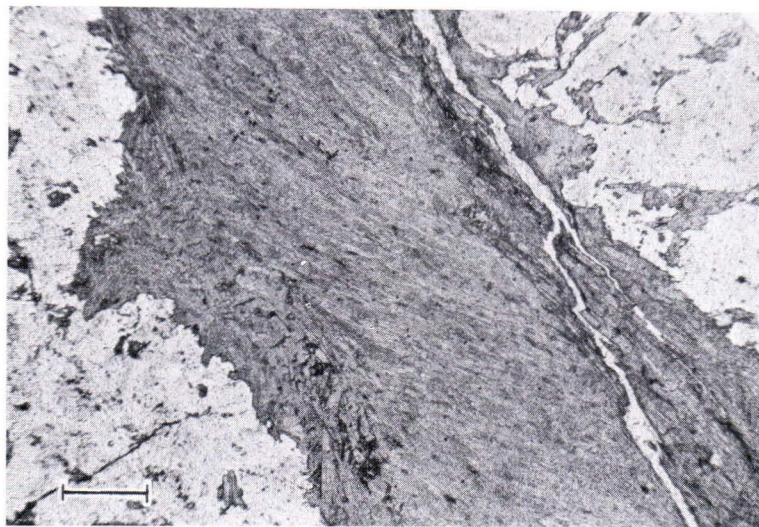


FIG. 19. Section across an alkaline amphibole vein (dark grey); there is also a little carbonate in the vein; the pale grey mineral is alkali feldspar. Plane polarised light. Drill hole 196 at 88.4 metres. B. M. 1973, P20(80). Scale line, 0.5 mm.

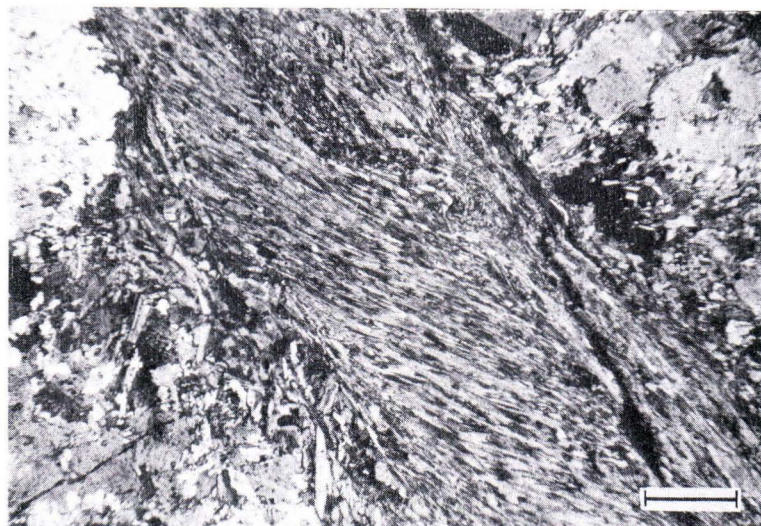


FIG. 20. Same as Fig. 19 but crossed polarisers, to show the fibrous nature of the alkaline amphibole and its general orientation along the vein. Scale line, 0.5 mm.

little apatite may occur, but in one thin section of amphibole-phlogopite rock from borehole 70 apatite comprises some 30 per cent of the rock. Zeolite has been identified in one section and probable cancrinite in another.



FIG. 21. A layer of alkaline amphibole rock (to the right, higher relief) adjacent to phlogopite rock. Plane polarised light. Drill hole 70 at 201.3 metres. B. M. 1973, P20(77). Scale line, 0.5 mm.

The syenitic fenites encountered on the fenite-carbonatite contact in borehole 70 are of especial interest in showing the highest grade of fenitization developed at Sokli. The most noteworthy features of these fenites are as follows: there are all gradations from pyroxene fenite, through pyroxene-amphibole fenite to amphibole fenite (see Fig. 15); phlogopite is exceptionally abundant in some samples and is always associated with amphibole; feldspar is usually clear or only slightly turbid and is dominantly albite; all the minerals are coarse-grained, pyroxene, for instance, forms stout prisms and not the fibrous aggregates characteristic of the lower grade fenites; the cross-cutting fenite veinlets are hardly discernable. These features combine to give the pyroxene syenitic fenites in particular, an 'igneous' appearance and indeed some specimens, if taken in isolation, could not be distinguished from igneous syenites.

Potassic fenites and 'phlogopitization'

A very distinctive group of fenites characterised by high K_2O values has been recognised at Sokli. They form only a small proportion of the total volume of fenites but are of considerable significance. They can be divided into three groups: firstly a group characterised by a general potassic feldspathization; secondly, a suite of potassium-rich metasomatic veins, and thirdly a group distinguished by the widespread development of phlogopite.

The first type of potassium metasomatism occurs only in specimens from boreholes 215 and 223 on the outer edge of the ESE part of the fenite aureole. The degree of fenitization is here low and the granite gneisses and biotite schists, which are the dominant rock types, contain feldspars that are only slightly turbid and have rare fenite veinlets. Whereas these normal fenites are grey, the potassic fenites are a distinctive pink to brick red. This red colour pervades the feldspars and may be concentrated along and in the vicinity of veinlets which form typical reticulate patterns. In section the colouration is reflected in an enhanced turbidity in the plagioclase feldspars, which may sometimes become almost opaque, but microcline remains fresh much longer. There is some concentration of iron oxides and carbonate along veinlets. Biotite is rapidly replaced by a fine-grained aggregate of untwinned feldspar with the traces of the cleavages outlined by iron oxides. Occasional patches of very fine-grained blue alkaline amphibole may occur along veinlets and a little aegirine is sometimes present.

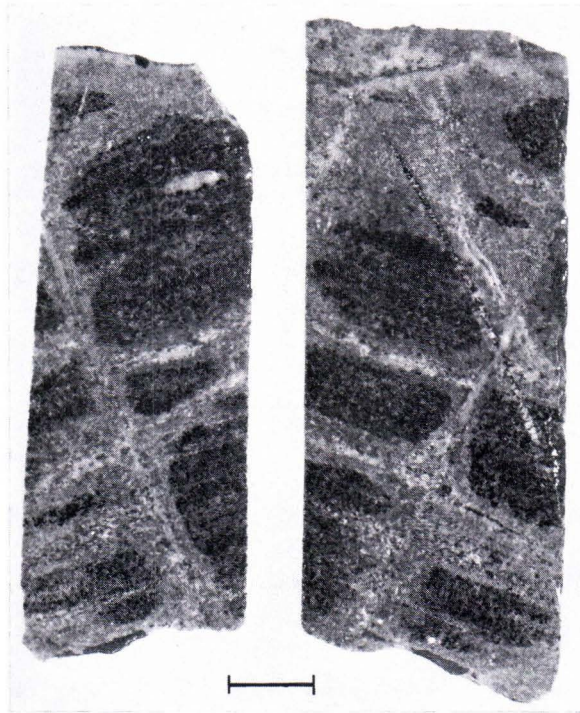


FIG. 22. A specimen of drill core showing amphibolite (dark grey to black) cut by veinlets of carbonate producing aureoles of potassium fenitization (grey). It is noteworthy that the foliation of the amphibolite has some control over the distribution of the fenitization. Drill hole 210 at 90.7 metres. B. M. 1973, P20(44). Scale line, 1.0 cm.

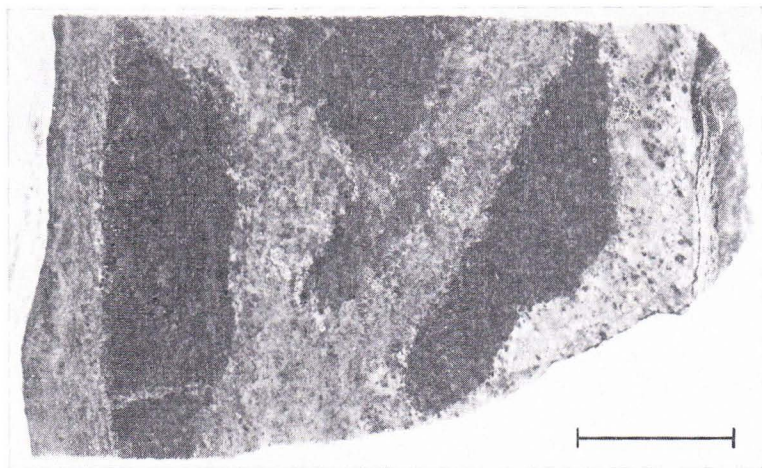


FIG. 23. A specimen of drill core showing amphibolite (black) being altered to potassic feneite along veins. Drill hole 200 at 157 metres. B. M. 1973, P20(58). Scale line, 1.0 cm.



FIG. 24. A rock consisting almost wholly of phlogopite; there are a few small crystals of alkaline amphibole also present. Rm 1117. Scale line, 0.5 mm.

The second type of potassic fenites consists of potassium-rich metasomatic veins which are common in the rocks from boreholes 243 and 210 in the ESE part of the aureole, and two examples have been recognised from borehole 200 on the SE part of the aureole. Whereas boreholes 215 and 223 were drilled mainly through granite gneisses and schists, 243 and 210 penetrated a considerable thickness of amphibolites

and hornblende schists, and it is to these latter rocks that the potassium-rich metasomatic veins appear to be restricted. It is probable that the style of potassium metasomatism is determined by the physical characteristics of the invaded rocks.

The veins are up to 3 or 4 cm wide and brick-red in colour. A central thread of carbonate is invariably present and the outer part of the zone of alteration to either side of the carbonate thread is sharply bounded against amphibolite or hornblende schist (Figs. 22 & 23). In section the zone to either side of the carbonate is seen to be composed of fine grained very turbid feldspar which is heavily impregnated and obscured by iron oxides, which are probably goethite or limonite. These oxides sometimes pseudomorph hornblende, but more commonly are disseminated throughout the rock. Scattered through this feldspar — iron oxide rock are irregularly shaped patches of very fine grained brown to olive green phlogopite, which sometimes appears to be secondary after hornblende. Phlogopite also occurs within and adjacent to the

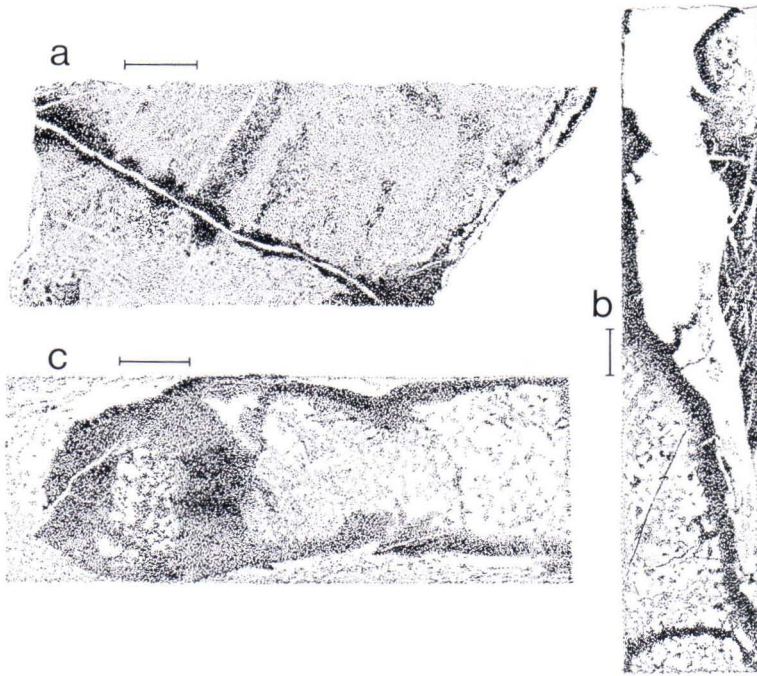


FIG. 25. Phlogopitization produced at carbonatite-fenite contacts. All three figures are based on drill core hand specimens. Scale lines, 1.0 cm.

(a) Carbonatite thread cutting amphibolite with an adjacent zone of phlogopitization (darker shading). Drill hole 243 at 98 metres. B. M. 1973, P20(19).

(b) A sinuous vein of carbonatite cutting syenitic fenite and producing a phlogopite-rich zone (darker shading) along the contact. Drill hole 255 at 112.16 metres.

(c) A fragment of fenite completely enveloped in carbonatite, with a dark phlogopite-rich reaction zone around it. Drill hole 255 at 110.0 metres.

carbonate veins, as irregular patches among feldspars, or as rounded masses either within the carbonate itself or as lobes within feldspar at carbonate — feldspar boundaries. Much of this phlogopite is developed manifestly by 'phlogopitization' of feldspar through the agency of the carbonate, and similar phlogopitization, although on a smaller scale, has also been observed associated with carbonate veinlets in the sodic fenites.

The third group of rocks which has undergone potassic metasomatism is particularly well shown in borehole 70, though single specimens from boreholes 196 and 243 are also to be included in this category. The characteristic feature of this group is a widespread replacement of feldspar by phlogopite to produce rocks which locally are entirely composed of phlogopite (Fig. 24). The development of phlogopite may be restricted to a zone along contacts with carbonate veins (Fig. 25), or be widely disseminated through the body of the rock, and it is commonly, though not always, associated with an alkaline amphibole.

The development of phlogopite along veins may result in a phlogopite rich zone up to 0.5 cm wide consisting of yellow-brown phlogopite crystals up to a millimetre long which are sometimes orientated perpendicular to the margin of the vein. The zone may be pure phlogopite or phlogopite and a blue alkaline amphibole (Fig. 26). There is some thin section evidence that phlogopite has replaced feldspar, whereas amphibole was either already present in the surrounding fenite or, if this fenite is

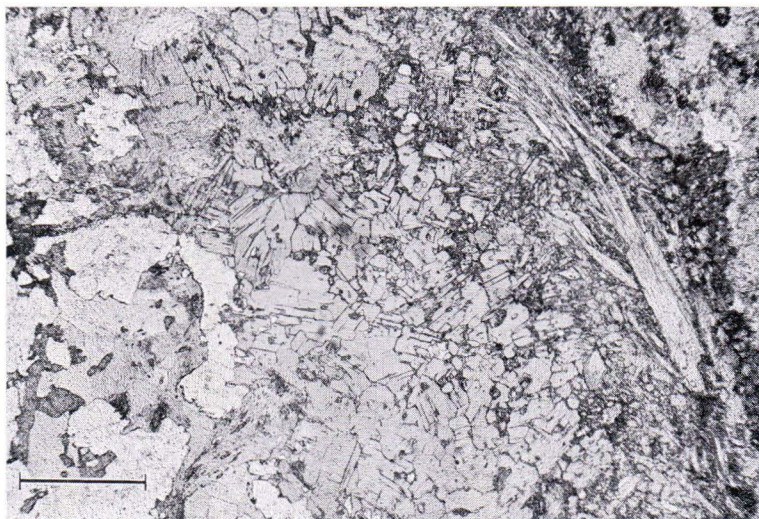


FIG. 26. Pyroxene-alkaline amphibole syenitic fenite (to the left) cut by a carbonatite vein (extreme right). Along the vein is an aureole of alkaline amphibole (bladed crystals concentrated nearer to the vein) and phlogopite (the most abundant mineral in the central part of the photomicrograph, and often with a well developed cleavage). A few aegirine crystals (dark grey) can be distinguished in the syenitic fenite amongst patches of alkaline amphibole (medium grey). Rm 1115. Scale line, 1.0 mm.

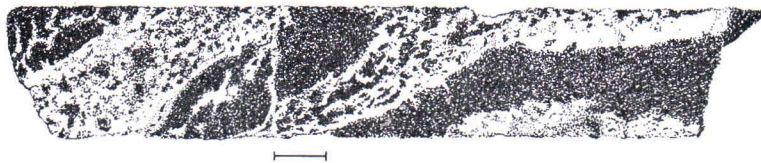


FIG. 27. A section of drill core comprising phlogopite-rich fenite from close to the carbonatite contact. The dark patches are mainly phlogopite with some alkaline amphibole. The white areas are alkali feldspar, carbonate, and apatite. Drill hole 70 at 201.3 metres. B. M. 1973, P20(77). Scale line, 1.0 cm.

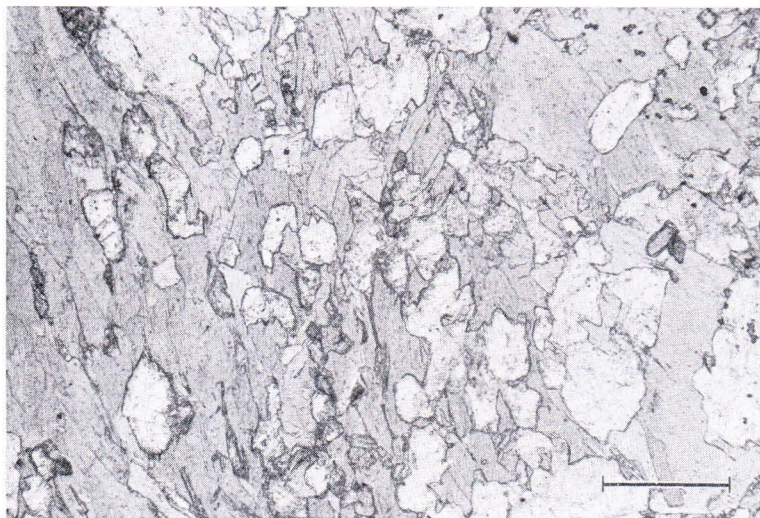


FIG. 28. Phlogopite (dark grey) developing around and replacing alkali feldspar (pale grey). Plane polarised light. Drill hole 70 at 202.5 metres. B. M. 1973 P20 78). Scale line, 0.5 mm.

pyroxene-bearing, has replaced the pyroxene. Phlogopite and amphibole are invariably present also within the carbonate veins.

In the more widely developed type of phlogopitization, which has been observed in rocks from borehole 70 only, the soft black phlogopite rock forms pods and lenses sometimes as much as 0.5 metres thick.(Fig. 27). In thin section the rock varies from small patches of almost pure phlogopite to phlogopite-amphibole rock. Small remnant areas of amphibole syenitic fenite which have resisted the replacement by phlogopite sometimes occur. The progress of the phlogopitization process can be seen in some syenitic fenites in which the phlogopite forms a discontinuous network extending around and between the feldspar grains which are gradually replaced inwards (Fig. 28).

The areal distribution of aegirine-bearing, amphibole-bearing and potassic fenites

Fig. 29 shows the distribution of aegirine and alkaline amphibole fenites and potassic fenites in the seven boreholes in the fenite aureole, plotted as a function of distance from the carbonatite contact. It is apparent that amphibole and aegirine occur throughout the aureole and that there is no correlation between their occurrence and the degree of fenitization. There is some bias, however, in the distribution of the potassic fenites of which the first two groups, i.e. those occurring as a general potassic feldspathization and as potassium-rich metasomatic veins, are concentrated in the outer parts of the aureole, particularly in borehole 215, whereas the third group of potassic fenites, which is characterised by the presence of phlogopite, is restricted to the inner part of the aureole.

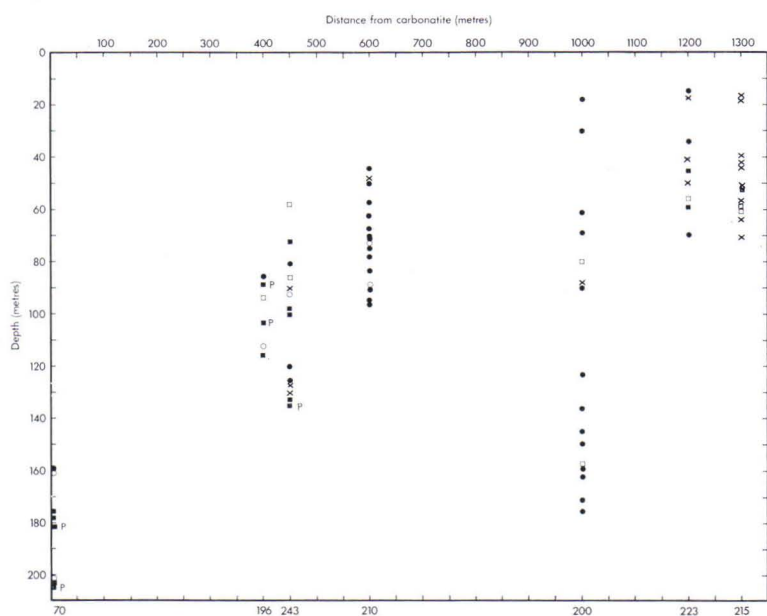


FIG. 29. Diagram illustrating the distribution of aegirine and alkaline amphibole-bearing and potassic fenites, together with areas of phlogopitization, as determined from thin sections, in the seven drill holes in the fenite aureole, the numbers of which are indicated, plotted against distance from the carbonatite-fenite contact. Filled circles, aegirine fenite; open circles, aegirine plus minor amphibole fenite; filled squares, amphibole fenite; open squares, amphibole plus minor aegirine fenite; X, potassic fenite; P, phlogopitization.

