Fenitization of some mafic igneous rocks in the Seiland province, northern Norway

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Against alkaline pyroxenite dykes, metamorphosed picrites in gabbro are converted into amphibole-clinopyroxene fenites. Increases in Al, Ti, Fe^3, Ca, K and Mn accompanied fenitization, Mg fell, and Cu, Sr, Y, Zr, Nb, La, Ce, and Nd were augmented. Mafic rocks against litchfieldite pegmatites were fenitized to mafic carbonatite or ijolite, felsic rocks to aegirine-augite syenites. Carbonatitic fenites developed by the introduction of Fe^3, Ca, K, Mn, P, and C, and the abstraction of Si and Al. Zn, Rb, Y, Zr, Nb, and the light REE increased during fenitization. Ijolitization was caused by increases in Na, K, Al, and Fe^3, while Si, Fe^2, Mg, and Ca decreased. Fenitization was probably achieved through the agency of strong chloride brines.

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The chemical and mineralogical changes involved in the evolution of fenites from mafic and ultramafic igneous rocks are poorly known, particularly in comparison with the 'classic' fenites developed from felsic palaeosomes. This is principally a result of the limited number of alkaline complexes and carbonatites emplaced into an environment of basic igneous activity (Table 1).

Two main hypotheses have been advanced regarding major-element variations during the fenitization of mafic rocks. According to Verwoerd (1966), both acid and basic rocks undergo essentially the same process during fenitization, involving enrichment in alkalies, especially sodium, and depletion of silica. Iron and magnesium are often removed from mafic rocks while they are added to felsic rocks, the former in large amounts (McKie 1966). The behaviour of calcium and aluminium is variable both in southern African mafic fenites, and in salic fenites in general, while the addition of large amounts of carbonate ions is said to be unique to the Goudini complex (Verwoerd 1966). Based on a study of fenitized garnet amphibolites in the aureole of the Callander Bay complex and a comparison with other occurrences of fenitized mafic rocks, Currie & Ferguson (1972) conclude that the content of Si, Al, Na, K and H in the standard cell increases while Ti, Fe, Mg and Ca decrease. Since Si is depleted in the associated felsic rocks and Na, Al, Fe, Mg, and Ca are augmented, the contrasting fenites tend to converge towards the composition of a melanocratic nepheline syenite. Currie & Ferguson (1972) regard the Callander Bay fenites as typical in composition and origin, but apparently disregarded the contrary data presented by Verwoerd (1966) for south African fenites of mafic parentage.

The textural development of mafic igneous rocks during fenitization is highly variable. In general, existing minerals are replaced by alkaline varieties, and few new phases are nucleated; either feldspar or the mafic minerals may be attacked first (Verwoerd 1966). The same minerals as in 'classic' fenites are typical of fenitized mafic rocks, viz: sodic amphiboles, aegirine-augite, aegirine, and alkali feldspars (Verwoerd 1966). Nepheline can appear if the fenitization progresses beyond von Eckermann's 'saturation point'. Biotite, unlike that in salic rocks which is commonly replaced by aegirine-augite or alkali amphibole at an early stage of fenitization, may be stable and increase in amount throughout fenitization (Johnson 1961). Even in those cases where CO_2 has been introduced, calcite seems to be a relatively uncommon mineral in the southern African mafic fenites, the carbonate-bearing phases usually being cancrinite and scapolite (Verwoerd 1966). However, calcite occurs in fenitized basic rocks associated with the Blue Mountain nepheline syenite (Payne 1968), and is a vein mineral in many fenites derived from mafic rocks (Johnson 1961, Garson 1962, Verwoerd 1966).

Regarding the role of CO_2, Verwoerd (1966) makes the tentative suggestion that it may be

Table 1.   Compilation of reported occurrences of fenitized mafic rocks.

Complex	Fenitized rocks	Source of fenitization	Gains	Losses	References
Spitzkop, E. Transvaal	Gabbro	Ijolite?	Na, Ca, K, P, C	Mg, Si, Fe, Al	Strauss & Truter 1951, Verwoerd 1966
Messum, S.W. Africa	Basalt, dolerite, gabbro	Nepheline syenite	Na, Al, H, K	Si, Ca, Fe, C	Mathias 1956, Verwoerd 1966
Nemegosenda Lake, Ontario	Gabbro	Alkaline rock/ søvite	no analytical data		Parsons 1961
Lillebukt/ Pollen, Stjernøy, Norway	Metagabbro	Carbonatite	H_2O, CO_2, P_2O_5, $?K_2O$	?	Heier 1951 Oosterom 1963
Dorowa, Rhodesia	Dolerite	Ijolite/ carbonatite	K_2O, Na_2O, CaO, Fe, P_2O_5	SiO_2	Johnson 1961, Verwoerd 1966
Tundulu, Nyasaland	Dolerite	Nepheline syenite/carbona- tite	no analytical data		Garson 1962
Breivikbotn, Sørøy, Norway	1. Metagabbro	Syenite/ carbonatite	Fe^{3+}, Mn, Y, Zr, Nb	Al_2O_3	Sturt & Ramsay 1965
	2. Metagabbro	Nepheline syenite?	SiO_2, Al_2O_3, Na_2O, K_2O	FeO_3, FeO, MgO, CaO	
Goudini, Transvaal	Norite	Carbonatite	Na, CO_3, OH, Fe	Si, Al, Ca, Mg	Verwoerd 1966
Swartbooisdrif, S.W. Africa	Anorthosite	Nepheline syenite/ carbonatite	Na, CO_3 OH	Si	Verwoerd 1966
Vishnevogorsk, Urals, Soviet	Greenschist	Alkaline "solutions"	Al, K, Na, Sr, Ba, Nb, Zr, RE, P	Si, Fe, Ca, Mg, Ti, Mn	Borodin & Pavlenko 1974
Khibina, Kola, Soviet	Diabase	Khibinite	K, Na, Mg, Fe, Al, Ti followed by: K, Na, Al, Si	Ca, Si Ca, Mg, Fe, Ti	Borodin & Pavlenko 1974
Mboži, S.W. Tanzania	Gabbro	Nepheline syenite	K, Na, Al, Si, P	Ca, Mg, Fe, Ti	Brock 1968
Blue Mountain, Ontario	Amphibolite	Nepheline syenite	K_2O, Na_2O Al_2O_3, H_2O, CO_2	CaO, MgO FeO	Payne 1968
Callander Bay, Ontario	Garnet amphibolite	alkaline rock/ carbonatite	Si, Al, Na, K, H	Ti, F, Mg, Ca	Currie & Ferguson 1972

necessary to distinguish between fenites associated with alkaline intrusives alone, and those in conjunction with a carbonatitic phase. Many other authors have discussed the relative importance of alkaline rocks versus carbonatites as the source of fenitizing solutions (King & Sutherland 1960, Dawson 1964, Woolley 1969).

It has been known for a considerable time that alkaline intrusives and carbonatites were emplaced in the syn-Caledonian Seiland province towards the close of an extended period of basic and ultrabasic magmatism (Hoel & Schetelig 1916, Barth 1927, 1953, Strand 1952). However, fenitization of mafic host rocks was not described until quite recently when an aegirine-augite pyroxenite from the Breivikbotn alkaline complex was recognised as a metasomatized metagabbro (Sturt & Ramsay 1965). Field evidence from the same complex, as well as from the Dønnesfjord area (Appleyard 1965), suggested the fenitic derivation of gneissic nepheline syenites (litchfieldites) from both psammitic metasediments and metagabbros, consequent upon the emplacement of volatile-rich nepheline syenite magmas. Heier (1961) attributed an assumed absence of fenitization of the gabbros surrounding the major Lillebukt alkaline complex to a lack of alkalies in the metasomatizing agent. The mafic rocks were believed to have been converted to 'hornblendite' when gaseous H_2O and CO_2 were introduced during carbonatite emplacement. However, it was suggested that the biotite-rich bands in the central carbonatite originated by reaction of gabbro with potassium-rich carbonatite (Heier 1961:150). A similar conclusion was reached by Oosterom (1963) for both the Lillebukt and Pollen complexes; metasomatic introduction of H_2O, CO_2, and P_2O_5 was held to be responsible for the origin of both the hornblendites and carbonatites.

An unusual aspect of the Seiland province is that fenitization occurred during the course of orogenesis and Barrovian metamorphism. The deformed fenites of the Breivikbotn Complex are cut by metabasic dykes which record upper greenschist facies metamorphism (Sturt & Ramsay 1965). Deformed basic dykes post-dating the emplacement of the alkaline pyroxenites and titanaugite syenites of the Kræmmervik Complex, and intruding the associated fenites, are fine-grained schistose amphibolites metamorphosed in the almandine-amphibolite facies (Robins 1974).

The present account describes the textural and chemical evolution of fenites derived from mafic dykes and gabbroic rocks crosscut by composite alkaline pyroxenite/melanocratic syenite pegmatites and litchfieldite pegmatites. Both of these groups of alkaline intrusives embrace a wide range of chemical variation in individual dykes; typical analyses are listed in Table 2. One characteristic of the felspathoidal syenite dykes not illustrated in Table 2, and which distinguishes them from the alkaline pyroxenites, must be emphasised since it is almost certainly of major importance in the interpretation of the respective fenites: The syenites are typically rich in calcite, either as patches representing a carbonatitic mesostasis, or as large segregations containing albite, apatite, and biotite, which are viewed as the result of the co-existence of immiscible syenitic and carbonatitic fluids (Robins 1972). The pyroxenite/melanocratic syenite dykes, however, never contain calcite in more than accessory amounts (Robins 1974).

By collecting from fenitized mafic dykes, one of the major problems in petrochemical studies of fenitization, viz. initial homogeneity of composition, is as effectively guaranteed as is possible. The changes in chemistry recorded in fenitized dykes are compared in certain cases with changes which occurred in gabbroic rocks whose initial composition was considerably less uniform. A limited amount of data referring to the fenitization of almandine-amphibolite facies psammitic metasediments are also presented for comparison.

The method employed has a further advantage: There can be no doubt of the identity of the source of the fenitizing agents. The fenitic aureoles are relatively narrow with respect to the associated intrusions, which are themselves minor and, in all cases, widely separated by unfenitized rocks.

Fenites associated with an alkaline pyroxenite/melasyenite dyke

The field relationships of the intrusive rocks and their associated ultramafic fenites within the small Kræmmervik alkaline complex, located on the south coast of the island Seiland, have been described in an earlier account (Robins 1974). Attention is directed here towards the changes which occurred within two narrow mafic dykes within metagabbro which were cut and fenitized

Table 2. Typical major- and trace-element compositions of the alkaline pyroxenite and litchfieldite pegmatites associated with fenitization.

