

Metasomatized (fentized) quartzites from the Borralan Complex, Scotland

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SUMMARY. Fentized quartzites are described from three localities around the Borralan alkaline igneous complex. Chemical and electron-probe analyses of amphiboles, pyroxenes, micas, and feldspars are given. Early-formed amphiboles are calcic, but these are replaced by alkaline varieties with increasing fentization. Rock analyses indicate a 'straight line' rate of increase of Ti, $\text{Fe}^{2+} + \text{Fe}^{3+}$, Mg, Al, K, and a more variable increase of Ca and Na atoms, at the expense of Si atoms. The simple composition of the unaltered quartzite allows the accurate calculation of bulk changes during fentization. The final product of the alkali metasomatism is a syenite lying close to the albite-orthoclase minimum though the primary source of the fentizing fluids was probably a highly potassic magma.

DURING recent mapping of the Borralan Complex a new group of rocks was found, which prove to be fenites. Although there are numerous descriptions of fenites in the literature they have not been described previously from Britain. The Borralan fenites are also of particular interest because they comprise fentized quartzites. Most fenites occur in schist terrains, the heterogeneity of which makes it difficult to derive accurately their original composition, and hence the chemistry of the fentization process. In the Borralan area the simple chemistry of the parent quartzite helps in elucidating the chemical gains and losses involved in the metasomatism.

Fig. 1 is a map of the complex, which comprises a central plug of syenite and quartz syenite enveloped by an earlier suite of nepheline syenite, pseudoleucite syenite, malignite, and various ultramafic rocks (Woolley, 1970).

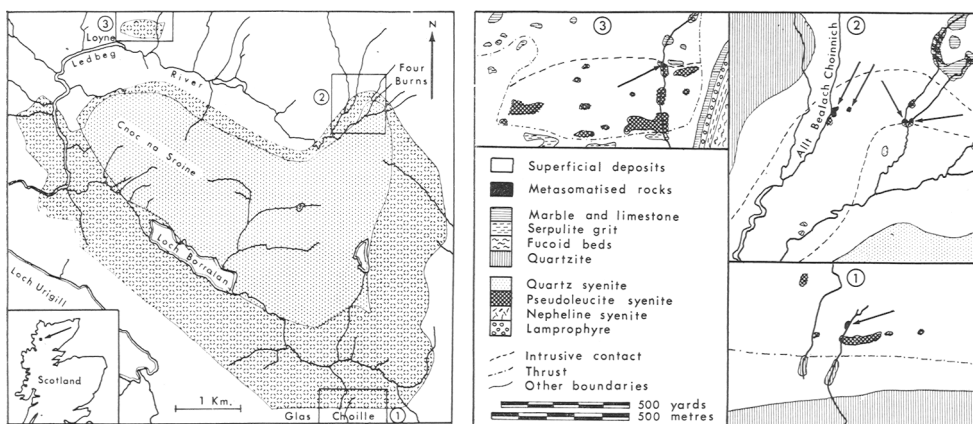
Field relations

The rocks forming the subject of this account are found at three localities (fig. 1), and at each locality they are closely associated with pseudoleucite syenites. Exposure is poor, particularly at localities 1 and 2 (fig. 2), so that the relationship between metasomatized and igneous rocks can only be surmised.

Locality 1 is on the north side of Glas Choille (fig. 1) and consists of a single small outcrop in the western bank of a stream (fig. 2). A series of hillocks of pseudoleucite syenite occur to the south and south-east, but there is no evidence as to their relationship to the metasomatized rock.

The second locality is on the north-east side of the complex (figs. 1 and 2). One exposure is in the east bank of the Allt Bealach Choinnich, and a second forms a small knob some 30 m to the east. In rocks from both exposures a distinct planar structure is apparent, and the second exposure weathers in an unusual, knobby manner.

Pseudoleucite syenite crops out in the bank of the stream 20 m to the south. At the junction of the two most northerly of the four prominent streams known as the Four Burns (figs. 1 and 2), metasomatized rock is exposed in the bed of the stream. It is cut by aplite and syenite porphyry veins. Muscovite-rich syenite of the pseudoleucite series crops out some 60 m up the more northerly stream.



FIGS. 1 and 2: FIG. 1 (left). The Loch Borrallan Complex. Rounded ornament, earlier rock suite; dotted ornament, later syenites. The location of the three areas shown on a larger scale as fig. 2 are indicated. FIG. 2 (right). Geological maps of the Glas Choille (locality 1) Four Burns and Allt Bealach Choinnich (locality 2), and Loyne (locality 3) areas. The arrows indicate the outcrops of metasomatized rocks.

Locality 3, north-east of the cottage at Loyne, comprises a thrust mass of pseudoleucite borolanite roofing against limestone and with some evidence of a limestone floor (Woolley, 1970, p. 175 and Fig. 3, section A-B). A low cliff, over which a stream tumbles, on the north-east side of the mass exposes a lens, at least two feet thick and some five to six feet long, of a dark, blue-grey rock, which appears to be wholly enclosed in borolanite. However, shearing and the similarity in appearance of the lens and the host rock makes delimitation difficult. Occasional pink syenite veins cut this lens.

Petrography

Glas Choille. The rock exposed at Glas Choille is tough, even grained, dark-green to grey, and cut by two systems of veins: pink, feldspathic veins up to two cm in width, and a network of very fine, pale-green veinlets. The feldspathic veins are commonly flanked by a distinctive pale-green reaction zone (fig. 3).

These rocks are seen in thin section to vary according to the close proximity, or otherwise, of veins. When free of veins, or more than three or four mm away from one, the rock is composed essentially of quartz, amphibole, and alkali-feldspar with lesser amounts of pyroxene, and minor biotite, ore, apatite, and sphene. Quartz varies in different sections from some 10 to 50 vol. %; it forms aggregates and isolated crystals up to 0.3 mm diameter with fretted margins commonly penetrated

by amphibole needles. Intra-quartz boundaries are sutured and identical to those displayed by deformed Cambrian quartzites adjacent to the Borralan Complex.

Feldspar is much finer grained than quartz and together with the amphibole envelopes and extends between the quartz grains producing a pseudo-porphyrific appearance. The feldspar is dominantly a potassic one and builds amoeboid-shaped crystals; a little finely twinned sodic plagioclase is present.

Modal amphibole ranges from 10 to 30 %. Texturally it is very variable, forming isolated and sheaved acicular crystals, euhedral, stubby prisms, or, most commonly, anhedral sieved crystals of very irregular shape. All types may occur in one small area of rock, or within a single cluster of crystals. Variations of colour and birefringence within crystals and aggregates suggest the intergrowth of two or even three different amphiboles. Colour varies from colourless through pale-green to green, and through shades of pale-blue to lilac, but the blue colouration is usually restricted to the vicinity of veins.

Subhedral to anhedral aegirine-augite occurs as randomly distributed clusters and lines of grains defining some of the fine veins. These veins are not continuous or sharply delimited. Biotite, pleochroic from pale yellow-brown to reddish-brown, is unevenly distributed producing occasional open clusters; it is often associated with ore. Both pyrite and magnetite occur as small euhedra and occasional larger anhedral grains. Sphene, strongly pleochroic in shades of reddish-brown, and acicular apatite are present.

The green veinlets may be of the discontinuous type, mentioned above, or may be more substantial, up to two mm in width, and comprising aegirine-augite solely, or aegirine-augite together with occasional patches of matrix rock suggesting that these veins, like the finer ones, are of metasomatic origin. Amphibole, sphene, and limonite are also sometimes concentrated along veinlets.