Possible mobilization of fenites

As already pointed out many of the rocks of borehole 70 are coarse grained with textures comparable with those of igneous rocks, and some rocks from this borehole



FIG. 30. Specimen of drill core showing a layer of coarse syenitic fenite with relatively sharp contacts against finer grained fenite. The coarser rock may represent a rheomorphosed fenite. Drill hole 210 at 73 metres. B. M. 1973, P20(41). Scale line, 1.0 cm.



FIG. 31. A specimen of drill core showing contact of coarse and fine grained syenitic fenite, similar to Fig. 30. Drill hole 210 at 72 metres. B. M. 1973, P20(38). Scale line, 1.0 cm.

display 'swirling structures', particularly in phlogopite-rich parts, which may indicate mobilization of the fenites close to the carbonatite contact.

Two lengths of core from borehole 210 show sharp contacts between very coarse grained fenite and a much finer grained variety (Figs. 30 & 31). One of these specimens consists of a coarse zone four centimetres wide with finer grained rock to either side (Fig. 30). Both the coarse and fine grained varieties are pyroxene syenitic fenites with very minor amphibole. The pyroxene in the coarser rock varies from fine grained fibrous aggregates to coarser aggregates of euhedral prisms, and the feldspars form large plates up to 0.5 cm in diameter. These specimens constitute perhaps the best evidence from Sokli of limited mobilization of the fenites, but it is possible, though unlikely, that the coarser and finer grained fenite types reflect original compositional differences in the country rocks.

Mineralogy

Feldspar

Feldspar was separated from some 50 rocks and investigated on a diffractometer in the ranges $2\theta = 20-23^\circ$ and $29-31^\circ$. The chemically analyzed specimens of un-fenitized granitic gneiss contain microcline with high obliquity values, obtained from the $1\bar{3}1-1\bar{3}1$ peaks, though the presence of albite peaks precludes accurate measure-

ment. Diffractometer traces of feldspars separated from the four analyzed amphibolites and hornblende schists show albite as the only component in three of them, while in the fourth, which is the most potassic, a potassium feldspar can just be detected. Measurement of the $\bar{2}01$ sodic feldspar peak, and using the data of Bowen and Tuttle (1950), gave feldspar compositions for two specimens of $Ab_{93} Or_7$ and $Ab_{90} Or_{10}$, which matches fairly well with the normative feldspar compositions from the rock analyses.

In 15 of the 26 feldspar fractions separated from syenitic fenites sodic feldspar only could be detected, while in the rest only very small peaks corresponding to a potassic feldspar phase could be identified. The results indicated compositions varying between $Ab_{95} Or_5$ and $Ab_{99} Or_1$.

Feldspar from the two most potassic fenites which have been analyzed (nos. 61 & 75, Tables 10 & 12) together with those from four analyzed potassic veins were amongst the feldspars investigated. Diffractograms of feldspars from rocks 61 and 75 are dominated by the presence of potassic feldspar with small sodic feldspar peaks just detectable. The compositions of the potassic feldspar, estimated from the 201 peaks, appear to be very close to $Or_{100} Ab_0$. The sodic feldspar $\bar{2}01$ peaks are too diffuse to measure accurately. The potassic feldspar is a microcline having obliquity values of 0.78 in both rocks. The feldspar of the most potassic of the veins (68) gave similar results with a potassic feldspar phase close to $Or_{100} Ab_0$ having an obliquity of 0.75, but the sodic feldspar peaks are more pronounced in this rock. Feldspars from the other three separated veins have distinct $\bar{2}01$ peaks for both potassic and sodic feldspars, for which in 72 potassic feldspar ($\bar{2}01$) is greater than sodic feldspar ($\bar{2}01$), while the reverse holds in 74 and 66. The indicated relative abundances of the feldspars match closely the normative feldspar compositions of the rocks. The compositions of the two feldspar phases in the three veins are $Ab_{96-99} Or_{4-1}$ and $Ab_0 Or_{100}$, or very close to it. The potassic feldspar is triclinic.

Amphibole

Eleven alkali amphiboles have been separated and chemically analysed; the results are given in Table 4 and some details of nomenclature, colour, texture, etc., are given in Table 5. There was not enough material for the determination of the water content of two of the specimens (17, 24) and these have been calculated to 23 (O, OH, F). Total alkalis are greater than 2.5 atoms per half unit cell for all except 24, in which they are 2.4. The Y group is dominated by iron and magnesium, which have a close reciprocal relationship (Fig. 32). These features together place these amphiboles in the arfvedsonite-eckermannite series, and taking the subdivisions of this series at mg ratios ($100 \text{ Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mn})$) of 30 and 70 as recommended by Deer, Howie and Zussman (1963, Fig. 89), four amphiboles prove to be eckermannites and the rest magnesio-arfvedsonites (but see below).

TABLE 4

Chemical analyses of alkaline amphiboles and ferro-tschermakitic hornblende

	16	17	18	19	20	21	22	23	24	25	26	27
SiO ₂	51.09	54.40	52.24	52.68	51.88	52.86	51.82	53.39	56.66	54.77	56.27	42.43
TiO ₂	1.08	1.82	0.75	0.90	0.47	0.55	1.35	0.33	0.30	1.28	0.28	1.70
Al ₂ O ₃	3.03	0.96	1.93	2.51	4.21	1.75	2.09	2.35	0.66	0.57	0.41	11.59
Fe ₂ O ₃	12.77	10.18	11.88	9.76	9.77	9.75	8.86	7.99	5.76	8.65	4.52	6.11
FeO	6.53	6.08	5.72	6.51	5.14	4.67	4.30	4.60	3.84	2.91	2.92	14.31
MnO	0.32	0.27	0.21	0.38	0.41	0.37	0.27	0.29	0.70	0.55	0.92	0.40
MgO	11.30	11.29	12.56	12.97	13.74	15.21	16.02	16.16	17.48	16.02	18.77	7.90
CaO	1.57	0.71	1.14	1.92	2.23	1.32	3.73	2.83	4.14	1.63	4.47	10.76
Na ₂ O	9.14	7.71	9.59	8.97	9.11	9.40	8.66	8.75	7.62	9.59	7.78	1.68
K ₂ O	1.05	2.50	0.94	1.05	0.59	1.03	1.02	1.02	1.86	1.09	1.88	0.91
H ₂ O ⁺	1.05	—	1.60	1.52	1.48	1.26	0.90	1.12	—	1.07	0.94	1.55
H ₂ O ⁻	0.02	—	0.04	0.03	0.03	0.03	< 0.01	0.07	—	0.03	0.06	nil
F	1.27	1.03	1.56	1.21	1.08	1.76	1.29	1.41	1.75	2.10	1.80	0.04
others	0.53	0.55	0.45	0.22	0.23	0.15	0.31	0.39	0.09	0.38	0.10	—
	100.75	97.50	100.61	100.63	100.37	100.11	100.63	100.70	100.86	100.64	101.12	99.38
O ≡ F	0.53	0.43	0.66	0.51	0.45	0.74	0.55	0.60	0.74	0.88	0.76	0.02
	100.22	97.07	99.95	100.12	99.92	99.37	100.08	100.10	100.12	99.76	100.36	99.36
trace elements in p.p.m.												
Cr	200	200	100	100	< 100	< 100	< 100	200	< 100	200	< 100	—
Li	nil	—	nil	nil	nil	nil	nil	nil	—	nil	nil	—
Nb	200	1 000	200	200	tr	100	100	< 100	nil	100	tr	—
Ni	100	300	50	100	100	5	100	100	50	15	50	—
Cu	175	300	nil	nil	nil	nil	nil	nil	nil	nil	30	—
Zn	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	—
V	1 800	400	1 500	300	600	300	500	500	100	600	300	—
Zr	1 500	2 000	1 500	1 000	1 000	700	1 500	2 000	200	1 800	300	—
Y	nil	nil	nil	nil	nil	nil	25	nil	nil	nil	nil	—
Sr	50	20	50	90	100	70	170	150	420	100	200	—
Ba	100	300	100	100	< 100	100	100	100	500	100	< 100	—
Rb	30	60	45	30	30	40	30	30	60	40	40	—
Ga	40	5	60	25	50	25	25	25	tr	25	5	—
Sn	20	—	50	25	40	100	50	50	—	25	nil	—
Co	50	100	50	100	100	50	—	100	150	—	120	—
Pb	tr	30	nil	50	—	300	—	—	—	—	—	—

The dominance of the Y group by magnesium and iron and the relationship between them is shown in Fig. 32 using both the new data here presented together with analyses taken from the literature. Ferric iron exceeds ferrous for the Sokli amphiboles (Fig. 33 a) and there is a distinct decrease in this ratio from eckermannitic to arfvedsonitic amphiboles as a group. It is noteworthy that up to 2 % fluorine has been found in these amphiboles.

Kempe (1969, Fig. 1) showed on a plot of mg ratio against weight per cent MgO a linear relationship for the arfvedsonite-eckermannite series but he had data for only three amphiboles with mg ratios > 70. The new data shows that there is a well defined slope change at an mg ratio of about 50 (Fig. 33 b). This slope change sepa-

Numbers of ions on the basis of 24 (O, OH, F), or 23 oxygens for analyses 17 and 24 for which water has not been determined

	16	17	18	19	20	21	22	23	24	25	26	27
Si	7.528	7.638	7.597	7.631	7.487	7.656	7.530	7.684	7.586	7.841	7.964	6.424
Al	0.526	0.159	0.331	0.429	0.716	0.299	0.358	0.399	0.104	0.096	0.068	2.069
Ti	0.120	0.192	0.082	0.098	0.051	0.060	0.148	0.036	0.030	0.138	0.030	0.194
Fe ³⁺	0.416	1.076	1.300	1.064	1.061	1.063	0.969	0.865	0.580	0.932	0.481	0.696
Fe ²⁺	0.805	0.714	0.696	0.789	0.620	0.566	0.523	0.554	0.430	0.348	0.346	1.812
Mn	0.040	0.032	0.026	0.047	0.050	0.045	0.033	0.035	0.079	0.067	0.110	0.051
Mg	2.482	2.362	2.722	2.800	2.955	3.283	3.470	3.466	3.488	3.418	3.959	1.782
Ca	0.248	0.107	0.178	0.298	0.345	0.205	0.581	0.436	0.594	0.250	0.678	1.746
Na	2.611	2.099	2.704	2.519	2.549	2.639	2.440	2.441	1.978	2.652	2.157	0.493
K	0.197	0.448	0.174	0.194	0.109	0.190	0.189	0.187	0.318	0.199	0.340	0.174
OH	1.032	—	1.552	1.469	1.425	1.217	0.873	1.075	—	1.022	0.888	1.567
F	0.592	—	0.718	0.554	0.493	0.806	0.593	0.642	—	1.022	0.806	0.019
Z	8.00	7.80	7.93	8.00	8.00	7.95	7.89	8.00	7.69	7.94	8.00	8.00
Y	4.92	4.37	4.82	4.86	4.94	5.02	5.14	5.04	4.61	4.90	4.96	5.02
X	3.06	2.65	3.06	3.01	3.00	3.03	3.21	3.06	2.89	3.11	3.17	2.41
100 Mg (Mg+Fe ²⁺ + Fe ³⁺ + Mn)	52.4	56.5	57.4	59.6	63.0	66.2	69.5	70.4	71.6	71.7	80.9	41.0

For details of amphibole types, localities, and rocks from which they were separated see Table 5. In calculating the formulae of amphiboles 17 and 24, for which there are no water determinations, the values for F were ignored.

Major elements and Cr, Sr, Ba, and Rb by A. J. Easton; trace elements by V. K. Din.

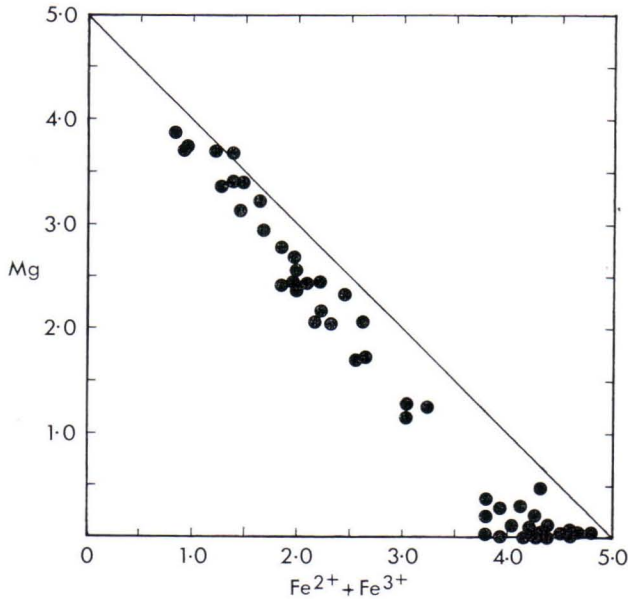


Fig. 32. Plot of Mg against (Fe²⁺ + Fe³⁺) for arfvedsonites, magnesio-arfvedsonites, and eckermannites using new data and data taken from the literature including Borley (1963), Brock *et al.* (1964), Deer, Howie, and Zussman (1963), Kempe (1969), Kempe and Deer (1970), McKie (1966), Nash and Wilkinson (1970), Nayak and Neuvonen (1964), Nickel and Mark (1965), Sutherland (1969), and Velde (1971).

TABLE 5

Some details of the amphiboles for which chemical data are given in Table 4

number	B. M. number	drill hole and depth	nomenclature of Deer, Howie and Zussman (1963)	suggested new nomenclature	general colour	crystal forms	rock type from which separated
16	1973, P20 (14)	243 at 72.5 m.	magnesioarfvedsonite	ferri-eckermannite	pale green-yellow	acicular cross-cutting masses	alkaline amphibole syenitic fenite
17	» (25)	243 at 132 m.	»	» »	deep green-lilac	stubby prisms	alkaline amphibole (phlogopite) syenitic fenite
18	» (67)	223 at 45.3 m.	»	» »	blue-green	very fine grained fibrous masses	alkaline amphibole quartz fenite
19	» (73)	70 at 161 m.	»	» »	very pale-green	euhedral stubby prisms	aegirine-augite-alkaline amphibole syenitic fenite
20	» (76)	70 at 200.5 m.	»	» »	pale green-lilac	stout prisms	aegirine-augite-alkaline amphibole syenitic fenite
21	» (77)	70 at 201.3 m.	»	» »	deep green-blue	stubby prisms	alkaline amphibole-phlogopite rock
22	» (78)	70 at 202.5 m.	»	» »	medium green-lilac	stubby prisms	phlogopite-alkaline amphibole syenitic fenite
23	» (80)	196 at 88.4 m.	eckermannite	» »	medium green-lilac	acicular cross-cutting masses	alkaline amphibole-phlogopite syenitic fenite
24	» (81)	196 at 93.5 m.	»	» »	deep green-lilac	stout prisms	alkaline amphibole-aegirine syenitic fenite
25	» (82)	196 at 103 m.	»	» »	deep green-lilac	stout prisms	alkaline amphibole-phlogopite syenitic fenite
26	» (84)	196 at 115.5 m.	»	eckermannite	deep green-lilac	short prisms	alkaline amphibole syenitic fenite
27	1973, P19 (8)	trench 29	ferro-tschemakitichornblende		olive-green to yellow	short prisms	unfentized amphibolite

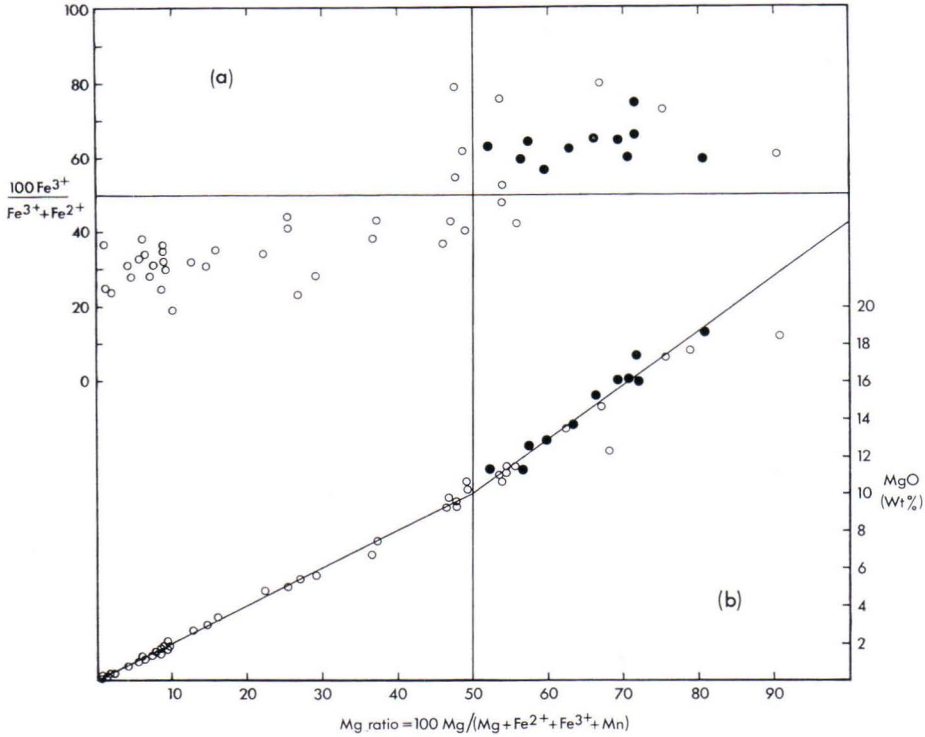


FIG. 33. (a) Plot of mg ratio ($100 \text{ Mg}/\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mn}$) against ferric iron ratio ($100 \text{ Fe}^{3+}/\text{Fe}^{3+} + \text{Fe}^{2+}$) for arfvedsonites, magnesio-arfvedsonites, and eckermannites. Filled circles, new Sokli data; open circles, data taken from literature as specified for Fig. 32.

(b) Plot of mg ratio against weight per cent MgO for arfvedsonites, magnesio-arfvedsonites, and eckermannites. Symbols as for (a) above. Attention is drawn to the change of slope at an mg ratio of about 50.

rates those amphiboles with mg ratios > 50 , in which $\text{Fe}^{3+} > \text{Fe}^{2+}$ from those of mg ratio < 50 , in which $\text{Fe}^{2+} > \text{Fe}^{3+}$, and is probably an arithmetic effect of the differing atomic weights of ferrous and ferric iron.

Deer, Howie and Zussman (1963) placed the boundary between eckermannite and magnesio-arfvedsonite at an mg ratio of 70 because of a supposed change in attitude of the optic axial plane from perpendicular to (010) in the arfvedsonites to parallel to (010) in the eckermannites. The optical data on which this is based is very sparse but it is hoped at some future date to investigate optically the amphiboles separated during this work, as they conveniently span the crucial range.

Consideration of the slope change at an mg ratio close to 50 on Fig. 33 b and the change of $\text{Fe}^{3+} : \text{Fe}^{2+}$ ratio corresponding to this (Fig. 33 a), — which is caused by the variation of Fe^{2+} through the series not through any significant change of Fe^{3+} (Fig. 34) — suggests that a more satisfactory division of the arfvedsonite-eckermannite

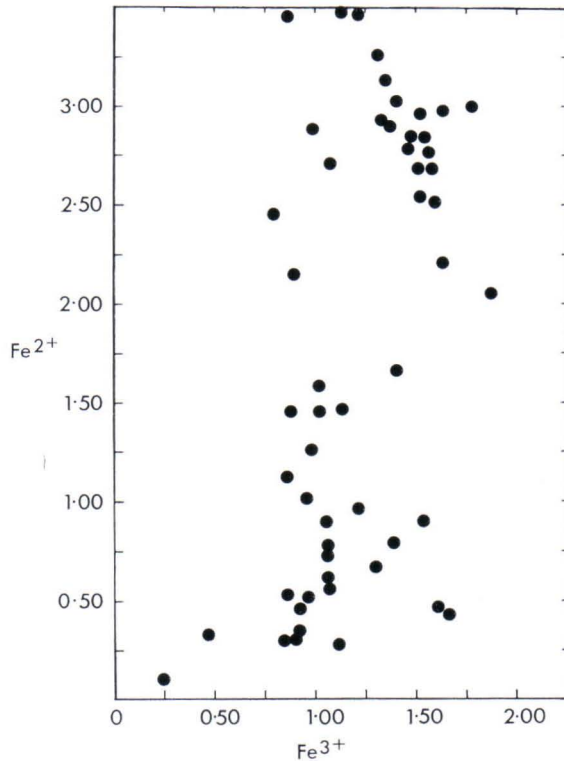


FIG. 34. Plot of Fe^{3+} against Fe^{2+} for arfvedsonites, magnesio-arfvedsonites, and eckermannites using the new Sokli data and the data taken from the literature as specified with Fig. 32.

series would be at this point. On this basis the arfvedsonites have mg ratios < 50 and the eckermannites > 50 . This would remove the anomaly of Deer, Howie and Zussman's scheme in which an amphibole with an mg ratio of, say, 69 is called arfvedsonite — with the prefix 'magnesio' — although it lies closer to pure eckermannite than pure arfvedsonite. It also has the advantage of a chemical basis, for the determination of the optical properties of the arfvedsonite-eckermannite amphiboles present formidable difficulties, so that only rarely can optical criteria be applied anyway.