	1	2
SiO_2	39.8	54.5
TiO_2	2.8	0.5
Al_2O_3	7.4	20.3
Fe_2O_3	8.0	5.8
FeO	12.8	3.6
MnO	0.5	0.1
MgO	6.4	0.4
CaO	17.7	2.3
Na_2O	2.0	7.1
K_2O	0.4	3.7
P_2O_5	1.2	0.2
H_2O	0.3	0.7
	99.3	99.2
FeO^x	20.0	8.8

	1	2
Cu	n.d.	22
Zn	103	61
Rb	11	86
Sr	424	597
Y	14	14
Zr	196	61
Nb	30	48
La	96	44
Ce	139	72
Nd	76	27

1. Arithmetic mean of 2 alkaline pyroxenites.

2. Bulk major-element composition of a thin litchfieldite pegmatite; trace elements are the arithmetic mean of 4 analyses.

FeO^x = total iron as FeO

n.d. = not detected

by a thinner composite alkaline pyroxenite/melasyenite pegmatite (Fig. 1). Megascopically, fenitization is restricted to an aureole extending up to 1 m from the alkaline intrusive, though chemically its effects can still be detected at
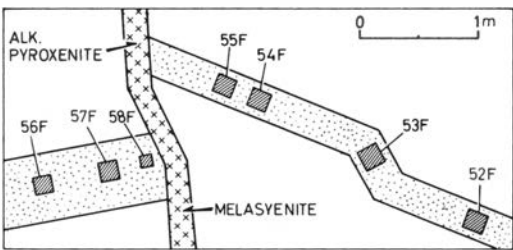

Fig. 1. Sampling plan for mafic dykes striking into the fenitic aureole of a composite alkaline pyroxenite/melasyenite pegmatite. Kræmmervik, Seiland.

twice this distance. The sampling carried out on the dykes is, to a certain extent, complimentary: Three samples (56–58F) were collected from one dyke at distances of 1 m and less from the alkaline pyroxenite-melasyenite contact; the other dyke was sampled at four localities (52–55F) at distances of 0.5 m and more from the intrusive contact. Together, these samples provide a reasonably clear picture of the fenitization produced during the emplacement of the alkaline dyke.

Mineralogical and textural development

The mineralogical changes exhibited by samples 56–58F are schematized in Fig. 2. 56F is dominated by pre-fenitization mineral assemblages and textures; effects of fenitization are restricted to a very limited amount of small, clear, non-pleocroic diopsidic pyroxene grains. Compositionally an alkali picrite (Table 3) and texturally a blastoporphyritic foliated amphibolite, it contains phyric forsteritic olivine surrounded by orthopyroxene coronas, embayed clinopyroxene phenocrysts containing exsolved hercynitic spinel plates, and plagioclase as small strongly-zoned polygonal grains and larger porphyritic crystals. Brown amphibole is, however, the dominant mineral which, together with the polygonal plagioclase, forms an amphibolite-facies assemblage. In petrography and composition, the unfenitized dyke coincides with the common post-F_2 mafic dyke-rocks in the Seiland province. With progressive fenitization, represented by 57 and 58F, the amount of amphibole increased in amount, and simultaneously changed its composition as reflected by its pleochroic scheme. Plagioclase and relict pyrogenic·clinopyroxene were the first minerals to disappear, while olivine remained largely un-

Table 3. Analyses from two mafic dykes cut and fenitized by an alkaline pyroxenite/melanocratic syenite dyke in the Kræmmervik complex.

|	58F	57F	56F		55F	54F	53F	52F
Dist.fr.contact	10cm	40cm	100cm		50cm	100cm	200cm	300cm
SiO_2	42.27	42.92	43.98		42.82	42.88	43.87	43.09
Al_2O_3	11.12	10.17	10.08		11.88	12.38	12.06	11.58
TiO_2	2.33	1.74	1.41		1.86	2.10	1.86	1.98
Fe_2O_3	3.14	2.78	1.47		2.45	3.31	2.44	2.01
FeO	11.24	10.48	11.06		9.06	8.66	8.74	9.06
MgO	10.01	16.24	18.95		13.57	12.68	13.63	14.89
CaO	13.45	10.11	9.10		11.42	11.32	10.80	11.55
Na_2O	1.68	1.99	2.07		2.15	2.13	2.30	2.06
K_2O	0.99	1.00	0.33		1.63	1.20	0.98	0.95
MnO	0.35	0.25	0.19		0.21	0.20	0.18	0.18
P_2O_5	0.21	0.18	0.16		0.37	0.43	0.32	0.35
H_2O^+	1.14	0.91	0.84		0.99	1.10	0.75	1.28
CO_2	0.50	0.20	0.20		0.45	0.65	0.90	0.25
	98.43	98.97	99.84		100.48	99.04	98.83	99.23
Cations in stand. cell of 100(O)								
Si	26.8	26.8	27.0		26.7	26.4	27.0	26.5
Al	8.2	7.4	7.2		8.6	8.9	8.7	8.3
Ti	1.1	0.8	0.7		0.9	1.0	0.9	0.9
Fe'''	1.5	1.3	0.7		1.1	1.5	1.1	1.0
Fe''	6.0	5.5	5.7		4.7	4.5	4.5	4.6
Mg	9.5	15.1	17.4		12.6	11.6	12.5	13.7
Ca	9.1	6.8	6.0		7.6	7.5	7.1	7.6
Na	2.0	2.4	2.4		2.6	2.5	2.7	2.4
K	0.8	0.8	0.2		1.3	1.0	0.8	0.8
Mn	0.2	0.1	0.07		0.1	0.1	0.07	0.07
P	0.08	0.1	0.1		0.2	0.2	0.2	0.2
H	4.8	3.8	3.4		4.1	4.5	3.1	5.3
C	0.4	0.2	0.2		0.4	0.6	0.7	0.2
	70.5	71.1	71.1		70.9	70.3	69.4	71.6
Trace elements (ppm)								
Cu	26	19	16		30	31	27	23
Zn	101	106	93		92	86	79	79
Rb	12	28	7		45	20	18	21
Sr	572	408	287		395	430	420	395
Y	32	21	13		24	21	17	18
Zr	159	70	45		128	121	94	99
Nb	110	44	20		71	59	43	40
La	46	25	9		40	32	27	30
Ce	91	56	36		72	68	53	52
Nd	61	32	23		38	38	27	30
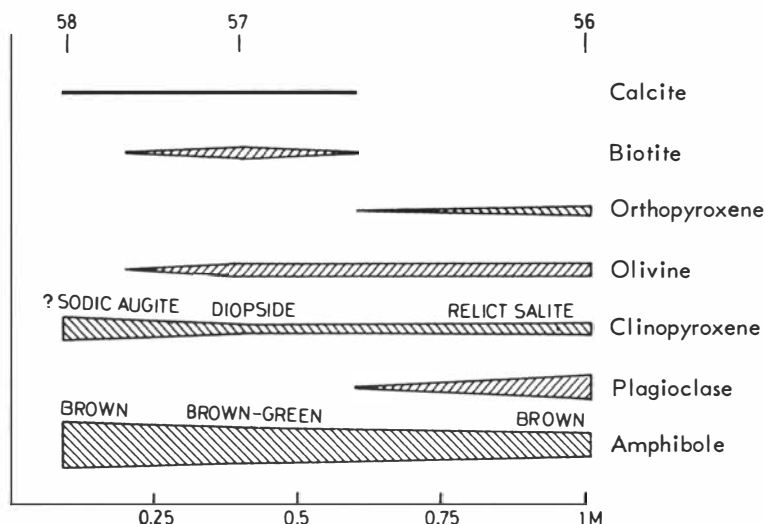
Fig. 2. Plot of mineralogical changes within a blasto-porphyritic amphibolite with increasing grade of fenitization. Abscissa gives the mean distance of the samples from the contact with an alkaline pyroxenite/melasyenite pegmatite (see Fig. 1).

affected until the highest grades of fenitization were attained. Mica appears in 57F and is relatively abundant but clearly was unstable during further fenitic modification; it is absent from 58F. Polygonal clinopyroxene increases in amount towards the alkaline pyroxenite and becomes pleochroic in pale greens to pink in sample 58F. The product of fenitization has, therefore, a rather simple, four-phase mineralogy not unlike that of the alkaline pyroxenite itself (Robins 1974).

The sample series 52–55F shows few differences from the sequence of mineralogical changes described above. The sample farthest from the alkaline pyroxenite dyke also has a picritic composition (Table 3), but is richer in both Ti and K than sample 56F, reflected principally in the presence of biotite. The latter is found in all the samples in this series. Like 58F, 55F collected 0.5 m from the intrusive contact, has a simple mineralogy dominated by a green amphibole together with polygonal, colourless clinopyroxene, biotite, and oxides.

Changes in major-element geochemistry

Major-element analyses of the seven mafic dyke samples, together with the respective standard cells calculated on the basis of 100(0) (see McKie 1966), are reported in Table 3 and selected oxides plotted in Fig. 3.

In the series 56–58F, fenitization resulted in a large progressive decrease in MgO, and a much smaller and hardly significant reduction in SiO_2.

Al_2O_3 increased slightly, but to no significant degree, while a series of oxides including TiO_2, total Fe as Fe_2O_3, MnO, CaO, K_2O, and P_2O_5 show definite and consistent increases. The parallelism of the curves in Fig. 3(a) for Fe_2O_3* and Fe_2O_3 shows that the increase in iron was mainly due to augmentation of Fe^3. The outstanding and unusual aspect of the chemical change is the decrease which occurred in Na_2O during fenitization at the same time as the concentration of K_2O was trebled. Na_2O remains, however, more or less constant in the samples from the other mafic dyke, but K_2O still rises steadily as the alkaline pyroxenite is approached. Apart from the claims of von Eckermann (1948), later disproven (McKie 1966), an increase of K_2O without a concomitant rise in Na_2O only seems to have been observed in the fenites developed from granitic rocks around the Brent Crater (Currie 1971), although it is commonly observed in feldspathized zones associated with carbonatite emplacement (Wooley 1969).

