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THE ALKALINE COMPLEX OF THE BREIVIKBOTN AREA, SØRØY, NORTHERN NORWAY

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WITH APPENDIX
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(A preliminary description of the geology of the Dønnesfjord area, Sørøy)

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Abstract.

The alkaline rocks of the Breivikbotn area have been emplaced into highly folded and metamorphosed igneous and sedimentary rocks during the period of the Caledonian orogeny. They form an integral part of the complicated sequence of plutonic events that occurred during the orogeny, and were broadly syn-tectonic in relation to the second major period of deformation (F2). They have in fact been strongly folded and sheared by late expressions of this movement phase.

The alkaline rocks at Breivikbotn fall into two distinctive groups in terms of their field-relationships, mineralogical and chemical compositions. These are referred to as rocks of the Nepheline Syenite and Carbonatite Associations respectively. The first of these comprise nepheline syenite gneisses and pegmatites, alkali-syenite gneisses (without nepheline) and alkali feldspar-biotite-magnetite pegmatites. The majority of the pegmatites and some of the sheets of nepheline syenite are intrusive types and appear to have resulted from the intrusion of a highly fluid pegmatite magma. Other rocks of this associaton such as the alkali-syenite gneisses, most of the nepheline syenite gneisses and some of the pegmatites, however, are products of metasomatism effected by fluids and emanations from the pegmatite magma. The rocks of the Carbonatite Association comprise syenites which vary from melanocratic to leucocratic in type, fenites and carbonatites. With the exception of the fenites these all appear to be intrusive rocks and to follow a well-defined pattern of crystallisation differentiation, carbonatite being the final late intrusive phase.

The two major groups of alkaline rocks are distinctive in terms of their geochemistry. The rocks of the nepheline syenite association are characterised by their high Al and Na contents, whilst the rocks of the carbonatite association are relatively deficient in Al and rich in K. The trace element contents of the rocks in the two groups are also highly distinctive, and one particularly marked feature is the progressive enrichment in Ba and Sr in the rocks of the carbonatite association. Within the rocks of the nepheline syenite association the geochemical trends of fenitization have been traced both in terms of major and minor elements. Comparisons have been made with alkaline rocks from many other areas, particularly with the neighbouring island of Stjernöy where alkaline rocks have been extensively described by Heier (1961, 1964).

The alkaline rocks of the Breivikbotn area are considered to have been derived from a common parent magma deep in the earths crust. Sub-magmas are thought to have been derived from this common parent and to have pursued separate and independent lines of crystallisation differentiation. Extensive metasomatic activity accompanied the intrusion of the various igneous rocks producing fenites and nepheline syenite gneisses. The ultimate source magma is postulated as a deep-seated ultrabasic magma, possibly alkali peridotite.

I. Introduction

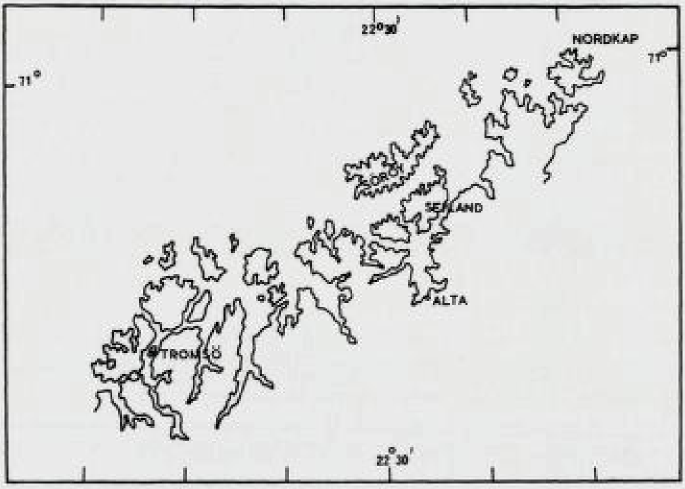

Fig. 1. Map of north-west Norway (scale 1 : 2,500,000) showing location of Söröy.

The island of Söröy is situated off the mainland of West Finnmark (Fig. 1) near the town of Hammerfest (lat. 70° 30′ N., longit. 23° 80′ E.), and lies within the main belt of the West Finnmark Eo-Cambrian succession. The island is mainly composed of variable metasedimentary rocks which have been extensively folded and metamorphosed during the Caledonian orogeny. The plutonic history is complex and is dominated by the emplacement of large masses of basic and ultrabasic rocks which form part of the West Finnmark–North Troms petrographic province. Rocks of this province have been described in a number of accounts particularly by Barth (1953) in a description of the layered gabbro complex in the south of the island of Seiland, and by Heier (1961) and Oosterоom (1963) in papers describing the basic rocks of the neighbouring island of Stjernöy. On the mainland the basic rocks of the Øksfjord area have been described by Krauskopf (1953), those of the Sandland peninsula by Ball et alia (1963) and the geology of parts of the Lyngen peninsula in a thesis by Randall (1958). Some aspects of the geology of these regions are also mentioned in a number of accounts by Karl Pettersen in the middle of the last century. The gabbroic rocks of the province often show a well developed layering and other features comparable to those described in accounts of the Skaergaard intrusion (Wager and Deer 1939) and Stillwater, Montana

(Hess 1960). The tectonic setting, however, is very different. The West Finnmark–North Troms gabbros are situated in the heart of the Caledonian orogenic belt and were furthermore emplaced during the orogeny. On Söröy it has been demonstrated (Sturt 1962, Stumpfl and Sturt 1964) that the basic igneous rocks have been emplaced in a series of distinct intrusive phases.

A common feature of the Söröy–Seiland–Stjernöy–Øksfjord areas is the occurrence of alkaline rocks of the Nepheline Syenite–Carbonatite–Fenite association. The alkaline rocks of Seiland have been briefly described by Hoel and Scheitig (1916) and more fully by Barth (1924, 1953) in accounts of coarse nepheline syenite pegmatite (canadite) dykes from the south of the island. Similar occurrences in the Øksfjord area have been mentioned by Krauskopf (1953). Considerable quantities of nepheline syenite are present on the island of Stjernöy (at present being mined by Nordkapp Nefelin A/S) and are associated with carbonatite (Strand 1951, Heier 1961, 1964, Oosteroom 1963). The occurrence of nepheline bearing gneisses in the Breivikbotn area of Söröy has been briefly mentioned by one of us (Sturt 1961). Here nepheline syenite gneisses and pegmatites are associated with fenites and with carbonatites and related syenites. In all the areas cited the alkaline rocks were apparently late in the sequence of structural, magmatic, and metamorphic events.

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II. The general geology and structure of the Breivikbotn area

In the Breivikbotn area the general situation is of a complexly folded and metamorphosed group of sedimentary rocks which are intruded by two gabbro plutons, the one extending from south of Breivikbotn village to Dönnesfjord and the other occurring at Hasvik. The metasediments are also intruded by a later group of basic and intermediate igneous rocks varying from norites to diorites, and are further riddled by a plexus of granitic, syenitic, basic and ultrabasic sheets and dykes. One of the latest major events to occur in the area was the emplacement of the varied suite of alkaline rocks, which form the subject of the present account.

The metasedimentary rocks comprise a sequence of psammites, pelitic schists and gneisses, graphite schists, limestones and calc-silicate rocks. Fossils are absent from the major part of the succession, but limestones containing archaeocyathids have been discovered. The preliminary investigation of these organisms, by Dr. C. H. Holland of Bedford College, London, indicates a lower Cambrian age for at least part of the succession. In spite of the general lack of fossils the well preserved current bedding and occasional scour and fill structures in quartzites near Hasvik and examples of current bedding near Veines have enabled us to establish the following order of stratigraphical succession:

Top	HELLEFJORD SCHIST GROUP	
	BREIVIK GROUP	Upper Staurolite Mica Schist White Saccharoidal Quartzite Lower Graphite Schist
	FALKENES LIMESTONE GROUP	Limestone Calc-Silicate Schists
	STORELV GROUP	Upper Garnet Mica Schist Mixed Schist and Psammite Lower Mica Schist with psammite ribs.
Bottom	KLUBBEN QUARTZITE	

It is considered by the authors that this succession can be directly correlated with that of the Sandöfjord area to the north-east (Ramsay and Sturt 1963), though much of the intervening ground still remains to be mapped. The Storelv formation at Sandöfjord, however, contains more clearly defined sub-divisions than at Breivikbotn. This is perhaps a consequence of lateral facies variation during sedimentation. The succession above the Falkenes Limestone has been given a separate name and is well-developed to the north-east of Breivik.

The metasedimentary rocks have been affected by at least two major phases of folding. The earliest phase results in the formation of folds on the mesoscopic scale varying from overturned asymmetric to isoclinical in style, and on the larger scale produces recumbent folds of considerable amplitude. The prominent schistosity of the rocks is apparently related to this folding episode. The axes of the early (F1) folds are extremely variable in trend though in the Breivikbotn area they are generally between N—S and NNE.—SSW. These early structures are refolded by a second set of folds (F2) whose axes vary, in the Breivikbotn area, between N—S and NNE.—SSW. and account for the more obvious disposition of the strata. The F2 structures make a marked swing in trend towards E—W in the Sandöfjord area (Ramsay and Sturt 1963). This change is mirrored in a similar swing to a N—S trend in the Langstrand—Skarfjordham area further to the north-east (at present being studied by Mr. D. Roberts). There is also a third set of structures (F3) developed and on a minor scale. Although the fold episodes are conveniently labelled as F1, F2 and F3 the two earlier are very complicated and each consist of a series of phases often punctuated by minor intrusive and metamorphic events (see Fig. 71).

The metasedimentary rocks are mainly in the almandine amphibolite facies of regional metamorphism, although several phases of metamorphism of differing grade can be distinguished. The highest grade conditions, however, were established during the interval between the first (F1) and second (F2) phases of folding. This metamorphic episode is characterised by the development of the minerals almandine garnet, staurolite, kyanite and sillimanite in the pelitic schists accompanied by the crystallisation of plagioclase feldspar which varies in composition between An_{28} and An_{35}. The minerals diopside and tremolite/actinolite are typically developed in the impure calcareous horizons. This main phase of regional metamorphism was accompanied by a rather patchy granitization in the Breivikbotn area. This latter, however, is quite intense locally with the ultimate development of migmatitic gneisses and pegmatites.

The emplacement of the main Breivikbotn gabbro probably occurred during the closing stages of the F1 movements, though it was extensively sheared by a late expression of these movements. The gabbro was evidently intruded into country rocks which were already metamorphosed to a low grade regional assemblage. The marginal country rocks have undergone high-grade contact metamorphism with the development of the typical mineral assemblage hypersthene-corundum-spinel in the pelitic schists. It can be demonstrated both in the field and in thin-sections that a distinctive hornfelsic fabric has been overprinted onto the schistosity developed during the early (F1) folding. The contact metamorphic assemblage and its associated fabric is, however, partly obscured by the subsequent almandine-amphibolite facies metamorphism and granitization. Abundant relics of this earlier phase of contact metamorphism are preserved particularly within porphyroblasts developed during the regional metamorphism and as small patches which were incompletely recrystallised. To the north of Breivikbotn the original contact relationships of the gabbro to the metasedimentary rocks have been partly obscured by strong shearing movements at the gabbro junction and by the emplacement of later basic and dioritic rocks. The gabbro itself is in the condition of a gabbro-amphibolite, and the banded and sheared portions of the intrusion show asymmetrical folds of the F2 phase which are often of considerable amplitude and have steep to overturned middle limbs. Reconnaisance mapping shows that the Breivikbotn gabbro extends eastwards to Dönnesfjord, where its most eastern extension is being investigated by Dr. E. C. Appleyard of Bedford College, London.[1] The emplacement of a group of rocks varying from norite to leuco-gabbro through pyroxene-mica-diorite to fairly acid diorite was the latest phase of basic igneous activity and apparently occurred after the main almandine amphibolite facies metamorphism and during the early stages of the F2 movement episode. These rocks pre-date the emplacement of nepheline syenites and are also cut by occasional basic dykes. They were nonetheless affected by green schist facies metamorphism rising locally to almandine amphibolite facies conditions. Many minor intrusions of basic and ultrabasic igneous rocks also occur along with intrusive sheets and dykes of granitic materials. These minor intrusives have been emplaced at many different stages and exhibit, as a consequence, varying intensities of metamorphism. Rather similar occurrences of dyke-rocks have been described, and figured, by Barth (1953) from Seiland. It is not proposed, at this stage, to give more than this brief introduction to the problems of the basic igneous rocks of the area, for they will be considered elsewhere as will be the details of the structure and metamorphism.

[1] Described in the Appendix.

III. Field relationships and petrography of the alkaline rocks

The alkaline rocks of the Breivikbotn area consist of alkali syenite— and nepheline syenite gneisses and pegmatites, alkali-feldspar magnetite pegmatites, occasional corundum bearing syenites and carbonatites with associated coarse grained syenites (shonkinites and leucocratic syenites). They were emplaced during the second phase (F2) fold movements.

Two distinct groups may be recognised:

(A) *Nepheline Syenite Association*

Nepheline syenite gneisses and pegmatites, nepheline-free syenite gneisses, alkali feldspar magnetite pegmatites, and fine grained syenites (often corundum bearing).

(B) *Carbonatite Association*

Carbonatites, carbonatite breccias, shonkinites, leucocratic syenites, syenite aplites, and fenites.

The two groups retain their identity, although they occur in close proximity, and were emplaced essentially simultaneously, they never occur in intimate association with each other.