The feldspathic veins comprise turbid, sutured, occasionally Carlsbad-twinning feldspars up to two mm diameter with interstitial patches of much finer grained potash feldspar and oligoclase. Aegirine-augite forms patches and lenses of irregular distribution or comprises a regular central zone to the vein (fig. 3). Pyroxene also defines a reaction zone along vein contacts, varying from a few grains width to five or six mm. This zone consists of some 50 to 60 % pyroxene, with the rest composed of fine-grained feldspar, and it appears to develop through the replacement by pyroxene of the quartz and amphibole of the adjacent rock. There is some evidence that the pyroxene-rich patches in the veins represent altered country rock.

In some sections there is a noteworthy concentration of biotite near the veins, and it seems that biotite increases in abundance once all the quartz has been replaced.

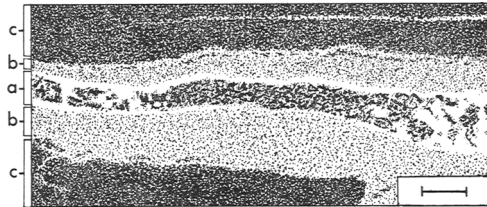


FIG. 3. Fensitized quartzite cut by syenite vein, Glas Choille (1970, P34 (44)). A, syenite vein with aegirine concentrated towards the centre, B, pyroxene-rich zone, C, quartz-alkali-feldspar-alkali-amphibole rock. The scale line is 5 mm.

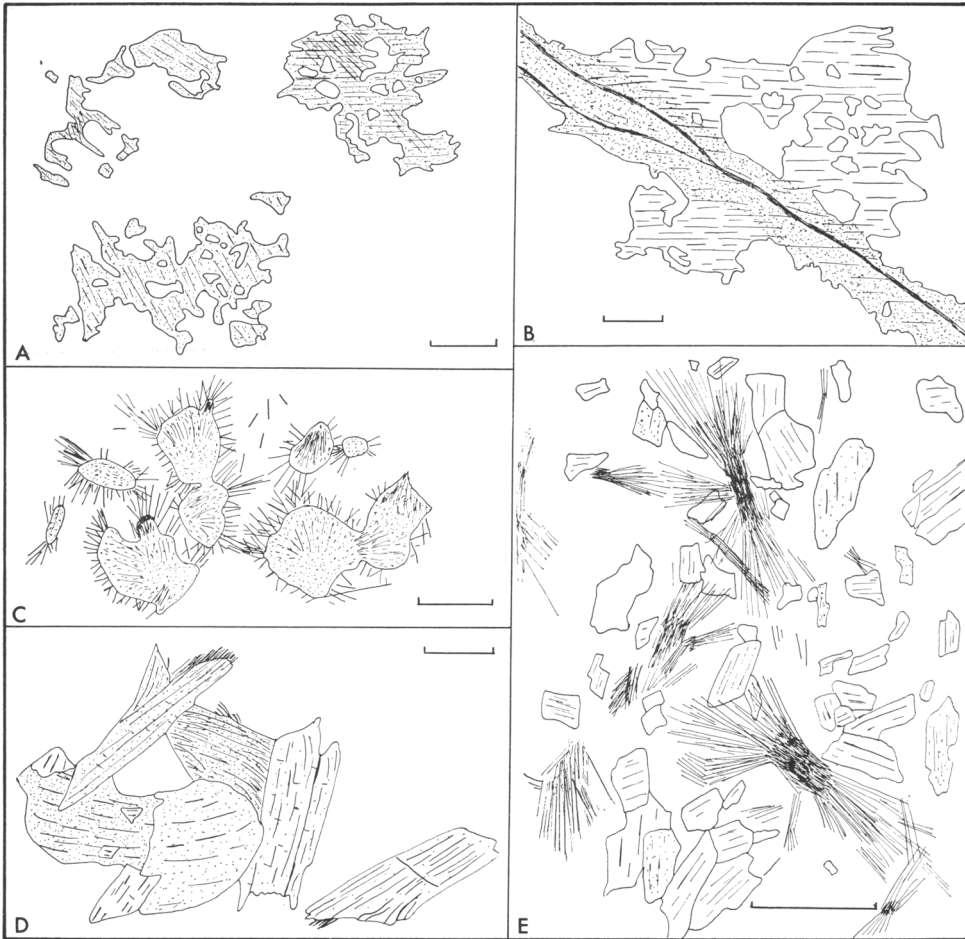
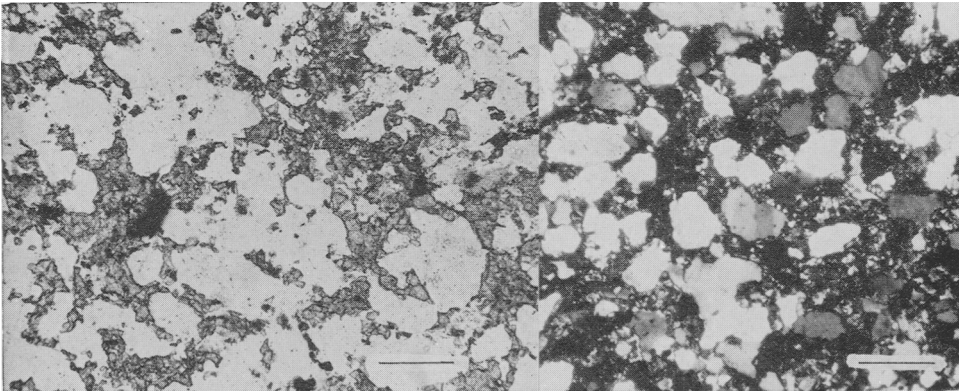


FIG. 4. Amphibole textures; all drawings are based on photomicrographs. A, spongy actinolitic hornblendes with inclusions of quartz and alkali-feldspar; junction of the two more northerly of the Four Burns (B608). B, spongy actinolitic hornblende with quartz inclusions cut by alkali-amphibole vein. In the vicinity of the vein the green hornblende is altered to a blue alkali-amphibole (B608). C, rounded bunches of alkali-amphibole crystals with surrounding radiating amphibole needles; Loyne (B290C). D, Stout prisms of alkali-amphibole; Loyne (B288). E, Radiating aggregates of fine alkali-amphibole needles in a biotite-rich rock; Loyne (1970, P34 (5)). The scale lines are 0.1 mm in length.

Four Burns. The metasomatized rock outcropping at the junction of the two burns (fig. 2, locality 2) is grey and faintly banded. It comprises some 50 to 60% quartz forming sutured grains between and extending around which are lightly sericitized potash feldspars, a little fresh, finely twinned sodic plagioclase, and two distinct varieties of amphibole. The commoner amphibole is a green variety developing complex, spongy forms enveloping and penetrating between the quartz grains (fig. 4A and B). The second, and less abundant, amphibole is a blue variety that occurs as small stellate clusters of acicular crystals, as rims to green amphibole, or concentrated,

together with limonite, along veinlets of less than a millimetre width (fig. 4B). Occasional flakes of reddish-brown biotite are present, while anhedral grains of magnetite are common.