The sample series 52–55F naturally exhibits less-pronounced changes in major-element geochemistry than 56–58F taken much closer to the source of the fenitizing fluids. However, apart from the discrepancies shown by 55F, which probably may be ascribed to primary inhomogeneity, similar trends can be observed. The principal changes are the fall in MgO, and the increase in Fe_2O_3 (and MnO) and K_2O. Al_2O_3 again undergoes a slight rise while SiO_2, CaO, Na_2O and TiO_2 remain more or less constant.
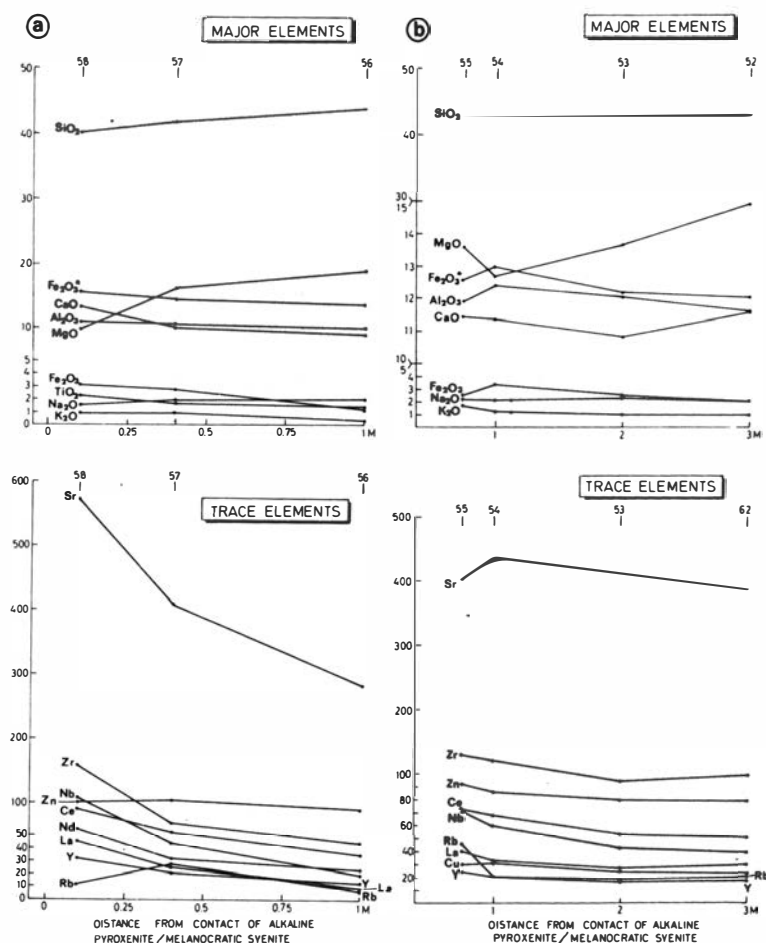
Fig. 3. Chemical changes occurring within dykes of picritic composition as they are traced into the fenitic aureole of an alkaline pyroxenite/melasyenite pegmatite. Note that the ordinate scale is expanded at low concentrations.

Regression analysis of the contents of the unit cells calculated for samples 56–58F, reveals that Al, Ti, Ca, Fe^3, and Fe^2 and H vary linearly with Mg; correlation coefficients are sensibly -1.0 in each case. Widely-varying slopes for the least-squares regression lines prove that these correlations are not induced by Mg variation within a unit cell of constant cationic content. K, however, shows no more than a moderate negative correlation with MgO ($r = -0.73$), but has a perfect negative correlation with Si. Mg and Na vary sympathetically ($r = 0.96$). The variations in cations in the unit cells are interpreted as a result of the replacement of Mg + Na by Ca, H, Fe, Al, Ti, C, and Mn, in that order of importance, and the replacement of Si by K. The numerical relationships are such that Si and (Mg, Na) ions seem to have been exchanged with 3 K and 0.88 (0.14 Al + 0.05 Ti + 0.11 Fe^3 + 0.04 Fe^2 + 0.42 Ca + 0.02 Mn + 0.19 H + 0.03 C) ions respectively; the total number of cations in the unit cell remained constant during ionic exchange to within 1%.

Changes in trace-element geochemistry

With the exception of Zn which remained moderately constant, the analysed traces in the fenitization series 56–58F underwent spectacular increases (Fig. 3, Table 3) varying from 62.5 to 450.0% of the concentrations in the least fenitized sample (Table 7). Nb and La concentrations were most affected, being more than quadrupled, followed by Zr which rose two and a half times, and Nd, Ce and Y, which had their values increased one and a half times. Sr and Cu concentrations were augmented by close to 100 and 63% respectively. Rb shows an irregular,

Fig. 4. Relict rhythmic layering in the outer part of a fenite aureole associated with a litchfieldite pegmatite emplaced in gabbro. Primary plagioclase and clinopyroxene are pseudomorphed by zeolites and amphibole respectively. Svensenes, Seiland.

but not unsystematic fluctuation; the highest values for the element coincide with the biotite-bearing fenite sample. A surprising feature of the fenites is that they contain concentrations of certain trace elements, namely Cu, Y and Nb, which exceed by far those recorded in the two analyses of alkaline pyroxenite (Table 2). This phenomenon is also exhibited by the fenitization series 52–55F. In general, more modest changes in trace-element concentration are characteristic of the latter. Rb shows, however, a pronounced rise in the most fenitized sample. Excluding Rb, Nb remains the element most affected by addition relative to its initial concentration, followed by the light REE, Y, and Zr (Table 7).

Regression analysis of the trace elements in the samples 56–58F suggests that two groups with different behaviours exist (see also Fig. 3): Zn and Rb values have a reasonable fit with a least-squares straight line (r = 0.91), the concentration of Zn being 0.54 of that for Rb, both elements apparently being correlated with the occurrence of modal biotite; the other traces show interelement correlations better than r = 0.97 and similar, but negative, correlations with Mg. Using La as abscissa, the regression lines for Cu, Sr, Y, Zr, Nb, Ce, and Nd have slopes varying from 0.27 (Cu), through 0.51 (Y), 1.05 (Nd), 1.50 (Ce), 2.47 (Nb), 3.14 (Zr), to 7.71 (Sr).

Trace-element variation in the sequence 52–55F is generally similar to that described above, with the exceptions of Sr, Cu, Zn, and Rb. Sr and Cu are correlated neither with the other traces nor with each other; both, however, have moderate to distinct negative correlation with Mg. Zn and Rb are well correlated with the remaining trace metals, all of which show moderately or strongly related variations. Thus all the traces, excepting Sr and Cu, vary sympathetically with K, rather than antipathetically with Mg as in the samples 56–58F. Excluding sample 55F from consideration does not result in an improved negative correlation with Mg for the majority of traces. Relative to La as abscissa, the following slopes of the least-squares regression lines for individual traces are similar to those listed above: 0.55 (Y); 2.65 (Zr); 2.37 (Nb); 2.65 (Zr). Zn concentrations are equal to 0.42 Rb, also similar to their relationships in samples 56–58F.

Fenites associated with litchfieldite pegmatites

Two zones can be recognised within the commonest type of fenitic aureole developed in mafic hosts around litchfieldite pegmatites. In the outermost zone reconstitution is almost entirely mineralogical, primary textures, and structures such as rhythmic layering being largely preserved (Fig. 4). In a narrow zone immediately adjacent to the pegmatites, gabbroid hosts and crosscutting mafic dykes alike are totally reconstituted into silico-

carbonatites possessing a streaky Liesegang-type banding. The latter consists of discontinuous narrow bands dominated by calcite and apatite, in alternation with bands rich in amphibole.

A different mode of fenitization observed in gabbroic rocks results in macroscopic textural preservation, but re-organisation on the microscopic scale without the development of more than accessory amounts of calcite. Both of these contrasting fenitic trends are described, the commoner trend by employing five samples from a fenitized mafic dyke and six samples of reconstituted gabbro, the other in lesser detail, with two gabbro samples.

Mineralogical and textural development of carbonatitic fenites

Mineralogical changes occurring within a 50 cm wide dyke which is cut at right angles by the Skarvbergnes litchfieldite pegmatite described and figured by Robins (1972), are sketched in Fig. 5. Sample 34F, collected 2.5 m from the 3–4 m wide litchfieldite, is megascopically unfenitized; it is a xenomorphic-granular amphibolite dominated by brown amphibole, with lesser amounts of fresh, zoned plagioclase, diopsidic clinopyrozene, and accessory biotite and oxides. During progressive fenitization of this primary mineralogy, as represented by samples 35 and 36F, biotite increased in abundance while the metamorphic pyroxene eventually disappeared. Plagioclase decreased in amount and simultaneously changed in composition from an andesine to albite. In the intermediate stage of fenitization

represented by 35F, plagioclase is clouded by tiny, unidentifiable patches and blades, and exhibits a strong marginal zoning to albite. Amphibole also changed in composition during fenitization, shown by the variation in its pleochroism from browns through brown-greenish brown to brown-green, and the diminution of its 2V. In sample 36F, the amphibole is tentatively identified on the basis of its optics as a ferrohastingsite. The only new phases which nucleated during fenitization were calcite and apatite, both of which are abundant in 36F; they both occupy an interstitial textural role.

The mineralogy of the fenitized mafic dyke (38F), which crosses a strongly deformed amphibole syenite and is cut by a litchfieldite a few metres north of the locality of the fenites described above, is similar to that of 36F. Biolite, calcite, and apatite are, however, less abundant. The unfenitized dykerock, which is completely transformed into fenite over a distance of only 10 cm, is a blastoporphyritic and blastophitic amphibolite. During fenitization, the relict igneous fabric disappeared in favour of a xenomorphic-granular ferrohastingsitic amphibole aggregate with interstitial biotite, calcite, and apatite.

The metasomatic transformation of the metagabbro mineralogy as schematized in Fig. 6 is believed to be fairly typical, apart perhaps from the lack of clinopyroxene at high grades of fenitization. Sample 39F retains a pre-fenitization texture and mineralogy, consisting of strongly-zoned plagioclase clouded by calcite and amphibole specks, and in places sericitised, amphibole of metamorphic origin replacing
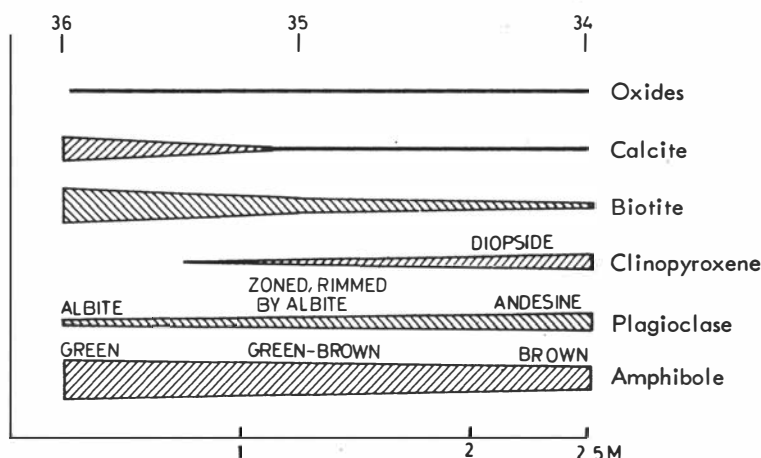

Fig. 5. Schematic plot of the changes in mineralogy within an amphibolite with fenitization. Abscissa gives the mean distance of the samples from the contact of a litchfieldite/carbonatite pegmatite.
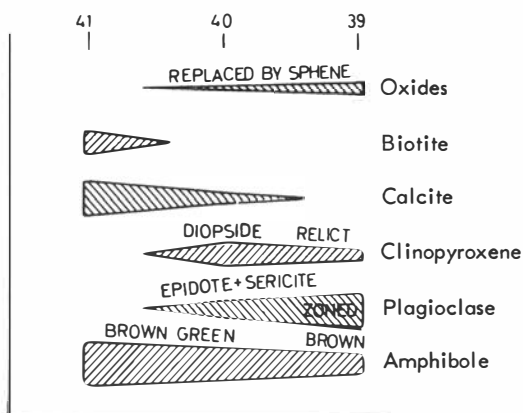
Fig. 6. Mineralogical changes occurring in metagabbro with increasing grade of fenitization towards the same litchfieldite/carbonatite pegmatite referred to in Fig. 5. Grade of fenitization increases to left along abscissa.