Generally the carbonatite and its associated syenitic rocks appear to be intrusive types, whereas many of the nepheline bearing rocks, particularly the gneisses, are products of alkaline metasomatism. Intrusive phenomena are generally rare, in this latter group of rocks, except in the pegmatitic members and in sporadic fine-grained syenites.

A. *ROCKS OF THE NEPHELINE SYENITE ASSOCIATION.*

Nepheline syenites are abundant in the Breivikbotn area and are concentrated within the main Breivikbotn gabbro and in the country rocks to the west of this intrusion, although occasional examples do occur to the east of the mass. The nepheline syenites occur principally as gneisses and as pegmatites. Within the nepheline gneisses intrusive phenomena are generally rare, though occasional cross-cutting dilational sheets are to be found.

(1) *The Nepheline Syenite and Associated Gneisses.*

Nepheline syenite gneisses constitute the main bulk of the nepheline bearing rocks of the Breivikbotn area. They are associated with biotite-plagioclase, hornblende-biotite-plagioclase, and biotite-plagioclase-microline gneisses, and appear to be the ultimate products of a period of alkaline metasomatism. The nepheline syenite gneisses are essentially composed of nepheline, plagioclase (An_{6-14}), microcline and biotite in varying proportions (Table 1), with accessory apatite, muscovite, zircon and ore minerals (principally magnetite and pyrite); occasional examples also contain aegirine-augite, hastingsitic amphibole, sphene and microscopic grains of yellow pyrochlore. Secondary minerals include sodalite, cancrinite, muscovite, calcite, and zeolites. Nepheline is sometimes pseudomorphed by felty masses of very fine-grained unidentifiable alteration products of the type commonly called "hydronephelite" when pink or red and "gieseckite" when greenish in colour. Apart from nepheline and its alteration products the associated nepheline-free gneisses contain a similar mineral assemblage to that of the nepheline syenites and in fact grade into the latter (Table 2). The one exception is the occasional presence of the mineral corundum in the nepheline-free gneisses.

The nepheline syenite gneisses and the associated alkali gneisses have two principal modes of occurrence:—

(a) As metasomatic replacements of the metasediments, and

(b) as metasomatic replacements along shear zones in the metagabbro.

They also occur as sporadic intrusive sheets and dykes.

(a) *Nepheline syenite and associated alkali gneisses in the metasediments.*

This mode of occurrence of the nepheline syenite gneisses is mainly seen at two coastal localities between the settlements of Haraldseng and Baarvik, in a series of small exposures on the peninsula south-west of Breivikvotn, and in a few small patches to the north of Breivikbotn.

The largest of these occurrences is on the small peninsula of Hvitness, which is about 1 km. north-east of Baarvik. At this locality the exposure is virtually complete and it is possible to examine with great detail the relationships between the nepheline syenite gneisses and the metasedimentary country rocks, on the excellent wave-washed exposures. Within the nepheline syenite gneisses many features can be observed indicating the derivation of the gneisses through a process of fenitization of the country metasediments. Abundant evidence can also be found of the progressive rheomorphism and mobilisation of these gneisses into cross-cutting intrusive sheets and dykes.

The northern contact of the nepheline syenite gneisses at Hvitness with the country metasediments is quite sharp (Fig. 2). The country rocks consist of a sequence of fairly gently dipping psammites, pelitic

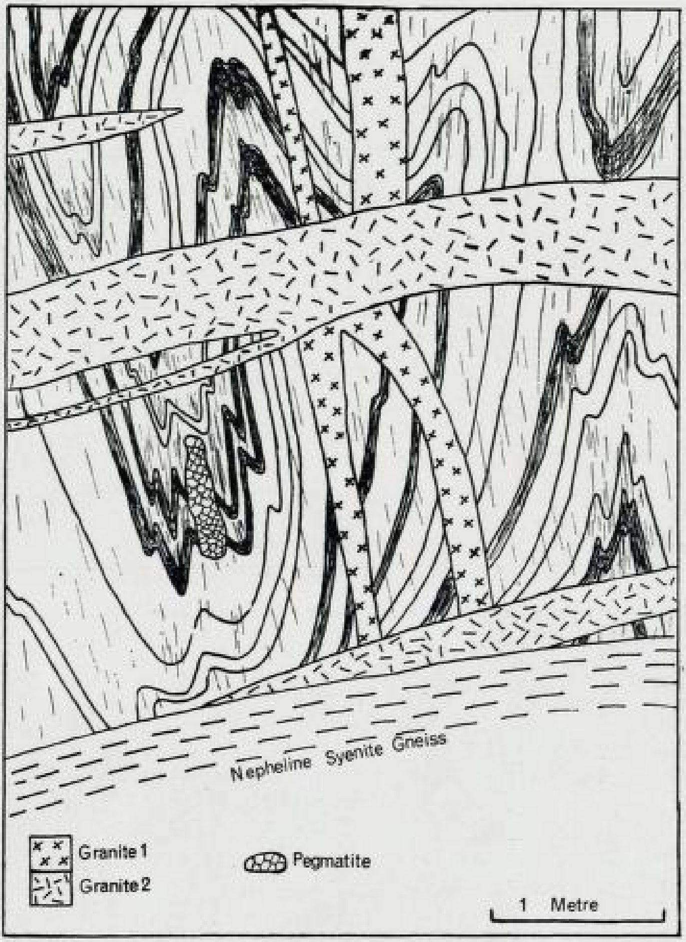

Fig. 2. Sharply transgressive contact of nepheline syenite gneiss with country rocks. The psammites and semi-pelites are involved in tight F1 folds with well developed axial planar schistosity; these are cut by two generations of granitic dykes. Note also the segregation of granite pegmatite in an F1 fold closure. The schistosity of the nepheline syenite gneisses is parallel to the contact. Hvitness.

and semi-pelitic schists and gneisses which are involved in many tight minor fol sdwhich are dominantly F1 in age. The minor folds (F1) are transected by a plexus of small basic and granitic dykes (see Fig. 2). At this northern contact the nepheline syenite gneisses cut sharply across all these structures with the exception of a small cross-cutting metadolerite dyke, some 35 cm. wide, which dips 70° towards the east

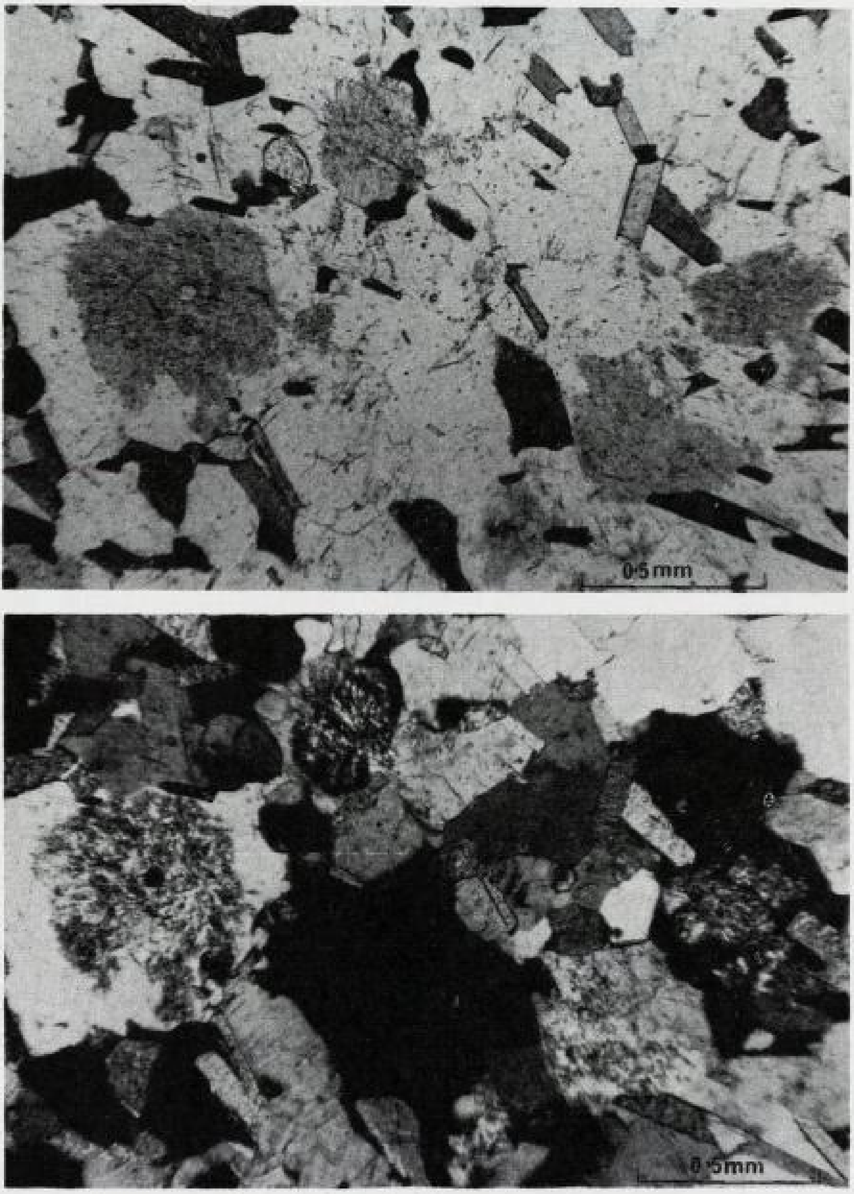

Fig. 3. Photomicrographs to show corroded basic cores to albite-oligoclase in alkali-gneiss (albite/oligoclase, microcline, biotite, apatite). (Slide No. SB102.)
(a) Plane polarized light.
(b) X-Polarized light.

with a 022° strike. In spite of the sharp contact there are signs of alkali metasomatism of the metasediments associated with the emplacement of the nepheline syenite gneisses. It has been indicated in the introduction (p. 9) that the metasediments are in the almandine amphibolite facies of regional metamorphism and contain plagioclase feldspar in the composition range An_{26-35}. As the contact of the nepheline syenite gneisses is approached, however, the feldspars become much altered into sericite, epidote and calcite and a new generation of plagioclate (An_{6-12}) forms as rims about the corroded varieties (Fig. 3). Towards the contact the plagioclase is almost entirely of the more al-

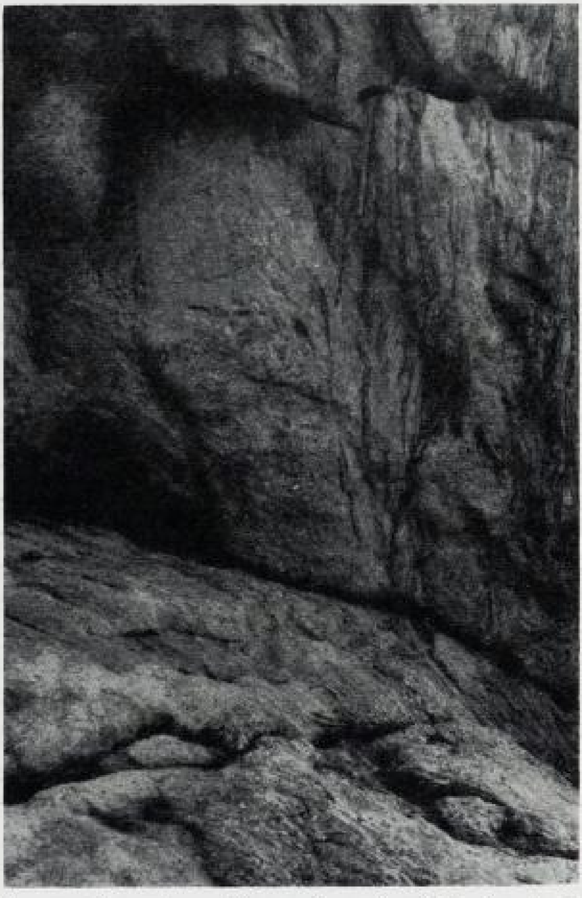

Fig. 4. Nepheline syenite gneisses, with country rock schist relics showing no signs of disruption. Hvitness.

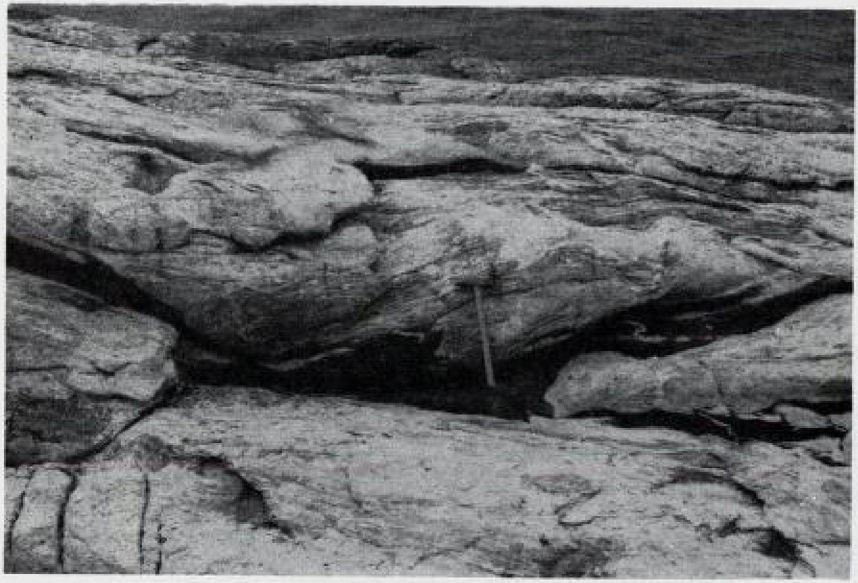

Fig. 5. Nepheline syenite gneisses showing relic structure of country rock inclusions. The figure also shows segregations of dark biotite which contain lenses of calcite. Hvitness.

bitic variety. Accompanying this change there is also an increase in the amount of microline. The granitic dykes depicted in Fig. 2 show the late development of rims of granular albite and microline about hair perthite. An interesting phenomenon at this contact is a small vein of coarse feldspars (albite/oligoclase and microline) and nepheline, given off from the nepheline syenite gneiss, and in which the nepheline crystals are elongated at right angles to the vein wall. At the north-east of the outcrop, the gneisses are observed to pass imperceptibly into a nepheline syenite pegmatite dyke some 5 metres wide which is following an approximately N—S fracture.