Further subdivision is possible as follows:

Arfvedsonite	— mg ratio 0— 25
Magnesio-arfvedsonite	— mg ratio 26— 50
Ferri-eckermannite	— mg ratio 51— 75
Eckermannite	— mg ratio 76—100

The prefix 'ferri' follows the usage of Leake (1968) who recommended that it be used for calciferous amphiboles when $\text{Fe}^{3+} > \text{Fe}^{2+}$. In the majority of amphiboles in this series in which the mg ratio > 50 , Fe^{3+} is greater than Fe^{2+} (Fig. 33 a). Applying this nomenclature to Sokli amphiboles only one is now an eckermannite while all the rest are ferri-eckermannites (Table 5).

There is a distinct colour change through the series which corresponds closely to the variation in mg ratio, such that those rich in iron are strongly coloured in shades of blue and green, which becomes paler as the mg ratio increases through shades of green and lilac to very pale green. There appears to be no relationship between crystal habit, texture, and chemical composition, but there is a correlation of amphibole composition with distance from the carbonatite contact, which is illustrated by Fig. 35. There is a general increase in the mg ratio of the amphiboles towards the carbonatite contact.

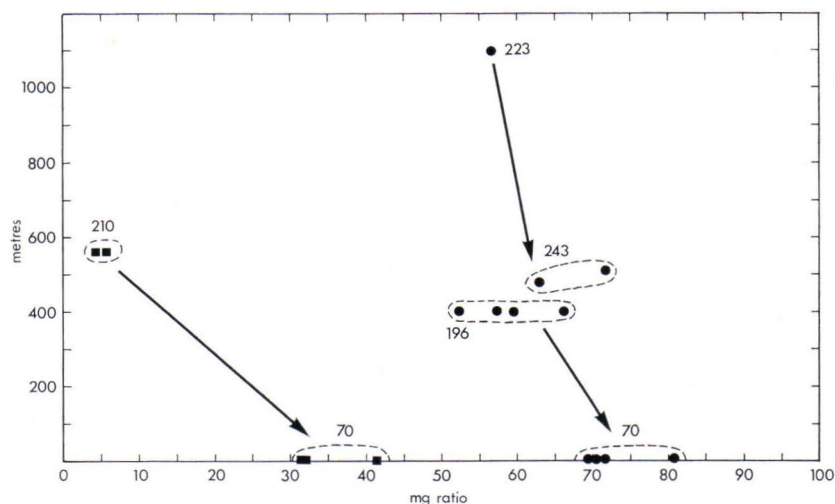


FIG. 35. Plot of the mg ratios of Sokli alkali amphiboles and pyroxenes shown as a function of distance from the carbonatite-fenite contact. Circles, amphiboles; squares, pyroxenes. The numbers of the drill holes from which the specimens were taken are indicated.

Pyroxene

Five pyroxenes were separated and analyzed (Table 6). Numbers 28 and 29 are from drill hole 210 some 500 metres from the carbonatite/fenite contact, and three (30 to 32) are from drill hole 70 which cuts the contact. The pyroxene analyses from drill hole 70 rocks have been adjusted to allow for 2.8%, 5.3% and 7.4% alkaline amphibole contamination, which was estimated from fluorine data on the pyroxenes and the known amounts of fluorine in the amphiboles. Trace element data for pyroxenes 30, 31 and 32 are not given because of the amphibole contamination.

TABLE 6
Chemical analyses of aegirines and aegirine-augites

	28	29	30	31	32
SiO ₂	51.74	52.40	53.12	53.98	53.03
TiO ₂	1.75	1.25	1.18	1.26	1.63
Al ₂ O ₃	1.92	1.34	0.84	0.80	0.81
Fe ₂ O ₃	26.44	28.20	18.14	15.99	19.80
FeO	1.97	1.38	2.33	2.31	1.75
MnO	0.10	0.07	0.62	0.55	0.41
MgO	0.82	0.67	5.15	6.31	4.21
CaO	0.57	0.41	8.43	9.32	6.72
Na ₂ O	13.32	12.82	9.36	8.21	10.24
K ₂ O	0.05	0.28	0.08	0.07	0.00
H ₂ O ⁺	0.74	0.82	0.66	0.75	0.90
H ₂ O ⁻	0.06	0.06	0.01	0.03	0.05
others	0.36	0.49	0.00	0.00	0.00
Total	99.84	100.19	99.92	99.58	99.55

trace elements in p.p.m.

Cr	200	200			
Nb	600	1 500			
Ni	10	10			
Zn	nil	nil			
V	1 000	1 000			
Zr	800	800			
Y	nil	nil			
Sr	30	30			
Ba	100	<100			
Rb	<10	20			
Co	nil	—			
Ga	50	50			

Numbers of ions on the basis of 6 oxygens

Si	1.992	2.014	2.014	2.036	2.020
Al	0.087	0.061	0.038	0.036	0.036
Ti	0.051	0.036	0.034	0.036	0.047
Fe ³⁺	0.766	0.816	0.517	0.454	0.568
Fe ²⁺	0.063	0.044	0.074	0.073	0.056
Mn	0.003	0.002	0.020	0.018	0.013
Mg	0.047	0.038	0.291	0.355	0.239
Ca	0.024	0.017	0.342	0.377	0.274
Na	0.994	0.955	0.688	0.600	0.756
K	0.002	0.014	0.004	0.003	0.000
Z	2.00	2.01	2.01	2.04	2.02
Y	1.01	1.00	0.97	0.97	0.96
X	1.02	0.99	1.03	0.98	1.03

28. Aegirine from aegirine syenitic fenite. Drill hole 210 at 83 m. (B. M. 1973, P20(42)).

29. Aegirine from aegirine quartz fenite. Drill hole 210 at 95 m. (B. M. 1973, P20(45)).

30. Aegirine-augite from aegirine-augite-(alkali amphibole) syenitic fenite. Drill hole 70 at 159 m. (B. M. 1973, P20(72)).

31. Aegirine-augite from aegirine-augite-alkaline amphibole syenitic fenite. Drill hole 70 at 161 m. (B. M. 1973, P20(73)).

32. Aegirine-augite from aegirine-augite-alkaline amphibole syenitic fenite. Drill hole 70 at 200.5 m. (B. M. 1973, P20(76)).

Analyses 30, 31 and 32 have been corrected for contamination by amphibole (for details see text). Major elements and Cr, Sr, Ba, and Rb by A. J. Easton; trace elements by V. K. Din.

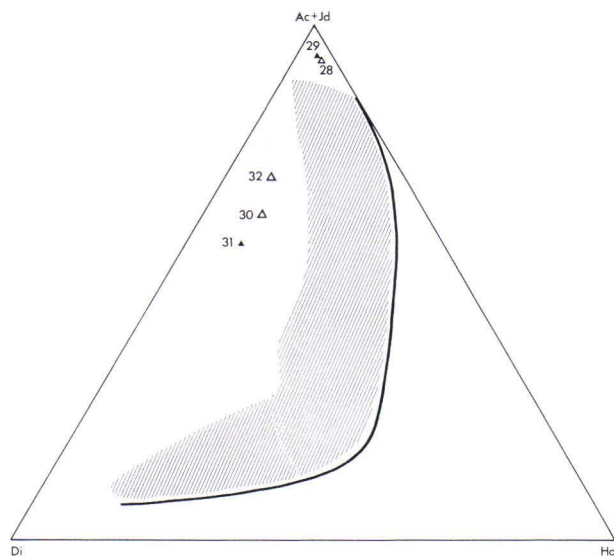


FIG. 36. Plot of Sokli pyroxenes in terms of acmite + jadeite — diopside — hedenbergite. Numbers correspond to analyses in Table 6. For significance of triangular plots see text. Shaded area includes pyroxenes from alkaline rocks of East Africa (Tyler and King, 1967); heavy line defines trend of pyroxenes of the Morotu district, Japan (Yagi, 1966)

High H_2O^+ values were found in all the pyroxenes and these are too high to be caused by amphibole contamination and appear to be real. These high values are unexplained. The pyroxene formulae, however, are calculated on a water-free basis.

The pyroxenes are plotted on an acmite + jadeite-diopside-hedenbergite diagram (Fig. 36) according to the method of calculation recommended by Yoder and Tilley (1962), in which the size of the triangles represent the 'error of closure' proportional to the Tschermak's molecule and titanite. Tschermak's molecule is low in these pyroxenes because Si is relatively high and so Al^{iv} is low. The two pyroxenes from borehole 210 are aegirines while the other three are aegirine-augites. The trend which these five pyroxenes define close to the Ac + Jd — Di side of the triangle is very unusual as compared, for instance, with the alkaline series pyroxenes of East Africa (Tyler and King, 1967) or the Morotu district series of Japan (Yagi, 1966).

The hedenbergite-poor nature of the pyroxenes seems to be a reflection of the rock composition, particularly the ferric to ferrous iron ratio. The aegirine-bearing rocks have ratios of 8 : 1 and 12 : 1, whereas the rocks with aegirine-augite have ratios between 3.5 : 1 and 6 : 1. These high ratios, combined with the low total iron values of the rocks, must suppress the production of hedenbergite molecule.

Measurements of $a : z$ for pyroxenes in sections from seven of the boreholes in the fenites gave values consistently of 9° or less, indicating aegirine. Only in borehole 70,

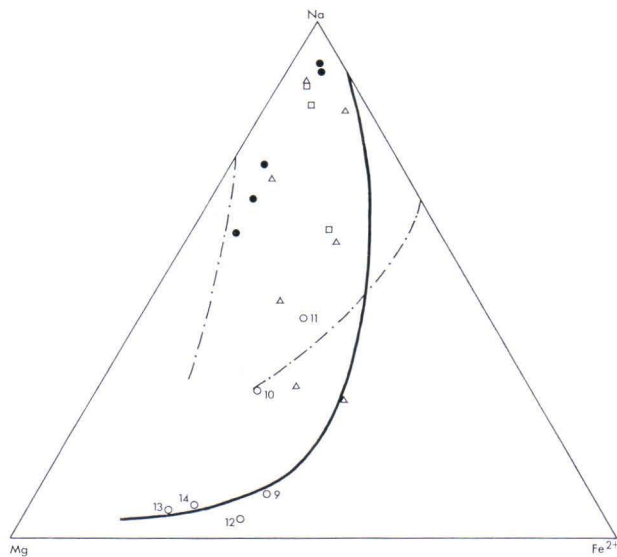


FIG. 37. Plot of pyroxenes from fenites in terms of Na—Mg—Fe²⁺. Solid circles, Sokli pyroxenes; open triangles, East African fenite pyroxenes (Tyler and King, 1967; Sutherland, 1969); open squares, Oldonyo Dili fenite pyroxenes (McKie, 1966); open circles, Alnö fenite pyroxenes (von Eckermann, 1966). For numbers adjacent to Alnö pyroxenes see text. Heavy line defines trend of pyroxenes from the Morotu district, Japan (Yagi, 1966); dot-dash lines define area of pyroxenes from crystalline schists according to Yagi (1966, Fig. 7).

which cuts the carbonatite contact, are values characteristic of aegirine-augite (19—20°) encountered. It is apparent, therefore, that whatever the nature of the country rock the first pyroxene produced by fenitization is aegirine, and only in the innermost part of the fenite aureole are chemical conditions such that aegirine-augite is produced. This effect parallels the change in mg ratio in the amphiboles (Fig. 35).

As a result of her work on East African fenites Sutherland (1969, p. 123) was able to show a relationship between pyroxene composition and proximity to the carbonatite contact; high grade syenitic fenites containing aegirine-augite and lower grade fenites aegirine. The data from Sokli and from Sutherland (1969) and two other pyroxenes from East African fenites (Tyler & King, 1967), together with three pyroxenes from fenites at Oldonyo Dili (McKie, 1966), and six pyroxenes from Alnö fenites (von Eckermann, 1966), are shown on an Na—Mg—Fe²⁺ plot (Fig. 37). Two of the Oldonyo Dili pyroxenes are aegirines and one an aegirine-augite which McKie (1966, p. 284) thought reflected a difference in composition of the primary rock, but Sutherland (1969, p. 123) has suggested that this may not necessarily be so. It is difficult from McKie's analyses of the rocks from which the pyroxenes were separated, to decide which rock is the most highly fenitized, since all three are syenitic fenites.

One of the Alnö pyroxenes is from a nepheline fenite (von Eckermann, 1966, Table 3, no. 9), two from fenites (op.cit.nos 10 & 11) (the caption for no. 11 describes it as from »a leucocratic nephelinitic fenite«); and three (op.cit.nos. 12, 13 and 14) from basic fenites. All are from close to carbonatite contacts and range from aegirine-augite to diopsidic aegirine-augite. In the Alnö Memoir (von Eckermann, 1948, p. 30) aegirine is described from the fenites but von Eckermann comments that the aegirine content of the pyroxenes (based on optical determinations) is dependent on the type of migmatite which has been fenitized (op.cit. p. 30). It is difficult to decide whether von Eckermann's nepheline fenites or basic fenites represent the higher grade of fenitization, so that the direction of pyroxene compositional change at Alnö, the trend of which is apparent on Fig. 37, is open to doubt. This difficulty might be resolved by data on pyroxenes from Alnö low grade fenites. There is no information available on the grade of fenitization of the two fenite pyroxenes analysed by Tyler and King (1967).

No analyses are available of fenite pyroxenes from the Fen Complex, Norway, except for an approximate 'spectral' analysis (Saether, 1957, p. 16) which does not distinguish ferrous from ferric iron. However, Saether describes the pyroxenes as aegirine-augite shading into aegirine and gives a: z as 'small'. In a large collection of fenites from the Fen Complex made by one of us (ARW), the pyroxenes in the lower grade fenites are always aegirine, but a specimen of syenitic fenite 0.5 metres from the melteigite contact 80 metres west of Melteig Farm is an aegirine-augite with a: z = 40°. This observation suggests that at Fen also there is a decrease in acmite content of the pyroxenes with increasing fenitization.

The 21 fenite pyroxene analyses available are of widely differing compositions (Fig. 37) as characterises the pyroxenes of crystalline schists, for which the suggested limits given by Yagi (1966, Fig. 7) are shown on Fig. 37 together with the trend for the Morotu district alkaline volcanic Series of Japan (Yagi 1966, Fig. 6). It would appear, therefore, that there is a complete series of pyroxenes possible in the fenites from aegirine to diopsidic aegirine augites, as there are in igneous pyroxenes, except that the field is rather more variable for the fenites in terms of Fe²⁺ — Mg substitution.

Phlogopite

Five micas have been analysed (Table 7) and all are phlogopite. One (33) is from an amphibole-phlogopite fenite in which there are broad selvages along carbonate veinlets consisting almost wholly of phlogopite; another (34) is from an alkaline amphibole-phlogopite fenite forming layers in fenitized hornblende schist. Three specimens come from drill hole 70 on the fenite — carbonatite contact and occur in a phlogopite-apatite sövite vein (35), a phlogopite-alkaline amphibole rock forming irregular masses in carbonatite (36), and an alkaline amphibole-phlogopite syenitic fenite (37).

TABLE 7
Chemical analyses of phlogopites

	33	34	35	36	37
SiO ₂	41.82	40.68	40.64	42.04	41.33
TiO ₂	0.45	1.05	0.43	0.76	0.76
Al ₂ O ₃	11.69	12.13	11.46	10.31	10.50
Fe ₂ O ₃	1.88	4.59	2.54	2.15	1.51
FeO	6.48	8.18	7.00	8.30	9.56
MnO	0.20	0.27	0.17	0.24	0.25
MgO	21.82	18.37	22.98	21.77	20.94
CaO	1.22	0.59	0.98	0.75	0.27
Na ₂ O	1.22	1.24	0.71	0.48	0.64
K ₂ O	8.86	7.43	9.59	10.12	10.56
H ₂ O ⁺	2.17	2.21	2.26	1.41	1.47
H ₂ O ⁻	0.22	2.11	0.01	0.02	0.27
F	2.09	1.12	1.33	1.68	2.26
others	0.19	0.56	0.11	0.12	0.14
	100.31	100.53	100.21	100.15	100.46
O ≡ F	0.88	0.47	0.56	0.70	0.95
	99.43	100.06	99.65	99.45	99.51
	trace elements in p.p.m.				
Cr	300	1 200	<100	<100	<100
Nb	nil	200	nil	100	<100
Ni	75	400	tr	100	280
Cu	tr	25	tr	tr	nil
Zn	nil	nil	nil	nil	nil
V	200	300	100	50	25
Zr	60	50	25	40	50
Y	nil	nil	nil	nil	nil
Sr	130	20	90	70	20
Ba	700	2 000	600	500	500
Rb	310	245	270	410	440
Ga	50	75	200	100	100
Co	50	125	110	—	80

All five phlogopites are rather similar with little variation in the mg ratio, and they contain a moderate amount of fluorine.

Chemical relationships among co-existing minerals

Of the chemically analyzed minerals in the Sokli fenites there are two amphibole-pyroxene and two amphibole-phlogopite co-existing pairs. The chemical relationships between these pairs are illustrated in Figs. 38 & 39 on which are also plotted three amphibole-pyroxene pairs from fenites described by Sutherland (1969) and one by McKie (1966), together with an amphibole-biotite pair from a fenite at Oldonyo Dili (McKie 1966). Although on Fig. 38 there is some crossing of tie-lines, it is apparent that there is some approach to equilibrium with respect to the partitioning of magne-

Table 7 Numbers of ions on the basis of 24 (O, OH, F)

	33	34	35	36	37
Si	6.123	6.112	5.991	6.284	6.214
Al	2.108	2.148	1.991	1.817	1.851
Ti	0.050	0.119	0.048	0.085	0.086
Fe ³⁺	0.207	0.519	0.282	0.242	0.171
Fe ²⁺	0.794	1.028	0.863	1.038	1.202
Mn	0.025	0.034	0.021	0.030	0.032
Mg	4.762	4.114	5.049	4.850	4.693
Ca	0.191	0.095	0.155	0.120	0.044
Na	0.346	0.361	0.203	0.139	0.187
K	1.655	1.424	1.804	1.930	2.026
OH	2.120	2.215	2.223	1.406	1.475
F	0.968	0.532	0.620	0.794	1.075
Z	8.00	8.00	7.98	8.00	8.00
Y	5.98	6.07	6.26	6.35	6.25
X	2.19	1.88	2.16	2.19	2.26
A	3.80	2.75	2.84	2.20	2.55

- 33. Phlogopite from phlogopite-amphibole syenitic fenite. Drill hole 243 at 98 m. (B. M. 1973, P20(19)).
 - 34. Phlogopite from phlogopite-amphibole syenitic fenite layer within less fenitized hornblende schist. Drill hole 243 at 100 m. (B. M. 1973, P20(20)).
 - 35. Phlogopite from phlogopite-apatite carbonatite vein cutting amphibole syenitic fenite. Drill hole 70 at 178 m. (B. M. 1973, P20(75)).
 - 36. Phlogopite from phlogopite-amphibole rock. Drill hole 70 at 201.3 m. (B. M. 1973, P20(77)).
 - 37. Phlogopite from phlogopite-amphibole syenitic fenite. Drill hole 70 at 202.5 m. (B. M. 1973, P20(78)).
- Major elements and Cr, Sr, Ba, and Rb by A. J. Easton; trace elements by V. K. Din.