The rock exposed along the Allt Bealach Choinnich shows a clear banding, which is undoubtedly after bedding. It varies from a quartz-alkali-feldspar-pyroxene to a quartz-alkali-feldspar-pyroxene-amphibole rock in which the quartz grains are up to 0.2 mm diameter, have fretted margins, and are partially replaced by feldspar and pyroxene (figs. 5 and 6). The feldspar, dominantly potassic but with some sodic



FIGS. 5 and 6: FIG. 5 (left). Photomicrograph showing the development of pyroxene around and between quartz grains in a rock from Allt Bealach Choinnich (B682). Ordinary light. Scale line is 0.2 mm. FIG. 6 (right). Same as Fig. 5 but with crossed polarizers.

plagioclase, is interstitial to and penetrates between the quartz grains. The pale-green, anhedral pyroxene forms clusters and strings of grains among and between the quartz (fig. 5). A green amphibole, which is absent from some specimens and parts of some thin-sections, forms small grains, usually intergrown with pyroxene. A blue amphibole is rare. Reddish-brown sphene and magnetite are plentiful, while some brown biotite occurs.

The small outcrop to the east of Allt Bealach Choinnich has two main constituents: a fine-grained, homogeneous dark-grey rock cut by thin, criss-crossing, pale-green veins; and a coarser, somewhat heterogeneous rock with a peculiar knobby weathered surface. The coarser rock consists volumetrically of some 44 % quartz grains, which have fretted margins and the fabric of which is broken up by a reticulated pattern of heavily sericitized alkali feldspar, chlorite, and brown biotite. Epidote forms isolated grains and cross-cutting veinlets. The opaque mineral is pyrite.

The finer grained rock consists of some 17 % quartz grains, 54 % slightly chloritized biotite and the rest heavily sericitized alkali feldspar and a little pyrite and epidote. Neither amphibole nor pyroxene has been detected in the rocks of this outcrop. As with the other rocks in this series, the thin-section evidence suggests the growth of feldspar and mafic minerals at the expense of quartz with the replacing minerals developing most readily along the quartz grain boundaries.

The *Loyne* rocks are dark purple, and cut by a few feldspathic veins up to two or

three cm in thickness, while a network of fine veinlets is discernible in some specimens. A faint banded pattern is sometimes apparent.

There is a complete series, often within a single thin-section, from alkali-feldspar–amphibole to alkali-feldspar–biotite rocks. Potash feldspar and sodic plagioclase have very complex, sutured margins, and strain shadows and bent twin lamellae indicate deformation; indeed, the plagioclase twinning appears to be partly the result of mechanical deformation. The feldspar is fresh except in biotite-rich rocks in which it tends to be turbid.

The amphibole, which may constitute as much as 40 vol. %, is of two distinct textural types; it forms subhedral prisms, often with ragged terminations (fig. 4D), and it builds rounded, sub-radiating masses of fibrous crystals with an outer bristling margin of acicular needles (fig. 4C and E). The colour is characteristically a shade of blue with a pleochroic scheme such as α neutral, β lilac, γ blue-green, but there is considerable variation of shade, often within a single crystal, in the range blue, mauve, violet. In some specimens the cores to the amphibole crystals are colourless to pale-green, while the rims are a deep-blue.

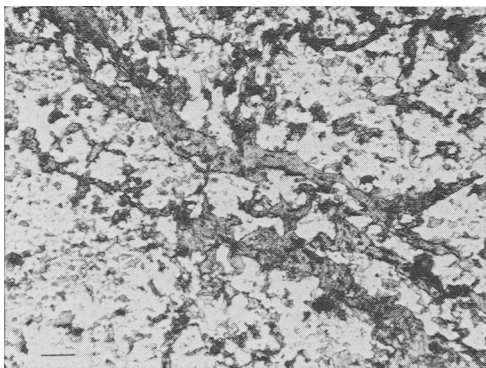


FIG. 7. Cross-cutting alkali amphibole veinlets. Most of the high relief mineral is amphibole; there is some biotite and ore. Specimen 1970, P₃₄ (7) from Loyne. Scale line is 0.2 mm.

Amphibole makes the veinlets apparent in hand specimen (fig. 7), and even in biotite-rich rocks the veinlets are always amphibole.

Biotite, pleochroic from yellow to dark-brown, and modally up to 60 %, forms subhedral to anhedral flakes up to 0.1 mm. The alternation of pure biotite with biotite–amphibole layers, on a scale of two to four mm, develops a layering in the more biotite-rich rocks. A pale-green phlogopite has been identified in one specimen, in which it forms numerous rounded aggregates of minute flakes.

Pyrite is abundant in some rocks, and absent in others, while sphene is similarly variable in quantity. Patches of calcite occur.

The feldspathic veins comprise turbid alkali-feldspar plates up to 5 mm, and accessory biotite and sphene. They are cut by rare veinlets of blue amphibole.

The borolanite that encloses the feldspar–amphibole–biotite rock contains occasional pseudoleucites, and consists essentially of potash feldspar and melanite garnet, with biotite, sericite after feldspar, and accessory sphene, magnetite, and aegirine.

Petrochemistry

In table I six chemical analyses of metasomatized rocks from Glas Choille, Loyne, the Four Burns area, and the Allt Bealach Choinnich locality are given, together with an analysis of a syenite vein from Glas Choille. Analyses 5 and 6 were made on lighter

and darker portions cut from the same specimen from Allt Bealach Choinnich, which in its richness in biotite, lack of amphibole and pyroxene, and fineness of texture is considered to have different antecedents from the others.

The interpretation of the chemistry of these rocks is based on the fundamental assumption, as revealed by microscopic examination, that they were originally quartzites subsequently altered by metasomatic processes. When considering bulk chemical changes during metasomatism it is advantageous to compare cationic concentrations on a standard anion cell, the case for which has been argued fully by McKie (1966, p. 262). The cationic concentrations per 100 anions for the rocks listed in table I are given in table II. These data can be taken as addition, or in the case of silica, subtraction (50 minus the Si figure) values for the atom by atom movement of cations. Silica has, of course, left the system, while of the added elements aluminium is the most abundant followed by sodium, magnesium, potassium, and ferrous iron. Calcium is variable.

Fig. 8 has been constructed using the data of table II including an average of three analyses of Cambrian Pipe rock and Basal Quartzite from Strathcarron, Ross and Cromarty, and from Ord, Skye (Sabine *et al.*, 1969, *anal.* 895-7). This average value closely matches chemically the stratigraphically identical quartzites of the Borralan vicinity. The good straight line correlation is apparent between Si and Al, K, Mg, total Fe, and Ti and there is poor correlation of Si with Na and Ca. The (visual) best line fits through the Al, K, Mg, total Fe, and Ti points, when extrapolated, pass through, or close to, the quartzite point near Si 50, suggesting a quartzite parental rock. The relatively poor correlation of Ca with Si may be due to secondary carbonate. This is reflected in the CO₂ analyses (table I); limestone is abundant in the Borralan area. The poor correlation of Na with Si is caused by rocks 5 and 6, which are exceptionally rich in biotite and have low Na₂O values.

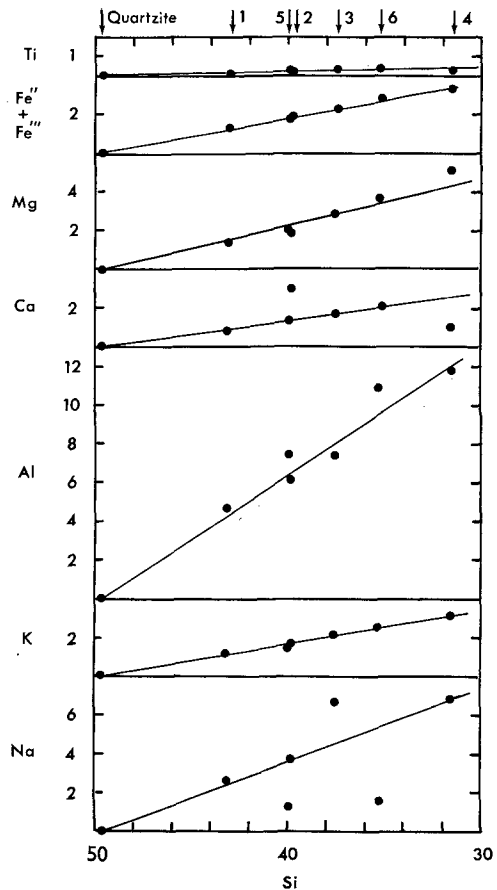


FIG. 8. Variation in cationic concentrations per 100 oxygens for the major elements of the rocks given in table II. For details of the quartzite analysis see text.