Fig. 7. Changes in major- and trace-element chemistry of an amphibolite dyke sampled at various distances from a litchfieldite/carbonatite pegmatite. Values from Table 4. Note that the ordinate for major elements is discontinuous.

clinopyroxene, Fe-Ti oxides, and hercynitic spinel. The amphibole is a brown variety where overgrowing clinopyroxene, and involved in symplectitic intergrowth with hercynite where replacing Fe-Ti spinel and hercynite, but is turquoise against plagioclase. With fenitization, plagioclase exited from the assemblage, after being first pseudomorphed by zoned epidote prisms embedded in sericite and fibrous, radiating zeolite. Amphibole increased in amount and its composition became uniform and changed towards ferrohastingsite(?) in the same way as described above. Calcite, biotite, and apatite appeared and increased in amount as fenitization progressed, relict oxides were increasingly replaced by sphene, and the banding mentioned earlier developed. In this example, a new clinopyroxene is present in sample 40F but is absent in the most fenitized gabbro. In the series 62, 64 and 63F, while the relict pyroxene is increasingly replaced by amphibole and sphene, a clear pale-green clinopyroxene nucleates as separate grains or forms outgrowths on the pyroxene relicts. In the most metasomatized of this series of samples, the clinopyroxene has assumed an aegirine-augitic composition and may form parallel growths or almost symplectitic intergrowths with amphibole.

Changes in major-element geochemistry

Major-element analyses of the 5 dyke samples and 6 samples of metagabbro, together with standard cells calculated for 100(0), are listed in
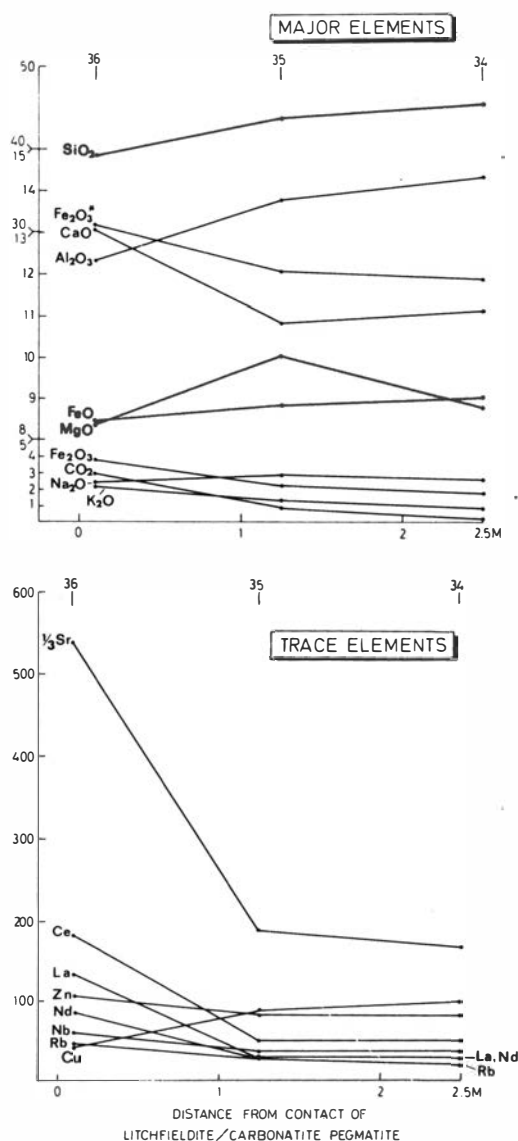
Tables 4 and 5, and plotted against distance from the source of the metasomatizing fluids or an arbitrary scale of increasing fenitization in Figs. 7–9.

In the mafic dykes, fenitization was accompanied by a quite marked fall in both SiO_2 and Al_2O_3 (Figs. 7, 8). FeO also decreased but was outweighed by increasing Fe_2O_3 such that total Fe as Fe_2O_3 rose. While Na_2O changed
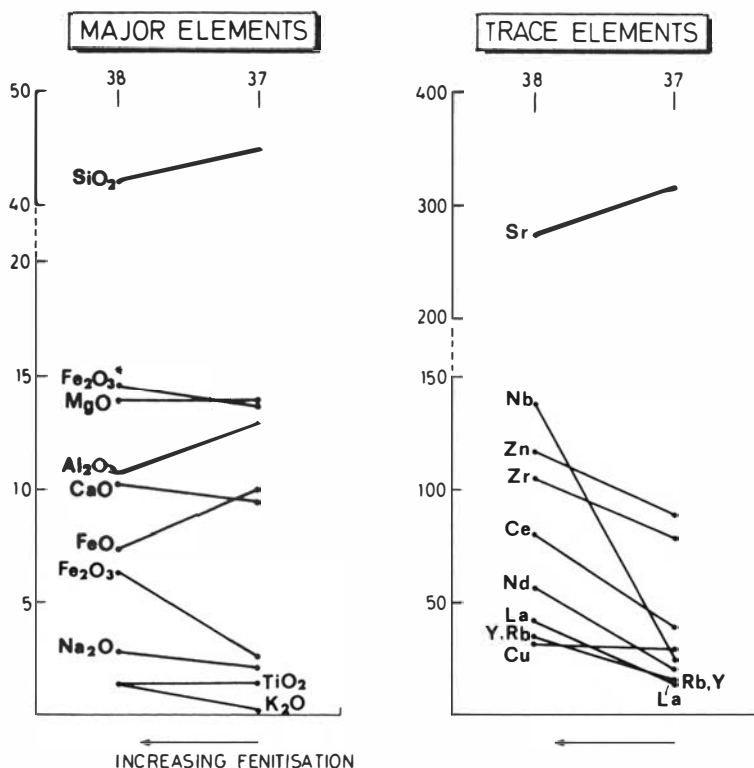
Fig. 8. Chemical changes induced in an amphibolite dyke by fenitization against a litchfieldite pegmatite. Values from Table 4.

little, both fenitization series show a marked increase in K_2O, accompanied by augmentation in CO_2, P_2O_5, MnO and CaO. H_2O varies in opposite directions in the two dykes during modification and in both cases MgO and TiO_2 show no evidence of systematic changes in concentration.

The variations in Si, Al, and H in the standard cells for samples 34–36F (Table 4) fit straight-line regression curves exactly ($r = 1.00$), while K, Fe^3, Mn, Ca, P, and C are correlated negatively with these cations to better than $r = -0.96$. It is clear from the standard cells that the increase in Ca is too low for C to have been introduced only in the form of calcite, but there is a numerical possibility for P to have been added solely as apatite. If the latter is assumed correct then the remaining increase in Ca is sufficient to allow about half of the C to have been transported as calcite. The variations in the standard cells (Table 7) suggest that 1.0 (0.43 Si $+ 0.15$ Al $+ 0.41$ H $+ 0.01$ Fe^2) was exchanged with 0.9 (0.16 Fe^3 $+ 0.26$ Ca $+ 0.11$ K $+ 0.02$ Mn $+ 0.05$ P $+ 0.39$ C), while constancy was maintained to within 1% in the content of the standard cell.

Similarly, the standard cells for samples 37 and 38F change with fenitization by the replacement of 1.0 (0.32 Si $+ 0.36$ Al $+ 0.32$ Fe^2) by 1.6 (0.27 Fe^3 $+ 0.08$ Mg $+ 0.10$ Ca $+ 0.11$ Na $+ 0.11$ K $+ 0.004$ Mn $+ 0.03$ P $+ 0.06$ C), the cationic content of the standard cell increasing by 3.2%.

Although the chemical data for fenitized gabbros adjacent to litchfieldite pegmatites cannot be regarded as so reliable as that for the dykerocks and therefore is not analysed in detail, Table 5 and Fig. 9 show much the same type of major-element evolution for these hosts during fenitization. Samples 39–41F, collected from the same locality as the dykes described above, show a marked reduction in SiO_2 and Al_2O_3, and a pronounced fall in Na_2O. MgO varies little while TiO_2, Fe_2O_3, FeO, CaO and MnO increase. Large rises occur in K_2O, CO_2, and P_2O_5.