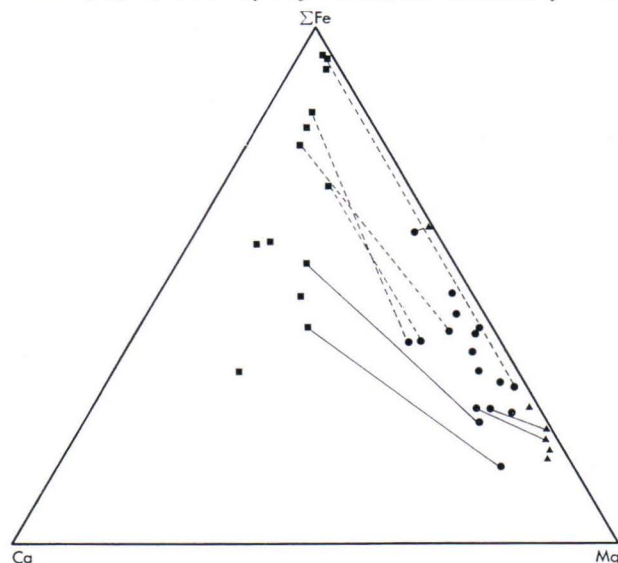


FIG. 38. Plot of fenite amphiboles (circles), pyroxenes (squares), and micas (triangles) in terms of total Fe—Ca—Mg using Sokli data, of which co-existing pairs are joined by tie lines; and three amphibole — pyroxene pairs of Sutherland (1969), and an amphibole — pyroxene and amphibole — mica pair of McKie (1966) which are joined by dashed tie lines.

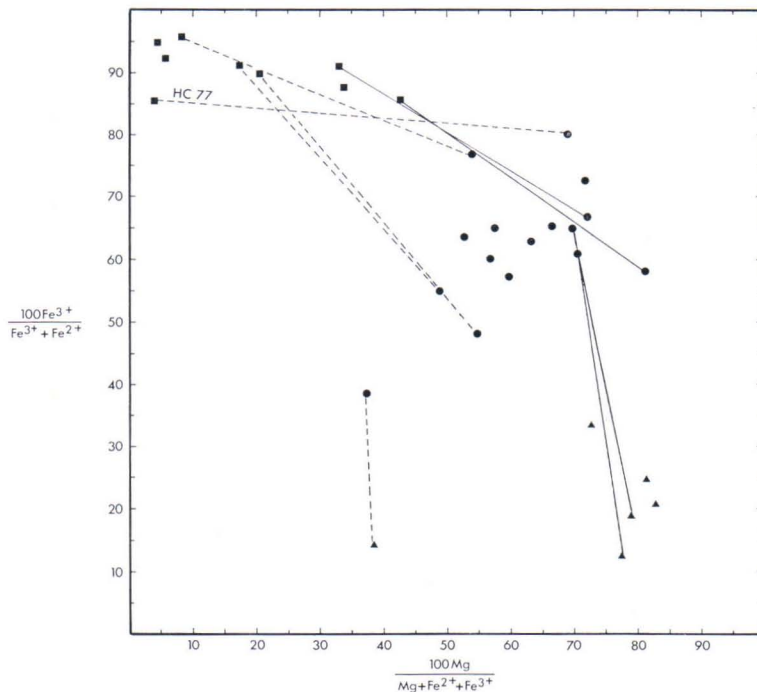


FIG. 39. Plot of mg ratio ($100 \text{ Mg} / \text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+}$) against ferric iron ratio ($100 \text{ Fe}^{3+} / \text{Fe}^{3+} + \text{Fe}^{2+}$) for fenite amphiboles, pyroxenes and micas using the same data and symbols as in Fig. 38.

sium and iron, in that aegirine-augites co-exist with the most magnesian amphiboles, and the more aegirine-rich pyroxenes co-exist with more iron-rich amphiboles. The same feature is illustrated by Fig. 39, but the pair HC77 (Sutherland 1969) is aberrant in that the ferric/ferrous iron ratio of the amphibole is rather higher than would be expected.

Apart from the data given in this paper, it appears that only one analyzed mica from a fenite associated with carbonatite is reported in the literature. This is a biotite from a quartz-bearing magnesio-arfvedsonite fenite at Oldonyo Dili (McKie, 1966, Table 10, Bt 3). Analyses of phlogopites from fenitized quartzites of the Borralan Complex (Woolley *et al.*, 1972) are not used because they are associated with nepheline syenites and not carbonatite. Although the data are scarce, the parallel tie-lines of the amphibole-mica pairs on Fig. 39 suggest that, as with the amphibole-pyroxene pairs, iron and magnesium vary sympathetically, the more iron-rich Oldonyo Dili biotite co-existing with an arfvedsonitic amphibole, while the Sokli magnesium-rich micas co-exist with eckermannitic amphiboles.

The data on co-existing mineral pairs in fenites, although rather limited as yet, indicate therefore that, in spite of the fact that fenites are metasomatic rocks of rather

variable composition and are characterised microscopically by replacement textures, the mineral phases are sensitive to chemical variations and approach equilibrium assemblages.

A further feature worthy of note on Fig. 39 is the relative state of oxidation and Mg/Fe ratios of the pyroxenes, amphiboles and micas. The pyroxenes are most iron-rich and most highly oxidized, the micas the most iron-poor and least oxidized, while the amphiboles have intermediate values for both. This feature is of considerable significance with regard to the paragenesis of these rocks, as described later.

Petrochemistry

Forty six rocks have been analysed including eight unfenitized 'country rocks' and 38 fenites, all of which were taken from drill cores. The analyses are given in Tables 8, 10 and 12.

The analyses have been recalculated to a standard cell of 100 anions, a procedure first advocated by McKie (1966) for comparative work with fenites. Most of the Sokli fenites however are exceptionally rich in carbonate, and a number of them have CO₂ values in excess of 10 %, indicating contents of approximately 20 % by volume of carbonates. Although the chemical changes during fenitization are intimately related to the composition of the carbonates, the first aim in any chemical study of fenites must be to discover what changes have taken place in the country rocks as a result of fenitization. The main interest therefore must be in the silicate phases of the fenite. Because of the large volume of carbonate in the Sokli fenites it has been found that the principal changes in concentration of the major elements are obscured if the analyses are recalculated to a standard anion cell as they stand. To overcome this the analyses were recalculated to atoms, then carbonate was removed, together with the equivalent amounts of calcium, magnesium and ferrous iron. The carbonate-free analysis was then recalculated to 100 anions (Tables 9, 11 and 13). This recasting of the analyses assumes that most of the carbonate was simply added to the rock with a consequent increase in volume, and therefore in order to follow the changes in the number of cations during fenitization, the country rocks should be compared with the fenites on a carbonate-free basis. Although the basic assumption may be challenged, it is considered to be a good approximation, and results in a considerable decrease in the scatter of plotted analyses points on some diagrams which would seem to substantiate this.

The carbonate in the fenites is rarely pure calcite, but contains varying proportions of magnesium and iron. To allow the calculation of the analyses to a carbonate-free basis, while taking into consideration the presence of magnesium and iron, it proved necessary to analyse the carbonates. They were extracted by boiling the powdered rock with 2 % or 4 % acetic acid, filtering, diluting, then determining Fe, Mg, and Ca in

TAB-
Chemical analyses

	38	39	40	41	42	43	44	45	46
SiO ₂	56.31	56.18	48.93	53.42	59.25	59.42	56.04	54.72	60.92
TiO ₂	0.16	0.39	0.88	0.51	0.83	0.49	0.53	0.64	0.46
Al ₂ O ₃	10.37	14.43	11.01	12.59	11.69	14.18	14.89	10.92	14.30
Fe ₂ O ₃	3.57	2.65	4.82	5.94	8.41	5.10	3.83	9.23	5.93
FeO	1.19	0.34	4.77	1.05	0.73	0.65	1.86	0.90	0.67
MnO	0.27	0.16	0.29	0.32	0.13	0.20	0.18	0.22	0.09
MgO	7.20	1.64	6.84	2.82	2.06	1.24	3.02	2.32	0.95
CaO	4.73	7.04	5.28	6.30	1.91	3.16	4.44	4.00	1.62
Na ₂ O	9.39	9.81	6.86	8.66	10.15	9.10	7.87	9.38	10.48
K ₂ O	0.79	0.32	2.25	0.83	0.85	2.47	1.48	1.04	1.00
H ₂ O ⁺	0.69	0.37	1.01	0.42	0.44	0.44	0.68	0.43	0.27
H ₂ O ⁻	0.16	0.21	0.75	0.28	0.19	0.17	0.22	0.35	0.04
P ₂ O ₅	2.02	0.87	0.03	0.99	0.04	0.09	0.16	0.20	0.01
CO ₂	2.20	4.92	5.73	5.77	2.31	3.28	3.15	4.46	2.21
F	1.00	0.19	0.25	0.22	0.11	0.03	0.51	0.11	0.02
Cl	nil	—	—	—	—	—	—	—	—
S	0.01	0.07	0.18	0.25	0.05	0.29	0.03	0.01	0.01
others	0.247	0.173	0.322	0.445	0.503	0.367	0.332	0.445	0.292
	100.31	99.76	100.20	100.81	99.65	100.68	99.22	99.37	99.27
O ≡ F, Cl, S	0.426	0.115	0.195	0.218	0.071	0.158	0.078	0.051	0.013
Total	99.88	99.65	100.01	100.60	99.58	100.52	99.14	99.32	99.26

trace elements

Cr	25	tr	410	50	65	< 5	40	40	35
Li	45	nil	15	40	50	5	50	30	5
Nb	150	150	200	200	200	200	150	250	300
Ni	55	tr	165	75	5	80	100	90	80
Cu	15	13	20	15	15	5	10	10	10
Zn	235	80	175	165	130	200	90	140	900
V	400	4	300	200	350	340	300	250	350
Zr	300	120	200	200	600	200	200	400	150
Y	100	10	nil	50	nil	nil	25	10	nil
Sr	490	430	460	560	690	250	450	375	150
Ba	40	650	470	2 000	1 900	1 500	1 200	2 000	210
Rb	5	2	35	nil	10	50	45	10	5

38. Alkaline amphibole syenitic fenite. Drill hole 243 at 72.5 m. (B. M. 1973, P20(14)).
39. Alkaline amphibole-aegirine syenitic fenite. Drill hole 243 at 96 m. (B. M. 1973, P20(16)).
40. Alkaline amphibole-phlogopite syenitic fenite. (fenitized hornblende schist). Drill hole 243 at 135 m. (B. M. 1973, P20(26)).
41. Aegirine-alkaline amphibole syenitic fenite. Drill hole 210 at 71.2 m. (B. M. 1973, P20(38)).
42. Aegirine-(alkaline amphibole) syenitic fenite. Drill hole 210 at 72 m. (B. M. 1973, P20(38)).
43. Aegirine syenitic fenite. Drill hole 210 at 77.5 m. (B. M. 1973, P20(40)).
44. Aegirine syenitic fenite. Drill hole 210 at 73 m. (B. M. 1973, P20(41)).
45. Aegirine syenitic fenite. Coarse grained type in sharp contact with 44 above. Drill hole 210 at 73 m. (B. M. 1973, P20(41)).
46. Aegirine syenitic fenite (coarse grained type). Drill hole 210 at 83 m. (B. M. 1973, P20(42)).
47. Aegirine quartz fenite (coarse grained type). Drill hole 210 at 95 m. (B. M. 1973, P20(45)).
48. Aegirine-(alkaline amphibole) syenitic fenite. Drill hole 200 at 171 m. (B. M. 1973, P20(61)).
49. Aegirine syenitic fenite. Drill hole 200 at 171 m. (B. M. 1973, P20(61)).
50. Aegirine-(alkaline amphibole) syenitic fenite (coarse grained type). Drill hole 200 at 175 m. (B. M. 1973, P20(62)).

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of sodic fenites

47	48	49	50	51	52	53	54	55	56	57	58
54.92	56.95	46.36	58.11	62.42	62.21	46.63	57.83	58.58	51.98	51.10	45.16
0.67	0.41	0.23	0.73	0.27	0.21	1.17	0.48	0.17	0.25	0.35	0.61
7.86	13.87	12.06	11.36	14.88	14.00	11.69	12.09	14.03	10.62	12.89	11.24
13.76	4.94	3.76	8.45	3.63	2.48	4.75	5.13	2.06	4.49	3.16	3.57
1.02	0.97	2.60	0.92	0.53	0.64	5.55	1.02	2.15	1.56	3.05	3.21
0.16	0.35	0.80	0.33	0.13	0.18	0.29	0.20	0.12	0.28	0.29	0.48
1.75	2.50	4.11	2.17	1.38	3.04	5.36	3.34	6.06	6.21	4.97	5.51
2.93	3.74	7.39	2.04	3.29	3.80	8.29	5.06	1.79	7.13	5.84	8.48
9.01	10.20	6.43	10.70	10.00	9.06	7.18	9.59	8.26	8.38	7.75	7.14
2.08	0.48	2.63	0.50	0.81	1.24	1.27	0.81	2.48	1.14	1.64	0.99
0.34	0.25	0.24	0.18	0.27	0.40	1.05	0.30	0.76	0.69	0.50	0.56
0.08	0.03	0.05	0.07	0.04	0.02	0.25	0.07	0.57	0.21	0.14	0.24
0.03	0.24	0.06	0.20	0.34	0.32	0.19	0.62	0.37	0.80	0.22	0.10
4.20	4.52	12.09	2.87	1.32	1.71	5.87	2.95	1.60	5.50	7.84	12.82
0.03	0.15	0.03	0.21	0.05	0.19	0.25	0.21	0.63	0.71	0.37	0.19
—	—	—	—	—	—	—	—	—	—	—	—
0.10	0.12	0.68	0.08	0.01	nil	0.62	0.04	nil	0.09	0.43	0.23
0.599	0.505	0.736	0.640	0.230	0.179	0.435	0.506	0.245	0.293	0.271	0.406
99.54	100.22	100.26	99.56	99.60	99.68	100.85	100.25	99.88	100.33	100.81	100.90
0.063	0.123	0.353	0.128	0.03	0.08	0.415	0.108	0.267	0.344	0.371	0.195
99.48	100.10	99.90	99.43	99.57	99.60	100.43	100.14	99.61	99.99	100.44	100.70

in p.p.m.

60	20	90	65	15	40	95	20	65	15	55	55
20	35	nil	90	10	10	15	25	90	55	60	50
800	100	100	200	100	nil	100	100	100	150	100	300
65	80	80	65	80	80	75	80	190	65	100	90
15	10	10	10	nil	10	20	15	10	5	30	25
75	115	65	85	55	85	175	85	100	140	225	75
500	300	450	125	50	70	250	400	80	300	300	300
200	200	100	300	300	200	150	500	200	400	150	100
nil	25	25	5	tr	tr	10	40	nil	150	30	25
1 500	2 400	2 800	1 600	860	760	810	990	560	585	800	785
1 300	900	2 400	2 800	460	300	1 800	1 800	400	320	180	1 500
30	5	40	5	nil	nil	20	nil	50	15	10	10

51. Aegirine-augite -(alkaline amphibole) syenitic fenite (coarse grained type). Drill hole 70 at 159 m. (B. M. 1973, P20(72)).
52. Aegirine-augite-alkaline amphibole syenitic fenite. Drill hole 70 at 161 m. (B. M. 1973, P20(73)).
53. Alkaline amphibole-phlogopite syenitic fenite (femitized hornblende schist). Drill hole 70 at 181.8 m. (B. M. 1973, P15(11)).
54. Aegirine-augite-alkaline amphibole syenitic fenite. Drill hole 70 at 200.5 m. (B. M. 1973, P20(76)).
55. Alkaline amphibole-phlogopite -(aegirine) syenitic fenite. Drill hole 70 at 202.5 m. (B. M. 1973, P20(78)).
56. Alkaline amphibole-phlogopite syenitic fenite. Drill hole 196 at 88.4 m. (B. M. 1973, P27(80)).
57. Alkaline amphibole-phlogopite syenitic fenite. Drill hole 196 at 103 m. (B. M. 1973, P10(32)).
58. Aegirine-alkaline amphibole syenitic fenite. Drill hole 196 at 111.8 m. (B. M. 1973, P20(83)).

Minerals in rock names which are bracketed signifies present in only minor amounts.

For location of drill holes see Fig. 2.

Analyst: V. K. Din.

FeO; H₂O and CO₂ determined by G. C. Jones. F determined by A. J. Easton.

Compositions of sodic fenites recast in cations per 100 oxygen anions after

	38	39	40	41	42	43	44	45	46
Si	33.43	34.13	31.43	33.16	35.33	35.28	33.82	34.11	35.83
Ti	0.71	0.18	0.43	0.24	0.37	0.22	0.24	0.30	0.20
Al	7.26	10.33	8.33	9.21	8.22	9.93	10.59	8.02	9.91
Fe ³⁺	1.59	1.21	2.33	2.77	3.77	2.28	1.74	4.33	2.62
Fe ²⁺	0.49	0.03	1.91	0.04	0.36	0.15	0.94	0.00	0.13
Mn	0.14	0.06	0.16	0.17	0.06	0.10	0.09	0.11	0.04
Mg	6.12	1.36	5.19	1.66	1.29	0.47	1.88	1.05	0.27
Ca	1.40	0.77	0.62	0.76	0.01	0.15	1.18	0.45	0.00
Na	10.81	11.55	8.54	10.42	11.74	10.47	9.21	11.34	11.95
K	0.60	0.25	1.84	0.66	0.65	1.87	1.14	0.83	0.75
OH	2.73	1.50	4.33	1.74	1.75	1.74	2.74	1.79	1.06
P	1.01	0.45	0.02	0.52	0.02	0.04	0.08	0.10	0.00

For details of rock types and localities see Table 8.

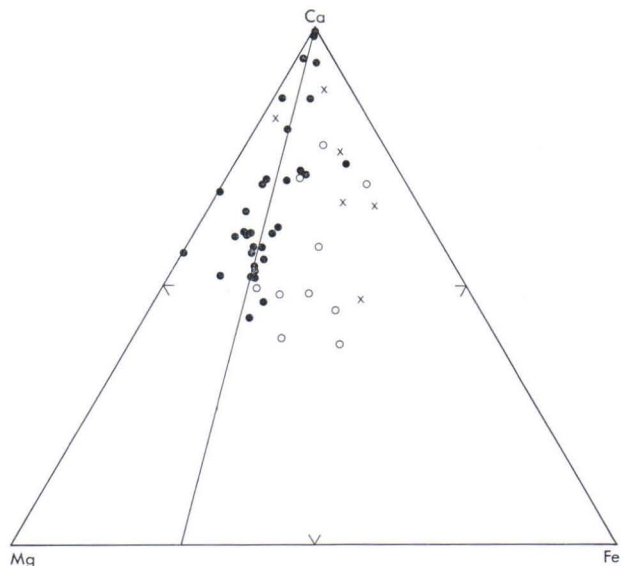


FIG. 40. Plot of the proportions, in atoms, of Ca, Mg, and Fe (total iron calculated as Fe²⁺) in carbonates extracted from fenites. For details of technique see text. Solid circles, sodic fenites; open circles, potassic fenites; crosses, carbonatites. The line drawn from the Ca corner has been taken through the sodic fenite points only.

the solutions directly by atomic absorption. The reproducibility of the results was usually quite good, but sometimes it was necessary to average two or three determinations. Some of the fenites, particularly those enriched in potassium, are highly ox-

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removal of C and equivalent amounts of Ca, Mg and Fe²⁺ (see text)

47	48	49	50	51	52	53	54	55	56	57	58
34.70	34.52	32.11	35.19	35.95	35.92	30.18	34.61	34.40	32.59	32.71	31.11
0.32	0.19	0.12	0.33	0.12	0.09	0.57	0.22	0.07	0.12	0.17	0.32
5.85	9.91	9.85	8.11	10.10	9.53	8.92	8.53	9.71	7.85	9.72	9.13
6.54	2.25	1.96	3.85	1.57	1.08	2.31	2.31	0.91	2.12	1.52	1.85
0.08	0.19	0.00	0.14	0.25	0.30	2.84	0.36	1.06	0.38	0.91	0.01
0.08	0.18	0.27	0.17	0.06	0.09	0.16	0.10	0.06	0.15	0.16	0.28
0.57	0.91	0.00	1.17	1.18	2.61	4.95	2.80	4.90	4.90	2.62	1.70
0.00	0.33	0.00	0.07	1.00	1.02	0.95	1.16	0.25	1.42	0.00	0.00
11.04	11.98	8.63	12.56	11.17	10.14	9.01	11.13	9.40	10.19	9.62	9.54
1.68	0.37	2.32	0.39	0.60	0.91	1.05	0.62	1.86	0.91	1.34	0.87
1.43	1.01	1.11	0.73	1.04	1.54	4.53	1.20	2.98	2.89	2.13	2.57
0.02	0.12	0.03	0.10	0.17	0.16	0.10	0.31	0.18	0.42	0.12	0.06

dized, an effect which is not due to weathering but is a usual feature of potash fenitization. The solutions obtained from these rocks are enriched in iron, but no convenient chemical method could be found for distinguishing iron derived from carbonate from that derived from iron oxides. The procedure adopted was, therefore, as follows. All the acetic acid extraction data were plotted in the triangular diagram Ca—Mg—Fe (Fig. 40) and, if the potassic fenites are excluded, a reasonable line can be drawn through the plots from the Ca corner. The potassic fenites lie on the iron-rich side of the line. These points were then projected onto this line from the Fe corner and the intersection taken as the carbonate composition. This technique is an arbitrary one and it certainly obscures any real compositional differences there may be between the carbonates in the sodic and potassic fenites, but short of obtaining electron probe analyses of the carbonate for each rock, which must be difficult because of finely disseminated oxides in some rocks, no other course seemed open. Rocks containing less than 1% CO₂ were not acid treated and for these the carbonate was taken to be entirely CaCO₃, the errors resulting from such a simplification being negligible.