TABLE I. *Chemical analyses, norms, and modes of metasomatized quartzites*

	1	2	3	4	5	6	7	A
SiO ₂	80.73	71.47	66.17	54.51	72.84	61.43	61.55	98.83
TiO ₂	0.39	0.64	0.79	0.89	0.70	0.97	0.51	0.02
Al ₂ O ₃	7.52	9.33	11.12	17.27	11.60	16.11	15.03	0.38
Fe ₂ O ₃	0.43	1.16	2.80	2.32	0.96	0.78	2.67	0.03
Cr ₂ O ₃	n.d.	n.d.	n.d.	0.19	n.d.	n.d.	n.d.	—
FeO	2.71	2.98	2.24	4.83	3.07	5.24	1.65	0.07
MnO	0.04	0.04	0.07	0.08	0.07	0.12	0.18	—
MgO	1.78	2.30	3.39	6.00	2.66	4.34	1.88	0.02
CaO	1.55	5.26	2.93	1.60	2.31	3.53	3.55	0.02
Na ₂ O	2.60	3.50	6.05	6.07	1.24	1.47	4.16	tr
K ₂ O	1.84	2.49	3.03	4.16	2.14	3.58	8.35	0.23
H ₂ O ⁺	0.39	0.28	0.40	1.60	1.60	1.98	0.39	0.06
H ₂ O ⁻	0.10	0.08	0.11	0.07	0.10	0.11	0.16	0.19
P ₂ O ₅	0.09	0.11	0.15	0.15	0.12	0.17	0.13	tr
CO ₂	0.16	0.22	0.41	n.d.	0.53	0.37	0.42	—
F	0.07	0.07	0.29	0.24	0.03	0.06	0.08	—
O ₂ ≡F	100.40	99.93	99.95	99.98	99.97	100.26	100.71	99.85
	0.03	0.03	0.12	0.10	0.01	0.03	0.03	—
Sum	100.37	99.90	99.83	99.88	99.96	100.23	100.68	—
<i>Norms</i>								
Q	52.0	30.8	13.7	0.0	48.6	23.2	0.0	—
C	0.0	0.0	0.0	0.2	4.6	4.7	0.0	—
Or	10.9	14.7	17.9	24.6	12.6	21.2	49.3	—
Ab	22.0	29.6	40.3	39.4	10.5	12.4	30.8	—
An	3.4	2.4	0.0	7.0	7.3	14.1	0.0	—
Ne	0.0	0.0	0.0	6.5	0.0	0.0	0.0	—
Ac	0.0	0.0	8.1	0.0	0.0	0.0	3.8	—
ns	0.0	0.0	0.4	0.0	0.0	0.0	0.0	—
Di	2.2	17.6	8.8	0.0	0.0	0.0	11.3	—
Hy	7.4	0.7	7.2	0.0	10.4	18.4	0.3	—
Ol	0.0	0.0	0.0	14.8	0.0	0.0	0.3	—
Mt	0.6	1.7	0.0	3.4	1.4	1.1	1.9	—
Il	0.7	1.2	1.5	1.7	1.3	1.8	1.0	—
Ap	0.2	0.3	0.3	0.4	0.3	0.4	0.3	—
cc	0.4	0.5	0.9	0.0	1.2	0.8	0.9	—
H ₂ O ⁺	0.4	0.3	0.4	1.6	1.6	2.0	0.4	—
H ₂ O ⁻	0.1	0.1	0.1	0.1	0.1	0.1	0.2	—
Others	0.1	0.1	0.3	0.4	0.0	0.1	0.1	—
Total	100.4	100.0	99.9	100.0	99.9	100.3	100.6	—
<i>Modes</i>								
Quartz	54.1	33.5	9.0	—	43.6	17.4	—	—
Feldspar	25.8	34.2	46.4	—	33.0	—	—	—
Feld. + musc.	—	—	—	—	—	28.1	—	—
Biotite	3.1	0.4	1.3	—	—	—	—	—
Biot. + chlor.	—	—	—	—	—	—	—	—
+ epidote	—	—	—	—	21.9	—	—	—
Biot. + epidote	—	—	—	—	—	—	—	—
+ opaques	—	—	—	—	—	54.5	—	—
Amphibole	16.1	—	—	—	—	—	—	—
Amph. + pyrox.	—	29.5	41.7	—	—	—	—	—
Opaques	0.9	1.1	1.6	—	1.5	—	—	—
Sphene	—	0.4	—	—	—	—	—	—
Blue amph.	—	0.9	—	—	—	—	—	—

TABLE II. *Composition of metasomatized quartzites in cations per 100 anions*

	1	2	3	4	5	6	A
Si	43·15	39·83	37·58	31·61	40·02	35·33	49·71
Ti	0·16	0·27	0·34	0·39	0·29	0·42	0·00
Al	4·74	6·13	7·44	11·80	7·51	10·92	0·15
Fe ³⁺	0·17	0·49	1·20	1·01	0·40	0·34	0·01
Fe ²⁺	1·21	1·39	1·06	2·34	1·41	2·52	0·02
Mn	0·02	0·02	0·03	0·04	0·03	0·06	0·00
Mg	1·42	1·91	2·87	5·19	2·18	3·72	0·01
Ca	0·89	3·14	1·78	0·99	1·36	2·18	0·01
Na	2·69	3·78	6·66	6·82	1·32	1·64	0·00
K	1·25	1·77	2·20	3·08	1·50	2·63	0·14
H ⁺	1·39	1·04	1·51	6·19	5·87	7·60	0·19
H ⁻	0·36	0·33	0·42	0·27	0·37	0·42	0·42
P	0·04	0·05	0·07	0·07	0·06	0·08	0·00
C	0·12	0·17	0·32	—	0·40	0·29	0·00

Key to Tables I and II:

1. Quartz-feldspar-amphibole rock, junction of the two most northerly of the Four Burns (B608).
 2. Quartz-feldspar-amphibole-pyroxene rock, Allt Bealach Choinnich (B682).
 3. Quartz-feldspar-amphibole-pyroxene rock, Glas Choille (B777).
 4. Amphibole-biotite syenite, Loyne (1970, P34 (5)).
 5. Quartz-feldspar-biotite rock, east of Allt Bealach Choinnich (B683, light portion).
 6. Quartz-feldspar-biotite rock, east of Allt Bealach Choinnich (B683, dark portion).
 7. Potassic syenite, from vein cutting B777, Glas Choille.
- A. Average Cambrian quartzite of NW. Scotland; from Sabine *et al.*, 1969, *anal.* 895-7. The heterogeneity of the rocks 4 and 7 made it difficult to obtain meaningful modes.