In the sample series 62-64F, taken from the margin of a 2 m thick litchfieldite member of the pegmatite complex extending inland from the shore of Store Kufjord at Svensenes (Robins 1971), there is no evidence for a progressive diminution in SiO_2 (Fig. 9). Both Al_2O_3 and Na_2O were, however, dramatically reduced with fenitization, and are accompanied by a fall in CaO. Fe_2O_3, FeO, and MnO show increases, in the
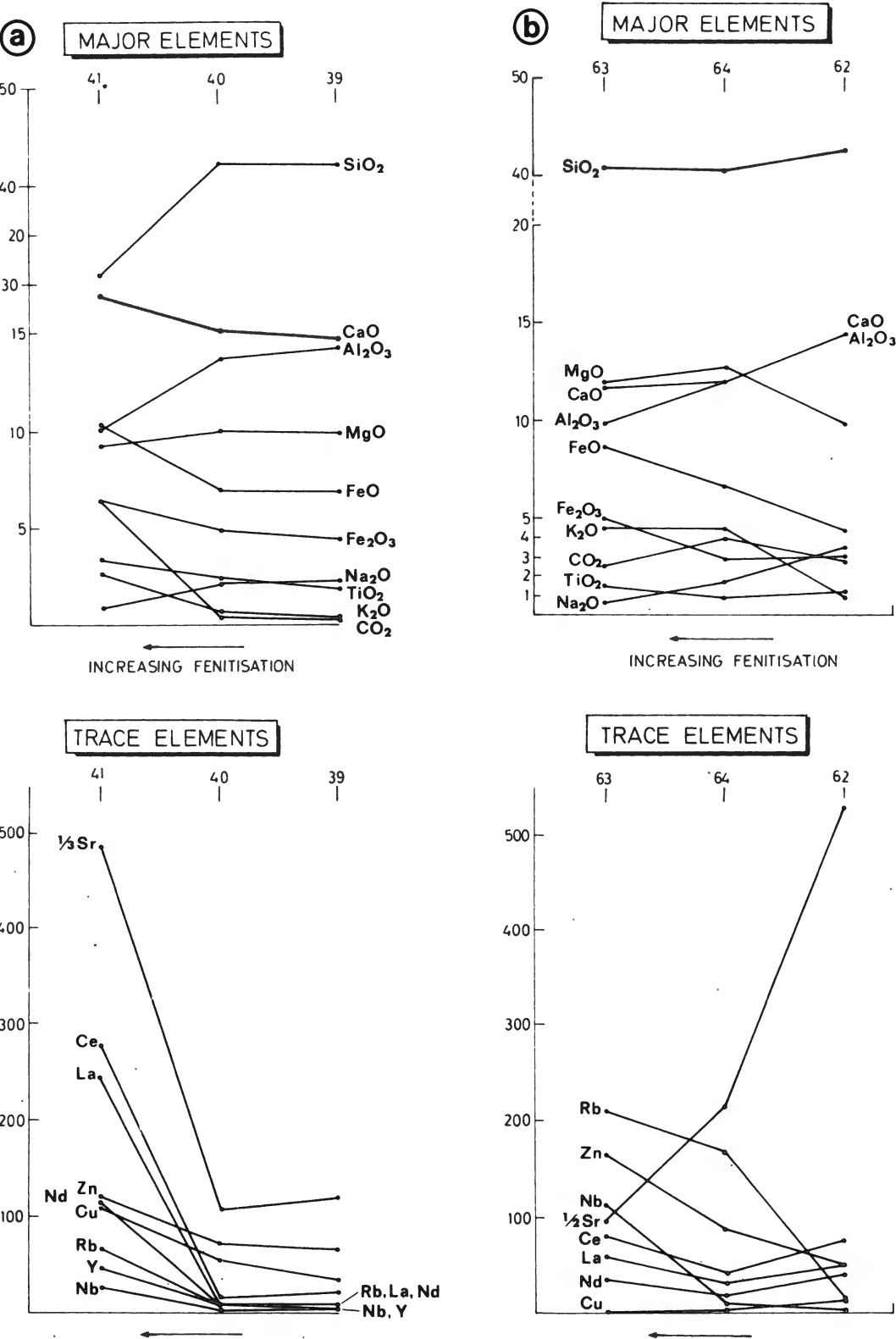
Fig. 9. Variations in petrochemistry produced in metagabbros from Skarvbergnes (a.) and Svensenes (b.) by fenitization adjacent to litchfieldite pegmatites. Values from Table 5.

Table 4.   Analyses from two mafic dykes cut and fenitized by litchfieldite pegmatites, Skarvbergnes.

	36F	35F	34F		38F	37F
Dist.fr.contact	10cm	125cm	250cm		fenitized	unfenitzed
SiO_2	39.30	43.94	45.65		42.25	45.01
Al_2O_3	12.33	13.80	14.37		10.37	12.86
TiO_2	2.12	2.46	2.45		1.44	1.58
Fe_2O_3	3.80	2.26	1.84		6.32	2.58
FeO	8.45	8.84	9.06		7.43	9.97
MgO	8.39	10.02	8.82		13.95	13.94
CaO	13.08	10.83	11.15		10.22	9.54
Na_2O	2.71	2.93	2.68		2.87	2.29
K_2O	2.18	1.40	1.13		1.45	0.65
MnO	0.33	0.17	0.15		0.27	0.18
P_2O_5	0.81	0.37	0.39		0.46	0.29
H_2O^+	0.50	1.08	1.20		0.84	0.50
CO_2	2.95	0.90	0.25		0.45	n.d.
	97.05	99.00	99.15		98.68	99.49
Cations in stand. cell of 100 (O)						
Si	25.0	27.0	27.9		26.5	27.7
Al	9.2	9.9	10.2		7.9	9.3
Ti	1.0	1.1	1.1		0.7	0.7
Fe'''	1.8	1.1	0.8		2.9	1.2
Fe''	4.5	4.5	4.6		3.9	5.1
Mg	7.9	9.2	8.0		13.1	12.8
Ca	8.9	7.1	7.3		6.9	6.3
Na	3.4	3.5	3.1		3.4	2.7
K	1.7	1.1	1.0		1.2	0.5
Mn	0.2	0.06	0.06		0.1	0.07
P	0.5	0.2	0.2		0.3	0.1
H	2.1	4.4	5.0		3.5	2.1
C	2.6	0.7	0.2		0.4	0.0
	68.8	69.9	69.5		70.8	68.6
Trace elements (ppm)						
Cu	43	88	98		32	28
Zn	108	78	81		117	88
Rb	48	28	21		35	17
Sr	1619	566	504		274	317
Y	44	17	16		34	18
Zr	156	118	119		105	78
Nb	60	37	39		138	25
La	133	28	29		42	16
Ce	184	49	51		81	39
Nd	85	29	30		57	21

n.d. = not detected

Table 5   Analyses of fenites derived from gabbros or eucrite adjacent to litchfieldite pegmatites.

	Skarvbergnes			Svensenes			Stjernøy	
	41F	40F	39F	63F	64F	62F	18F	17F
fenitization	>	>		>	>		fenitized	unfenitzed
SiO_2	31.07	42.32	42.18	41.02	40.46	42.65	43.03	46.58
Al_2O_3	10.02	13.73	14.23	9.92	12.03	14.43	22.58	21.26
TiO_2	3.35	2.47	2.18	1.50	0.94	1.19	0.50	0.75
Fe_2O_3	6.48	4.82	4.51	5.01	2.97	3.17	2.39	1.31
FeO	10.26	6.85	6.92	8.66	6.60	4.38	1.34	3.37
MgO	9.26	9.94	9.83	12.04	12.84	9.89	6.04	7.24
CaO	16.82	15.15	14.72	11.84	12.06	14.56	15.78	16.25
Na_2O	1.04	2.22	2.29	0.71	1.74	3.57	6.82	1.51
K_2O	2.66	0.71	0.45	4.59	4.57	1.08	1.59	0.08
MnO	0.37	0.13	0.13	0.37	0.23	0.14	0.05	0.07
P_2O_5	0.90	0.03	0.03	0.23	0.04	0.08	0.05	0.11
H_2O^+	0.61	1.04	0.84	0.90	0.65	0.80	0.1	0.6
CO_2	6.45	0.55	0.50	2.62	4.05	2.80	0.5	0.4
	99.29	99.96	98.81	99.41	99.18	98.74	100.77	99.53
Cations in stand. cell of 100 (O)								
Si	19.8	26.1	26.3	25.7	24.9	25.9	25.9	27.5
Al	7.5	8.9	10.4	7.2	8.7	10.2	15.9	14.7
Ti	1.6	1.2	1.0	0.7	0.4	0.5	0.2	0.3
Fe'''	3.1	2.2	2.1	2.3	1.4	1.4	1.1	0.6
Fe''	5.5	3.5	3.6	4.5	3.4	2.2	0.7	1.7
Mg	8.8	9.1	9.1	11.3	11.8	8.9	5.4	5.4
Ca	11.5	10.0	9.8	7.9	8.0	9.5	10.2	10.3
Na	1.3	2.6	2.6	0.8	2.0	4.1	8.0	1.7
K	2.2	0.6	0.34	3.7	3.6	0.9	1.2	0.06
Mn	0.2	0.05	0.05	0.2	0.1	0.05	0.02	0.02
P	0.5	0.02	0.02	0.1	0.03	0.06	0.04	0.08
H	2.6	4.2	3.4	3.8	2.6	3.2	0.4	2.3
C	5.6	0.5	0.4	2.2	3.4	2.3	0.4	0.3
	70.2	69.0	69.1	70.4	70.3	69.2	69.5	66.0
Trace elements (ppm)								
Cu	109	55	35	n.d.	2	14	44	36
Zn	120	72	67	164	87	50	28	31
Rb	67	10	9	209	168	16	4	3
Sr	1458	323	362	194	431	1056	503	507
Y	47	6	5	36	25	17	2	6
Zr	43	27	28	80	30	44	8	16
Nb	27	2	6	112	10	3	n.d.	n.d.
La	244	8	9	59	32	49	3	11
Ce	276	16	22	80	43	75	6	19
Nd	112	6	12	36	18	41	5	12

n.d. = not detected

case of Fe_2O_3 an irregular one, while MgO and TiO_2 vary unsystematically. The dramatic enrichment in K_2O, and P_2O_5 is again in evidence. Each of the fenites are rich in CO_2 but no trend can be observed in its variation.

In the standard cells for samples 39–41F, Si is perfectly correlated with Na and Mg ($r = 1.00$), but more poorly with Al ($r = 0.87$). K correlates with $Fe^3 + Fe^2$, Ca, Ti, C, P, and Mn to better than $r = 0.98$, and has a near-perfect negative correlation with Si ($r = -0.99$). Fenitization caused the replacement of 1.0 ($0.59 \text{ Si} + 0.2 \text{ Al} + 0.03 \text{ Mg} + 0.12 \text{ Na}$) by 1.17 ($0.05 \text{ Ti} + 0.08 Fe^3 + 0.15 \ Fe^2 + 0.13 \text{ Ca} + 0.14 \text{ K} + 0.01 \text{ Mn} + 0.04 \text{ P} + 0.40 \text{ C}$), the cationic content of the unit cell increasing by 1.59%.

Changes in trace-element geochemistry

Fenitization of the mafic dykes was accompanied by augmentation of the light REE, Y, Nb, Zr, Rb, and Zn. Of these elements, Ce and La show the largest absolute and relative enrichments respectively in sample 36F, while Nb in 38F increased most both absolutely and relative to its initial concentration in sample 37F (Table 7). Sr, like Cu, shows opposite behaviours in the two dykes; in one it increases by over 1000 ppm with fenitization, and in the other it falls slightly. This feature is common to the fenitized gabbros. In one of the two gabbro series both Sr and Cu undergo addition, in the other both elements are depleted, while all other traces are enriched, some even to the extent of thousands of percent of their initial concentrations. All of the elements, except Rb, have much higher concentrations in 36F than in the average litchfieldite quoted in Table 2. A similar situation is encountered in the most fenitized of the gabbros collected from Skarvbergnes (41F), with the addition of lower Zr and Nb than in the average litchfieldite. In this fenite, the light REE in particular reach extreme values.

Exclusive of Rb, which has a correlation coefficient of -1.00 with Cu, all the enriched traces in samples 34–36F have inter-element correlations of $r = 1.00$. The different behaviour of Cu and Rb can be seen in Table 4 and Fig. 7; these elements react to fenitization farther from the source of the metasomatizing fluids. Thus at 125 cm from the source, an increase in Rb and decrease in Cu has already occurred, while the other trace metals largely retain their original concentrations. Both Rb and the other traces

concentrated during fenitization, however, have correlation coefficients around 0.99 with K and other major cations which increased due to metasomatism. Referring the individual elements to La as abcissa, least-squares regression lines have the following highly varying slopes: 0.21 (Nb); 0.22 (Rb); 0.27 (Zn); 0.26 (Y); 0.36 (Zr); 1.28 (Ce); 0.53 (Nd); 10.37 (Sr).