Sodic fenites

Analyses of 21 sodic fenites are given in Table 8, and five rocks which are also sodic fenites are given in Table 12 with the potassic fenites, because they are cut by metasomatic potassic fenite veins, and it is convenient to present together the chemical data for veins and enclosing rock.

In plotting a variation diagram to follow any changes in the major elements during fenitization it was found that sodium is a more useful index of degree of fenitization than silicon, because during fenitization silicon may be added or subtracted, whereas

TABLE 10

Chemical analyses of fenitized schists and granite gneisses showing trends of potassic fenitization

	59	60	61	62	63	64
SiO ₂	66.39	63.69	57.17	69.97	69.16	64.85
TiO ₂	0.34	0.28	0.51	0.24	0.25	0.27
Al ₂ O ₃	15.01	15.27	14.41	15.99	14.51	14.90
Fe ₂ O ₃	1.61	2.07	2.23	0.38	0.96	0.98
FeO	1.19	0.28	0.90	0.97	0.14	0.74
MnO	0.06	0.12	0.06	0.02	0.05	0.09
MgO	1.80	0.88	2.24	0.70	0.87	0.92
CaO	2.56	3.12	3.98	2.38	1.15	1.75
Na ₂ O	3.80	2.46	1.59	5.75	4.55	3.92
K ₂ O	3.90	8.41	11.81	1.84	5.76	7.57
H ₂ O ⁺	1.05	0.79	0.74	0.48	0.34	0.28
H ₂ O ⁻	0.59	0.44	0.56	0.11	0.21	0.06
P ₂ O ₅	0.05	0.04	0.04	0.08	0.004	0.09
CO ₂	0.61	2.17	3.15	0.42	1.36	2.26
F	0.11	0.04	0.13	0.05	0.02	0.06
S	0.16	0.10	0.10	0.01	nil	0.10
others	0.287	0.307	0.964	0.181	0.163	0.357
	99.52	100.47	100.58	99.57	99.50	99.20
O ≡ F, S	0.126	0.067	0.105	0.026	0.008	0.075
Total	99.39	100.40	100.48	99.55	99.49	99.12

trace elements in p.p.m.

Cr	145	75	25	10	30	25
Li	75	20	10	25	5	5
Nb	50	100	220	nil	100	100
Ni	130	110	55	65	105	65
Cu	40	100	10	10	20	10
Zn	185	190	205	70	45	35
V	150	100	150	nil	25	250
Zr	150	100	3 000	100	150	100
Y	nil	20	50	nil	nil	nil
Sr	180	105	290	650	190	690
Ba	1 000	1 500	3 600	500	650	1 400
Rb	105	160	165	55	110	210

59. Lightly fenitized quartz biotite (muscovite) schist. Drill hole 215 at 40 m. (B. M. 1973, P20(3)).

60. Fenitized quartz biotite schist. Drill hole 215 at 42.2 m. (B. M. 1973, P20(4)).

61. Alkaline amphibole (aegirine) ultra potassic syenitic fenite. Drill hole 215 at 52 m. (B. M. 1973, P20(7)).

62. Lightly fenitized biotite granite gneiss. Drill hole 223 at 17.5 m. (B. M. 1973, P20(64)).

63. Fenitized biotite granite gneiss. Drill hole 223 at 40.9 m. (B. M. 1973, P20(66)).

64. Aegirine potassic quartz fenite. Drill hole 200 at 136 m. (B. M. 1973, P20(55)).

Rocks 59, 60 and 61, and 62 and 63 form two series illustrating trends of potassic fenitization. 59 and 62 are not, of themselves, potassic fenites.

Analyst: V. K. Din.

FeO; H₂O and CO₂ determined by G. C. Jones. F determined by A. J. Easton.

TABLE 11

Chemical analyses of fenitized schists and granite gneisses showing trends of potassic fenitization, recast in cations per 100 oxygen anions after removal of C and equivalent amounts of Ca, Mg and Fe²⁺ (see text)

	59	60	61	62	63	64
Si	37.32	36.90	35.04	38.46	38.98	37.87
Ti	0.14	0.12	0.23	0.10	0.11	0.12
Al	9.94	10.43	10.41	10.36	9.64	10.26
Fe ³⁺	0.68	0.90	1.03	0.16	0.41	0.43
Fe ²⁺	0.56	0.13	0.43	0.45	0.00	0.10
Mn	0.03	0.06	0.03	0.01	0.02	0.04
Mg	1.51	0.01	1.92	0.57	0.44	0.25
Ca	1.07	0.97	1.13	0.23	0.00	0.10
Na	4.14	2.76	1.89	6.13	4.97	4.44
K	2.80	6.22	9.24	1.29	4.14	5.64
OH	3.94	3.05	3.03	1.76	1.28	1.09
P	0.02	0.02	0.02	0.04	0.02	0.04

For details of rock types and localities see Table 10.

sodium is consistently added. Fig. 41 is a plot of Na against the major elements for sodic fenites and unfenitized country rocks, using the values for the 100 anionic cell given in Table 9.

The group of rocks with Na values greater than 8.5 are all syenitic fenites, being approximately saturated with regard to silica but with a varying mafic mineralogy. The

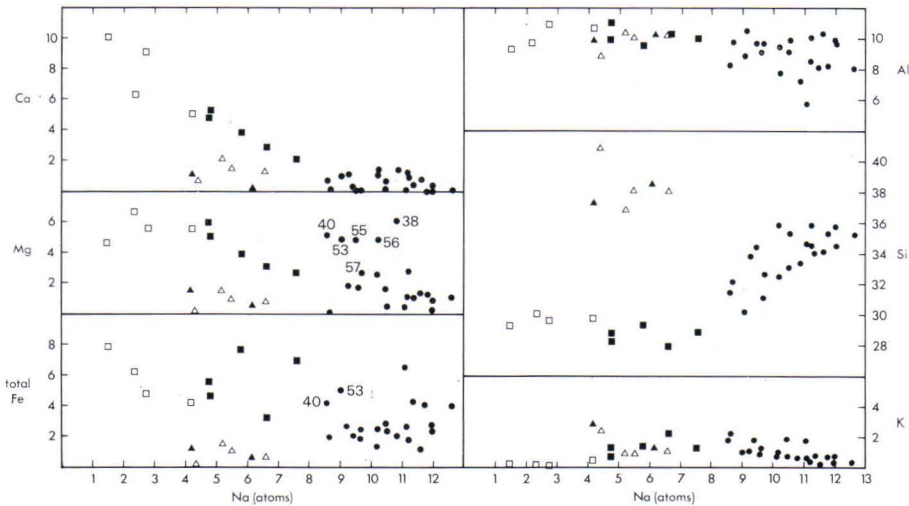


FIG. 41. Plot of the major elements in the sodic fenites and unfenitized country rocks against sodium. The data used are those recast to 100 oxygens after adjustment for carbonate (see text). Open squares, unfenitized amphibolites and hornblende schists; open triangles, unfenitized granite gneisses; filled squares, fenitized amphibolites and hornblende schists from which potassic veins were separated; filled triangles, very slightly fenitized reddened gneisses; filled circles, sodic syenitic fenites. For numbered Mg and Fe points see text.

significance of their distribution on Fig. 41 might be clearer if it were known from what type of country rock each syenitic fenite was derived, but this is hard to judge because of changes of mineralogy and texture during fenitization.

The principal changes in the major elements during fenitization apparent from Fig. 41 are as follows:

1. There is a considerable addition of sodium.
2. The syenitic fenites have Si values between those of the unfenitized amphibolites and the gneisses; Si has therefore been added to the former and subtracted from the latter.
3. There may be a slight overall decrease in Al.
4. There is probably a slight addition of Fe to the gneisses, but there is no definite trend for the fenitized amphibolites. It is noteworthy that the syenitic fenites for which the origin can confidently be ascribed to amphibolite (Fig. 41, Nos. 40 & 53) are richer in iron than most of the other syenitic fenites, indicating, in part at least, that the tenor of iron is related to the composition of the original rock.
5. The five rocks from which potassic fenite veins were cut indicate decreasing Mg values, but there is a wide spread of Mg amongst the syenitic fenites. Of the syenitic fenites with the higher Mg values two are derived from amphibolite (Fig. 41, nos 40 & 53); two are cut by fibrous amphibole veinlets (Fig. 41, nos. 38 & 56); and the other two rocks numbered on Fig. 41 (nos. 55 & 57) are rich in phlogopite as well as amphibole, and come from boreholes close to the sövite contact. The significance of these syenitic fenites rich in Mg are discussed later.
6. There is a considerable decrease of Ca in the amphibolites but little change in the gneisses. That the decrease in Ca is not a spurious effect due to calculating the rocks free of carbonate is shown by Fig. 42 in which the 'raw' Na and Ca

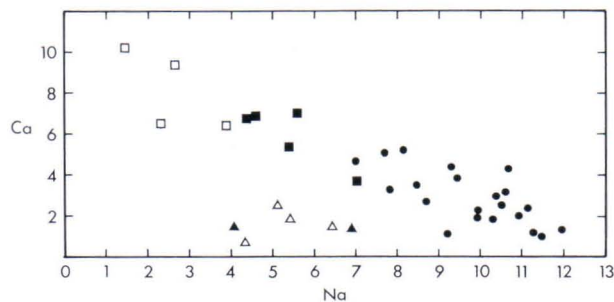


FIG. 42. Plot of Ca against Na for unfenitized country rocks and sodic fenites, using analyses recalculated to 100 oxygens but not adjusted for presence of carbonate, as used in Fig. 41. Note that there is slightly more scatter than in the Ca—Na plot of Fig. 41, particularly amongst the sodic fenites, but that the overall trend remains the same. Symbols as for Fig. 41.

TABLE 12

Chemical analyses of fenites and associated potassic fenite veins cut from them, and an ultrapotassic fenite vein

	ROCK 65	VEIN 66	ROCK 67	VEIN 68	ROCK 69	VEIN 70	ROCK 71	VEIN 72	ROCK 73	VEIN 74	VEIN 75
SiO ₂	45.94	42.22	41.10	43.77	46.20	44.38	45.69	37.49	45.27	40.88	44.33
TiO ₂	0.87	0.77	0.78	0.53	0.80	0.69	1.99	1.87	1.93	2.24	1.04
Al ₂ O ₃	13.55	12.15	12.77	12.22	15.31	12.63	12.61	9.61	13.17	11.53	11.87
Fe ₂ O ₃	3.64	8.43	4.82	4.03	3.31	5.84	6.15	4.02	5.41	2.09	7.14
FeO	7.63	1.05	3.51	2.96	6.39	0.53	9.16	6.34	9.02	6.82	0.68
MnO	0.24	0.37	0.47	0.41	0.27	0.53	0.26	0.56	0.25	0.48	0.45
MgO	6.60	2.29	5.18	3.80	5.77	2.05	4.74	5.27	4.25	4.39	2.61
CaO	10.44	11.81	11.22	8.56	10.91	10.75	8.18	9.92	5.65	8.33	9.59
Na ₂ O	3.88	4.70	5.00	2.04	4.01	3.53	4.63	3.38	6.07	4.38	1.09
K ₂ O	1.29	2.95	2.60	7.65	1.06	5.74	1.68	5.01	1.61	3.62	9.40
H ₂ O ⁺	1.94	2.03	1.76	0.90	2.47	1.58	0.79	0.43	1.30	0.81	1.25
H ₂ O ⁻	0.79	0.98	0.76	0.69	0.77	0.82	0.13	0.23	0.35	0.37	0.77
P ₂ O ₅	0.08	0.05	0.17	0.03	0.31	0.07	0.38	0.28	1.03	0.53	0.06
CO ₂	2.82	9.73	9.42	11.92	2.68	9.87	3.12	14.84	4.20	12.52	9.90
F	0.10	0.04	0.35	0.04	0.15	0.02	0.16	0.06	0.32	0.09	0.15
S	0.03	0.16	0.03	0.17	0.06	0.14	0.13	0.46	0.16	0.53	0.21
others	0.392	0.527	0.628	0.428	0.566	0.582	0.267	0.361	0.387	0.601	0.526
	100.23	100.26	100.57	100.15	101.04	99.75	100.07	100.13	100.38	100.21	101.07
O≡F, S	0.057	0.097	0.162	0.102	0.093	0.078	0.134	0.255	0.215	0.303	0.168
Total ..	100.17	100.16	100.41	100.05	100.94	99.67	99.93	99.85	100.16	99.91	100.90
trace elements in p.p.m.											
Cr	180	150	200	130	180	125	50	75	50	35	90
Li	30	10	20	10	35	5	35	10	20	5	10
Nb	nil	250	100	250	nil	300	150	500	100	500	600
Ni	190	155	190	130	180	125	115	90	105	85	105
Cu	65	85	40	70	70	85	35	30	30	25	30
Zn	125	140	360	225	430	465	155	120	165	130	1100
V	400	250	150	150	290	125	400	360	360	150	250
Zr	100	50	200	50	100	50	250	200	150	90	100
Y	nil	nil	nil	nil	nil	nil	25	nil	25	nil	nil
Sr	410	565	1100	520	315	475	270	850	1200	1200	850
Ba	1600	2600	2800	1800	3070	3000	490	440	900	2800	845
Rb	20	50	80	120	10	75	10	55	45	50	150

65. Lightly fenitized (alkaline amphibole and aegirine) hornblende-pyroxene schist. Drill hole 243 at 58 m. (B. M. 1973, P20(13)).

66. Potassic fenite vein with phlogopite. Cut from rock 65 above.

67. Lightly fenitized (minor aegirine) biotite schist. Drill hole 210 at 50 m. (B. M. 1973, P20(27)).

68. Potassic fenite vein. Cut from rock 67 above.

69. Lightly fenitized hornblende schist. Drill hole 210 at 48 m. (B. M. 1973, P20(28)).

70. Potassic fenite vein. Cut from rock 69 above.

71. Fenitized (alkaline amphibole, aegirine and phlogopite) hornblende schist. Drill hole 200 at 123 m. (B. M. 1973, P20(54)).

72. Potassic fenite vein with phlogopite. Cut from rock 71 above.

73. Fenitized (aegirine and alkaline amphibole) hornblende schist. Drill hole 200 at 157 m. (B. M. 1973, P20(58)).

74. Potassic fenite vein with phlogopite. Cut from rock 73 above.

75. Ultrapotassic fenite with phlogopite. From thick fenite vein. Drill hole 243 at 129.2 m. (B. M. 1973, P20(24)).

Analyst: V. K. Din.

FeO; H₂O and CO₂ determined by G. C. Jones. F. determined by A. J. Easton.

TABLE 13

Compositions of fenites and associated potassic fenite veins cut from them, and an ultrapotassic fenite vein, recast in cations per 100 oxygen anions after removal of C and equivalent amounts of Ca, Mg and Fe²⁺ (see text)

	ROCK 65	VEIN 66	ROCK 67	VEIN 68	ROCK 69	VEIN 70	ROCK 71	VEIN 72	ROCK 73	VEIN 74	VEIN 75
Si	28.70	28.69	27.92	30.81	28.22	30.25	29.23	28.38	28.94	29.23	30.42
Ti . . .	0.41	0.39	0.40	0.28	0.37	0.35	0.96	1.06	0.93	1.20	0.54
Al . . .	9.98	9.37	10.23	10.14	11.02	10.15	9.51	8.58	9.92	9.72	9.60
Fe ³⁺ . .	1.71	4.31	2.46	2.13	1.52	3.00	2.96	2.29	2.60	1.13	3.69
Fe ²⁺ . .	3.91	0.30	0.77	0.33	3.16	0.00	4.64	1.77	4.31	0.00	0.00
Mn . .	0.13	0.21	0.27	0.24	0.14	0.31	0.14	0.36	0.14	0.29	0.26
Mg . .	5.96	1.62	3.06	0.40	5.01	1.05	3.87	0.33	2.77	2.92	0.83
Ca . . .	4.85	0.56	2.84	0.00	5.25	0.00	3.80	0.56	2.00	0.00	0.00
Na . . .	4.70	6.19	6.59	2.78	4.75	4.66	5.74	4.96	7.52	6.07	1.45
K	1.03	2.56	2.25	6.87	0.82	4.99	1.37	4.84	1.31	3.30	8.23
OH . . .	8.08	9.20	7.98	4.23	10.06	7.18	3.37	2.17	5.54	3.86	5.72
P	0.04	0.03	0.10	0.02	0.16	0.04	0.20	0.18	0.56	0.32	0.04

For details of rock types and localities see Table 12.

values are plotted rather than the recalculated values after removal of carbonate. There is still a noticeable decrease of Ca in the amphibolites, in spite of the presence of carbonate, but there is some increase of Ca in the fenitized gneisses, which is probably due to the presence of carbonate.

- There is a slight increase in K in the five rocks from which the potassic fenite veins were separated, but this is probably indicative of incomplete separation of the veins, or the presence of a few potassic veinlets. Otherwise there is very little change in potassium, except possibly for a real, but small, increase in the fenitized amphibolites.

These results may be summarised as follows:

	<i>Gains</i>	<i>Losses</i>	<i>No definite trend</i>
<i>amphibolites</i>	major Na & Si	major Ca	Al, K, Mg, Fe
<i>gneisses</i>	major Na; minor Fe	major Si	Al, K, Mg, Ca

Fig. 43a is a plot of Na against the oxidation ratio $100 \text{ Fe}^{3+} / (\text{Fe}^{3+} + \text{Fe}^{2+})$. There is an increase in this ratio with fenitization from amphibolites with values around 10 to some syenitic fenites which contain only ferric iron. The one point which stands apart from the others is one of the rocks cut by potassic fenite veins, and its high aberrant oxidation ratio may be due to the presence of some potassic fenite veinlets, which is also indicated by the rather higher potassium values for this rock. If a smooth curve is drawn through all the points three of the four rocks from which potassic veins were separated lie above the curve giving oxidation ratios just a little higher than usual.

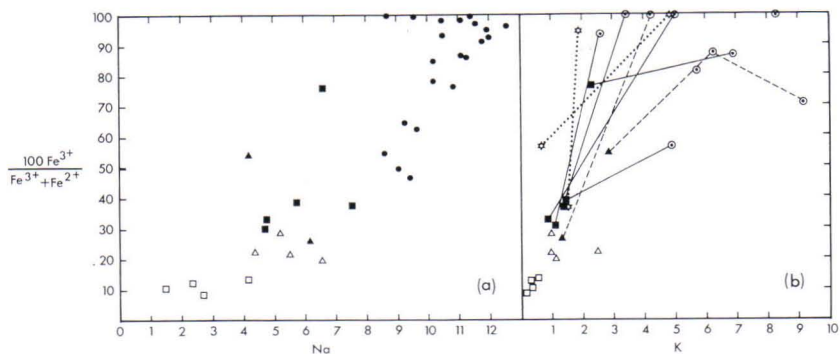


FIG. 43. (a) Plot of Na against the oxidation ratio $100 \text{ Fe}^{3+} / \text{Fe}^{3+} + \text{Fe}^{2+}$ for unfenitized country rocks and sodic fenites. Same data and symbols as in Fig. 41.

(b) Plot of K against the oxidation ratio $100 \text{ Fe}^{3+} / \text{Fe}^{3+} + \text{Fe}^{2+}$ for unfenitized country rocks and potassic fenites. Symbols of unfenitized rocks as in previous diagrams. Circles with dots joined by tie lines to filled squares are potassic fenite veins and the host rocks which they cut; circles with dots joined by dashed tie lines to filled triangles are the potassic reddened gneiss series; two other potassic fenites are represented by circles with dots. Two sets of stars joined by dotted tie lines are potassic fenite veins and their host rocks from Kangankunde, Malawi (Woolley, 1969). The very marked increase of oxidation ratio concomitant with an increase of K is apparent.