Fig. 9 is based on the weight norms of quartz, nepheline, and kalsilite, and it is apparent that the series 1 to 4 defines a radial from the Qz corner, the rather high value of Na₂O for rock 3 being compensated normatively by the production of acmite. Rocks 5 and 6 define a more potassic trend. The densities of rocks 1 to 3 were determined and these, combined with the modal quartz values, allowed the calculation of the composition of the equivalent quartz-free rocks, which are plotted on fig. 9 as open circles and joined to their parental rocks by tie lines. The calculated rocks can be considered as having the compositions, in terms of silica, alumina, soda, and potash, towards which the series 1 to 3 is trending, and the plotted position of rock 4 close to these points lends credence to the hypothesis that this rock represents the ultimate product of the metasomatism. The proximity of 4 and the calculated rocks to the minimum on the Ab-Or join at 1000 kg/cm² pressure H₂O is noteworthy and it has been pointed out elsewhere (Woolley, 1969, p. 206) that syenitic fenites tend to cluster around this minimum.

The analysis of a syenitic vein (table I, *anal.* 7) reveals a two to one ratio of potash to soda, which contrasts with the two to one ratio of soda to potash for the rock it cuts (table I, *anal.* 3). However, as previously described, the syenite veins have reaction zones enriched in sodic pyroxene, suggesting the derivation of the excess soda from the veins.

Mineralogy

Amphiboles. Three full chemical analyses and a number of electron probe analyses of amphiboles are given in table III. The chemical analyses have been calculated to 24 oxygens and the probe analyses, because of the lack of data for water, to 23. The

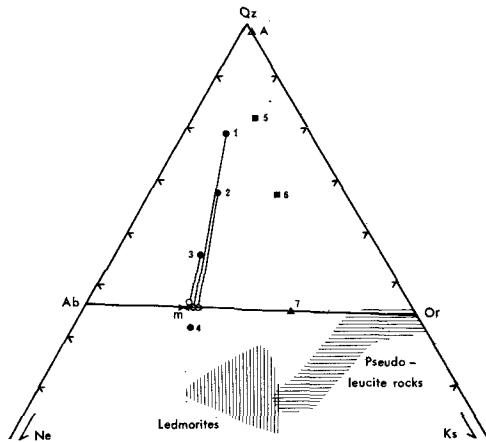


FIG. 9. Variation of the metasomatized rocks in terms of weight normative quartz-nepheline-kalsilite. Filled circles = analyses 1 to 4; open circles = analyses 1 to 3 calculated free of modal quartz; filled squares = biotite-rich rocks, analyses 5 and 6; filled triangle = syenite vein, analysis 7; open triangle = average quartzite, analysis A; m = minimum on Ab-Or join at 1000 kg/cm² (Bowen and Tuttle, 1950). The areas occupied by pseudoleucite rocks and rocks of ledmorite type of the Borralan Complex are shaded.

recalculated Si values from the probe analyses are high, as are the Y group totals. This is mainly because the total iron is calculated as being in the ferrous state. In analysis 20 for instance, if all the iron is calculated as ferric the Si value comes down from 8.116 to 7.681 while the Y group total is reduced from 5.314 to 4.739. The chemical analyses show that ferric iron is probably more abundant than ferrous in these amphiboles.

Of the chemically analysed amphiboles, number 8, from Glas Choille, is a subcalcic actinolite with rather high sodium, using the nomenclature of Leake (1968), while numbers 16 and 17, both from Loyne, belong to the riebeckite-glaucophane group of Miyashiro (1957), one of them being a crossite and the other a magnesioriebeckite. Considering all the analyses reported in table III, four (8, 13, 14, 23) are calcic amphiboles having Ca contents greater than one atom per

formula unit, with commensurately low Na values of less than one, while the rest are alkali-amphiboles with Na greater than one, and often greater than 1.5. The full analyses indicate that ferric iron is much more abundant than ferrous in the alkali-amphiboles, but the oxidation state of the iron is not available from the probe analyses, making classification difficult for these relatively iron-rich amphiboles.

Consideration of the chemical and optical evidence suggests a five-fold grouping, which is indicated on fig. 10. Group I comprises actinolitic hornblendes from the Four Burns and green actinolite cores to crystals at Loyne; II is the subcalcic actinolite from Glas Choille. Group III amphiboles are from Glas Choille and have the highest Mg/Fe ratios—they are probably richterites. Group IV includes the chemically analysed crossite and magnesioriebeckite, blue rims on actinolite crystals (24), other Loyne specimens, and a blue vein-amphibole from the Four Burns. Group V amphiboles are riebeckites having deeper colours than those of IV, and the highest Na and Fe values. They are found as rims on the actinolitic hornblendes from the Four Burns,

and in one specimen from Loyne are concentrated along an igneous contact. The dominant colours of the five groups are I = green and pale-green, II = pale-green, III = pale-blue, IV = blue, V = deep-blue. Extinction values are I, γ : [001] = 20°, II, γ : [001] = 20°, III, γ : [001] = 38°, IV, α : [001] = 5-7°, V, α : [001] = 5-10°.

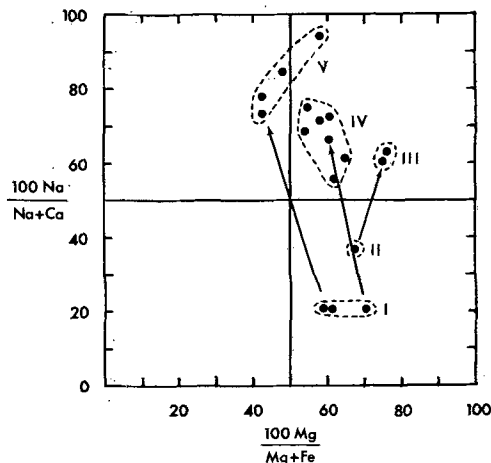


FIG. 10. Plot of 100 Na/(Na+Ca) against 100 Mg/(Mg+Fe) for the amphiboles of table III. The arrows indicate the compositional variations between the actinolitic hornblende and actinolite cores (anals. 13, 14, and 23), and the blue alkali-amphibole rims (anals. 11, 12, and 24) of the zoned amphiboles from the Four Burns (see also fig. 11) and Loyne, and between the subcalcic actinolite (anal. 8) and the richterites (anals. 9 and 10) at Glas Choille. The significance of groups I to V is explained in the text.

The petrography of these rocks shows that green-coloured amphiboles develop in the earlier stages of metasomatism and are later replaced by blue varieties. Taking the full analyses as representative of this change, the sequence from subcalcic-actinolite (8) to crossite and magnesioriebeckite (16, 17) involves the substitution of sodium for calcium and a radical increase in the ferric/ferrous iron ratio. The probe results confirm the increase in sodium and also indicate an over-all increase in the Fe/Mg ratio (fig. 10). The Glas Choille amphiboles change from green (fig. 10, group II) to blue (fig. 10, group III) in the vicinity of syenite veins, and the chemical changes involved are also nicely shown by electron-probe analyses of cores and rims of zoned crystals from the Four Burns and from Loyne (table III, 11 to 14, 23, and 24). The arrows on fig. 10 emanating from group I indicate the increase in the Na/Ca and Fe/Mg ratios for these zoned crystals. Electron-probe traverses across one such zoned crystal (fig. 12) show (fig. 11) the reciprocal relation of Ca, Mg, and Al with Fe and Na.