Traces in the gabbro series 39–41F are also highly correlated with each other ($r > 0.96$), and correlate positively with K and other cations of similar behaviour. The following slopes of the least-squares linear regressions for individual traces referred to the common base of La vary widely, and differ, in some cases considerably, from those derived from the fenitized dyke; despite the fact that both rock types shared a common fenitising agent: 0.27 (Cu); 4.47 (Sr); 0.07 (Zr); 0.10 (Nb); 1.08 (Ce). Slopes for Zn (0.21), Rb (0.24), Y (0.18) and Nd (0.44) are, however, generally similar to the equivalent slopes for the fenitized dyke.

Mineralogical and textural development of an ijolitic fenite

A litchfieldite pegmatite cutting moderately homogeneous, deformed gabbroic cumulates on the southern shore of Stjernöy is associated with a distinctive fenitic aureole extending 0.3 m from its margins. Within the aureole, the cumulates retain their macroscopic fabric but plagioclases take on a pink colouration and pyroxenes are replaced by bright green aggregates. Microscopically, the sampled fenite (18F) retains relicts of the primary pyroxene, olivine is unaltered, whilst plagioclase is completely pseudomorphed. The latter is replaced either by fibrous zeolite, in places preserving the initial grain-boundary pattern, or by a vermicular intergrowth of nepheline and clinopyroxene. Amphibole, zoned outwards from brown-green to turquoise, rims remnants of the earlier clinopyroxene and is continuous with nepheline-amphibole symplectites after plagioclase, lacking the clinopyroxene which is present away from such original grain boundaries. The mineralogy and texture of this unusual fenite strongly resemble a 'theralite' from the Spitzkop complex (Strauss & Truter 1951, Verwoerd 1966).
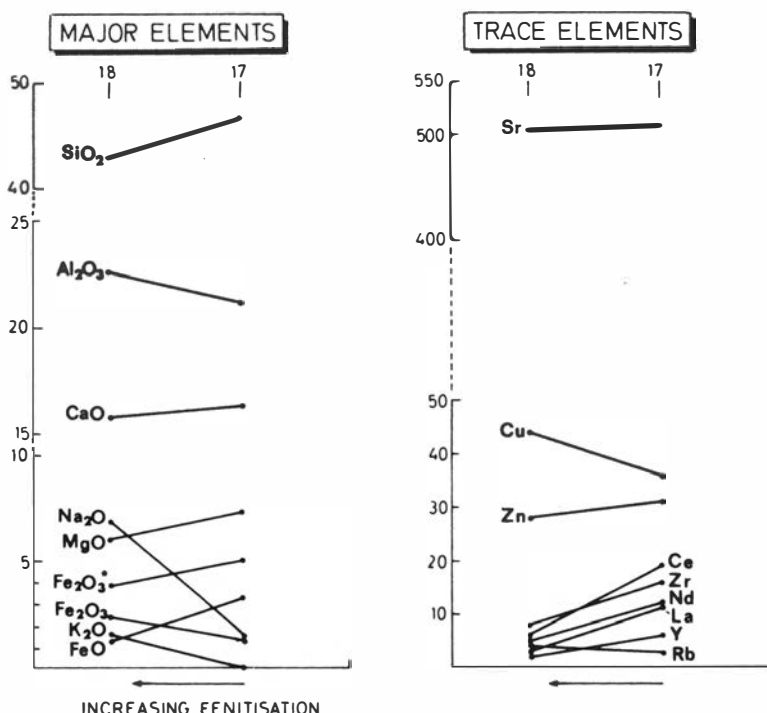
Fig. 10. Chemical changes associated with the transformation of gabbro (17F) to an ijolitic fenite (18F) beside a litchfieldite pegmatite. Data from Table 5.

Changes in major-element geochemistry

The unique feature of the major-element composition of the ijolitic fenite (18F) is its massive enrichment in alkalies, mainly soda, compared with an equivalent gabbro (17F) outside the aureole (Table 5, Fig. 10). Accompanying the increases in Na_2O and K_2O are smaller rises in Al_2O_3, which in the other fenites associated with litchfieldites decreases, and Fe_2O_3. SiO_2, FeO, and total Fe, however, fell with metasomatism, as did MgO and to a much more minor degree CaO, TiO_2, MnO, and P_2O_5. Fenitization was achieved by the replacement of $(0.44 \, Si + 0.28 \, Fe^2 + 0.28 \, Mg)$ by $2.54 \, (0.13 \, Al + 0.05 \, Fe^3 + 0.69 \, Na + 0.12 \, K)$, causing an increase of 5.3% (3.5 cations) in the content of the standard cell.

The evolution of the Spitzkop 'theralite' was similar, but involved the addition of significant Ca and the abstraction of limited amounts of Al (Verwoerd 1966).

Changes in trace-element geochemistry

In contradiction with the fenites described above, there was little change in the concentrations of Cu, Zn, Rb, and Sr with ijolitization, and decreases occurred in Y, Zr, Nb, and the light REE to the extent of between 50 and 73% of their initial concentrations (Fig. 10, Tables 5 and 7).

Fenitization of psammitic metasediment

In every case so far observed of litchfieldite pegmatites in contact with amphibolite-facies psammitic metasediments, the metasomatic aureole developed is characterised by 'classic' alkali feldspar-aegirine-augite fenites. A brief description of the evolution of these based on two samples adjacent to a single, isolated litchfieldite – one strongly fenitized (77F), the other illustrating the initial phases of fenitization (76F) – is provided here for comparison with the trends for mafic rocks described earlier.

The felsic bands in 76F consists of quartz, strongly-zoned and occasionally antiperthitic plagioclase, and perthitic alkali feldspar. Aegirine-augite occurs as more or less continuous rims between feldspars and quartz, and apatite and zircon occur in accessory amounts. Thin mafic bands contain the highly undersaturated association of biotite, feldspars, corundum, and hercynitic spinel, but the same

Table 6.   Analyses of a psammitic metasediment and its fenitized equivalent adjacent to a litchfieldite pegmatite, Hakkstabben.

	77F	76F			77F	76F
	fenitized	unfenitzed		Trace elements (ppm)		
SiO_2	55.16	69.37		Cu	7	26
Al_2O_3	19.48	13.39		Zn	133	85
TiO_2	1.13	0.85		Rb	131	96
Fe_2O_3	2.15	0.55		Sr	375	287
FeO	6.27	4.35		Y	18	70
MgO	2.64	1.47		Zr	78	393
CaO	2.88	1.41		Nb	74	25
Na_2O	5.99	5.01		La	71	48
K_2O	3.68	2.76		Ce	117	92
MnO	0.20	0.08		Nd	69	52
P_2O_5	0.26	0.09				
H_2O^+	0.30	0.45				
CO_2	-	-				
	100.14	99.78				

Cations in stand. cell of 100 (O)		
Si	32.3	38.6
Al	13.3	8.7
Ti	0.5	0.4
Fe'''	0.9	0.2
Fe''	3.1	2.0
Mg	2.3	1.2
Cu	1.5	0.5
Na	5.7	5.4
K	2.7	2.0
Mn	0.1	0.03
P	0.2	0.06
H	1.2	1.6
	65.1	61.0

− = not determined

The major-element chemical changes with fenitization are essentially identical with those described for felsic rocks by McKie (1966): A large decrease in Si was accompanied by a substantial increase in Al, significant rises in Fe^3, Fe^2, Ca, Na, K, and limited increases in Ti, Mn, and P (Table 6, Fig. 11). The cationic content of the standard cell rose by 6.7% (4.1 cations).

The concentrations of the traces Zn, Rb, Sr, Nb, and the light REE all increased in the strongly fenitized psammite relative to sample 76F, while Cu, Y, and particularly Zr, show large reductions (Fig. 11).

accessories. In the pelitic bands, which have an unchanged mineralogy in the more fenitized sample, corundum and hercynite probably represent products of the desilication of original sillimanite and almandine garnet respectively. At the higher grade of fenitization represented by 77F, quartz is no longer present in the psammitic bands and aegirine-augite has increased in amount. The mineralogical changes and textures observed in the dominant psammitic parts of the fenitized metasediment resemble those described in detail by von Eckermann (1948) for metasomatized gneissic granites around the Alnö complex.

Discussion

Common features of the mafic fenites

Excepting one case in which Si varies little, all the fenites show more or less marked depletion in this cation, as well as increases in K. The potassic nature of the fenitization is well illustrated in Table 7; consistent increase in K is generally accompanied by small increases in Na or Na-depletion, resulting in every case in higher $K/K + Na$ ratios. Augmentation in Fe^3 is shown by all fenites, total Fe increases in almost all cases, while Fe^2 may either increase or decrease. Mn usually accompanies introduction of Fe^3. C was consistently added, in limited amounts in the fenites associated with the alkaline pyroxenite, but to significant or substantial degrees in the fenites bordering litchfieldite pegmatites.
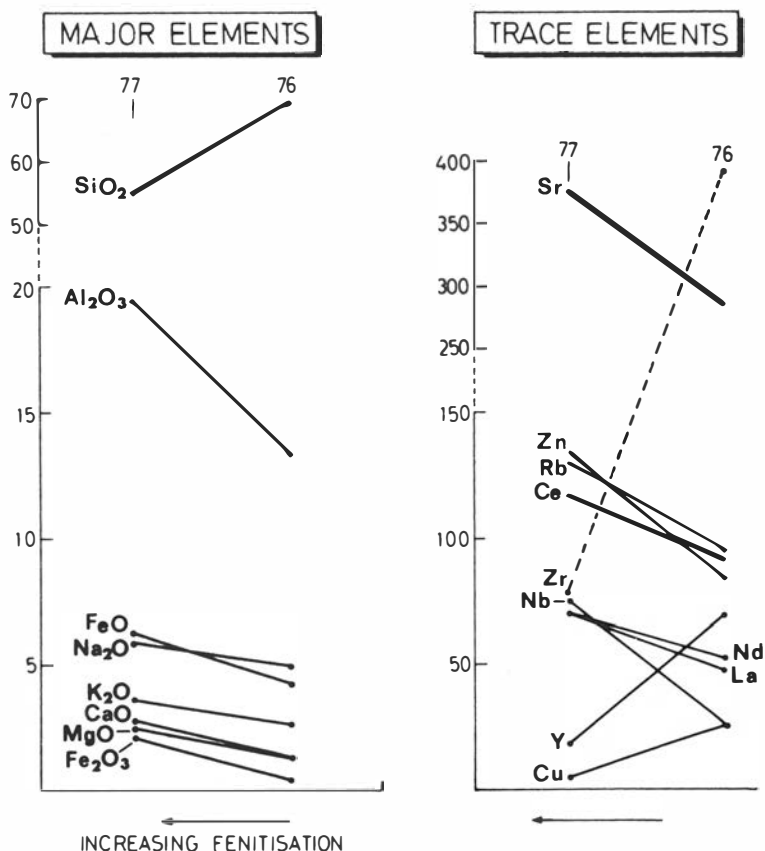
Fig. 11. Changes in major- and trace-element composition of psammitic metasediment with fenitization along a litchfieldite pegmatite. Values from Table 6.