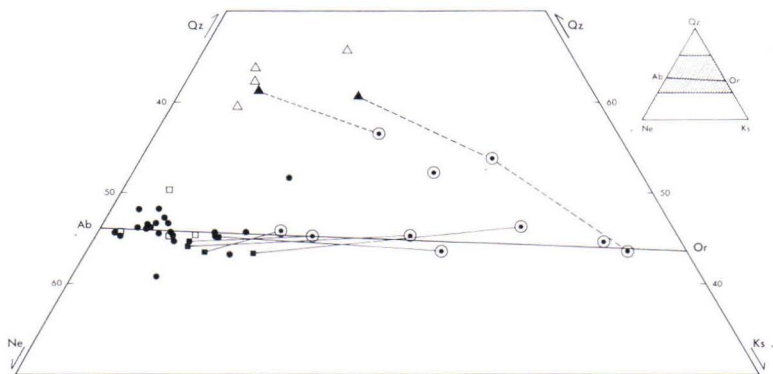


FIG. 44. Plot of all fenites and unfenitized country rocks in part of the weight normative system quartz — nepheline — kalsilite. Symbols as in Figs. 41 and 43 (b). The strongly potassic trends of the potassic fenite veins, and the reddened gneisses is apparent, contrasting markedly with the sodic character of the sodic syenitic fenites.

The sodic fenites and country rocks are plotted on Fig. 44 in terms of weight normative quartz-nepheline-kalsilite. There is a marked clustering of the sodic fenites about the Ab—Or join towards the albite end. Although the syenitic fenites derived from amphibolite show little or no change in position, in terms of this diagram, those derived from gneisses have been depleted markedly in quartz component. This diagram also emphasises the lack of data for fenites having compositions

between the extremes of the syenitic fenites and the country rock gneisses (see also Fig. 41). The one sodic fenite which lies markedly above the Ab—Or join is traversed by numerous small quartz veins. The difficulty of finding intermediate compositions appears to be a usual one. For instance, the 20 country rocks and fenites from Alnö analysed by von Eckermann (1948) fall into two distinct groups with none of intermediate composition (see Woolley, 1969, Fig. 5).

Potassic fenites

The potassic fenites comprise the buff-coloured metasomatic veins, together with certain of the fenitized gneisses which have a characteristic reddish colour. To follow the chemical changes involved in the formation of the veins five of them were separated from their enclosing rock, and rocks and veins analysed (Table 12). Specimen 75 is also taken from a vein but from one of rather larger than normal size. Also analysed were three reddened gneisses from borehole 215 and two from borehole 223, which were chosen to illustrate progressive metasomatic changes of a potassic type (Table 10). Specimen 64 is another similar reddened gneiss.

The marked increase in potassium which distinguishes the potassic from the sodic fenites is illustrated by Fig. 45. Not only is there a radical increase in potash in these rocks, but there is a distinct decrease in soda. However, four of the five rocks from which the potassic veins were cut were originally amphibolites, or hornblende schists, and it is noteworthy that these have definitely undergone sodic and not potassic metasomatism. The two reddened schist series confirm the general potassic trend.

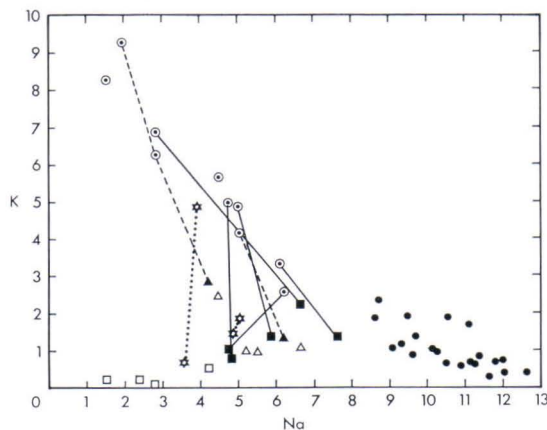


FIG. 45. Plot of Na against K (recalculated to 100 oxygens and adjusted for removal of carbonate) for all fenites and unfenitized country rocks. The two distinct trends of sodium and potassium enrichment are apparent. Symbols as in Figs. 41 and 43 (b).

In the same way that it was found convenient to plot a variation diagram of the sodic fenites against sodium, the most illustrative abscissa for the potassic fenites is potassium. The resulting diagram (Fig. 46), on which veins and host rocks are joined by tie-lines, indicates the following changes in the major elements during potassic fenitization:

1. A considerable increase in potassium
2. A marked decrease in sodium but, as pointed out above, the rocks cut by the potassic fenite veins contain a higher tenor of sodium than the rocks from which they were derived, suggesting that they underwent sodium metasomatism before the potassium-rich fenite veins were formed.
3. There is very little significant change in silicon or aluminium.
4. The veins reveal a marked decrease in total iron, magnesium and calcium, but there is little change in these elements in the gneiss series, in which they are low anyway. There is a very high proportion of carbonate in the veins, but the data plotted on Fig. 46 have, of course, been calculated free of carbonate. However, even if Ca, Mg and Fe are not removed as carbonate, a decrease in Fe and Mg still occurs, but in three out of five Ca increases.

The changes may be summarised as follows:

	<i>Gains</i>	<i>Losses</i>	<i>No definite trend</i>
<i>amphibolites</i>	major K	Na, Fe, Mg, Ca	Si, Al
<i>gneisses</i>	major K	Na	Si, Al, Fe, Mg, Ca

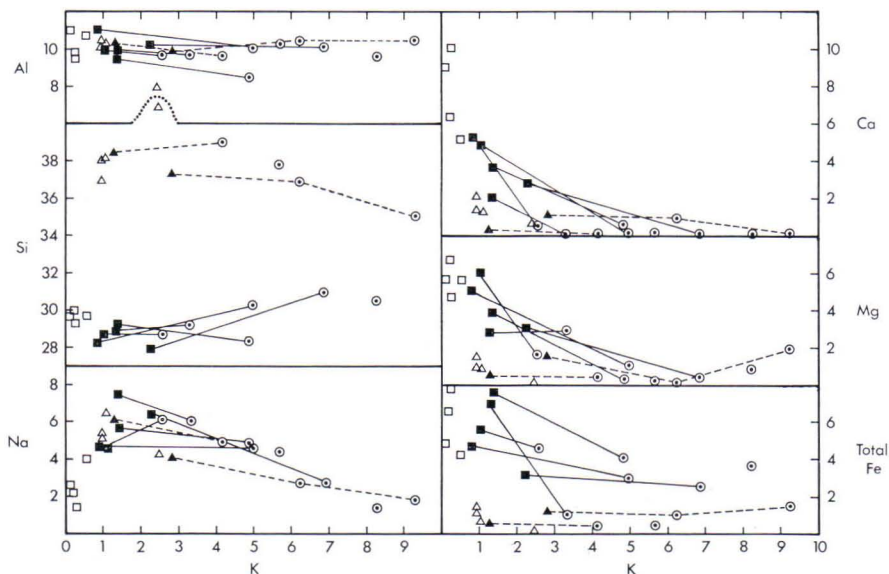


FIG. 46. Plot of the major elements in the potassic fenites and unfenitized country rocks against K, using atoms recast to 100 oxygens and adjusted after removal of carbonate. Symbols as in Figs. 41 and 43(b).

The weight normative quartz-nepheline-kalsilite plot (Fig. 44) indicates a strong convergence on the orthoclase composition point. There is little or no change in silica saturation between the veins and their host rocks, but the gneisses, besides becoming more potassic with increasing fenitization, become also distinctly poorer in normative quartz.

A distinctive chemical feature of the potassic fenites is the marked increase in oxidation ratio with increase in potassium, as illustrated by Fig. 43 b. A number of the potassic fenites are completely devoid of ferrous iron. This increase in the oxidation ratio parallels that occurring in the sodic fenites, but is noteworthy in the potassic fenites for the fact that along the edges of the metasomatic veins the change occurs within a few millimetres of rock. Also shown on Fig. 43 b are the trends obtained from similar potassic fenite veins and associated fenites from Kangankunde, Malawi (Woolley, 1969) which also show an increase in potassium with a parallel increase in oxidation ratio.

Minor elements

Data on a range of minor elements are given in Tables 1, 3, 8, 10 and 12 and variations of some of these elements are given in Fig. 47 for which the sodic fenites are plotted against Na and the potassic fenites against K. As with the major elements, tie lines join separated potassic veins and the associated rocks and the two gneiss series which show increasing potassium fenitization. Noteworthy features revealed by the data are as follows:

Yttrium: There is little variation except that one or two sodic fenites indicate some enrichment.

Zinc: No apparent significant variation.

Nickel: Amongst the sodic fenites there appears to be some loss of nickel from fenites derived from amphibolites, but no significant change in fenites originating as schist or gneiss, and the same trend is apparent for the potassic fenites, with the potassic veins consistently poorer in nickel than their host rocks.

Chromium: There is a marked decrease in chromium from the amphibolites to the sodic syenitic fenites, but no apparent change of the low values pertaining in the schists and gneisses. The same feature occurs in the potassic fenites.

Copper: Although there is no apparent trend amongst the potassic fenites, with sodic fenitization the rather variable values of the country rocks are reduced to evenly low values of 30 p.p.m. or less in the syenitic fenites.

Vanadium: The vanadium results for sodic fenites are interesting in spite of the complete lack of any trend. The notable difference in vanadium values of the country rock amphibolites and gneisses and schists is perpetuated into the syenitic fenites suggesting that vanadium is comparatively inert during sodic fenitization. In contrast, there is some indication that during potassic fenitization the high values of the amphibolites are reduced.

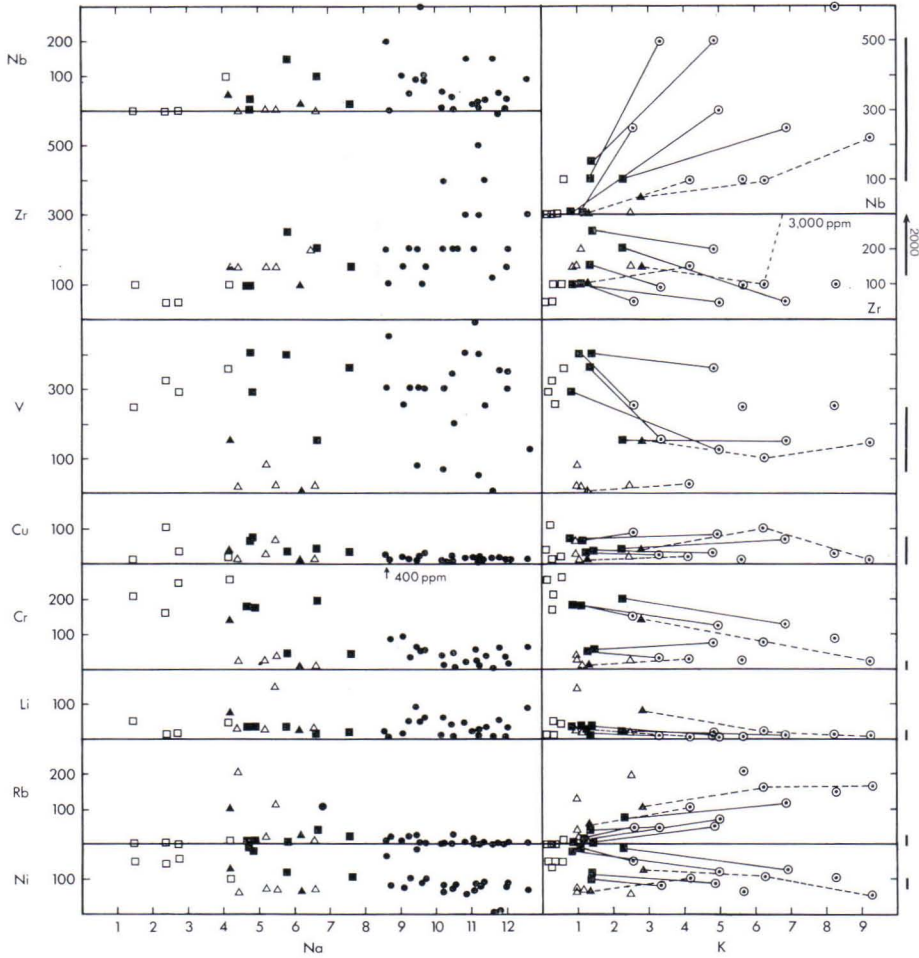


FIG. 47. Plot of selected trace element data against Na for sodic fenite series and K for potassic fenite series. The heavy lines on the right of the diagram indicate the range of these elements found in the carbonatite samples. Symbols as in Figs. 41 and 43(b).

Zirconium: While sodic fenites derived from amphibolite have enhanced zirconium values, and a few sodic fenites show considerable enrichment in this element, there is a broad overlap of the majority of the sodic fenites with the unfenitized schists and gneisses so that no conclusions can be drawn as to changes of zirconium in the latter. In contrast, there is a modest decrease in the potassic fenite veins, but overall the tenor of zirconium is little changed in the potassic fenites.

Niobium: There is a very marked correlation between niobium and potassium. The niobium values of seven of the eight country rocks are negligible, but considerable niobium is detected in all the potassic fenites. Although there is a distinct increase in

niobium during sodium fenitization also, this is not so marked as in the potassic fenites.

Lithium: There is no apparent variation in lithium in the sodic fenites, but there is a definite decrease in this element in the potassic fenites.

Rubidium: Although only two of the analyzed country rocks contain appreciable amounts of rubidium, the constantly low values of the sodic fenites indicate that this element either decreases or remains at low levels. In contrast there is a definite increase in rubidium in the potassic fenite veins and the two gneiss series, indicating a distinct positive correlation of rubidium with potassium.

Barium: There is a considerable increase in the barium values in many of the sodic and potassic fenites, but barium is remarkable for the wide range of values occurring. There is a tenfold increase in some fenites, whereas in others there is little change. Barium is higher in some of the potassic veins than the associated rocks, but it is lower in others. There is no correlation between barium and CO₂ in the rock so that these variations are not controlled by the amount of carbonate present.

Strontium: There is a distinct increase in strontium amongst the sodic fenites derived from amphibolite, but any changes in the gneisses are obscured by one of the country rocks which has high strontium values. The same holds for the potassic fenites for which strontium has increased amongst the amphibolites but for which there appears to have been little change in the gneisses.

The ratio of barium to strontium varies in the sodic fenites from 5:1 to 0.2:1, but for the majority of potassic fenites barium is greater than strontium, sometimes by as much as 10:1.

The variations in the minor elements during fenitization are summarised in Table 14.

TABLE 14
Gains and losses of minor elements

	Sodic fenites		Potassic fenites	
	Amphibolites	Schists and gneisses	Amphibolites	Schists and gneisses
Y				
Zn				
Ni	—		—	
Cr	—		—	
Cu	—	—		
V			—	
Zr	+		—	
Nb	+	+	+	+
Li			—	—
Rb		—	+	+
Ba	+	+	+	+
Sr	+		+	

+, significant gain; —, significant loss.

Relationship between rock chemistry and mineralogy

A sodic feldspar is common to all the syenitic fenites but the mafic minerals essentially comprise the four assemblages aegirine, aegirine + amphibole, amphibole, and amphibole + phlogopite, with complete gradation between pyroxene and amphibole, and amphibole and phlogopite syenitic fenites. These different assemblages reflect differences in bulk rock composition, particularly with regard to magnesium and iron. On the variation diagram (Fig. 41) the six numbered syenitic fenites have the highest Mg values and five of them consist of the assemblage amphibole + phlogopite, while number 38 contains amphibole only. All the rest of the syenitic fenites comprise either aegirine or aegirine + amphibole.

The major factor determining the presence or absence of pyroxene appears to be the ratio of Mg: total iron (Fig. 48). This ratio varies little amongst the country rocks, but fenitization produces a divergence towards either the iron corner or the magnesium corner of Fig. 48. Rocks with total iron > Mg develop pyroxene whereas those

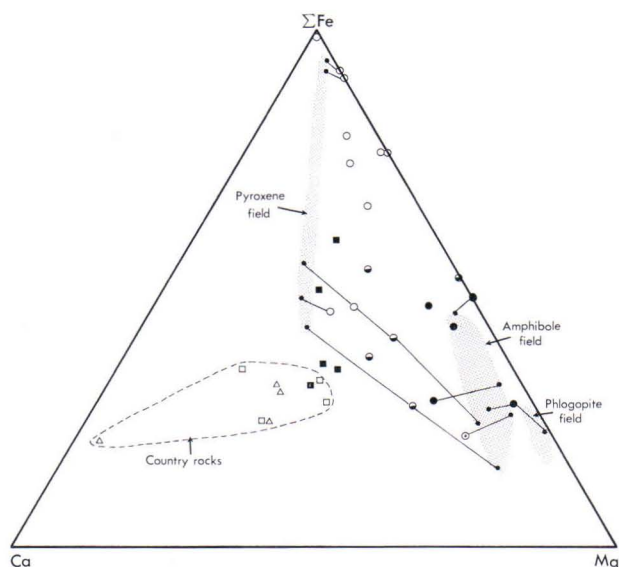


FIG. 48. Plot of sodic syenitic fenites in terms of $\text{Fe}^{3+} + \text{Fe}^{2+} - \text{Ca} - \text{Mg}$ (in atoms) to show variation of the mafic mineral assemblages. When a mineral phase or phases from a particular rock has been analyzed the mineral has been plotted and joined to the rock by a tie line. Mineral points are indicated by small filled circles and the general compositional fields of the amphiboles, pyroxenes, and phlogopites shaded. Open circles, fenite with pyroxene only; half filled circles, fenite with pyroxene and amphibole; solid circles, fenite with amphibole and phlogopite; circle with dot, fenite with amphibole only. Area of unfenitized country rocks is enclosed; open squares, amphibolites and hornblende schists; open triangles, granitic gneisses.

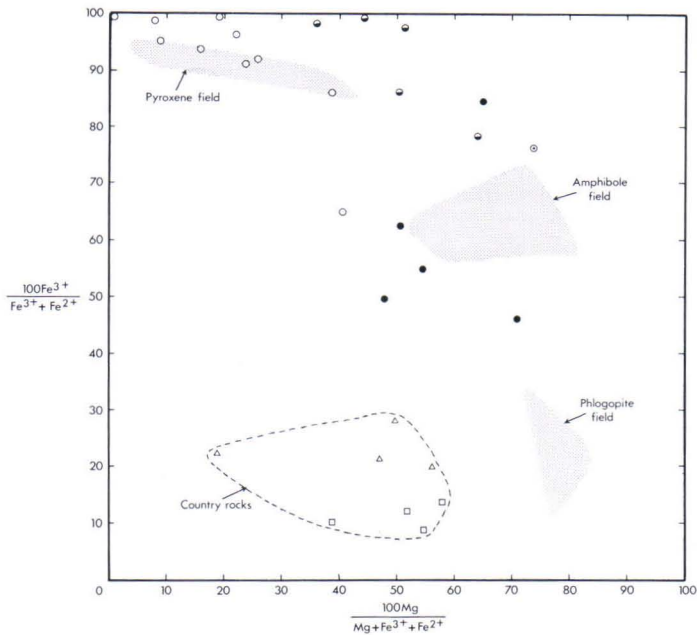


FIG. 49. Plot of oxidation ratio ($100 \text{ Fe}^{3+}/\text{Fe}^{3+} + \text{Fe}^{2+}$) against mg ratio ($100 \text{ Mg}/\text{Mg} + \text{Fe}^{3+} + \text{Fe}^{2+}$) for sodic syenitic fenites and unfenitized country rocks to show variation of mafic mineral assemblages. Pyroxene, amphibole, and phlogopite fields shaded. Symbols as in Fig. 48.

enriched in Mg develop an assemblage of amphibole with or without phlogopite or aegirine-augite. The difference in the Mg: ferric iron ratio between the different syenitic fenite types is emphasised by Fig. 49, which also shows that not only is iron relatively enriched in the pyroxene fenites, but the oxidation state of these rocks is also higher, ferrous iron being absent from some of them.