Pyroxenes. A probe analysis of a deep-green aegirine-augite (table IV, 25) from the vicinity of a feldspathic vein from Glas Choille has been recalculated so that ferric iron equals sodium in the atomic formula, a procedure that also improves the totals of the X, Y, and Z groups. The recast formula indicates a content of acmite of 29%. For a member of the aegirine-augite series this pyroxene is relatively poor in hedenbergite molecule, but it is remarkably close in composition to a pyroxene from a xenolith in borolanite from the Borralan Complex analysed by Tyler (Tyler and King, 1967, p. 12, anal. Bo. 270), which has Ac 33, Di 53, Hd 14, while pyroxene 25 has Ac 29, Di 54, Hd 17.

Recalculation of analysis 26 (table IV) to equalize ferric iron and sodium indicates an acmite content of only four%. This pyroxene, according to the nomenclature of

TABLE III. Wet chemical (^W) and electron-probe analyses of amphiboles

Glas Choille	Four Burns										Loyne									
	8 ^W	9	10	11	12	13	14	15	16 ^W	17 ^W	18	19	20	21	22	23	24			
SiO ₂	55.24	54.7	55.7	52.8	52.6	47.5	48.9	54.0	54.28	54.36	53.2	54.8	52.7	54.4	53.1	51.3	53.3			
TiO ₂	0.51	0.13	0.13	0.16	0.16	0.82	0.81	0.16	1.06	1.73	0.14	0.20	0.18	0.11	0.22	0.15	0.14			
Al ₂ O ₃	2.30	1.2	1.2	0.30	0.31	5.3	3.7	0.85	5.74	2.82	0.51	0.90	1.7	0.70	3.6	3.4	1.1			
Fe ₂ O ₃	4.24	—	—	—	—	—	—	—	8.09	11.03	—	—	—	—	—	—	—			
Cr ₂ O ₃	0.22	—	—	—	—	—	—	—	0.62	0.60	—	—	—	—	—	—	—			
FeO	8.28	9.5	10.1	22.5	22.2	14.8	16.1	18.2	5.59	5.53	15.3	16.7	20.0	14.1	14.6	11.6	15.9			
MnO	0.19	—	—	—	—	—	—	—	0.12	0.15	0.36	0.31	0.34	0.57	0.57	0.49	0.25			
MgO	14.04	16.7	17.0	9.3	9.1	12.6	13.0	11.7	10.05	10.47	13.7	12.9	10.3	14.5	12.4	15.6	13.9			
CaO	9.34	5.5	6.3	3.6	2.8	12.3	11.3	5.3	3.87	3.71	6.1	6.0	2.0	5.2	3.5	11.1	4.4			
Na ₂ O	3.04	5.3	5.4	5.6	5.6	1.8	1.6	4.2	5.38	6.20	4.3	6.0	6.2	4.6	5.2	1.6	4.7			
K ₂ O	0.80	1.3	1.3	0.34	0.34	0.23	0.34	0.35	1.16	0.80	0.52	0.22	0.24	0.83	0.94	0.19	0.57			
P ₂ O ₅	0.05	—	—	—	—	—	—	—	0.81	0.27	—	—	—	—	—	—	—			
H ₂ O ⁺	2.09	—	—	—	—	—	—	—	2.23	2.06	—	—	—	—	—	—	—			
H ₂ O ⁻	nil	—	—	—	—	—	—	—	0.21	0.32	—	—	—	—	—	—	—			
F	0.54	—	—	—	—	—	—	—	0.66	0.48	—	—	—	—	—	—	—			
O=F	0.23	—	—	—	—	—	—	—	0.28	0.20	—	—	—	—	—	—	—			
Sum	100.75	94.33	97.13	94.60	93.11	95.35	95.75	94.76	99.59	100.33	94.13	92.69	93.66	95.01	94.13	95.43	94.26			

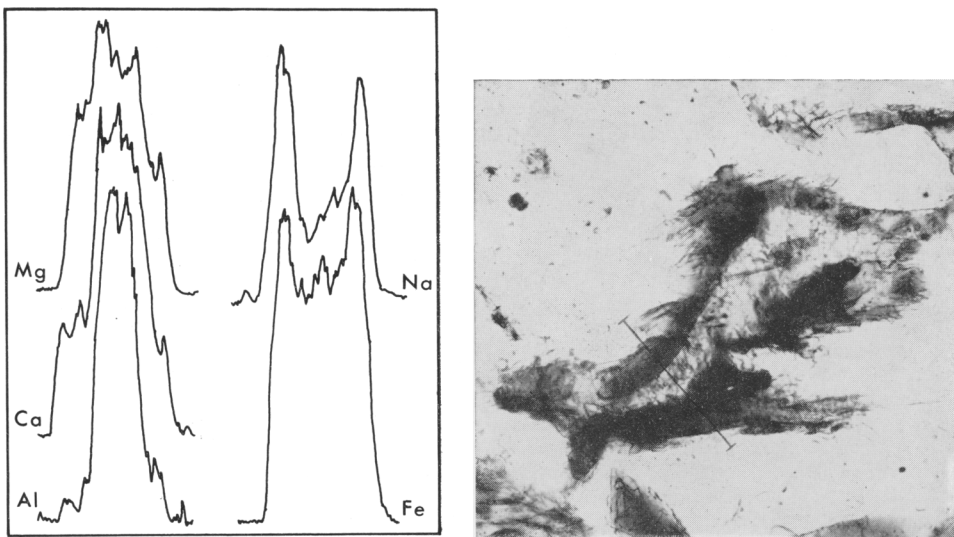
Numbers of ions on the basis of 24 (O, OH, F), or of 23 oxygen for the electron-probe analyses																	
Si	7.893	8.043	7.991	8.175	8.343	7.202	7.394	8.151	7.878	7.854	8.046	8.313	8.116	8.090	7.958	7.578	8.032
Ti	0.054	0.014	0.014	0.018	0.019	0.091	0.091	0.018	0.115	0.188	0.016	0.023	0.021	0.012	0.025	0.018	0.018
Al	0.387	0.208	0.203	0.055	0.057	0.946	0.654	0.151	0.981	0.626	0.091	0.161	0.309	0.123	0.636	0.586	0.200
Fe ³⁺	0.456	—	—	—	—	—	—	—	0.883	1.199	—	—	—	—	—	—	—
Cr ⁺	0.036	—	—	—	—	—	—	—	0.071	0.068	—	—	—	—	—	—	—
Fe ²⁺	0.989	1.168	1.212	2.914	2.910	1.876	2.035	2.298	0.678	0.667	1.935	2.119	2.576	1.754	1.830	1.429	2.001
Mn	0.022	—	—	—	—	—	—	—	0.014	0.018	0.046	0.040	0.044	0.072	0.072	0.062	0.027
Mg	2.990	3.660	3.635	2.146	2.125	2.841	2.925	2.632	2.174	2.255	3.088	2.917	2.364	3.214	2.770	3.434	3.124
Ca	1.429	0.867	0.968	0.597	0.470	1.994	1.826	0.857	0.453	0.537	0.989	0.107	0.330	0.829	0.562	1.757	0.706
Na	0.841	1.511	1.502	1.681	1.701	0.528	0.472	1.229	1.514	1.756	1.261	1.765	1.851	1.326	1.511	0.462	1.376
K	0.145	0.244	0.238	0.067	0.068	0.036	0.054	0.067	0.214	0.147	0.100	0.043	0.047	0.157	0.180	0.036	0.108
OH	1.993	—	—	—	—	—	—	—	2.160	1.986	—	—	—	—	—	—	—
F	0.244	—	—	—	—	—	—	—	0.303	0.219	—	—	—	—	—	—	—
Z	8.00	8.04	8.00	8.175	8.34	8.00	8.00	8.15	8.00	8.00	8.05	8.31	8.12	8.09	8.00	8.00	8.03
Y	4.83	5.05	5.06	5.13	5.11	4.96	5.10	5.10	4.79	4.88	5.18	5.26	5.31	5.17	5.29	5.11	5.37
X	2.42	2.62	2.71	2.35	2.24	2.56	2.35	2.15	2.18	2.42	2.35	1.92	2.23	2.31	2.25	2.26	2.19