At the southern contact the nepheline syenite gneisses, however, pass laterally into the schistose metasedimentary rocks, although occasional sharper contacts are still to be observed. Here the nepheline syenite gneisses are mainly seen to be replacements of the semi-pelitic and pelitic schists. Many beautiful examples of replacement phenomena are to be observed in the gneisses with lines of schist inclusions preserving perfect structural continuity (Fig. 4—5). In places the most delicate and detailed structures can be traced picking out the relict stratigraphy on all scales. Relict fold closures, still showing their original orienta-

Fig. 6. Nepheline syenite gneisses containing partly replaced relict fold closure. The figure also shows a biotite segregation. Hvitness.

Fig. 7. Nepheline syenite gneisses containing incompletely replaced relict conjugate fold, and biotite segregation. Hvitness.

Fig. 8. Thin-section of nepheline syenite gneiss illustrating late growth of nepheline (stippled). Nepheline is seen to form along grain boundaries, and to preferentially replace certain plagioclase twin lamellae (Slide no. SB.51).

tion which have been incompletely replaced, are also preserved and some of these appear to represent F2 closures (Fig. 6 and 7). It is impossible to draw a precise junction at this southern contact and the most obvious features are the increase in the amounts of albitic plagioclase and microcline, in the metasedimentary schist, with an attendant decrease in the amounts of biotite and of quartz as individual schist bands are traced laterally into gneisses containing nepheline. Similar mineralogical changes can be traced in the inumerable inclusions of country metasediments contained within the nepheline syenite gneisses.

The country metasedimentary schists show an imperceptible transition from quartz-bearing to quartz-free types as the nepheline bearing gneisses are approached. One of the more obvious features in the field is the concentration of quartz into small veinlets and segregations away from the nepheline bearing gneisses. The study of thin sections of such

rocks reveals a sequence of replacements during the metasomatic metamorphism. This is particularly well shown by the feldspathic minerals. Firstly the more basic feldspar (An_{26-30}) of the country rocks is replaced by more albitic plagioclase (Fig. 3) (An_{6-12}) followed by microcline and then nepheline (Fig. 8).
grain-boundaries of the other minerals to form a network pattern. The nepheline has also formed as a replacement along the cleavages and twin planes of the earlier feldspars. Examples are frequently found of nepheline porphyroblasts bearing inclusions of the two feldspars which are oriented within the host-grain (Fig. 9). In some instances biotite has been converted into either aegirine-augite or a hastingsitic amphibole but this replacement is not widespread.

The feldspars generally form fairly equant grains rarely exceeding 5 mm. in diameter and only exceptionally over 1 cm. Nepheline on the other hand may be distinctly prophyroblastic. Individual porphyroblasts up to 10 cm. in diameter have been observed at this locality. Nepheline also forms in flat lenses of small equant grains along the schistosity. In thin section nepheline is shown to have been the last of the felsic minerals to have crystallised, and is observed to finger along the

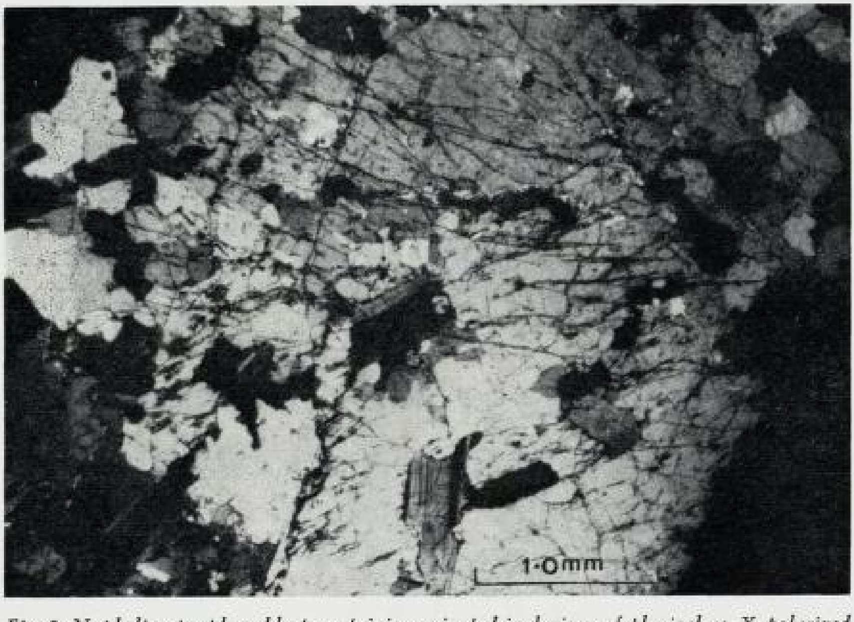

Fig. 9. Nepheline porphyroblast containing oriented inclusions of plagioclase. X-polarized light. (Slide no. SB.44.)

Evidence of interesting mineral replacements and reactions is also to be found in the country rock inclusions contained within the nepheline bearing gneisses. In one example (SB 187) the replacement of the original biotite schist to form an albite/oligoclase-microcline-biotite gneiss is well illustrated. Reactions have also taken place along the boundaries of biotite and calcite grains. The latter mineral has a porhyroblastic habit and apparently crystallised at the same time as the albite/oligoclase, and presumably represents a break-down product of more basic plagioclase formerly present in the rock. The reactions between biotite and calcite involve the growth of the minerals sphene and epidote (Fig. 10) along grain boundaries. Occasional inclusions of the country rocks in the gneisses still contain a little quartz but this is now either extremely fine-grained interstitial material or is segregated into small veinlets which cut across plagioclase and microcline grains, and in which the quartz grains are strongly strained. Within the nepheline syenite gneisses coarsely crystalline segregations of biotite occur as lenticular bodies along the schistosity containing mica flakes up to some 10 cm. in diameter (Fig. 5). These segregations may be upto 1 m. thick and 10 m. in length and also contain small lenses of calcite and of albitic plagioclase. The segregations of biotite and of calcite presumably represent material expelled during the formation of the nepheline syenite gneisses.

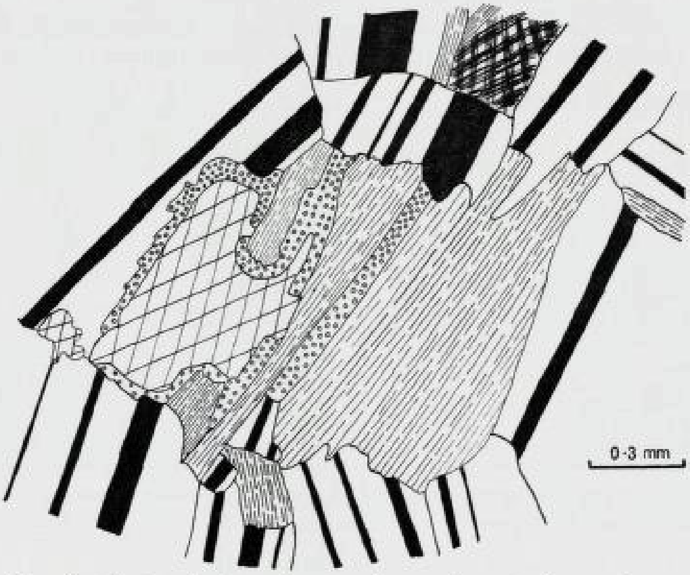

Fig. 10. Rims of epidote and sphene forming about calcite. Inclusion of semi-pelite in nepheline syenite gneiss. (Slide no. SB. 187.)

Fig. 11. Mobilized nepheline syenite gneiss with sharply transgressive junction with metasediments. Hvitness.

Although many of the features at Hvitness clearly point to a metasomatic origin for the nepheline syenite gneisses by the replacement of metasediments, there are indications that a mobile phase of nepheline syenite was also present. Such evidence is provided by the sharp northern contact of the nepheline syenite gneisses, the occasional abrupt and cross-cutting junctions even at the gradational southern margin, and by the pegmatite dyke to the north-east of the outcrop. More spectacular are thin dilational sheets and veins of nepheline syenite which cut both the metasediments and the nepheline syenite gneisses, though appearing to originate from the latter (Fig. 11). Such features suggest a relationship between the metasomatism and the presence of a highly fluid nepheline syenite magma, though some of the intrusive sheets may well represent mobilized gneisses. It is interesting to note that two examples of non-dilational nepheline syenite dykes also occur at this locality. These have a clearly replacive origin, and relict inclusions of metasedimentary schist can be traced without any disturbance of their trends across such dykes.

The other coastal locality where nepheline syenite gneisses have resulted from the metasomatic replacement of metasedimentary rocks occurs on a small headland to the east of Haraldseng. Here a group of steeply dipping psammites and semi-pelitic schists pass laterally into highly feldspathic albite/oligoclase-microcline gneisses which eventually develop nepheline. Again segregations of coarsely crystalline biotite with minor amounts of calcite are to be found in the gneisses.

Further examples are developed on the crags to the north of Kölevann. Here the metasedimentary rocks are composed of a series of psammites, semipelitic and pelitic micaschists which contain garnets and disc-shaped aggregates of sillimanite fibres. The latter are frequently altered into muscovite. The metasediments have been patchily granitized to produce porphyroblastic granite gneisses, fine-grained even textured granite and coarse irregular pegmatites. The last named are often quite extensive and consist of quartz, patch perthite, microcline, plagioclase (An_{26}), muscovite, biotite, tourmaline and in one instance small crystals (up to 2 cm.) of beryl. These pegmatites are sometimes very coarse with individual feldspar crystals up to half a metre in length and tourmaline crystals reaching a maximum length of about 20 cm. They also show beautifully developed graphic intergrowth textures of quartz in potash feldspar. On one set of crags just north of the footpath leading from Breivikbotn to Holmbugten the metasedimentary schists pass laterally into feldspathic gneisses which becomes nepheline-bearing (Fig. 12). The junction between the nepheline syenite gneisses and the country rocks, at this locality, is everywhere gradational though in some cases the transition is very rapid. At one point along the eastern contact the nepheline syenite gneisses cut pegmatitic granite, and tourmaline bearing relicts of the pegmatite are preserved, without disruption in the marginal part of the gneiss. An interesting feature of this occurrence is that the pegmatite relicts in the nepheline syenite gneisses are now practically devoid of quartz, whereas away from the gneiss the pegmatite is very quartz rich and there is evidence of silicification of the country rocks. Many inclusions of the country rock schists can be traced in the nepheline syenite gneisses, and are seen to preserve the trends of the country rocks. These inclusions show various stages of incorporation into the gneisses by the progressive growth of porphyroblasts. In one example (SB.502)[1] relict garnets occur and still contain abundant inclusions of quartz although the groundmass is entirely composed of plagioclase, microcline and aegirine-augite. Segregations

[1] Thin-sections referred to in the text, are in the collection of the Geology Department, Bedford College, London.

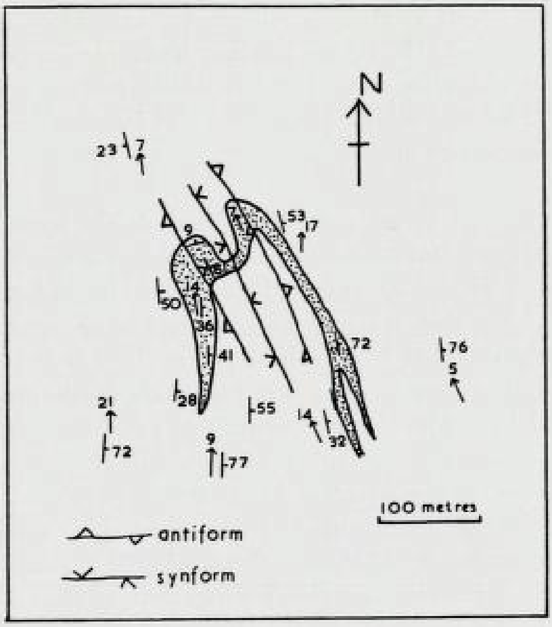

Fig. 12. Sketch-map of folded nepheline syenite sheet (stippled) in metasediments. 2 km. west of Breivikbotn.

of coarsely crystalline biotite are again common and are associated with small lenses of calcite. Aegirine-augite frequently occurs as a minor constituent and has formed at the expense of biotite. Occasional small segregations of albitic plagioclase and aegirine-augite are found, the latter mineral attaining a maximum length of 1 · 5 cm.

The nepheline syenite gneisses at this locality form a sheet up to 10 m. thick and with a dip conformable to the schistosity of the country metasedimentary rocks. The nepheline syenite gneisses are quite strongly deformed and are folded into two antiforms and a synform, and the lower limb of the western antiform is inverted (Fig. 12). The folding of the nepheline syenite gneisses is apparently F2 in age. Many minor folds (F2) occur both in the gneisses and in the country rocks whose axes are generally parallel to those of the main folds i.e. plunging gently towards the north.