Addition of P also characterises the latter. While the behaviours of Mg and Ti are irregular, Ca generally increases or remains constant. Al behaves differently in the two main fenite types; during fenitization accompanying pyroxenite emplacement it increases, but it is depleted in mafic rocks adjacent to litchfieldites. H is probably too affected by post-fenitization events to be interpreted in detail in every case, but there can be little doubt that H increased during the progressive fenitization represented by samples 56–58F or that it decreased in the series 34–36F. The gabbroid rocks fenitized by litchfieldite pegmatites are also remarkably poor in H_2O+. The behaviour of H appears on the basis of these two reliable cases to be controlled by that for C: Introduction of substantial C is accompanied by removal of H.

Changes in the cationic content of the standard cells in either positive or negative directions are characteristic of the fenitization, but the changes are invariably limited.

Apart from in the unusual ijolitic fenite, several of the analysed trace elements exhibit consistent behaviour in all fenites. Zn, Y, Zr, and the REE (La, Ce, and Nd) all increased during the progress of fenitization. Apart from Zn, which rises in concentration to a more limited degree, these elements are very sensitive indicators of fenitization. Sr behaves in an extremely irregular manner, some fenites being enriched, others being depleted. Large increases in Sr do, however, appear to be related to the introduction of large amounts of C. Cu may increase or decrease, apparently without system. The behaviour of Rb, as illustrated by fenites 56–58F, is tentatively interpreted as reflecting mineralogy. If biotite is stable at all grades of fenitization, as it is in all the studied series except 56–58F, Rb increases, but breakdown of biotite results in the release and removal of this element, even though K continues to rise.

Several of the trace elements reach concentrations in the fenites exceeding those of the as-

Table 7. Summary of the changes in the standard cells, and trace elements in ppm. and % of the initial concentration for the fenitisation series reported in Tables 2–6.

	mafic dykes/alk.pyrox.		mafic dykes/litchfieldite		gabbro, eucrite/litchfieldite			psammite/litchfieldite
	58–56F	55–52F	36–34F	38–37F	41–39F	63–62F	18–17F	77–76F
Si	− 0.2	+ 0.1	− 2.9	− 1.2	− 6.5	− 0.2	− 1.6	− 6.3
Al	+ 1.0	+ 0.3	− 1.0	− 1.4	− 2.9	− 3.0	+ 1.2	+ 4.6
Ti	+ 0.4	−	− 0.1	−	− 0.6	+ 0.2	− 0.1	+ 0.1
Fe^{III}	+ 0.8	+ 0.1	+ 1.0	+ 1.7	+ 1.0	+ 0.9	+ 0.5	+ 0.7
Fe^{II}	+ 0.3	+ 0.1	− 0.1	− 1.2	+ 1.9	+ 2.3	− 1.0	+ 1.1
Mg	− 7.9	− 1.1	− 0.1	+ 0.5	− 0.3	+ 2.4	− 1.0	+ 1.1
Ca	+ 3.1	−	+ 1.6	+ 0.6	+ 1.7	− 1.6	− 0.1	+ 1.0
Na	− 0.4	+ 0.1	+ 0.3	+ 0.7	− 1.3	− 3.3	+ 6.3	+ 1.3
K	+ 0.6	+ 0.5	+ 0.7	+ 0.7	+ 1.86	+ 2.8	+ 1.14	+ 0.7
Mn	+ 0.13	−	+ 0.14	+ 0.03	+ 0.15	+ 0.15	−	+ 0.07
P	−	−	+ 0.3	+ 0.2	+ 0.48	+ 0.04	− 0.04	+ 0.14
H	+ 1.4	− 1.2	− 2.9	+ 1.4	− 0.8	+ 0.6	− 0.9	− 0.4
C	+ 0.2	+ 0.2	+ 2.4	+ 0.4	+ 5.2	− 0.1	+ 0.1	n.d.
	−0.6	− 0.7	− 0.7	+ 2.2	+ 1.1	+ 1.2	+ 3.5	+ 4.1
Cu	+ 10(62.5)	+ 7(30.4)	− 55(56.1)	+ 4(14.2)	+ 74(211.4)	− 14(100.0)	+ 8(22.2)	− 19(73.1)
Zn	+ 8(8.6)	+ 13(16.4)	+ 27(33.3)	+ 29(32.9)	+ 53(79.1)	+ 114(228.0)	− 3(9.6)	+ 48(56.5)
Rb	+ 5(71.4)	+ 24(114.2)	+ 27(128.5)	+ 18(105.8)	+ 58(644.4)	+ 193(1206.2)	+ 1(33.3)	+ 35(36.5)
Sr	+ 285(99.3)	−	+ 1115(221.2)	− 43(13.5)	+ 1096(302.7)	− 862(81.6)	− 4(0.7)	+ 89(31.0)
Y	+ 19(146.1)	+ 6(33.3)	+ 28(175.0)	+ 16(88.8)	+ 42(840.0)	+ 29(170.5)	− 4(66.6)	− 52(74.3)
Zr	+ 114(253.3)	+ 29(29.3)	+ 37(31.1)	+ 27(34.6)	+ 15(53.5)	+ 36(81.8)	− 8(50.0)	− 315(80.2)
Nb	+ 90(450.0)	+ 31(77.5)	+ 21(53.8)	+ 113(452.0)	+ 21(350.0)	+ 109(3633.3)	−	+ 49(196.0)
La	+ 37(411.1)	+ 10(33.3)	+ 104(358.6)	+ 26(162.5)	+ 235(2611.1)	+ 10(20.4)	− 8(72.7)	+ 23(47.9)
Ce	+ 55(152.7	+ 20(38.4)	+ 133(260.7)	+ 42(107.7)	+ 254(1154.5)	+ 5(6.6)	− 13(68.4)	+ 25(27.2)
Nd	+ 38(165.2)	+ 8(26.6)	+ 55(183.3)	+ 36(171.4)	+ 100(833.3)	− 5(12.2)	− 7(58.3)	+ 17(32.7)

n.d. = not determined; −= no change

sociated alkaline intrusive. The metasomites adjacent to alkaline pyroxenite are relatively enriched in Cu, Y, and Nb, while against litchfieldites the fenites are consistently enriched in Zn, Y, Ce, and Nd and generally also enriched in La, Nb and Zr.

Petrogenesis

Fenitization was the result of the outward movement of ephemeral, dense gas phases rich in H_2O and CO_2 from intrusive, volatile-rich alkaline magmas. The fluids contained in every case higher concentrations of K, Fe^3, Ca, Mn, C, and P, and lower concentrations of Si than could be in equilibrium with the invaded mafic rocks. In addition, the gases derived from the parent magma to the alkaline pyroxenite contained excess Al and Ti, and a deficiency in Mg relative to the fluid phase stably co-existing with the mafic hosts; those derived from the litchfieldite magmas had a deficiency in Al. The K/Na+ K ratio of the introduced fluids was invariably higher than that of the pre-existing fluids. As they moved through the mafic rocks, the fenitizing fluids changed towards equilibrium compositions principally by means of exchange reactions and decomposition-addition reactions (Orville 1962).

Experiments designed to bear directly on the problem of fenitization have yet to be described. However, recent solubility determinations for H_2O and CO_2, almost certainly the major components of any fenitizing fluid, in melts of albite, nepheline, and diopside compositions (Mysen 1975, Rosenhauer & Eggler 1975, Kadik & Eggler 1975), may be applied to the present problem since the magmas associated with fenitization were dominantly composed of these potential minerals. The maximum solubility of CO_2 in the pure melts proves to be only 10–20% (molar) of the amount of H_2O that may dissolve, corresponding to 2–3wt% at pressures lower than 20kb. Maximum solubility for CO_2 occurs when $CO_2/(CO_2 + H_2O)$ in the system is < 1.0, the position of the maxima being significantly de-

pendent on total pressure but not on silicate chemistry or temperature. The divariant melting surfaces representing vapour compositions in equilibrium with albite and diopside crystals and their melts, and by inference also nepheline and melt, show temperature minima at pressures of about 5 kb. A most important implication of the data is that at pressures above 5 kb, rising magmas saturated in the two volatiles may distil off CO_2-rich vapour, while at lower pressures the vapour composition changes to become H_2O-rich. Burnham (1967) has shown that CO_2-bearing vapours in equilibrium with granite have a markedly lower solute content than a pure aqueous phase, suggesting that fenitization may be more pronounced at lower pressure, as deduced by von Eckermann (1948) on different grounds.

The pegmatitic fabric and abundance of calcite in the litchfieldites strongly suggests that they crystallized from volatile-rich magmas saturated with both H_2O and CO_2: Their emplacement during Barrovian metamorphism attests to a moderate-pressure environment. It is, therefore, probable that the gas phase given off from these magmas was CO_2-rich, according well with the analytical evidence for the introduction of large amounts of C during fenitization. The alkaline pyroxenites, however, do not contain significant amounts of calcite, and their associated fenites evolved with only very limited ingress of C. The dense gases released from their parent magma may have been dominated by H_2O. These deductions are weakly supported by the evidence of addition of H to the fenites associated with an alkaline pyroxenite intrusion, given by the most reliable data (56–58F), and the abstraction of H during the evolution of the fenites 35 and 36F adjacent to a litchfieldite pegmatite, as well as the low H_2O+ of other fenites connected to this type of intrusive.

According to Burnham (1967), an aqueous fluid co-existing with magma will contain the bulk of the Cl present, while F is strongly fractionated into the melt phase. This generalization is confirmed by the compositions of primary fluid inclusions in minerals from alkaline rocks determined by Sobolev et al. (1974). The total amount of $Na+K+Ca$ able to be dissolved in chloride-bearing solutions increases linearly with chloride concentration, while the content of Al and Si is depressed. The effect of increased CO_2 is, however, almost exactly the opposite; aqueous solubilities are reduced in the order $Si+Al \ll K+Na \ll Ca$ (Burnham 1967). In pri-

mary, aqueous fluid inclusions in alkaline rocks, CO_2 is the dominant dissolved gas, while the dissolved material, principally salts of Cl, HCO_3, and SO_4, reach concentrations of up to 50wt% (Sobolev et al. 1974). Currie & Ferguson (1972) deduced that fenitization around the Callender Bay complex was achieved through the agency of solutions with a salt content between 10 and 50wt%.