Key to Table III:

- 8. Subcalcic actinolite (1970, P34 (51)).
- 9. Richterite (B777).
- 10. Richterite (B777).
- 11. Riebeckite; blue rim on actinolitic hornblende (no. 13) (B608).
- 12. As above.
- 13. Actinolitic hornblende; green core to nos. 11–12 (B 608).
- 14. Isolated grain of actinolitic hornblende (B608).
- 15. Crossite, magnesioriebeckite type; in vein (B608).
- 16. Crossite; stellate masses (1970, P34 (6)).
- 17. Magnesioriebeckite; stellate masses, prisms and veins (1970, P34 (12)).
- 18. Crossite, magnesioriebeckite type; prisms (1970, P34 (13)).
- 19. Riebeckite; prisms concentrated at contact (1970, P34 (13)).
- 20. As above.
- 21. Crossite, magnesioriebeckite type; prisms (1970, P34 (7)).
- 22. As above.
- 23. Actinolite; isolated grains and green cores to no. 24 (1970, P34 (11)).
- 24. Crossite, magnesioriebeckite type; isolated grains and blue rims to no. 23 (1970, P34 (11)).

Wet chemical analyses (W) by C. J. Elliott, for which the atomic formulae have been corrected for apatite impurity.

Microprobe analyses by R. F. Symes, for which total iron is reported as FeO. The probe analyses were made using a Cambridge Instruments Geoscan at an accelerating voltage of 15KV and a current of 0.5×10^{-7} amps. Analysed silicates and oxides were used as standards. Results were corrected after the method outlined in Sweatman and Long (1969) using the B.M.-I.C.-N.P.L. Computer programme.



FIGS. 11 and 12: FIG. 11 (left). Elemental variation shown by electron probe in traverses across a zoned actinolitic hornblende-riebeckite crystal (B608). The higher values for Mg, Ca, and Al in the core and for Na and Fe in the rim are apparent. FIG. 12 (right). Photo-micrograph of zoned amphibole crystal. The line of the traverse illustrated in fig. 11 is indicated. Probe analyses 11 to 13 were made on this crystal.

TABLE IV. Probe analyses of pyroxenes, and atoms on basis of 6 oxygens

	25	26		25		26	
SiO ₂	52.1	50.7	Si	1.961	2.000	1.955	2.000
Al ₂ O ₃	0.69	1.5	Al ^{IV}	0.029		0.045	
TiO ₂	0.18	0.22	Al ^{VI}	0.002	0.023	0.006	1.039
FeO	14.6	10.5	Ti	0.005		0.006	
MgO	9.7	11.7	Fe ²⁺	0.166	1.013	0.297	0.041
CaO	17.3	22.4	Fe ³⁺	0.293		0.672	
Na ₂ O	4.0	0.55	Mg	0.547	0.997	0.925	0.967
K ₂ O	0.07	0.01	Ca	0.701		0.041	
	98.64	97.58	Na	0.293	0.003	0.001	
			K	0.003			

25. Aegirine-augite, Glas Choille (B777).

26. Sahlite, Allt Bealach Choinnich (B682).

Probe analyses for which total iron is reported as FeO. Ferric iron has been calculated by allotting equivalent molecular amounts of Fe₂O₃ to Na₂O.

Poldervaart and Hess (1951), is a sahlite and is probably typical of the pyroxenes of Glas Choille as well as the Allt Bealach Choinnich rocks.

Micas. A number of electron probe analyses and a full analysis by chemical methods of micas are given in table V. Assuming a division between biotite and phlogopite at

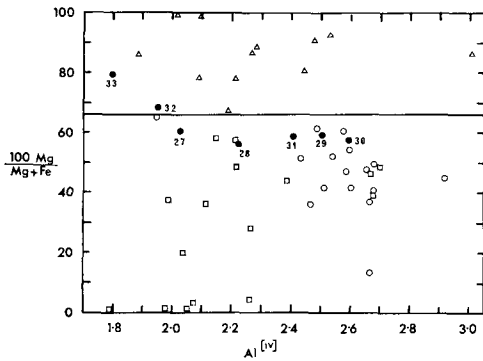


FIG. 13. Plot of 100 Mg/(Mg+Fe) against Al^{IV} for biotites and phlogopites. The filled circles are the micas given in table V; open symbols are for biotites and phlogopites taken from Deer, Howie, and Zussman (1962): circles, biotites from metamorphic rocks; squares, biotites from igneous rocks; triangles, phlogopites. The biotite-phlogopite boundary is taken at Mg:Fe = 2:1 (Deer, Howie, and Zussman, 1962, Fig. 13).

aluminum in which the principal mafic mineral is amphibole, together with pyroxene in the intermediately positioned no. 28.

Mg:Fe of 2:1 five of the analyses prove to be of biotites and two are phlogopites. Phlogopite no. 33 is the only green mica encountered in these rocks. It is restricted to one specimen from Loyne in which it forms rounded aggregates of tiny flakes. As is apparent from fig. 13, on which for comparison all the analyses of biotites and phlogopites in Deer, Howie, and Zussman (1962, 3) are plotted, the biotites are very magnesian, but there is very little variation in the Mg:Fe ratio. There is considerable variation in tetrahedral aluminium, however, which appears to be related to the over-all rock chemistry in so far as the three most aluminous biotites are from alumina-rich rocks in which the only mafic phase is biotite, with a little amphibole in no. 31, while the others are from rocks poorer in

TABLE V. *Wet chemical (31) and electron-probe analyses of biotites and phlogopite*

	27	28	29	30	31 ^W	32	33
SiO ₂	38.7	36.7	36.0	35.9	36.93	39.6	40.1
TiO ₂	0.72	2.1	3.2	3.2	2.10	1.6	0.42
Al ₂ O ₃	12.0	12.8	18.0	16.3	15.51	10.9	10.2
Fe ₂ O ₃	—	—	—	—	2.88	—	—
Cr ₂ O ₃	—	—	—	—	0.55	—	—
FeO	17.2	17.6	15.6	15.4	14.03	13.7	9.9
MnO	—	—	—	—	0.19	0.36	0.27
MgO	14.8	13.1	12.0	12.7	13.30	17.1	22.2
CaO	0.14	0.06	0.07	0.07	0.46	0.53	0.36
Na ₂ O	0.01	tr.	0.25	0.25	0.25	tr.	0.38
K ₂ O	9.4	9.5	9.8	9.6	10.56	10.1	9.3
P ₂ O ₅	—	—	—	—	0.07	—	—
H ₂ O ⁺	—	—	—	—	3.03	—	—
H ₂ O ⁻	—	—	—	—	0.17	—	—
F	—	—	—	—	0.47	—	—
O≡F	—	—	—	—	100.50	—	—
Total	92.97	91.86	94.92	93.42	100.30	93.89	93.13
<i>Numbers of ions on the basis of 22 oxygen:*</i>							
Si	5.980	5.784	5.416	5.500	5.599	6.003	5.996
Al	2.191	2.386	3.201	2.943	2.768	1.949	1.796
Ti	0.083	0.246	0.361	0.368	0.236	0.182	0.045
Fe ³⁺	—	—	—	—	0.328	—	—
Fe ²⁺	2.219	2.319	1.962	1.968	1.775	1.740	1.239
Cr	—	—	—	—	0.072	—	—
Mn	—	—	—	—	0.027	0.045	0.036
Mg	3.408	3.077	2.695	2.897	3.004	3.862	4.946
Ca	0.028	0.009	0.009	0.009	0.073	0.082	0.054
Na	0.003	—	0.072	0.074	0.072	—	0.108
K	1.858	1.912	1.880	1.876	2.040	1.950	1.778
OH	—	—	—	—	3.060	—	—
F	—	—	—	—	0.218	—	—
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	5.88	5.81	5.64	5.68	5.81	5.78	6.06
X	1.89	1.92	1.96	1.96	2.18	2.03	1.94
A	—	—	—	—	3.28	—	—