A few small outcrops occur in the crags just to the east of the occurence described above where nepheline syenite gneisses have also arisen as a result of the metasomatism of metasediments. In one of these localities biotite schists containing ellipsoidal aggregates of sillimanite fibres are involved. As the schists bearing the sillimanite pods are traced into plagioclase-microline-biotite and nepheline bearing gneisses the sillimanite is altered into albitic plagioclase and into muscovite. It is also altered into aggregates of:—

(i) Muscovite and corundum. These preserve the form of the original elliptical sillimanite knot, and are often surrounded by a rim of biotite. The relationships of the muscovite and corundum display considerable textural variations. The muscovite occurs as randomly oriented laths. There is usually a central zone where corundum occurs as abundant inclusions in the muscovite surrounded by a zone of muscovite, free of inclusions. The corundum inclusions occur either as irregular blebs with a random orientation, as elongated blebs whose preferred orientation pattern is obviously controlled by crystallographic directions in the host muscovite, or as masses of rod-shaped grains which have a preferred orientation pattern independent of the crystallography of the host muscovites. In the latter case the corundum rods are presumably following the orientation pattern of the sillimanite needles, established before the crystallisation of muscovite. (Fig. 13.)

(ii) Albitic plagioclase and corundum. The mutual relationships of the plagioclase and corundum are similar to those described for muscovite and corundum. Again the 'pods' have an outer skin of biotite. (Fig. 14.)

(iii) Albitic plagioclase, muscovite and corundum.

The textural relationships of corundum respectively with muscovite, albitic plagioclase and muscovite + plagioclase show quite clearly that these minerals crystallised at the same time within the pods. The transformations described apparently conform to the following equations:—

(i) $\underset{\text{Sillimanite}}{4Al_2SiO_5} + K_2O + 2SiO_2 + 2H_2O \rightarrow$

$\underset{\text{Muscovite}}{2(OH)_2KAl_3Si_3O_{10}} + \underset{\text{Corundum}}{Al_2O_3}$

(ii) $\underset{\text{Sillimanite}}{2Al_2SiO_5} + Na_2O + 4SiO_2 \rightarrow \underset{\text{Albite}}{2NaAlSi_3O_8} + \underset{\text{Corundum}}{Al_2O_3}$

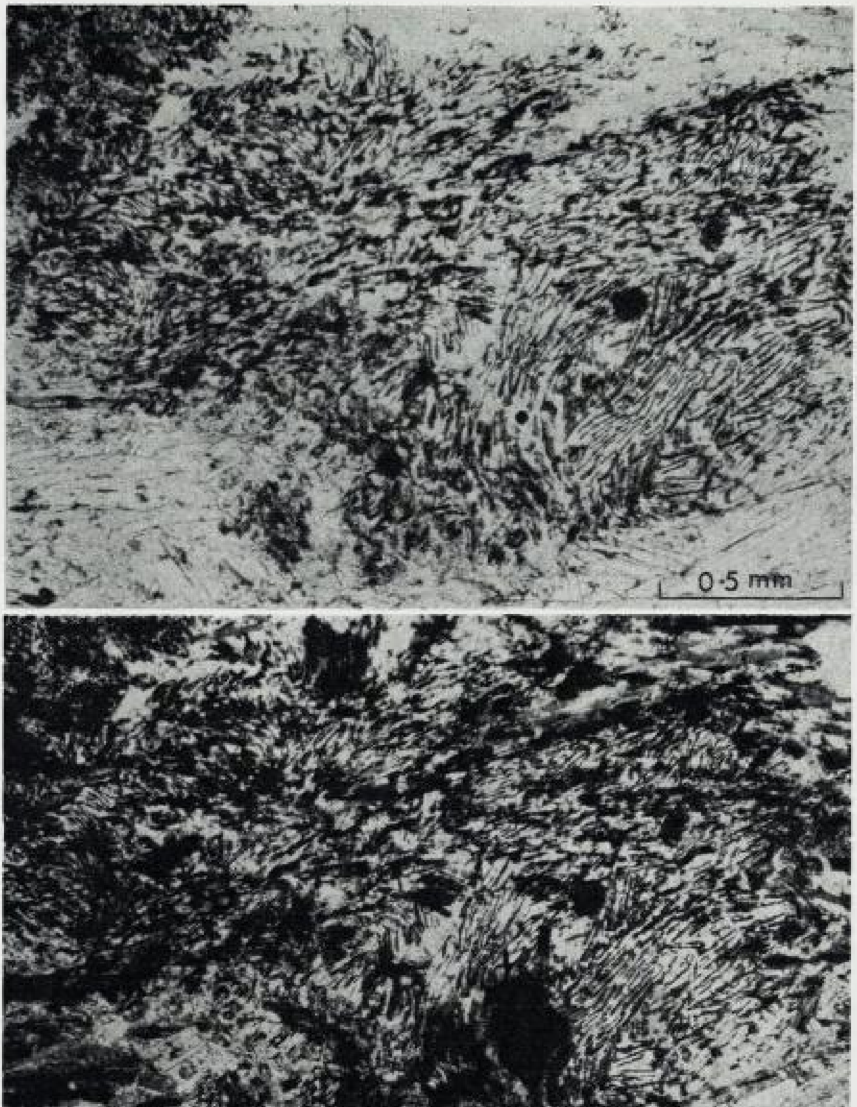

Fig. 13. Muscovite containing oriented corundum rods, the orientation being independent of that of the muscovite. (Slide no. SB.535.)
(a) Plane polarized light
(b) X-polarized light

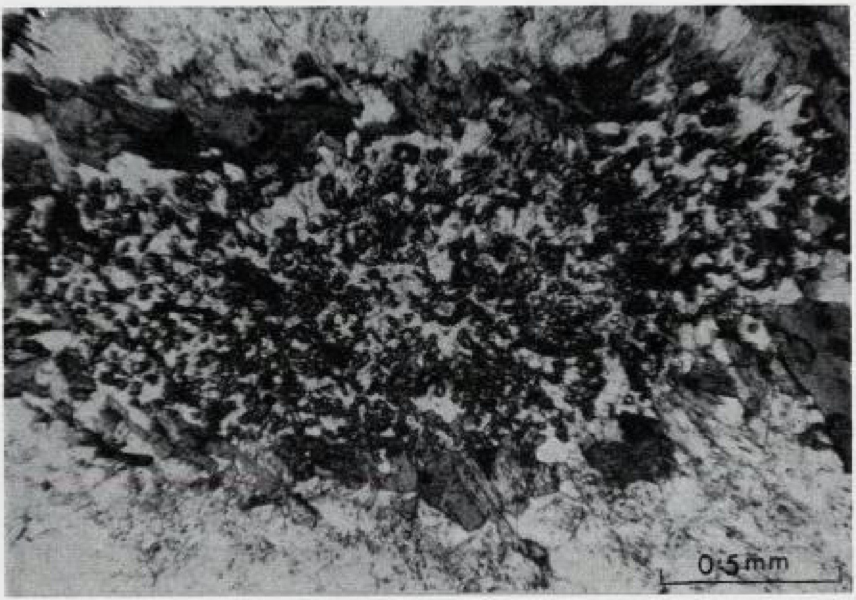

Fig. 14. Patch of albite and corundum surrounded by biotite in fenitized semi-pelite. Plane-polarized light. (Slide no. SB.536.)

(iii) $5Al_2SiO_5 + K_2O + Na_2O + 7SiO_2 + 2H_2O \rightarrow$
Sillimanite
$2NaAlSi_3O_8 + 2(OH)_2KAl_3Si_3O_{10} + Al_2O_3$
Albite Muscovite Corundum.

Thus during the metasomatic activity the sillimanite pods are converted into muscovite or albitic plagioclase, and in those cases in which insufficient silica was available to complete the transformation the excess alumina was used in the formation of the mineral corundum. In these rocks augen of microperthitic microcline are also present, and appear to be relics of the earlier almandine amphibolite facies assemblage.

Associated with these gneisses is an apparently intrusive sheet of nepheline syenite pegmatite some 2 m. thick, which consists of albite (An_7), microcline, nepheline, and biotite with accessory apatite, zircon and magnetite. The pegmatite sheet has a rude foliation parallel to its margin and is itself parallel to a set of brittle shears in the adjacent schists. These shears have a 342° strike and dip at 52° towards the west. Sheets of nepheline syenite and nepheline-free syenite gneisses are found

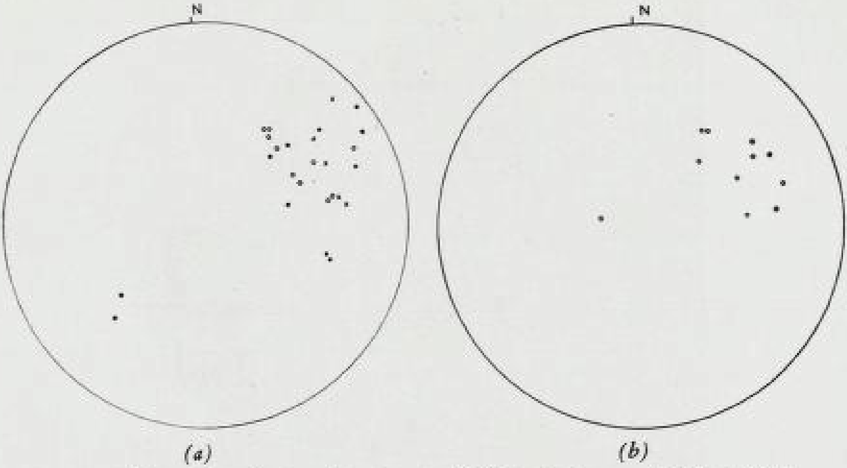

Fig. 15. Relationship of minor intrusions to F2-folds, 2 km. west of Breivikbotn.

(a) Poles to margins of nepheline syenite sheets (crosses); granite sheets (open circles) and basic sheets (solid dots).

(b) Poles to axial planes of F2-folds.

on many of the crags to the east of the pegmatite dyke, and are either parallel to the axial planes of F2 folds or have been emplaced along complementary shear planes related to the F2 folding (Fig. 15 a and b). These sheets are generally replacements along shear zones, though examples do occur which are undoubtedly intrusive. The relationship is by no means simple as in the same localities intrusive sheets of metadolerite, often sheared to biotite-hornblende-plagioclase schist, and schistose sheets of quartz-oligoclase-microcline granite (Fig. 16) also occur parallel to the axial planes of F2 folds. In some instances, where thick sheets of such granitic gneiss are present, the central portions are often highly sheared and become notably deficient in quartz. In such examples the plagioclase feldspar becomes rather more albitic and ultimately porphyroblastic crystals and segregations of nepheline are developed. The attitudes of these sheets and dykes, of highly varied composition, are expressed on a stereogram (Fig. 15 a). The dykes and sheets are seen to have their strongest grouping parallel to the axial planes of the F2 folds developed in this immediate locality (Fig. 15 b) and to related complementary shear planes.

A few small occurrences of nepheline syenite gneisses in the metasediments are to be found to the north of Breivikbotn. These gneisses

Fig. 16. Sheet of schistose quartz-oligoclase-microcline-muscovite granite along the axial plane of an F2-fold. 2 km. west of Breivikbotn.

again have a metasomatic origin. An example of a nepheline-sodalite syenite gneiss developed as a replacement of a shear-zone in semi-pelitic schists is shown in Fig. 17.

(b) *Nepheline syenite and associated alkali gneisses in the metagabbro.*

The other major occurrence of nepheline syenite and associated alkali gneisses is as replacements along shear zones developed in the metagabbro and the later basic rocks. The Breivikbotn gabbro is highly sheared in places, and the shear-zones frequently become the loci of metasomatic activity during the emplacement of the alkaline rocks.

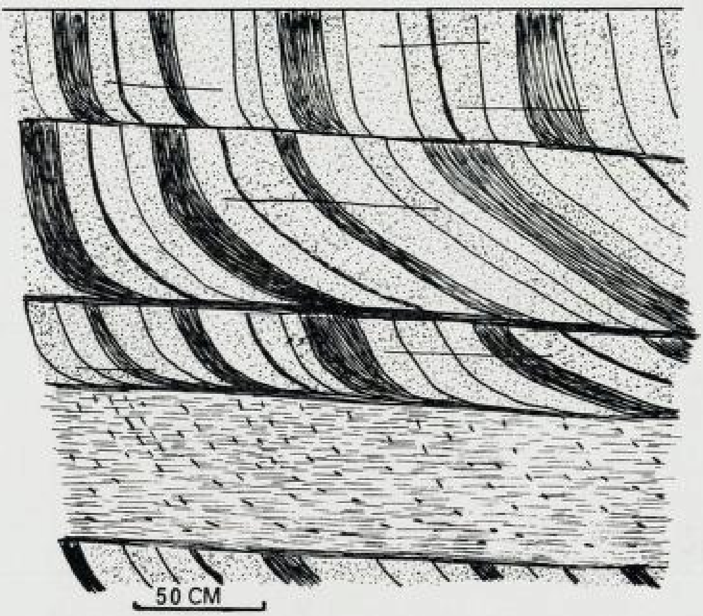

Fig. 17. Replacive nepheline syenite gneiss along F2-shear zone in psammite and semi-pelite. Large books of biotite pick out relict sedimentary banding. W. of Flågenvann.

Indeed the bulk of the nepheline syenites developed in the area are contained within the metagabbro. Occasional sheets of non-schistose nepheline syenite, which are of fairly coarse grain and have sharp contacts with unsheared metagabbro, also occur and may represent intrusions.

The strong shearing of the gabbro can be demonstrated to have occurred in two main stages:

(i) During late F1 movements, the effects of which are mainly concentrated in the area north of the village of Breivikbotn.

(ii) During the F2 folding a pattern of complementary low-angled and related vertical and near-vertical shears was developed. The complex nature of the F2 folding is illustrated by the way in which many of the low-angled shears are themselves folded by a later expression of the F2 deformation phase (Fig. 22). The later group of basic and intermediate rocks referred to earlier (p. 10) are also affected by the F2 shearing.