Rock chemistry taken together with petrography indicates that the amount and relative proportions of Mg and total iron in the syenitic fenites is determined either by the original composition of the rock, or by secondary metasomatic effects. Of the six numbered magnesium-rich rocks plotted on Fig. 41, 40 and 53 have petrographic features indicating that they were originally hornblende schists, and their high Mg and total iron contents together with low silica supports this. There has been little or no change in the Mg: total iron ratio in these two rocks (Fig. 48), and this lack of change is also indicated by Fig. 50 on which they plot very close to the unfenitized amphibolites and hornblende schists. Rocks 55 and 57 are both from borehole 70 close to the carbonatite contact and 55, and to a lesser extent 57, are rich in phlogopite which microscopic examination shows to develop at the expense of feldspar adjacent to carbonate veinlets. The high Mg contents of these two rocks appears, therefore, to be partly metasomatic in origin. Rocks 56 and 38 are characterised by cross-cutting

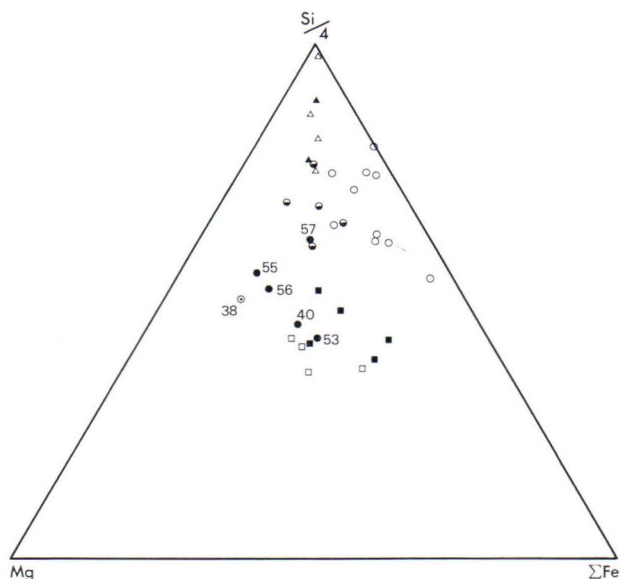


FIG. 50. Plot of sodic syenitic fenites and unfenitized country rocks in terms of $\text{Si}/4\text{--Mg--Fe}^{3+} + \text{Fe}^{2+}$; Filled squares are fenitized amphibolites and hornblende schists from which potassic veins were removed. Other symbols as on Fig. 48. For details of numbered points see text.

masses of fibrous amphibole, together with abundant phlogopite in 56. In these two rocks also, therefore, the Mg appears to be partly introduced.

In summary, the syenitic fenites with the highest Mg and Mg: total iron values comprise the assemblages amphibole and amphibole + phlogopite, and owe these features either to original rock composition, or to the secondary introduction of Mg. However, fenitized amphibolites and hornblende schists do not invariably result in amphibole-bearing assemblages. This can be seen on the variation diagram (Fig. 41) on which the Mg values of the amphibolites and hornblende schists cut by K-fenite veins fall consistently, but two of these rocks retain high iron values (Figs. 41 & 48) so producing pyroxene fenites. Apart from these two rocks there is a general tendency for the pyroxene fenites to have originated from gneisses of granitic composition, as is illustrated by Fig. 50 on which the pyroxene fenites cluster towards the Si corner with the unfenitized schists and gneisses.

Chemical variations in the constituent minerals are also sensitive to changes in rock composition. The pyroxenes in the most iron-rich rocks are aegirines, whereas rocks with intermediate Mg: total iron values contain aegirine-augite, with or without an amphibole (Fig. 48). Among the syenitic fenites with the assemblage amphibole plus phlogopite, or amphibole only, the tie-lines between rocks and co-existing amphiboles are sub-parallel (Fig. 48) indicating that the amphibole compositions are also sensitive to changes in rock composition. There is an overlap in Mg: total iron

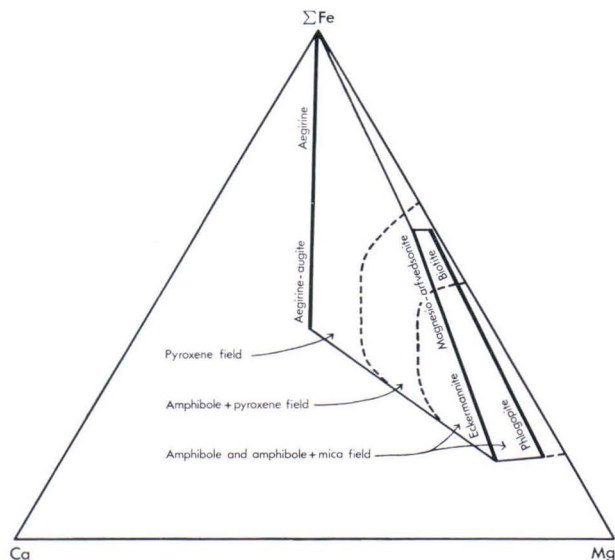


FIG. 51. Generalised $\text{Fe}^{3+} + \text{Fe}^{2+} - \text{Ca} - \text{Mg}$ diagram to indicate the fields of particular mafic mineral assemblages in Sokli sodic syenitic fenites. Heavy lines denote the general ranges of composition of the aegirine — aegirine-augite, eckermannite — magnesio-arfvedsonite, and phlogopite series. Approximate limits of fields indicated by dashed lines.

values of the aegirine-augite-bearing and the pyroxene-free assemblages, but the mineralogical difference here appears to be controlled by the Ca content of the rock; if Ca is very low then amphibole and phlogopite crystallize, while a moderate tenor of Ca leads to the production of aegirine-augite (Fig. 48).

These features are summarised on a generalised total Fe — Ca—Mg diagram (Fig. 51) on which the range of compositions of pyroxenes, amphiboles and micas in the Sokli fenites are given. For syenitic fenites from Sokli three compositional fields can be defined which will give rise to the respective assemblages pyroxene, pyroxene plus amphibole, and amphibole or amphibole plus phlogopite (Fig. 51).

DISCUSSION

In the preceding sections chemical and mineralogical data have been presented illustrating the changes which took place in the metamorphic aureole around the Sokli carbonatite intrusion. Because of the heterogeneity of the country rocks and the abundance of carbonate in the fenites, the bulk chemical changes were only described in general qualitative terms. However, in studying fenites it is of prime interest to know the overall quantitative chemical changes in the aureole. An attempt to elucidate

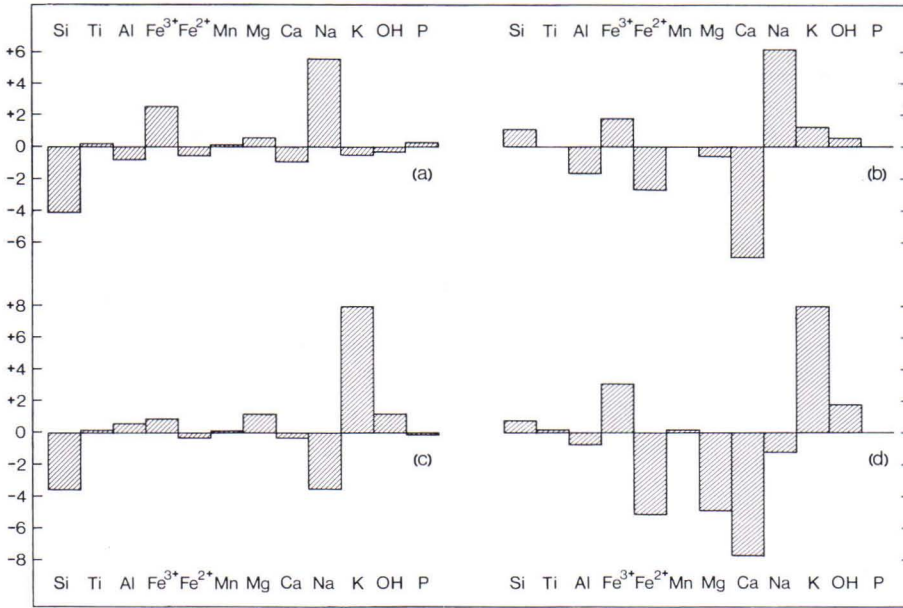


FIG. 52. Addition/subtraction diagram for major elements in Sokli fenites using atoms per 100 cations. (a) granite gneiss to sodic fenite, (b) hornblende schist/amphibolite to sodic fenite, (c) granite gneiss to potassic fenite, (d) hornblende schist/amphibolite to potassic fenite.

the changes in the Sokli aureole for the major elements and on a quantitative basis, is illustrated in the addition/subtraction diagrams of Fig. 52. These diagrams summarise the changes involved in passing from an average granitic gneiss (Table 1, anal. 1 to 4) to a sodic fenite (Table 8 analyses; but not including fenitized hornblende schists and phlogopite-rich rocks) and to a potassic fenite (Table 10, anal. 61); and an average hornblende schist/amphibolite (Table 1, anal. 5 to 8) passing to a sodic fenite (Table 8, anal. 40 and 53) and a potassic fenite (Table 12, anal. 75).

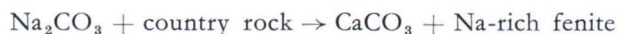
The formation of sodic fenites (Fig. 52 a & b) from granite gneiss involves loss of major Si, and gain of Na and Fe³⁺, while from hornblende schist/amphibolite Al, Fe²⁺, and Ca show significant losses, while Si, Fe³⁺, Na, K and possibly OH, are major additions.

The addition of silicon to the more basic rocks is of particular interest in demonstrating that fenitization is not always a de-silication process. The additional silicon is taken up by the alkaline amphiboles and pyroxenes which are richer in this element than the ferro-tschermakitic hornblende of the country rocks (Table 4). The loss of silicon from the gneisses and gain by the amphibolites means, because of the proportions of these rocks in the area of fenitization, that the total loss of silicon is marginally less than would be the case were the aureole composed solely of gneiss; nevertheless, silicon is depleted in the aureole more than any other element.

The destination of the fugitive silicon is always a problem when considering fenites. H. von Eckermann (1948) suggested that at Alnö it migrated inwards into the carbonatite, and Woolley (1969) favoured a combination of inward movement into the carbonatite and upward migration towards the surface, possibly in brines. Some of the high level carbonatites of the Rufunsa Valley in Zambia described by Bailey (1960) are extensively silicified, with the production in the carbonatite of 'silica/iron oxide rock' and 'brecciated quartz rock'. These quartz-rich rocks could represent a 'sink' for silicon which originated in a fenite aureole not as yet exposed. Because Sokli is a relatively deep fenite section one would not expect to see such silicon enriched rocks.

After silicon, the element having the greatest depletion is calcium, 66 % of the calcium in the gneisses and 90 % of that in the hornblende schists having been removed. It was shown earlier (Fig. 42) that the loss of calcium from the hornblende schists is not a spurious effect due to the calculation of the rocks free from carbonate, but that there is a considerable real removal of calcium. For the gneisses the total calcium in the fenites plus carbonate veins is about the same as in the unfenitized rocks. It would appear, therefore, that some calcium has been lost from the aureole, and that some has moved from the silicate mineral assemblage of the fenite into the carbonate veins. In this case the obvious 'sink' for the calcium is the carbonatite itself, so that the carbonate veins and veinlets must represent not only physical apophyses from the carbonatite, but also channels along which calcium moved inwards into the carbonatite. Such a conclusion immediately raises the problem of the original composition of the carbonatite veins in the more basic fenites. The above argument would obviously be paradoxical if the veins were considered to have been originally composed essentially of calcium carbonate; it is more likely that they were of some other composition, and acquired their present chemistry as a result of the fenitization process.

This dilemma is readily resolved if it is assumed that the present carbonatite veins initially were composed principally of alkali carbonates, perhaps akin to the Oldoinyo Lengai natrocarbonatite lava, analyses of which gave $K_2O = 6.5 - 7.6 \%$, $Na_2O = 29.0 - 30.0 \%$, $CaO = 12.7 - 19.1 \%$, $MgO = 0.4 - 2.35 \%$ (Dawson, 1966, Table 4), then loss of sodium ions to the surrounding rocks would involve the production of calcium carbonate thus:



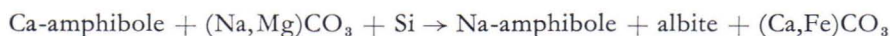
This process can be followed in more detail if the reaction of alkali carbonate with the rocks rich in hornblende is considered. The alteration of hornblende to an alkali amphibole during fenitization is readily demonstrated at Sokli, and can be followed chemically by comparing the analyzed ferro-tschermakitic hornblende (Table 4, No. 27) with one of the analyzed alkaline amphiboles, of which No. 17 (Table 4) is undoubtedly the product of alteration of a country rock calciferous amphibole. In Table 15 the chemical changes in going from the calciferous to the alkaline amphibole

TABLE 15

Elemental changes in alteration of a calciferous amphibole (Table 4, anal. 27) to an alkaline amphibole (Table 4, anal. 17) during fenitization, and composition of a phlogopite formed as a product of the same reaction (Table 7, anal. 34)

	calcium amphibole	sodium amphibole	product of alteration	phlogopite
Si	6.42	7.64	+1.22	6.11
Al (total)	2.07	0.16	-1.91	2.15
Ti	0.19	0.19	—	0.12
Fe ³⁺	0.70	1.08	+0.38	0.52
Fe ²⁺	1.81	0.71	-1.10	1.03
Mn	0.05	0.03	-0.02	0.03
Mg	1.78	2.36	+0.58	4.11
Ca	1.75	0.11	-1.64	0.09
Na	0.49	2.10	+1.61	0.36
K	0.17	0.45	+0.28	1.42

are summarised. The principal elements added to the alkaline amphibole are Si, Mg, and Na; and those removed are Al, Fe²⁺, and Ca. Such an alteration is readily expressed by the equation:



The albite accommodates the excess aluminium from the reaction, and silicon would be available from the fenitization of the gneisses. Commonly, however, phlogopite is also produced by fenitization of calciferous amphibole which would give the equation:



Both equations balance well, but no account is taken of the additional water and fluorine necessitated by the second equation. However, both were present in abundance in the Sokli aureole, and by comparison with the Oldoinyo Lengai natro-carbonatite lava, in which they are abundant, it is reasonable to conclude that they were present also in the Sokli carbonatite.

Thus the fenitization of the hornblende schists is readily accounted for by interaction with alkali carbonate magma or fluid, and supports the contention that the calcium now present in the carbonate veins, or a proportion of it, originated in the more basic rocks of the fenite aureole, not the carbonatite; and that the calcium removed from the fenite aureole migrated inwards along the veins into the carbonatite. This conclusion is of considerable significance with regard to the origin and nature of the carbonatite.

Verwoerd (1966) after comparing fenites from a number of complexes concluded that calcium »was added in greater or lesser amount in nearly every example with the exception of some of the basic rocks» (*op.cit.* p. 141). Verwoerd's findings with regard to basic rocks are the same as for Sokli, but the difference for other rocks is due to the calculation of Sokli rocks carbonate free.

After calcium the greatest loss from the hornblende schists is of Fe^{2+} , but this is partly accounted for by oxidation to Fe^{3+} , while there is a considerable gain in Fe^{3+} in the fenitized gneisses. Although some of this gain could represent a redistribution from the hornblende schists, there has been a net increase in iron in the aureole during fenitization for which the carbonatite is a ready source.

The only element added in large amounts to the sodic fenites is sodium, and the most likely source is the carbonatite which was probably emplaced as a melt containing a considerable proportion of alkalis, like that of the Oldoinyo Lengai natrocarbonatite lava. It would, therefore, have contained some 7 % K_2O as well as 29–30 % of Na_2O , and it is to be expected that this is the source of the potassium which is now concentrated in some of the potassic fenites.

The addition/subtraction diagram (Fig. 52) indicates that in the potassic fenites, apart from the alkalis, the elemental changes are similar to those of the sodic fenites, the only significant exception being the greater loss of magnesium from the hornblende schists. Whereas the sodic fenites derived from hornblende schist have only lost about 10 % of their magnesium, the potassic fenites have lost some 85 %. This is shown mineralogically by the presence of abundant alkaline amphibole and some phlogopite in the sodic fenites, but only minor phlogopite in the potassic fenites.

The fixation of magnesium in the sodic fenites by reaction of a magnesian alkali carbonate melt with calcium amphibole to form phlogopite and alkali amphibole has already been outlined. In the potassic fenites however, some magnesium is fixed by a different reaction whereby phlogopite is generated at the expense of potassium feldspar, a process referred to as 'phlogopitization' by Garson (1965, p. 42). This reaction is concentrated along carbonate veins cutting potassium feldspar, and hence it seems reasonable to assume that the magnesium needed to form phlogopite comes from the carbonate of the veins.

As explained in the petrographic section, the potassic fenites at Sokli include two types, in one of which the potassium-rich rocks comprise sharply cross-cutting zones, particularly within the more basic rocks, usually with a central thread, or vein, of carbonate which must be the source of the potassium, while the second type is characterised by a more diffuse reddening of the rocks and is restricted to granite gneisses in the outer part of the aureole. The second type could be interpreted as an early phase of potassium metasomatism which predates the main sodium metasomatism. Alternatively, reference to Fig. 52 a indicates that there has been a slight loss of potassium from the granite gneisses which have undergone sodic metasomatism, and it seems possible that the potassium lost from these rocks was driven ahead of the front of sodium metasomatism, and was fixed in the periphery of the aureole. Yet another possible explanation is that both types of potassic fenitization are aspects of the same process, but that their different appearances are related to the mechanical properties of the host rock. The granite gneisses, for instance, probably shatter more easily resulting in close veining, so that the metasomatising fluids can permeate widely and evenly. The hornblende schists, in contrast, are tougher and

break into sizeable blocks to the margins of which the metasomatising fluids are restricted. Evidence is at present lacking as to which of these petrogenetic models is correct for explaining the source of potassium in the diffuse type of potassic fenites, and their relationship to the sharply cross-cutting type.

Because the cross-cutting potassic fenites are clearly later than the sodic fenites, they pose problems with regard to the evolution of carbonatite. There could have been two phases of carbonatite emplacement at Sokli of which the first was enriched in sodium and the second in potassium. Alternatively, the carbonatite could have contained both alkalis, but lost the sodium preferentially at an earlier stage, an hypothesis which has been discussed with reference to the fenitization around Malawi carbonatites (Woolley, 1969), where there is usually a later collar of potassic fenites between the carbonatite and sodic fenites. However, the potassic fenitization at Sokli is on a smaller scale than that of the Malawi carbonatites, and generally potassic fenitization seems to be a high level effect, as suggested by Garson (1962). Sokli represents a rather deep level, so that the bulk of any potassium in the primary carbonatite magma would have been concentrated at a level above the present erosion surface. The idea of two distinct carbonatite episodes at Sokli, one sodium and the other potassium enriched, is not favoured, and it is considered more probable that sodium was lost preferentially from the carbonatite to the wall rocks, and that the last fraction of carbonatite melt, enriched in potassium, was squeezed into the sodic fenite envelope causing local enrichment in potassium.

Woolley (1969) has shown that the diagram quartz-nepheline-kalsilite is particularly useful in following the changes in the leucocratic constituents during fenitization. The diagram is used purely as a graphical construction; none of the data determined experimentally for this system and applicable to igneous rocks, applies to fenites. The diagram is limited in that it does not reflect the peralkalinity of many syenitic fenites, some of the sodium of which is represented normatively by acmite, or sodium silicate, but it does indicate rather well the bulk composition of the feldspar. A further restriction applies to fenites containing phlogopite the potassium of which is allocated normatively to feldspar, so that the orthoclase component of such rocks is inflated. If these limitations are kept in mind the diagram is a very useful one.

On Fig. 53 are plotted the Sokli fenites together with numerous fenites and the country rocks from which they were derived from 26 other localities. Most fenites are developed from granites, schists, and gneisses and plot in the central part of the Qz—Ab—Or triangle. The analyzed Sokli granite gneisses and hornblende schists are rather more sodic than the typical unfenitized country rock and the Sokli sodic fenites are, as a group, the most sodic fenites described.

Although in a composite diagram such as Fig. 53 there is a broad scatter from sodic to potassic fenites, if individual localities are considered it is usually found that there is a restricted, and often distinctive trend. In an earlier paper the data then available from nine localities were found to produce two trends, the first of which appeared to converge on the Ab—Or join approximately at the experimentally

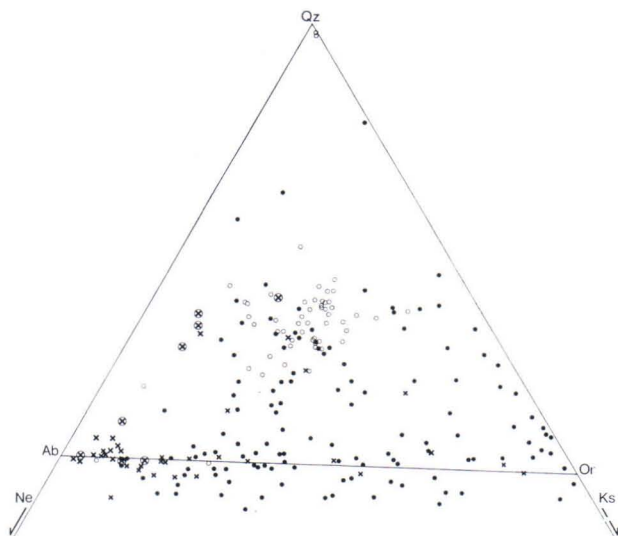


FIG. 53. Plot of fenites and the country rocks from which they were derived taken from the literature and plotted in the system quartz — nepheline — kalsilite (based on weight norms). Solid circles, fenites; open circles, country rocks; crosses, Sokli fenites; circled crosses, Sokli country rocks.

determined minimum, and the second of which then went towards the Or point (Woolley, 1969, Fig. 7). A trend towards the minimum was later found for fenitized quartzites from the Borralan Complex (Woolley *et al.*, 1972, Fig. 9). However, although it is apparent from Fig. 53 that the more abundant data now available still show some clustering about the Ab—Or minimum there are also numerous analyses well away from this point, and the Sokli syenitic fenites which cluster towards the Ab composition point occupy an area of the diagram for which there were no published analyses in 1969. It is now necessary to abandon the idea that sodic fenites are converging on the Ab—Or minimum.