27. Biotite, Glas Choille (B777).

28. Biotite, Allt Bealach Choinnich (B682).

29. Biotite, east of Allt Bealach Choinnich (B683).

30. As above.

31. Biotite, Loyne (1970, P34 (5)).

32. Phlogopite, Loyne (1930, P34 (7)).

33. Phlogopite, Loyne (1970, P34 (13)).

* Except the wet-chemical analysis, 31, which is calculated to 24 (O,OH,F).

Feldspars. Partial analyses of feldspars made by electron probe are given in table VI.

The two discrete feldspar phases in rocks 608 and 682 prove to be very close to pure potassium feldspar and pure albite, for which reference to the solvus in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 given by Bowen and Tuttle (1950) and applied as a geological thermometer by Barth (1951) suggests a temperature of crystallization of these rocks

TABLE VI. *Partial probe analyses of feldspars*

	34	35	36	37	38	39
SiO_2	63.5	65.8	67.1	64.8	68.3	68.2
Al_2O_3	19.4	18.1	19.9	18.9	19.9	19.7
CaO	0.11	—	0.29	0.35	0.29	0.23
Na_2O	0.51	0.21	10.4	0.21	10.5	10.2
K_2O	16.0	15.1	0.17	14.6	0.15	0.65
	99.52	99.21	97.86	98.86	99.14	98.98
<i>Mol %</i>						
Or	97.0	97.9	0.9	96.0	0.9	4.0
Ab	2.4	2.1	97.7	2.1	97.6	94.8
An	0.6	0.0	1.4	1.9	1.5	1.2

34. Orthoclase, from vein, Glas Choille (B777).

35. Orthoclase, Allt Bealach Choinnich (B682).

36. Albite, same rock as 35.

37. Orthoclase, Four Burns (B608).

38. Albite, same rock as 37.

39. Albite, Loyne (1970, P34(13.))

below 400 °C and perhaps as low as 300 °C. However, the feldspars could have reached their present compositions by equilibrating during slow cooling from higher temperatures, but this is thought to be unlikely on petrographic grounds.

The Or-rich nature of the vein feldspar (table VI, no. 34) is to be expected in view of the highly potassic composition of the vein as a whole (table I, no. 7) and the fact that much of the sodium in the veins is held in pyroxene.

Discussion

Although the term fenitization is ill-defined, it is generally taken to imply metasomatism of a strongly alkaline nature as evidenced by the formation of alkaline minerals, notably alkaline feldspars, pyroxenes, and amphiboles. The metasomatized quartzites forming the subject of this account are on textural, mineralogical, and chemical grounds undoubtedly referable to the fenites, but the only description known to the authors of fenites that originated from similar rocks is of the fenitized sandstones of Kikonde ridge near the Jombo intrusion, eastern Kenya (Baker, 1953), for which there are no chemical data.

At Loyne the fenite is included in a melanite syenite containing occasional pseudoleucites, while at the other two fenite localities pseudoleucite rocks outcrop close by. It is likely, therefore, that the source of the fenitizing fluids was the pseudoleucite

syenite, for which there are some 12 published and unpublished analyses. These plot within the horizontally lined area of fig. 9. The contrast between the ultra-potassic pseudoleucite rocks, the suggested source of the fenitizing fluids, and the fenites with $\text{Na} > \text{K}$ and trending towards the Ab-Or minimum, indicates that the chemical changes during fenitization are not dictated by the composition of the fluid source but by pressure-temperature conditions. The fact that potassic syenite veins are flanked by reaction zones particularly enriched in a sodic, and not a potassic, mineral is a further indication of this. However, it is probable that once the fenites have acquired a 'syenitic minimum' composition, they would change so as to approach the composition of the active magma, as in the production of ultra-potassic fenites around some carbonatites (Woolley, 1969, Fig. 12).

The biotite-rich fenites (fig. 9, nos. 5 and 6) cannot be accommodated by this hypothesis as they appear to lie on a straight line path, in terms of Qz-Ne-Ks (fig. 9), from quartzite to ultra-potassic syenite. However, the textural and field evidence suggests that these rocks have somewhat different antecedents from the other fenites. The knobby weathering resembles that of the Fucoïd beds that overlie the quartzites in the Cambrian succession of NW. Scotland, while the sharp variation, particularly in modal quartz and biotite (table I), within a single hand specimen suggests a rather heterogeneous pre-fenitization rock. The Fucoïd beds consist of shales with intercalations of dolomite and some quartzite horizons with low to moderate amounts of potash-feldspar (Bowie *et al.*, 1966, p. 127). A geochemical study (Bowie *et al.*, 1966) showed that the Fucoïd beds have a variable potash content averaging nearly eight %. It is probable that the biotite-rich fenites originally formed part of a potash-feldspar-bearing quartzite horizon within the Fucoïd beds, and hence were enriched in potash before fenitization.

Among the xenoliths occurring in the main outcrop of pseudoleucite borolanite at the eastern end of the complex are a group that are very similar both texturally and mineralogically to the more strongly fenitized quartzites. One specimen (B727), for instance, gives a mode of potash-feldspar 40.7 %, alkali amphibole 44.5 %, aegirine-augite 12.6 %, biotite 1.2 %; fluorite is also present. It is probable that these xenoliths represent quartzite fragments picked up and fenitized by the borolanite magma.

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Note added in proof. Since this paper was submitted for publication two papers have appeared on the subject of fenites in the Scottish Highlands (Deans *et al.*, 1971; Tanner and Tobisch, 1972). The fenites described by Deans *et al.* (1971) occur to the southwest of Inverness, and are of a regional type involving soda metasomatism of granite and Moine schist. One of their fenite types is associated with breccia dykes, but generally there is no field evidence as to the source of the metasomatizing fluids. However, the authors postulate the presence of carbonatite at depth.

The second account (Turner and Tobisch, 1972) also involves Moian rocks, which are located in the vicinity of Loch Houran on the west coast, and in Glen Cannich, which is to the west of the localities described by Deans *et al.* (1971). This metasomatism is also of a regional type and involves principally the introduction of sodium. There is rarely any field evidence as to the source of the metasomatism, but sometimes it can be traced to cross-cutting pegmatite dykes (Tanner and Tobisch, 1972, p. 177).

The majority of described fenite occurrences are from the aureoles of intrusions of carbonatite, ijolite, nepheline syenite, or syenite, and it would seem to be preferable to distinguish these from the kinds of fenite described by Deans *et al.* (1971) and by Tanner and Tobisch (1972), which usually cannot be seen to be associated with particular igneous bodies. Perhaps the terms 'contact' fenites and 'regional' fenites would be appropriate.

It may be that the regional types are genetically distinct from the contact types.

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