Fig. 18. Streaky feldspathisation of steeply inclined shear zone in metagabbro. N. of Hasfjordvann.

The effects of shearing in the gabbro range from the development of individual shear planes, along which little or no recrystallisation has taken place, to zones of up to 20 m. or so in thickness which have been subject to considerable metamorphic and metasomatic recrystallisation (Fig. 18 and 19). In the north of the area considerable parts of the metagabbro developed a schistosity as the result of the F1 movements. The shear-zones, most prominent in the south of the area, are mainly the consequence of the F2 deformation. The shear zones obviously post-date the main almandine amphibolite facies metamorphism, and large

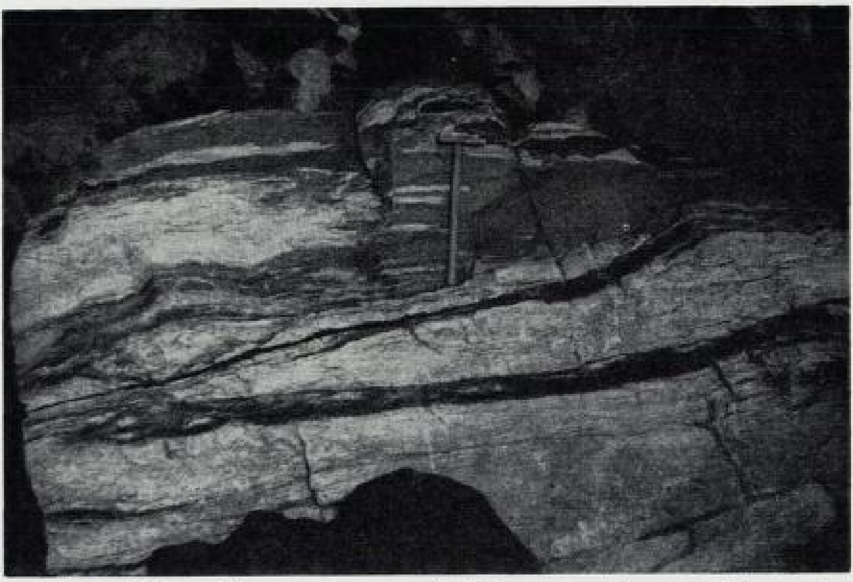

Fig. 19. Nepheline-sodalite syenite gneiss developing as a replacement of low-angled shear-zone in metagabbro. Note relict schistosity in the nepheline gneiss. 1 km. NE of Flågenvann.

poikiloblasts of hornblende are often sliced through by shear planes. The sheared metagabbro is now in the condition of hornblende, hornblende-biotite, or biotite schists. These contain plagioclase (An_{26-32}), and occasional examples also contain a more basic relict plagioclase, which is always highly saussuritized.

The sheared metagabbro has often been highly feldspathised (Fig. 19), with the development of plagioclase (An_{8-16}), microcline and more rarely a perthitic feldspar. Thick shear zones in the metagabbro, which have been feldspathised, are particularly conspicuous and stand out as white bands on the dark hillsides. Nepheline occurs, in many of the highly feldspathised shear zones, though this mineral may be absent or only sporadic in its occurrence. The sequence of crystallisation of the feldspathic minerals invariably follows the order:

Albite/Oligoclase → Microcline → Nepheline

though in some instances microline is absent. The more basic plagioclase (An_{26-32}), of the sheared metagabbro, is very much corroded in the fenitized zones. Frequent examples occur where this highly corroded variety is found as cores to the later albite/oligoclase. Where nepheline

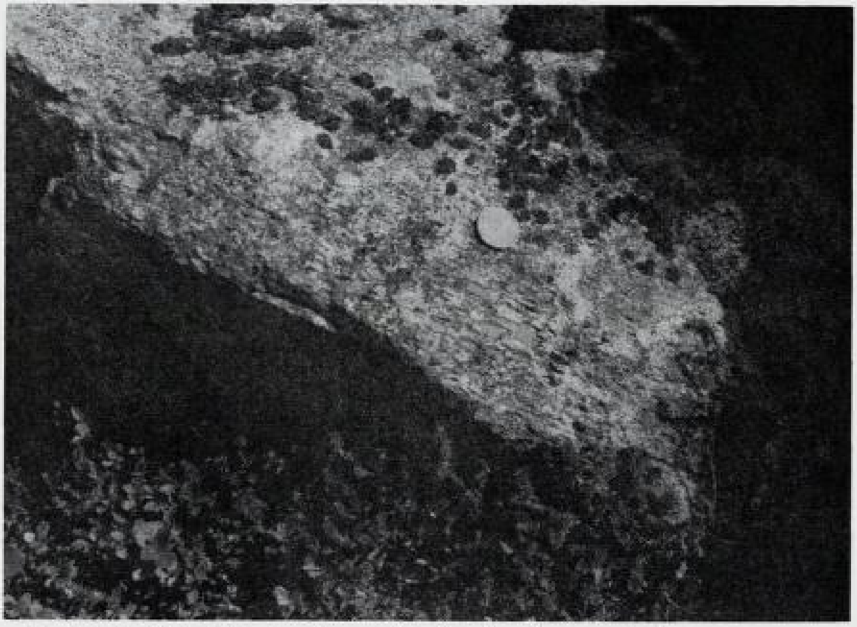

Fig. 20. Nepheline fingering along schistosity of replacive nepheline syenite gneiss. Roadside exposure between Haraldseng and Flågenvann.

Fig. 21. Large nepheline porphyroblasts in nepheline syenite gneiss. Over Flågenvann.

is present it is often developed as granular aggregates which finger along the schistosity (Fig. 20). It also frequently occurs as porphyroblasts and as glomeroporphyroblastic aggregates. Nepheline is also found in pegmatitic segregations in which individual crystals up to 20 cm. in diameter are not uncommon (Fig. 21). The hornblende of the sheared gabbro is a green-brown variety. In the zones of fenitization it becomes rapidly converted to biotite, or more rarely to aegirine augite. Generally the textural relationships are much the same as those described in detail for nepheline syenite gneisses formed from semipelitic schists. The schistosity of the nepheline syenite and associated gneisses, defined by the parallel arrangement of biotite (001), is gradually obliterated in the recrystallisation. Biotite is obviously replaced by feldspar, and the ultimate product is a coarse nepheline syenite in which only vestiges of the original schistose parent material remain. The nepheline syenites and associated gneisses contain many segregations of coarse biotite crystals, which often have small veins and lenses of calcite within them. These segregations presumably represent materials expelled during the metasomatic formation of the nepheline syenites. The mineralogy of the nepheline syenite gneisses developed as a result of the fenitisation of shear zones in the metagabbro is very similar to that of the nepheline syenite gneisses developed in the metasediments (Table 1). The exceptions are the greater amounts of the minerals aegirine-augite, amphibole, sphene, sodalite and scapolite.

The gabbro in its northern outcrop is thus a schistose sheeted body almost concordant with the regional banding. When the gabbro is traced in a southerly direction its contact with the metasediments becomes markedly transgressive. The gabbro in the south of the area is less thoroughly sheared by the F1 movements and becomes increasingly massive as it is traced southwards. The gabbro body is involved in a large F2 antiformal fold. This is reflected in the near vertical dip of the contact south of Breivikbotn village and its gentle westward inclination (15—20°) on Skoddefjell to the north of the village.

The prominent schistosity of the gabbro in the northern part of the area is reflected in the strongly rectilinear outcrop pattern of the nepheline syenite sheets, (Plate I). The similar disposition of the schistosities of the metagabbro and the nepheline syenite sheets is shown in Figs. 22 a and b. Where coarse grained massive amphibolite is present the F2 movements have produced shear zones. These are frequently followed by syenite sheets, increasing the complexity of the outcrop

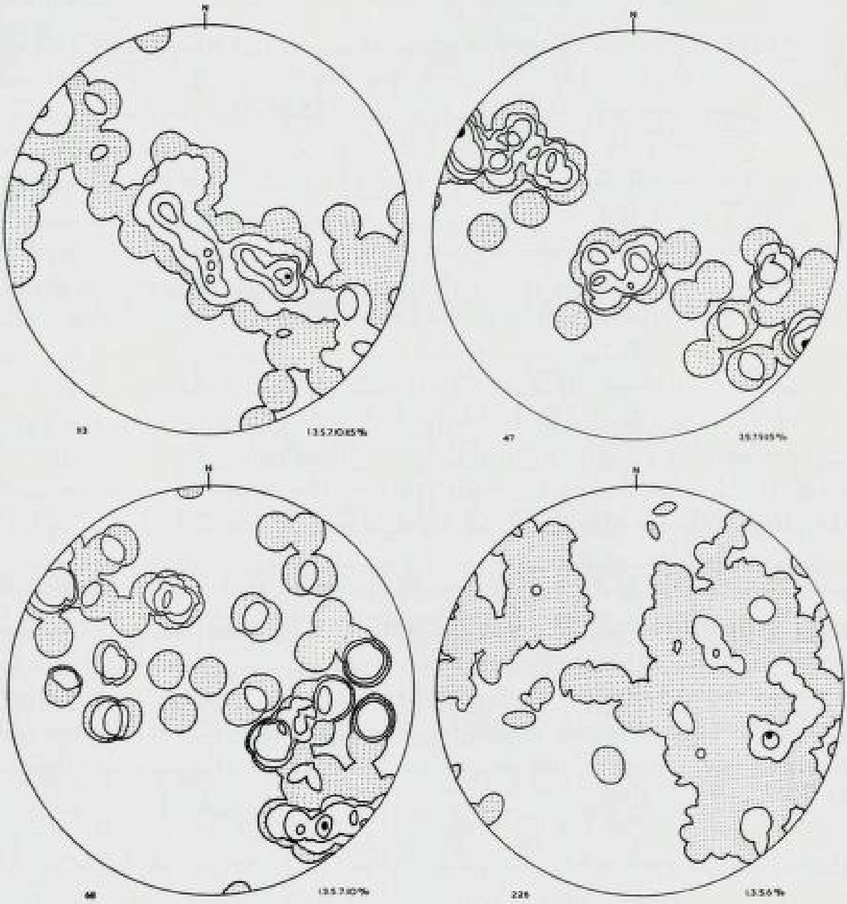

Fig. 22. Planar surfaces. The contour interval is indicated on the bottom right and number of observations. On bottom left of the diagrams:
(a) Schistosity in nepheline syenite from northern part of the area.
(b) Schistosity in metagabbro from northern part of the area.
(c) Shear zones in metagabbro.
(d) Schistosity in nepheline syenite from southern part of the area.

pattern. As the gabbro is traced southwards it rapidly becomes more massive and shear zones of varying attitudes, generated particularly during the F2 deformation, become the dominating structural features (Fig. 22). These shear zones provided paths of easy access for metasomatising fluids and emanations, and thick sheets of variably nepheline-bearing gneisses are developed within them. Many of these bodies are strongly folded as the result of later expressions of the F2 deforma-

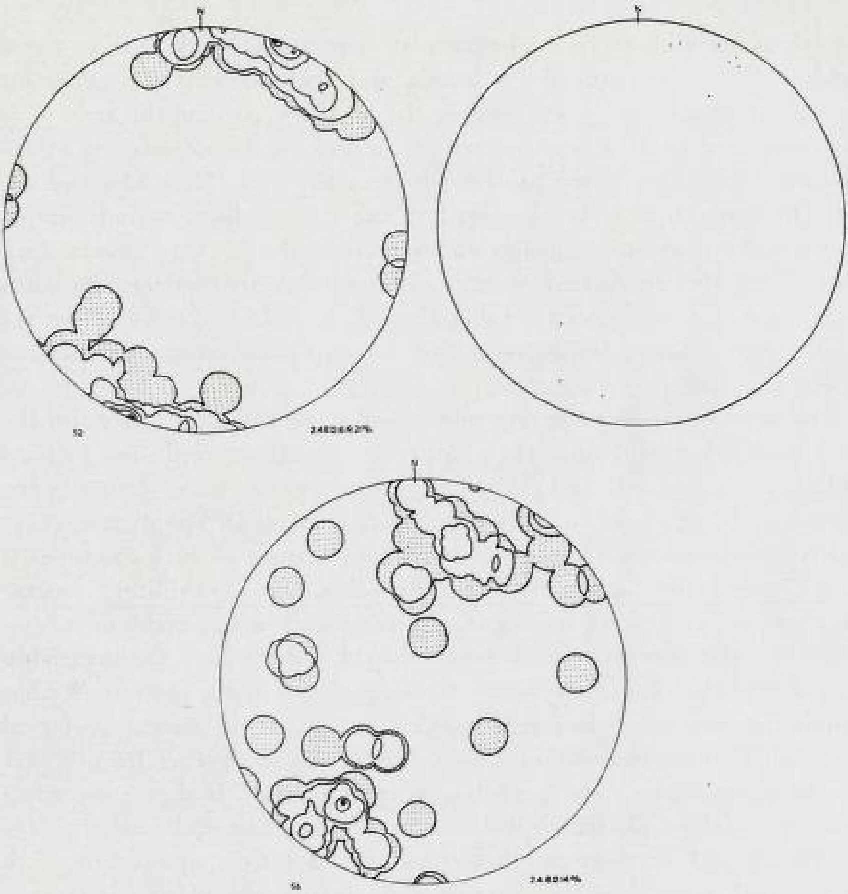

Fig. 23. Linear structures.
(a) Fold axes in nepheline syenite in northern part of the area.
(b) Fold axes and b.-lineations in meta-gabbro.
(c) Fold axes in nepheline syenite from northern part of the area.

tion. Thus the outcrop pattern of the nepheline syenite gneisses displays increasing complexity when traced from north to south (Fig. 22 a and d).