The partitioning of alkalies between alkali feldspars and alkali brines has been investigated by Orville (1963). At 2 kb, the solution in equilibrium with two alkali feldspars contained alkalies in a ratio fixed by the temperature. $K/K+Na$ varied from 0.26 to 0.18 (mol. %) with a fall in temperature from 670°–500°C, the ratio decreasing more slightly with increasing pressure. However, results obtained by Burnham (1967) indicate that the temperature dependence of $K/K+Na$ is restricted to pressures lower than 6 kb. Brines in equilibrium with both albite and nepheline have an alkali ratio less than 0.2 at 600°C and 1 kb (Wyart & Sabatier 1962). These results suggest that brines derived from crystallizing magmas and equilibrated with the single Na-rich feldspar of the alkaline pyroxenites and litchfieldites as they moved through the solidified wall zones of the pegmatites may have had $K/K+Na$ ratios less than about 0.3.

The majority of the analysed mafic fenites have $K/K+Na$ ratios equal to, or less than, 0.33, the exceptions being the gabbroic rocks fenitized by litchfieldite pegmatites (41F, 63F) where the alkali ratio exceeds 0.63. The metasomatic transfer of potassium from magmas richest in sodium has been discussed at some length by Woolley (1969). Neither the hypothesis of sodium expulsion followed by loss of potassium, or of sodium being preferentially held in the magma and expelled at the surface, are applicable to the fenites described here. However, the data presented by Orville (1963) can provide a partial explanation: At low pressures, brines in equilibrium with sodic alkali feldspar at magmatic temperatures may be in equilibrium with potassic alkali feldspar at the lower temperatures encountered in the metasomatic aureole. In only one case, however, is feldspar present in the fenitic assemblages described from the Seiland province, the alkalies being principally held in amphibole, as well as in biotite and clinopyroxene where these were stable. It is improbable that the alkali ratio for such mineralogies can be correlated in any simple way with that of the fenitizing so-

lutions. The alkali ratio of 0.29 for the fenitized psammite (Table 6), which contains two alkali feldspars in abundance, falls, however, in the correct range for a brine with $K/Na + K$ close to 0.25.

The high concentrations of some trace elements in the fenites, particularly the REE, Y, Nb, and Zr, require explanation. According to Kosterin (1959) and Mineyev (1963) (summarized in Haskin et al. 1966), complexing is necessary for transport of the REE, the heavy REE forming the more stable complexes with CO_2, F, Cl and PO_4. Kosterin (1959) favoured alkali carbonate complexes, REE being precipitated due to a lowering of either the CO_2 or alkali concentration of the solutions. According to Mineyev (1963), Fl is the most important complexing anion, metasomites enriched in the heavy REE being simultaneously rich in alkalies and fluorine. The REE in mafic fenites from the Seiland province show behaviours which do not contradict these suggestions. The REE elements reach the highest concentrations in fenites strongly enriched in C and the alkalies (Table 7), and La increases at a rate 2 to 4 times that of Y. The anomalous mafic fenite, which was affected by nephelinitization rather than fenitization (Woolley 1969), is also anomalous with respect to trace elements. In the corresponding fenitizing agent, trace elements must either have had unusually low concentrations or they maintained high solubility during the precipitation of alkalies. Y in the psammitic metasediment also is anomalous in that its concentration fell during fenitization while the light REE increased. The initial concentration of Y in this rock type was relatively high, and it is not possible to say on the basis of this single example whether the fall in Y was, for instance, a result of the breakdown of garnet during fenitization.

Comparison with other fenites in the Seiland province

The only pre-existing analytical data bearing on the character of the mafic fenites present in the Seiland province are that presented by Sturt & Ramsay (1965) from the Breivikbotn area of Sørøy. They recognised that mafic fenites related to nepheline-bearing syenites were distinctly different from those connected to mafic nepheline-free syenites and carbonatites. In the former type, sheared metagabbroic assemblages were feldspathised and, at higher grades of fenitization, nephelinitization occurred. Green-brown amphibole was rapidly converted to biotite or, more rarely, aegirine-augite, the final product being a nepheline-syenite gneiss. Related fenitization of metasediments resulted in rocks of similar mineralogy but poorer in mafics, sphene, sodalite, and scapolite. Against shonkinitic syenites, a hornblende schist (metagabbro) was metasomatized to a pyroxenitic fenite consisting of aegirine-augite, hastingsitic amphibole, sphene and albitic plagioclase, while psammites and semipelites were altered into aegirine-augite, perthite, albite fenites.

The chemical changes involved in the conversion of metagabbro to nepheline-syenite gneiss were postulated to be enrichment in SiO_2, Al_2O_3, and the alkalies (especially Na_2O), and strong progressive depletion in total Fe, MgO, and CaO. Rb, Sr, Zr, and Y all seemed to have been introduced. The source of the fenitizing agent was sought in a nepheline-syenite magma beneath. The compositions of the Breivikbotn nepheline-syenite fenites are coincident with those of litchfieldite pegmatites. However, the fenitization involved in their production was quite different in chemistry to that directly associated with the latter intrusions. In mafic rocks fenitized by litchfieldites, SiO_2 and Al_2O_3 decreased, total FeO and CaO increased, while changes in MgO tend to be insignificant; of the alkalies only K_2O shows consistent augmentation. The development of the ijolitic fenite is somewhat more similar, at least qualitatively, to that postulated for the Breivikbotn nepheline-bearing gneisses, but even here, SiO_2 fell while the basic oxides did not decrease to anything like the same degree, as demonstrated by the contrast in the final mineralogies. It is also clear that the fenitization of the metasediment associated with a litchfieldite pegmatite is very different from the fenitization of equivalent rocks described from Breivikbotn, the decrease in SiO_2 being much greater, while total FeO, MgO and CaO all increased. This trend is, however, similar to the changes which are believed to have occurred in metasediments in contact with the Breivikbotn carbonatites, except that in these Al_2O_3 was abstracted and SiO_2 fell only slightly; the mineralogy of these fenites is also comparable with those developed from metasediments in contact with the litchfieldite pegmatite.

The transition from hornblende schist to the aegirine-augite pyroxenite found at Breivikbotn corresponds to a large decrease in Al_2O_3, and

enrichment in Fe_2O_3, Mn, Y, Zr, and Nb (Sturt & Ramsay 1965). Possible changes in other elements could not be detected due to the absence of unfenitized relicts representative of the initial chemistry of the schist. The gross mineralogical re-adjustments during fenitization of the metagabbro are rather similar to those described here for mafic rocks fenitized by alkaline pyroxenite dykes. However, the analysed examples show increases in both Al_2O_3 and Fe_2O_3.

Comparison with fenites elsewhere

The ijolitization of gabbro, although apparently uncommon in the Seiland province, finds parallels with the fenitization of mafic rocks observed by Parsons (1961) at Nemegosenda Lake, Ontario, by Strauss & Truter (1950) in association with the Spitskop complex, South Africa, and is rather similar to the fenitization described by Mathias (1956) at Messum, Southwest Africa. In the two latter cases, the chemistry of the transformations involved additions and losses generally similar to those for the Finnmark ijolitic fenites, but differing in detail (see Tables 1 and 7).

The mineralogy of the mafic fenites associated with the majority of the litchfieldite pegmatites resembles to a certain degree metasomatized dolerites at Dorowa, Rhodesia, and Tundulu, Nyasaland. In both cases, the original feldspar was replaced by calcite, in the Dorowa example together with zeolites. Pyroxenes were converted to aegirine-augite, and biotite increases in amount with fenitization. The chemistry of the transformations at Dorowa proposed by Verwoerd (1966) (Table 1) are similar to those for the Seiland mafic fenites (Table 7), though in some cases conversion into a mafic carbonatite was considerably more advanced in the latter.

Perknitic fenites which developed from mafic rocks around alkaline pyroxenite intrusions are, as far as the authors are aware, unknown outside the Seiland province.

Conclusions

The chemical progress of fenitization exhibited by mafic rocks adjacent to alkaline pyroxenite and litchfieldite dykes in the Seiland province supports the generalisations made by Verwoerd (1966). Fenitization was accompanied by depletion in Si and enrichment in the alkalies, especially K, as well as Fe^{3+} Mn, total Fe, Ca, C, and P, the content of standard cells either increasing or decreasing within narrow limits.

There is absolutely no evidence of the fenitization trends claimed by Currie & Ferguson (1972) to be typical of mafic rocks. Far from converging on a mafic nepheline syenite composition, mafic and salic fenites associated with litchfieldite pegmatites diverge. Mafic rocks are usually converted into aegirine-augite-biotite-amphibole carbonatite, less frequently into ijolite, while felsic rocks are transformed into aegirine-augite syenite. In connection with alkaline pyroxenite intrusions, the mafic hosts are changed into perknites composed dominantly of amphibole and sodic titanaugite. The possibility mentioned by Currie & Ferguson (1972), that the course taken by the fenitization of the mafic rocks around the Callandar Bay complex may have been controlled by that of the felsic rocks in which they were embedded, probably requires more serious consideration than it has received.

The generation of K-rich mafic carbonatite by the fenitization of mafic igneous rocks by Na-dominated alkaline intrusions observed in the Seiland province adds a new dimension to the problem of carbonatite genesis. The amount of carbonatite resulting from this process is only minor, but similar processes on a scale equivalent to that observed around major alkaline intrusive complexes could result in sizeable carbonatite bodies. It has been suggested that biotite-rich bands in the main carbonatite within the Seiland province originated by potassium metasomatism of gabbroic rocks (Heier 1961). Recent studies of the Stjernøy carbonatites do not fully support this proposal, but has led to the recognition of fenitic silico-carbonatites in association with carbonatite intrusives into mafic rocks. Although few attach any weight to the fenitic hypotheses of carbonatite origin proposed by Tomkeieff (1961) and Kukharenko & Dontsova (1962), the Seiland fenites demonstrate that they are, nevertheless, realistic.

The alkaline intrusive-fenite association present in the Seiland province confirms the belief that fenitization is not restricted to carbonatite intrusion. However, it has been emphasised that the litchfieldite magma contained appreciable $CaCO_3$, and in some cases it was accompanied by an immiscible carbonatite melt (Robins 1972). Fenitization was probably achieved through the agency of strong chloride brines distilled off from the crystallizing magmas. The dense gas

evolved from the litchfieldite magmas apparently was richer in CO_2 than those originating from the alkaline pyroxenites. In both cases the $K/K + Na$ ratio may have been low, but the instability of feldspar in the majority of the mafic rocks in contact with the fenitizing solutions resulted in the fixing of potassium in biotite and amphibole, and in certain cases the removal of Na. The instability of plagioclase and K-feldspar, and the increase in the amount of biotite in the fenitic assemblage, may be a product of the desilication of already undersaturated rock types, and their high initial concentration of magnesium and iron.

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