If the plots on Fig. 53 are considered locality by locality they are found to fall into several broad trends a number of which are shown on Fig. 54. For this diagram trends have only been drawn where there is either abundant data which define a clear pattern or, as in the case of the Sokli potassic fenite veins, give an unambiguous trend. The Amba Dongar and Borralan data are important because the fenitized rocks are derived from quartzite, which removes the difficulty of following trends when the country rocks are of widely differing compositions. The Amba Dongar fenites show two distinct trends, though both are extremely potassic. The Borralan fenites are associated with syenites and nepheline syenites, not carbonatite, but petrographically

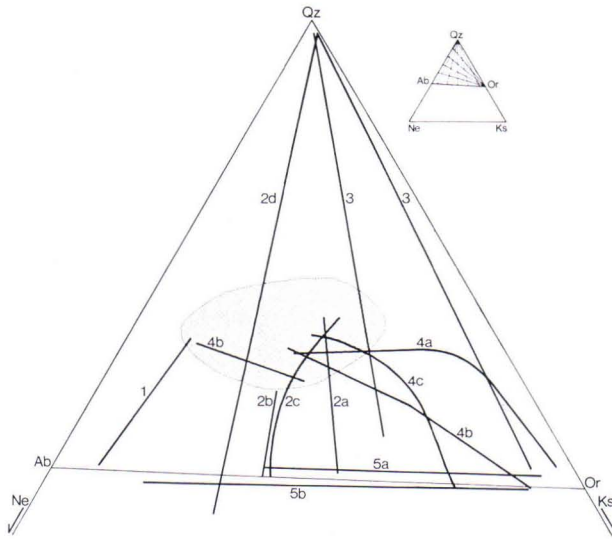


FIG. 54. Fenitization trends at a range of fenite localities plotted in the system quartz — nepheline — kalsilite. For classification of fenites based on these trends see Table 15. 1, Sokli; 2a Alnö; 2b, Chilwa Island; 2c, Callander Bay; 2d, Borralan; 3, Amba Dongar; 4a, Bukusu; 4b, Sokli potassic schist series; 4c, Brent Crater; 5a, Chilwa Island; 5b, Sokli potassic veins! Shading indicates area of the majority of country rocks.

these fenites are clearly comparable with those associated with carbonatite. The classic data of von Eckermann (1948) for Alnö is difficult to use because the country rocks and fenites show a very wide range of Na/K values. However, one series of four specimens was taken by von Eckermann (1948, p. 41, nos 6, 11, 15, and 18) at right angles to the carbonatite contact across the fenite aureole, and were considered to represent increasing fenitization of a particular granite gneiss country rock. The 12 analyses from Oldonyo Dili given by McKie (1966) have a diverse range of Na/K values, suggesting derivation from a wide range of country rock types and consequently no simple trend of the Na: K ratio can be defined.

The only localities meeting the criteria outlined above are Alnö (von Eckermann, 1948), Amba Dongar (Deans *et al.*, 1972), Chilwa Island (Woolley, 1969), Brent Crater (Currie, 1971), Callander Bay (Currie and Ferguson, 1972), Borralan (Woolley *et al.*, 1972), Bukusu (Baldock, 1973) and Sokli (this paper).

Data from these areas define straight or gentle curves on the Qz—Ne—Ks diagram. The trends are of two types; those diverging from the Qz point, and those that converge on the Or composition point (see generalized inset diagram, Fig. 54). The first group indicates de-silication and addition of both sodium and potassium, though in widely contrasting proportions; the second group may not involve de-silication,

TABLE 16
Classification of fenites

Fenite type	Characteristic features	Examples: numbers in parentheses refer to trends shown on Fig. 54.
NORMAL FENITIZATION		
1. Sokli type	Na and K added; alkali pyroxene and amphibole strongly sodic	Sokli (1)
2. Intermediate type	major Na and K	Alnö (2a), Chilwa Island (2b) Callander Bay (2c), Borralan (2d)
3. Amba Dongar type	major K; only minor Na	Amba Dongar (3)
POTASSIC FENITIZATION		
4. Bukusu type	Major K added only; no alkali pyroxene or amphibole; phlogopite sometimes K only	Bukusu (4a), Sokli potassic schist series (4b), Brent Crater (4c)
5. Chilwa type	potassic fenitization superimposed on normal fenitization	Chilwa Island (5a), Sokli potassic veins (5b), Tundulu, Kangankunde

but is characterised by an increase in the potassium: sodium ratio during fenitization. It is suggested that these trends encompass all the major changes in terms of normative quartz and alkali feldspar during fenitization, and that therefore, fenites can be classified into the five groups shown in Table 16.

Although this classification is purely descriptive, it may be that there is a genetic link between the different types. For instance, the different types of fenite may be related in terms of depth such that normal fenitization, particularly if it is very sodic, is a deep level phenomenon, whereas potassic fenitization of Bukusu type is a high level effect, but this awaits confirmation.

Verwoerd's proposed classification of fenites (1966, p. 143, Table 4) is based firstly on the type of rock fenitized (i.e. acid rocks and basic rocks); then secondly on whether sodium or potassium has been added in greater amount; and finally on whether CO₂ has or has not been added. This classification is useful but the system of sub-division based on original rock type is difficult to apply especially when considering aureoles of varied rock type. At Sokli, for instance, both basic and acid rocks have been subjected to the same fenitizing solutions. Separating these into different fenite categories would not be very useful, although admittedly there are mineralogical differences, and the chemical changes undergone during fenitization have been different. Nevertheless, whatever the original rock type, fenitization is characterized by the addition of alkalis, so that a subdivision based primarily on this feature is a logical one. Verwoerd's (1966) subdivision into two groups based on the ratio of added Na: K is the equivalent of types 1 to 3 of Table 16, but Verwoerd

contests the suggestion of Garson and Campbell Smith (1958) that late feldspathization at Chilwa Island is a distinct type of potassium fenitization, and in consequence Verwoerd does not have potassic types equivalent to 4 and 5 of Table 16.

The concentration of syenitic fenites close to the Ab—Or join in the Qz—Ne—Ks system (Fig. 53) is of considerable significance in considering whether carbonatites are capable of de-silication so as to produce silica undersaturated compositions. Although the Sokli carbonatite is very large and has a wide fenite aureole, no nephelinization has been observed. This holds for most carbonatites, so that the concentration of fenite analyses along the Ab—Or join probably represents the extreme of de-silication which can be produced by carbonatite. The relative abundance of feldspar phenocrysts in carbonatites and paucity of nepheline phenocrysts also supports this conclusion. At some carbonatite centres however, there has been nephelinisation, for example Tundulu in Malawi (Garson, 1962), where however it is associated with foyaite rather than carbonatite, and at Dorowa (Johnson, 1961) where nepheline-bearing pulaskitic fenites occur but they are associated with ijolite, and not with the carbonatite which is surrounded directly with syenitic fenites. At Alnö, however, von Eckermann (1948) interprets many of the nepheline-bearing rocks as being fenites resulting from the action of the carbonatite, but comparison with other complexes suggests that the nephelinisation at Alnö was caused by ijolites and nepheline syenites of primary origin, and not by the carbonatite.

Some idea of the probable temperatures obtaining during fenitization in the aureole at Sokli can be gained from the feldspar and phlogopite. The syenitic fenites of the innermost parts of the aureole contain a feldspar which is sometimes perthitic, indicating temperatures above the feldspar solvus. The work of Bowen and Tuttle (1950) on the albite — orthoclase series showed that at 1 Kilobar water pressure the solvus is at $660^{\circ} \pm 10^{\circ}\text{C}$ at a composition close to 55 % $\text{NaAlSi}_3\text{O}_8$, and Yoder *et al.* (1956) have shown that the solvus temperature increases by only about 14°C per kilobar increase in water pressure. The Sokli fenite feldspars are richer in the albite component than 55 %, but temperatures of crystallisation were probably in excess of 600°C in the inner part of the aureole.

Bailey (1966) has shown that the reaction $\text{orthoclase} + \text{dolomite} + \text{H}_2\text{O} \rightleftharpoons \text{phlogopite} + \text{calcite} + \text{CO}_2$ at 1 kilobar total pressure is strongly dependent on the partial pressures of H_2O and CO_2 , such that with excess H_2O and deficient CO_2 phlogopite + calcite is the stable assemblage above 340°C , below which orthoclase + dolomite is stable. With excess CO_2 , orthoclase + dolomite is stable up to 640°C . In the inner Sokli aureole close to the carbonatite the assemblage phlogopite + alkali amphibole is stable, and the phlogopite replaces feldspar. The proximity of the carbonatite suggests that the partial pressure of CO_2 would be high, so that from Bailey's (1966) data the presence of phlogopite indicates a temperature in excess of 600°C . Phlogopitization also occurs along the central parts of potassic fenite veins up to 450 metres from the carbonatite contact. The crystallization of potassium feldspar along the veins later followed by phlogopite, suggests either increasing temperatures,

or an increase in the relative pressure of water compared to that of CO_2 . Both factors probably applied, but in this part of the aureole water is probably more important, because of the crystallization of calcite taking up CO_2 , so that according to the data of Bailey (1966) the transition K-feldspar \rightarrow phlogopite will occur at lower temperatures.

Wyllie and Tuttle (1960) have shown that carbonatite melts can persist down to 600°C . From work on fluid inclusions in apatites from sövites Le Bas *et al.* (1972), report minimum melting temperatures of about 550°C . This evidence points to minimum temperatures at the inner fenite boundary of some 600°C . Upper temperatures are more difficult to estimate. Apart from a few veins which could represent rheomorphosed fenites, there is no evidence of melting, so that sub-liquidus temperatures are indicated. As amphibole and phlogopite are abundant a substantial pressure of water must have prevailed. If, therefore, a water vapour pressure of 2 kilobars is assumed the data of Bowen and Tuttle (1950) indicate an upper temperature limit of about 800°C .

On Fig. 55 the probable temperature gradient across the Sokli fenite aureole is given using the data discussed above to fix the temperatures at the carbonatite contact and within the innermost syenitic fenites. A very rapid decrease in temperature in the first few hundred metres from the carbonatite is deduced from the textures and mineralogy of the rocks. Thus the innermost fenites, shaded on Fig. 55, differ texturally from the other fenites principally in their coarse, granular textures which take on an 'igneous' appearance — indeed some of these rocks if studied in isolation could not be distinguished from igneous syenites. The relative homogeneity of these rocks suggests that any later diffusion or transport of elements has probably involved movement along crystal boundaries coupled with small scale solid diffusion. In contrast, movement of elements in the outer fenites seems to have been concentrated along veins and veinlets, and then along cracks, grain boundaries and cleavages, probably carried by

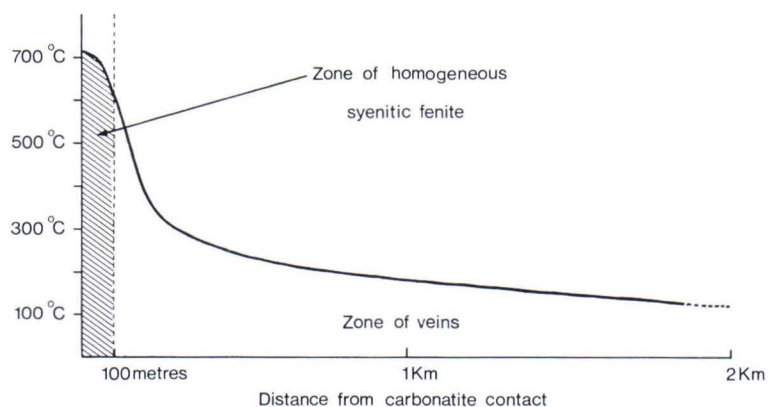


FIG. 55. Inferred temperature distribution in the Sokli fenite aureole at the peak of the metasomatism. For details of the 'zone of homogeneous syenitic fenite' and 'zone of veins', see text.

some fluid medium. There is a gradual increase in the effects of fenitization in the outermost part of the aureole followed by a relatively rapid change to the distinctive inner fenites (Fig. 55).

The rapid outward decrease in temperature is readily explained if the agent of fenitization is considered to be some form of outward streaming gas (fluid) from the carbonatite. From work on fluid inclusions from apatites in sövites Le Bas *et al.* (1972) report that »a fluid medium capable of transporting carbonatitic material can exist, not as a molten liquid but as a gaseous and mobile supercritical fluid from which carbonatites can crystallize directly». Work on fluid inclusions from apatites in fenites (A. Rankin, personal communication) shows the presence of only a gas phase. It is envisaged from these results that in the immediate environment of the carbonatite a mobile supercritical fluid existed of alkaline carbonatitic composition. Adiabatic expansion of this fluid, produced by outward movement, would cause very rapid cooling to produce the sharp temperature drop shown on Fig. 55. Within this inner zone there was probably little reaction between the carbonatitic fluid and the fenite, because the fenite would have already reached an equilibrium condition in which the maximum content of sodium was held (there may be more activity of potassium), but the high temperatures would induce relatively rapid recrystallization towards a coarser and more stable fabric. At the outer edge of the inner fenite zone chemical activity would be more vigorous with reactions such as the exchange of sodium in the fluid for calcium in the silicate phases and the crystallization of calcite taking place. Within this area a change probably took place in the nature of the fenitizing fluid. The fall in temperature probably led to dissociation of the fluid into gas, liquid, and solid phases, and it is the gas phase which was mainly responsible for the fenitizing activity in the rest of the aureole.

Although CO₂ was certainly one of the major components in the inner aureole the crystallization of calcite would reduce its partial pressure so that other gases became relatively more important. Evidence as to the nature of these gases is as follows:

hydration of feldspar	— H ₂ O
carbonate minerals	— CO ₂
micas (particularly along veins)	— H ₂ O and F
amphiboles	— H ₂ O and F
pyrite	— S, SO ₂

Of these gases fluorine is certainly particularly effective in elemental transportation and the analyses of the amphiboles indicate that fluorine is almost as abundant as water. The mechanism by which the fluorine acted as an agent for element migration is thought to be that referred to as 'chemical transport reactions' in the book of that name by Harald Schafer (1964). In the words of Schafer (1964, p. 1): »Chemical transport reactions are those in which a solid or liquid substance A reacts with a gas to form exclusively vapor phase reaction products, which, in turn, undergo the reverse reaction at a different place in the system, resulting in the reformation of

A . . . The process appears to be one of sublimation or distillation. Substance A however, does not possess an appreciable vapor pressure at the applied temperatures. The substance is transported chemically. In addition to a reversible heterogeneous reaction, a concentration gradient must be established. The latter can be the result of temperature gradients, changes in the relative pressures, or the differences in the free energy of formation of two substances.»

The reactions can often be achieved at only moderate temperatures. Nickel, for instance, is readily transported through an atmosphere of CO, moving from areas of low temperature e.g. 80°C to ones of higher temperature e.g. 200°C; the transport being achieved by diffusion of Ni(CO)₄ gas (Schafer, 1964, p. 36). Very many substances are listed by Schafer which have been transported in this way in the laboratory including Si, which can be transported as SiF₄, and SiO₂ which can be transported by H₂ and H₂O.

The movement of a complex may be simply by diffusion or by convection. If diffusion alone is adequate then the mechanism if applied to transport in fenites, would not require an abundance of the gas phase, but just enough to permeate the whole aureole, when the reaction would proceed once the necessary temperature, pressure, or chemical gradients had been established. A diffusion process up the temperature gradient could overcome the problem of transporting silicon inwards towards the carbonatite centre, as discussed earlier. Such transport would be difficult if there was a rapid outward flow of fenitizing gases. If, however, the suggestion that silicon moves inwards in the aureole is correct, then it implies either that there was no outward flow of the fenitizing fluids and all chemical transport was achieved by diffusion, or that the convection was slower than the inward diffusion of silicon.

By advocating this mechanism it is not implied that this is the only way whereby elements were transported in the fenite aureole, for the alkalis emanating from the carbonatite, for instance, in the inner part of the aureole at least, were certainly in a different condition, but 'chemical transport reactions' do provide a means for redistribution of elements within the aureole, and for the inward movement of elements against the temperature gradient.

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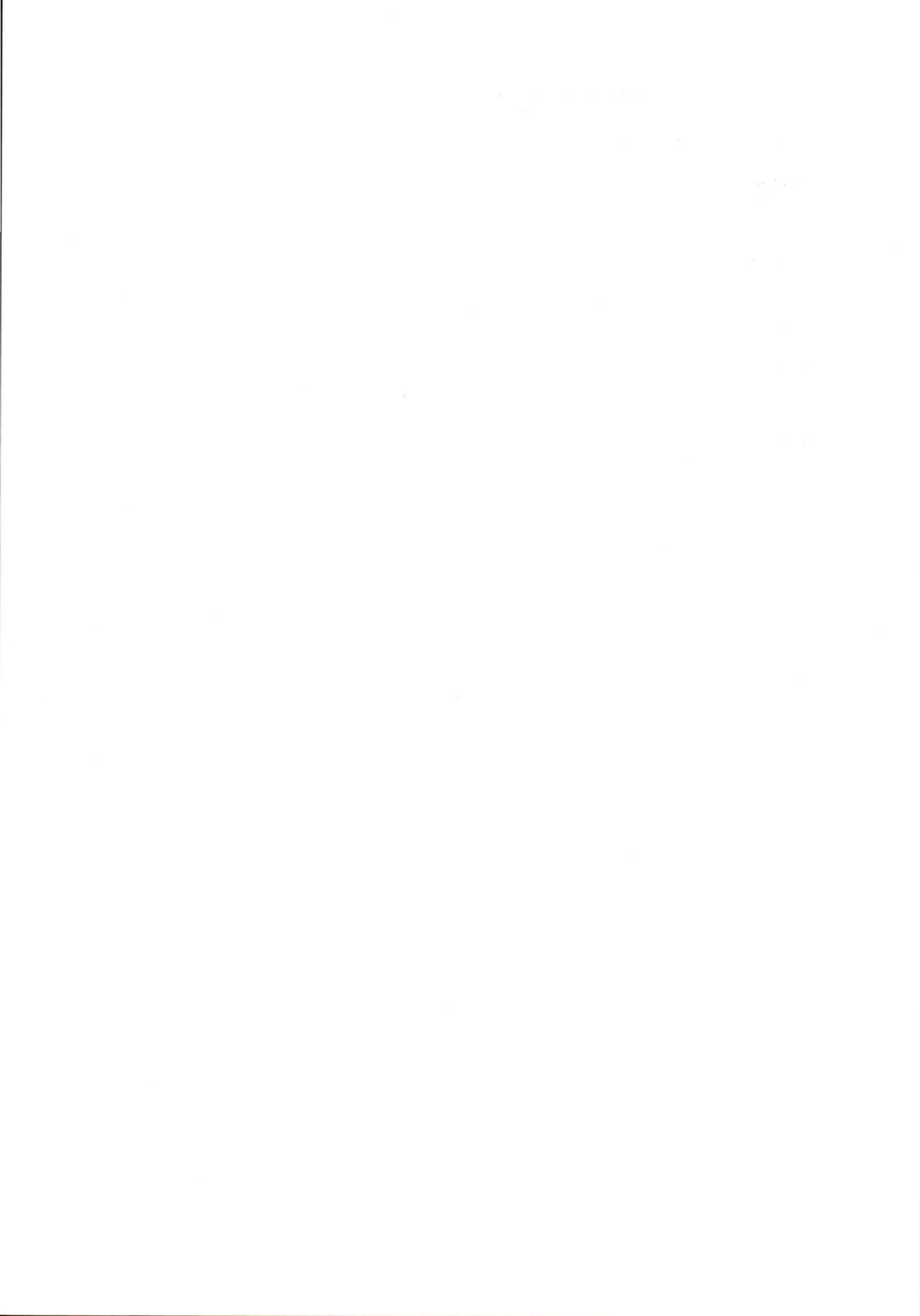
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