Deformation of the gabbro sheet and its contained nepheline syenite gneisses by the later F2 movements resulted in the formation of folds which have a generally gentle NNE–SSW trending axes (Figs. 23 a and c). The folds of the syenites are thus sensibly homoaxial with the F2 structures developed in the metasedimentary envelope. It can be observed (Figs. 23 a and c) that the folds in the nepheline syenite gneisses south of Breivikbotn have a less regular orientation. Many of them trend obliquely to the regional F2 b-axis, and their axes have a generally steeper plunge than is observed in the northern part of the area. This is considered to be a consequence of the less regular orientation of inclined shear zones in the southern part of the area (Figs. 22 a and d).

The many fold styles displayed in the syenite sheets include simple open and upright folds, geniculate asymmetrical folds with sheared long limbs, tightly compressed isoclines often with sheared out middle limbs (Fig. 24 a) and ptygmatic folds (Fig. 24 b). No examples of the refolding of folds or lineations within the nepheline syenite gneisses has been recorded.

In some instances recurring movement along the shear zones and the schistosity, has resulted in the production of augened nepheline gneisses. Highly augened and mylonitised nepheline syenites from Vatna, in the south of Söröy, have recently been discovered by D. Speedyman (personal communication), and an interesting feature of such examples is the presence of highly fractured nepheline often exhibiting mortar texture but exhibiting few signs of alteration. The aggregates of nepheline are also elongated into pencil-shaped rods, which are invariably parallel to the axes of the minor folds developed in the gneisses. Within such rods the nepheline has assumed an extremely strong preferred crystallographic orientation (Sturt 1961). An interesting feature that can be observed in the nepheline syenite gneisses, is that even when strongly deformed, the nepheline often has a fresh and unaltered appearance and furthermore has recrystallised into a grainfabric with polygonal grain shapes and stable grain boundaries (Voll 1960).

Well-developed examples of deformed nepheline syenite gneisses in the metagabbro occur on the small peninsula just to the north of Hvitness. At this locality a maze of nepheline syenite gneisses are found in the gabbro. The gneisses generally represent replacements along shear zones in the gabbro and they are often in the condition of nepheline augen gneisses. A notable feature of this occurrence is the presence of streaks of apparently metasedimentary material within the nepheline gneisses, and these may represent relicts of former sediment screens or inclusions in the gabbro. The nepheline syenite gneisses are involved in a series of folds as shown in Fig. 25. The gneisses are extremely strongly sheared on the southern limb of the main fold and pass eastwards into a strongly sheared zone that contains lenses and fragments of nepheline gneiss in a sheared gabbro matrix. As this shear zone is traced to the

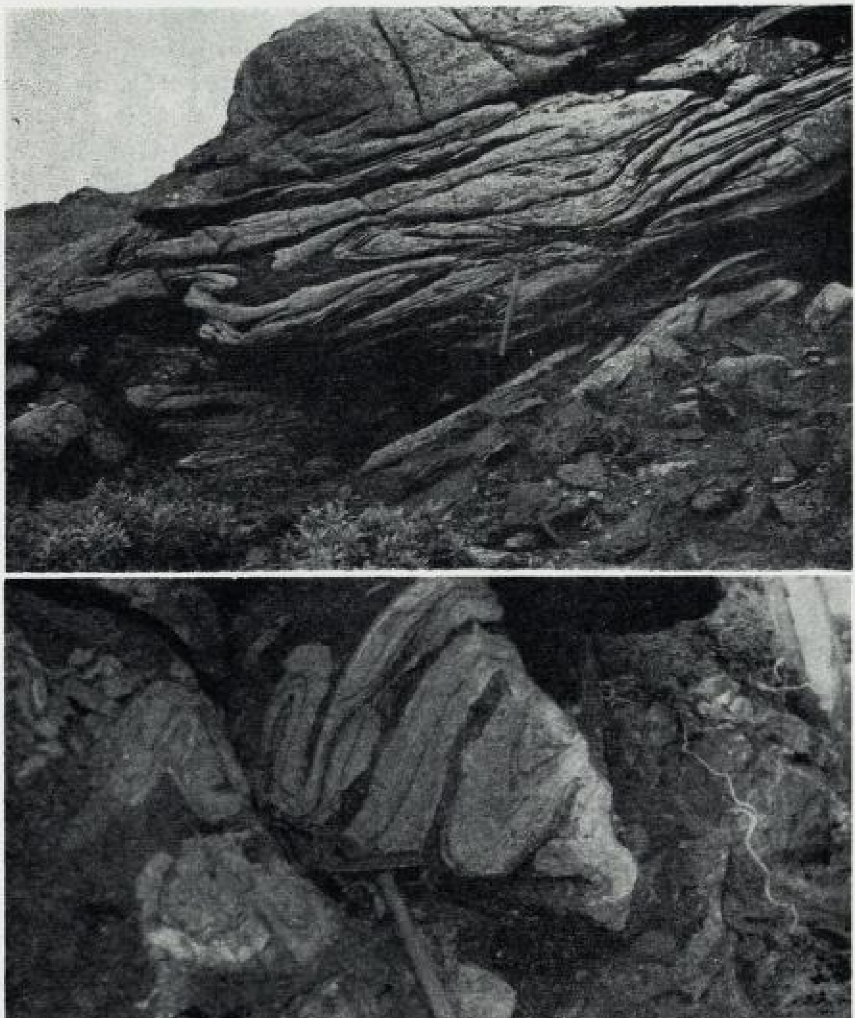

Fig. 24. Folded nepheline syenite gneisses (late F2 folds).

(a) Isoclinal folding of nepheline syenite gneisses developed in shear zone in metagabbro. Note how closures are sometimes completely sheared out. 2 km. south of Eggevann.

(b) Folding of nepheline syenite gneiss developed in metagabbro shear zone. The folds tend towards a ptygmatic style. 2 km. east of Breivikbotn.

east it widens into another body of nepheline syenite gneiss which is 3 m. at its maximum thickness, and which contains pegmatitic segregations with nepheline crystals up to 15 cm. in diameter. The folds affecting the nepheline syenite gneisses have a steep but variable WNW–ESE. plunge and appear to belong to the second phase of folding.

Nepheline syenite is not confined to the shear zones at this occurrence but is also found in a pattern of irregular net-veins which often connect one fold limb with another. To the south of the southern fold limb nepheline syenite veins are given off from the main body and are observed to follow a prominent set of joints which dip 38° towards the west and with a 025° strike. These veins appear to penetrate the large ultrabasic dyke shown in the map (Fig. 25) at one point. This dyke contains occasional coarse segregations of andesine/labradorite/hornblende-scapolite. The scapolite occurs as long sheaf-like fibres. Although the gneisses in the shear zones appear to have a metasomatic origin, the

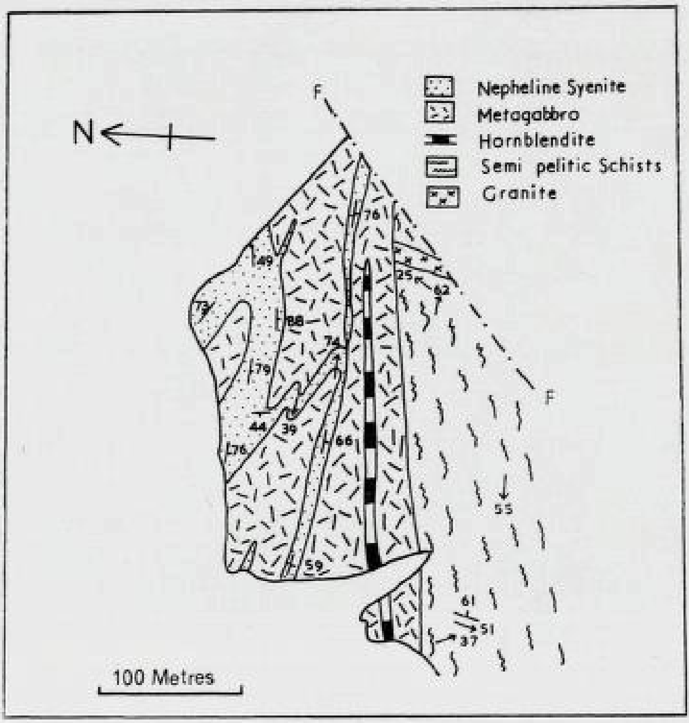

Fig. 25. Folded nepheline syenite gneisses in metagabbro. (The arrows indicate minor fold plunges.) Peninsula north of Hvitness.

net-veins are not so simply explained. Unfortunately it is not possible to establish whether the veins are dilational owing to the massive nature of the metagabbro host. Thus they may represent either the products of metasomatism along a pre-existing set of joints, or may be the result of mobilization of the nepheline syenite gneisses along the joints.

Other examples are to be found elsewhere in the area where the nepheline syenite gneisses have apparently been mobilized. One of these occurs on the hill to the north-west of Hasfjordvann, where a thick (15 m.) sheet of variably nepheline bearing gneiss occurs as a replacement along a shear zone in pegmatitic metagabbro. Here thin sheets of nepheline syenite, with a schistosity parallel to their margins, follow steep joints in the metagabbro above the gently dipping nepheline syenite gneisses. The contact of these veins with the main gneiss sheet, however, is obscured but they can be traced to within one metre of the gneisses. A further example occurs 2 km. south of Eggevann where a sheet of nepheline syenite has again formed as a replacement along a shear zone in the metagabbro. The sheet is folded into an antiform whose axis plunges 24° towards 207°. On the upper limb of the antiform, where the gneisses have a gentle dip, three dyke-like bodies of nepheline syenite are given off parallel to a set of joints in the metagabbro dipping at 80° towards the west and trending at 015°. The dykes vary in thickness from 70 cm. to 2 m. The syenite in the dykes is schistose and the schistosity is parallel to the dyke margins. In these exposures it is possible to examine the contact between the dykes and main gneiss sheet. In each case the schistosity is observed to curve up from the gently dipping gneiss sheet into the steeply inclined dykes. At the contact the syenite is strongly rodded in places. The rodding plunges 30° towards 215°.

Infrequent examples of thin non-schistose sheets of nepheline syenite also occur within unsheared metagabbro. These are invariably of coarse grain and have not been observed to have finer grained margins. Similarly sheets, up to 5 m. thick, of nepheline syenite occur connecting nepheline syenite pegmatite dykes in the manner of net-veins. Such sheets are often non-schistose having sharp contacts with unsheared metagabbro, and considered to probably be intrusive.

(2) *Nepheline Syenite Pegmatites.*

Nepheline syenite pegmatites are abundant in the area and particularly in the southern part. The pegmatites have a variety of forms:

(a) As segregations in the nepheline-syenite gneisses.
(b) As steep cross-cutting dykes, which may be up to 20 or 25 metres in width and cut indiscriminately through both metasediments and metagabbro.
(c) Associated with alkali-feldspar/magnetite pegmatites.

The first type of occurence has been referred to in the foregoing account of the nepheline syenite gneisses and represents metamorphic segregations in the gneisses. The cross-cutting dykes are generally vertical features which mainly have a NE–SW trend (Fig. 26), following a prominent joint set in the area. The majority of the nepheline syenite dykes certainly appear to be intrusive bodies and have sharply cross-cutting junctions which truncate the fold structures and basic-dykes in the country rocks. Occasional basic dykes, however, are observed to post-date the nepheline syenite pegmatite dykes; these belong to a steeply dipping N–S trending set.

The nepheline syenite pegmatites are often connected with the sheet-like bodies of nepheline syenite and associated gneisses, described above. To the north-east of Hvitness this phenomenon is particularly well

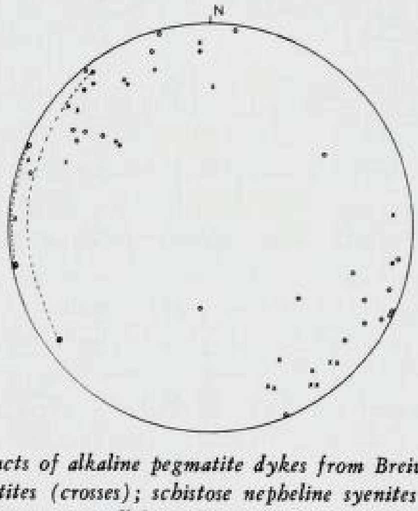

Fig. 26. Poles to contacts of alkaline pegmatite dykes from Breivikbotn area. (i) Nepheline syenite pegmatites (crosses); schistose nepheline syenites (solid dots). In one example the schistosity is not parallel to the contact; the dashed great circle connects the pole to the dyke margin (cross in circle) to the shistosity of the dyke (dot). (ii) Alkali-feldspar magnetite pegmatites (open circles). These are often sheared parallel to their margins; though in one example the schistosity is oblique to the contact and shown by dashed great circle connecting the pole to contact (open circle) to the schistosity (thick ring).

shown. Here three dykes of nepheline syenite pegmatite are connected by schistose sheets of nepheline bearing gneisses in a pattern resembling that of large scale net-veins. As the dykes are traced uphill they converge into a single dyke which finally flattens out into a sheet of nepheline syenite gneiss which has formed along a shear zone in the metagabbro. Throughout the area similar relationships are to be found between the pegmatite dykes and metasomatic gneisses formed along shear zones both in the metasediments and the metagabbros. Such features indicate an intimate relationship between a highly fluid nepheline syenite pegmatite magma crystallising in the pegmatite dykes and intense metasomatic activity along zones of easy access such as the shear zones. All the intrusive pegmatite dykes observed in the area were found to narrow markedly when traced in an uphill direction.

The mineralogy of the nepheline syenite pegmatite dykes is very similar to that of the nepheline syenite gneisses. It has been demonstrated that in the nepheline syenite gneisses perthitic feldspars are extremely rare, however, in the pegmatite dykes the alkali feldspar is usually a coarse perthitic or antiperthitic feldspar of patch or vein type. In many instances the perthitic nature of the alkali feldspars is visible to the naked eye in hand specimen. On the other hand the pegmatitic segregations within the nepheline syenite gneisses rarely contain perthitic

Fig. 27 (a).

Fig. 27. Zoned pegmatite with margins of alkali feldspar-magnetite pegmatite and central sheared zone with nepheline developed. Hvitness.

(a) Showing whole of zoned dyke. Man (for scale) is standing at contact between middle zone and eastern margin of alkali feldspar magnetite pegmatite.

(b) Sheared central zone with replacive pegmatite of nepheline—albite/oligoclase—microcline developed.

feldspars. The minerals within the pegmatites are often of considerable size, individual nepheline crystals of 25 cm. diameter are not uncommon and the largest observed was a little over half a metre. Euhedral and sub-hedral alkali feldspar crystals up to 20 cms. in length have been observed. The large phenocrysts are set in a granular matrix of nepheline and alkali feldspar with a little randomly oriented biotite. In some instances the phenocrysts of feldspars have been subjected to deformation with the development of such features as strained extinction, bent and broken twin lamellae and occasionally mortar structure.

Other occurrences of nepheline syenite pegmatite are intimately associated with alkali-feldspar/magnetite pegmatites. The structure within such dykes is often very variable and in most cases a zonal arrangement can be detected. The large dyke just to the north-east of Hvitness (Fig. 27 a) has outer zones of alkali-feldspar/magnetite/biotite pegmatite each some three metres thick, and a central zone of schistose biotite syenite about three metres thick containing segregations of nepheline-alkali feldspar pegmatite (Fig. 27 b). The central part of the dyke is seen to be highly sheared alkali feldspar-magnetite-biotite pegmatite of the border zones and the nepheline to always occur as porphyroblasts or as metamorphic segregations. Relationships of this type are very common and generally wherever the alkali feldspar-magnetite-pegmatites are highly sheared nepheline develops as a porphyroblastic mineral. In many of the alkali feldspar-biotite-magnetite pegmatite dykes the margins are strongly sheared (Fig. 28) and porphyroblastic nepheline is developed. In other instances of zoned pegmatites alkali feldspar-magnetite pegmatite and nepheline syenite pegmatite are both

Fig. 28. Alkali feldspar-magnetite-biotite pegmatite with sheared margin. Porphyroblastic nepheline occurs in the sheared margin. Eastern face of Riveren.

present as intrusive phases, and in all those examples examined the nepheline syenite pegmatites are invariably the later.

Near Hasfjordvann a nepheline syenite pegmatite dyke, two metres wide, appears to have developed by the metasomatic replacement of a vertical shear zone in the metagabbro. Many of the nepheline syenite dykes have been subjected to later shearing and often develop a rudimentary schistosity picked out by large books of biotite. This schistosity is generally parallel to the margin of the dykes but in one instance it is almost at right angles to the dyke walls although the dyke is one of the dominant NE–SW set. Where such later shearing is strongly developed augened nepheline gneisses result.

(3) *Alkali Feldspar-Magnetite-Biotite Pegmatites.*

These are often associated with nepheline syenite pegmatites as indicated above. They are intruded into both the metagabbro and the metasediments. Their trend is a little more irregular than that of the nepheline syenite pegmatites though they are steep dykes and sheets generally trending between NE–SW and E–W (Fig. 26). These pegmatites are also observed to thin and die out in an uphill direction. It can be shown that the steep dip of the country rocks and of the metagabbro contact in the south of the area is the consequence of their position in the middle limb of an F2 antiform. The dykes of nepheline syenite pegmatite and of alkali feldspar-magnetite-biotite pegmatite are intruded into and must post-date the formation of this steep limb.

The pegmatite dykes are composed mainly of perthitic alkali feldspar, biotite, and magnetite with accessory apatite, zircon, sphene and allanite and occasionally show the secondary development of zeolite (thomsonite and natrolite) after alkali feldspar. The feldspars and micas often attain a considerable size in these pegmatites with individual feldspars up to 15 cm. in length and books of biotite up to 25 cm. across. In a pegmatite dyke, on the hill just to the north-east of Hasfjordvann, crystals of brown sphene up to 5 cm. long were collected. Coarse syenites rather similar in appearance occur in association with the carbonatite, but these will be considered in the appropriate section.

(4) *Fine-Grained Syenite Dykes.*

Occasional examples of fine-grained syenite dykes associated with the nepheline syenites have also been discovered. In most cases it is difficult to ascertain their relative age relationships with the other alkaline rocks.

Two examples of dykes later than the nepheline syenite gneisses have been found. These are both almost pure plagioclase (An_{8-10}). rocks i.e. trending towards albitites. Biotite and corundum are prominent accessory minerals. They also contain muscovite, zircon, allanite and iron ores. One example of a plagioclase (An_8)—biotite-corundum syenite with accessory zircon, muscovite and pyrite was observed to form part of a net-vein pattern connecting nepheline syenite gneiss sheets in metagabbro.

Other fine-grained syenite dykes occur in the general vicinity of the nepheline-bearing rocks. These are often thin sheets following the axial planes of F2 folds, and vary from syenites rich in perthite to almost pure albite/oligoclase rocks. One example was observed containing molybdenite. It is possible that some of the fine-grained syenite dykes and sheets may be earlier than the main phase of alkaline activity in the area. This is indicated by one dyke, that is cut by nepheline syenite pegmatite, and was found to contain (SB 304) well-formed coronas of garnet about corundum grains. This is presumably a metamorphic effect, although whether it is a consequence of the main almandine amphibolite facies metamorphism or is related to one of the later phases, during the F2 deformation, is not certain.

(5) *Alteration of the Nepheline Syenites.*

Alteration of the nepheline syenites has been briefly referred to in the foregoing account. It is obvious that these alterations are the consequence of a series of reactions that occurred during a subsequent period of hydrothermal metamorphism. This is certainly a process late in the history of the alkaline rocks and appears to post-date the second (F2) phase of fold movements.

The hydrothermal solutions and emanations have mainly utilized the joints and shear planes produced during this period of deformation. Two main effects are observed during this late and essentially localized metamorphic event: —

(i) Hydrothermal metamorphism and vein infilling, and
(ii) A late-stage K-metasomatism confined to the joint system, and immediately adjacent rocks.

The nepheline syenites in the metasediments show relatively few effects of the hydrothermal metamorphism. Locally nepheline is marginally altered into muscovite and hydronephelite; and late pyrite is a fairly common feature. The minerals scapolite, sodalite and cancrinite are, however, rare in the rocks. Stronger effects of the hydrothermal metamorphism are to be seen in the nepheline syenite gneisses and pegmatites which occur in the well jointed metagabbro.

Hydrothermal alteration of the metagabbro.

The metagabbro shows, locally strong effects of the hydrothermal alteration and this is joint-controlled. The products of the hydrothermal alteration may be considered under two broad headings:—

(a) Joint infillings and veins.

(b) Marginal alteration of metagabbro against joint planes.

The joint infillings and veins are mainly composed of epidote/clinozoisite, various zeolites, chlinochlore, penninite, sphene, pyrite, albite, calcite, scapolite, biotite and in one instance adularia. The minerals in the veins and joint-infillings are primary hydrothermal products and magnificent fans and rosettes of epidote/clinozoisite, chlorite and zeolite are developed. The veins are often zoned and by a study of both the macroscopic and microscopic textures of the minerals it has proved possible to work out a general sequence of crystallisation of the primary vein-filling minerals. These relationships are particularly well shown on the hill just to the north-west of the long northern arm of Hasfjordvann.

Epidote/Clinozoisite.

This mineral often forms the marginal zone of the primary vein-filling and occurs as:—

(a) Large massive crystals, often euhedral, and up to 5 cm. long.

(b) As sheaf-like aggregates often with radial form, in which individual crystals may be up to 1.5 cms. in length, though more generally around 0.5 cm. long.

(c) As fine-grained granular material around 0.1 mm. in diameter.

In spite of the differences in habit there appears to be little variations in composition. They all have a similar pleochroic scheme α—colourless, β—very pale yellow, and γ—pale lemon-yellow. The refractive indices show little variation:

	α	γ
SB290	1.725	1.745
SB290B	1.728	1.753
SB290E	1.726	1.752
SB290I	1.725	1.762
SB290J	1.726	1.751

and indicate that the mineral lies midway in the epidote-clinozoisite series. The mineral also shows anomalous blue/grey polarisation colours in some of the thin-sections investigated.

Chlorite.

This is present both as clinochlore and as penninite. The chlorite can generally be observed to have been deposited later than the epidotic minerals in the primary vein fillings, and in veins where epidote is abenst chlorite forms the outer zone. The chlorite in the veins appears to be mainly a penninite (+ve) and shows anomalous ultramarine to black interference colours. The chlorites are developed either as radiating masses of chlorite laths with individual flakes up to 5 mm. long, or as masses of varying grain size with a completely random orientation.

In some instances stringers of elongated sphene granules occur as inclusions in the chlorite aligned parallel to the cleavage. The chlorites also show occasional secondary alteration to limonite along the cleavage, but this may be a later weathering phenomenon.

Sphene is frequently associated with chlorite and epidote/clinozoisite in the veins and occurs as irregular rounded grains up to 2 cm. across or as beautifully euhedral crystals up to 0.8 mm. in length.

Zeolite.

Several varieties of zeolite are present, principally the minerals natrolite and thompsonite. These minerals generally represent primary minerals in the vein infillings, and often form masses of radiating slender crystals, in which individuals may be up to a maximum of 4 cm. in length. In thin section they are observed as rosettes of fibres and also irregular masses of fibres and larger crystals which do not show any preferred orientation. Other zeolites present include analcite and scolechite. Occasionally albite is earlier than the zeolite in the veins, but as a general rule feldspar is one of the latest minerals to be developed.

Feldspar.

This is mainly a fairly pure albite (An_{2-4}) and occasional examples of adularia have benn observed.[1] The albite, is occasionally altered into zeolite, but in most instances the feldspars are observed to be among

[1] The authors are indebted to Dr. G. P. L. Walker for this identification and for identifying some of the zeolite samples.

the latest minerals to crystallise in the veins. They generally form large irregular crystals which cut sharply across the zeolite and chlorite rosettes. Calcite is also a late mineral in the veins but has usually formed earlier than the feldspars.

Pyrite.

Pyrite appears generally to post-date zeolite and forms good euhedral crystals in zeolite-rich areas.

In the centres of the veins large undeformed books of biotite up to 5 cm. across are occasionally observed.

Marginal to the vein-infillings and to quite barren joints a sequence of alterations and replacements of the minerals of the metagabbro has occurred. The first effect of these hydrothermal alterations is seen in the plagioclase feldspars which become replaced by scapolite. This type of alteration increases markedly towards the joints and joint-infillings, and the scapolite occurs both as a patchy alteration product and as small segregations and veins. As the joint infillings are approached the scapolite is altered into zeolite and epidote, as also is the remaining labradorite. Ilmenite is progressively altered to sphene. The hornblende, produced from pyroxene during the amphibolite facies metamorphism of the gabbro, is altered into biotite and chlorite. Very occasionally the hornblende has been completely pseudomorphed by large flakes of these minerals which still contain the schiller arrangement of minute ore inclusions inherited by the hornblende from the pyroxene. Secondary masses and euhedral grains of pyrite and irregular grains of calcite are common. In one example microline fingering along grain boundaries was observed.

Rare vein infillings mainly composed of microline and muscovite also occur and marginal to these considerable quantities of biotite and rarely microline are developed as an alteration of the metagabbro.

Hydrothermal alteration of the nepheline syenites.

The nepheline syenite gneisses and pegmatites in the metagabbro show particularly well the results of the hydrothermal alteration. This is especially noticeable where joint surfaces are coated with blue sodalite, often occurring as quite large grains. Associated with sodalite along the joints are large books of muscovite up to 5 cm. across, cubes and pyri-

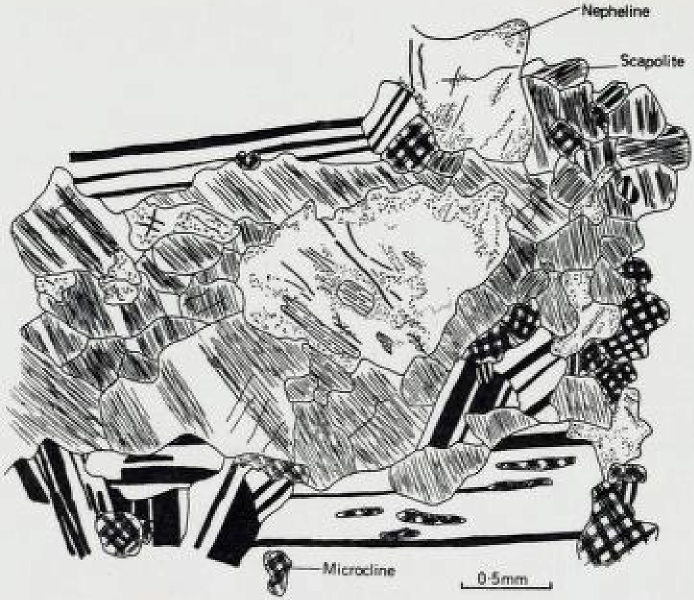

Fig. 29. Hydrothermal alteration of nepheline syenite gneiss with scapolite forming at the expense of plagioclase and nepheline. (Slide no. SB428B.)

Fig. 30. Hydrothermal alteration of nepheline syenite gneiss. Scapolite formed at expense of plagioclase and nepheline. Sodalite/albite symplectite formed from nepheline. (Slide no. SB.482B.)

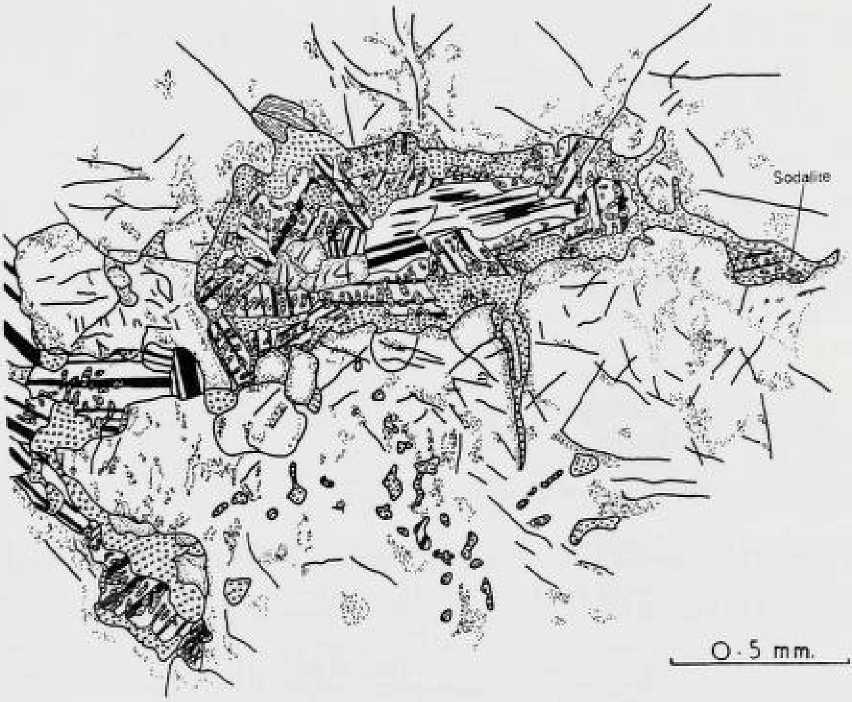

Fig. 31. Sodalite-albite symplectite formed by hydrothermal alteration of nepheline. (Slide no. SB.483.)

tohedra or pyrite and occasional fibrous zeolite (thomsonite). The mineral scapolite also occurs as a joint coating as acicular tapering crystals with a radial habit, individual crystals are up to 10 cm. in length.

Nepheline is altered into muscovite, cancrinite, hydronephelite, scapolite, sodalite and albite. In many instances the nepheline is almost entirely replaced by muscovite. The latter often occurs as large flakes which have a radial habit. This is probably a consequence of the K-metasomatism which accompanies the hydrothermal metamorphism and is particularly marked adjacent to small veins of microcline and muscovite formed along the joint planes. In many instances nepheline and plagioclase are both converted into scapolite (Fig. 29).

Nepheline is also extensively altered into sodalite[1], and in some instances into sodalite and albite. In the second case (Figs. 30 and 31) nepheline is marginally altered into sodalite which contains vermicular

[1] Refractive Index determinations of sodalite specimens: DMR—1 1.4859; SB—17 1.4861; SB—41 1.4872.

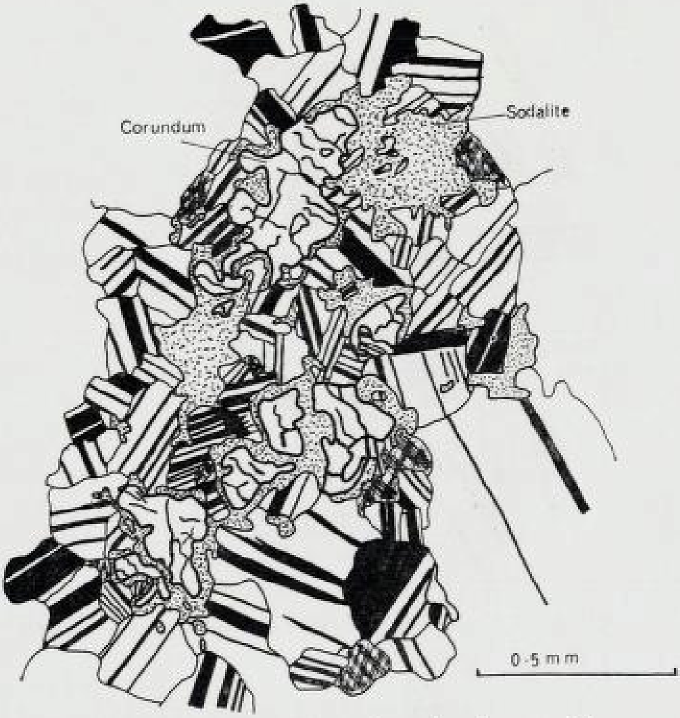

Fig. 32. Sodalite and corundum formed from albite/oligoclase. Nepheline syenite gneiss. (Slide no. SB.481.)

blebs of albite, and next to this is a zone of albite with vermicular blebs of sodalite. Thus during the breakdown of nepheline both sodalite/albite and albite/sodalite symplectites are formed. Such alterations are extremely rare and were only observed in two of the 117 thin-sections of nepheline syenites examined.

Nepheline is also altered into cancrinite. This is particularly marked where calcite is in contact with nepheline where fans of cancrinite are formed. Occasional examples of nepheline altered into zeolite have also been observed. The nepheline generally shows some signs of alteration into hydronephelite but the exact stage at which this alteration occurred is not certain. Another interesting reaction occurs (only observed in one thin-section) where albite/oligoclase has broken down to produce sodalite and corundum (Fig. 32).

Associated with the hydrothermal alteration of the nepheline syenites is the development of pyrite which occurs either as irregular masses up

Fig. 33. Sodalite (crosses) and late biotite formed about pyrite. Nepheline syenite gneiss. (Slide no. SB481.)

to 3 cm. across or as euhedra rarely exceeding 0.5 cm. in diameter. In one instance the pyrite is surrounded by a low relief, colorless isotropic mineral (Fig. 33) which is either analcite or sodalite. Pyrite grains are also frequently surrounded by biotite. The late biotite is also present in books up to 3 cm. across. Pyrite is also occasionally surrounded by muscovite.

The prevalence of the minerals scapolite and cancrinite in altered nepheline syenites within metagabbro attests to the greater availability of lime in this environment. It is also indicated by certain of the reactions described that a limited amount of silica is added to the nepheline syenites during the hydrothermal metamorphism.

B. *ROCKS OF CARBONATITE ASSOCIATION.*

The two main occurences of carbonatitic and associated rocks, which now occur in the narrow strips extending some 3 kilometres north of the south-east of Baarvik, once formed parts of a continuous belt and are now separated by a bay. (Plate I) The rocks of the belt consist of carbonatites, fenites, syenites of varied composition, and ultrabasic alkaline types. The rocks represent in part intrusive types though others appear to be the metasomatic products. The rocks of this group have generally been very strongly deformed and metamorphosed, and many have also been affected by considerable late hydrothermal activity and carbonate metasomatism. The rock types and their mutual relationships are best displayed on the shore-sections of Haraldseng and Baarvik where exposures are nearly complete. Inland however, degree of exposure is poor to moderate, and indeed in the belt southeast of Baarvik very poor, and here it has proved impossible to map the limits of the various rocks of the group. Intrusive or metasomatic carbonate rocks occur in two other localities in the area, but the carbonate rocks at these localities are of very different composition to the main carbonatite occurrences, and furthermore are not associated with alkaline rock types. These will be treated in a separate section.

From a consideration of their field relationships, petrography and geochemistry it is clear that the rocks of this group form a very distinctive association, although in general terms they are related geographically and temporally to the rocks of the nepheline syenite association. Within the rocks of carbonatite association there has occurred a sequence of intrusive, metasomatic, metamorphic and structural events which overlap the second major movement phase (F2). It will be recalled that a similar general sequence coinciding with the F2 deformation episode, was apparent during the evolution of the nepheline syenite group of alkaline rocks.

(1) *The Basic Alkaline Rocks.*

At the eastern margins of the shore-sections at Haraldseng and Baarvik the country metasediments (psammites and semi-pelitic schists) are overlain, apparently conformably, by a schistose highly basic alkaline rock which is up to 15 m. in thickness, (Fig. 34). This is essentially an aegirine-augite pyroxenite outcropping as a narrow strip and apparently dying out to the south-east of Baarvik. The pyroxenite is cut through by several generations of basic dykes, some of which are also highly sheared, and by occasional sheets of a coarse leucocratic alkalifeldspar biotite syenite. The earliest highly sheared basic dykes have a mineralogy similar to that of the pyroxenite, but later dykes have a different mineralogical composition. The pyroxenite consists of aegi-

Fig. 34. Shore-section Haraldseng. Foreground of semipelitic schists and psammites, overlain by aegirine-augite pyroxenite (black); in turn succeeded by shonkinites, etc. in middle distance.

rine-augite, hastingsitic amphibole, sphene and plagioclase (An_{8-12}) and accessory minerals include alkali-feldspar, apatite, allanite, biotite, magnetite and pyrite (Table 3). There has also been considerable secondary alteration with the formation of various zeolites at the expense of feldspar and the widespread, locally intense development of metasomatic calcite giving a blotchy appearance to the pyroxenite in many localities. The texture of the pyroxenite is somewhat variable with a tendency to a patchy concentration of the constituent minerals. Small oriented inclusions of aegirine-augite often occur in large amphibole plates, and the latter mineral frequently occurs as rims around large aegirine-augite crystals. Examples are also seen, however, of small oriented inclusions of hastigsitic amphibole within large aegirine-augite plates. These features indicate that although the amphiboles are generally later than the aegerine-augites in the crystallisation sequence their formation overlaps. The minerals of the pyroxenite rarely have good crystal shapes, though large (up to 5 mm.) perfectly euhedral crystals of sphene are very common in the pyroxenite.

In some localities the pyroxenite is shot through by net-veins of alkali-feldspar which is often considerably altered into zeolite (mainly thompsonite), and of garnet and chalky-white zeolite. The garnet is reddish-brown (plane-polarised light) and is in the melanite/andradite series. The garnets show a well developed zonal structure with alternating lighter and darker zones. The zeolite (mainly thompsonite) occurs in sheaves and fans of fibres. Feldspar is lacking in the examples of such veins that have been examined and it is not possible to state categorically whether the zeolite is a primary vein mineral or if it is in fact secondary after feldspar. The veins also contain minor amounts of the minerals aegirine-augite, hastingsitic amphibole, sphene, allanite, magnetite and pyrite in varying proportions.

The pyroxenite is intruded by several phases of basic dykes of varying orientation. Many of the basic dykes are highly schistose and in some cases contain hastingsitic amphiboles and less frequently aegirine-augite; these minerals are invariably developed at the expense of common brown or green-brown hornblende. Several generations of plagioclase feldspar are to be observed in the dykes. In the more schistose dykes two generations of plagioclase are to be found, an earlier generation (An_{28-34}), often corroded, whose shape conforms to the schistose texture of the rock and a later generation of plagioclase (An_{6-12}) forming polygonal grains around the earlier larger grains; very occasional polygonal grains of alkali feldspar of this later generation also occur. The feldspars are frequently altered into zeolite. In a few examples very rare highly corroded basic plagioclase around An_{50} is also present. Also intruded into the pyroxenite are occasional sheets of biotite-bearing syenite now schistose and composed essentially of phenocrysts of microcline microperthite and aegerine augite set in a granular mosaic of plagioclase (An_8) and, microcline, with biotite laths defining the schistosity of the rock. Accessory minerals include sphene which is highly pleochroic, apatite, allanite, magnetite, and pyrite. These syenite sheets certainly post-date most of the basic dykes, but two examples were observed of basic dykes cutting sharply through the syenite sheets. In some instances the relationships among the various dyke phases are obscured by the local carbonate metasomatism.

The schistosity of the pyroxenite is partly a pervasive structure which developed before the intrusion of the syenite sheets and many of the basic dykes, but it also consists of a later shearing which affects the basic dykes, the syenite sheets and the alkali feldspar net-veins. The garnet/zeolite veins and calcite veins are apparently later than all shear-

Fig. 35. Carbonate metasomatism of aegirine-augite pyroxenite. Haraldseng shore-section.

ing movements. The metasomatic introduction of carbonate has either accompanied or followed the later shearing. The carbonatisation of the pyroxenite is locally pervasive (Fig. 35) and affects also the basic dykes and syenite sheets. The metasomatic introduction of calcite into the pyroxenite is presumably related to the emplacement of the carbonatite. Indeed as the pyroxenite is traced northwards from the Haraldseng shore section the amount of secondary carbonate increases and the pyroxenite ultimately becomes brecciated with a carbonate matrix tailing northwards into intrusive carbonatite, which contains abundant xenoliths of the pyroxenite and of various syenites and country rocks. The carbonatite furthermore develops a well marked flow banding. Cutting the pyroxenite and later than the metasomatic carbonatisation is a series of veins of fairly pure calcite composed of large calcite crystals developing good rhombohedral and scalendohedral form. Associated with these veins are small masses of pyrite.

The origin of the aegirine-augite pyroxenite is problematic and there appear to be three possible explanations:

(a) That it crystallised from an alkaline ultrabasic magma.

(b) Basification of the country rocks, which do in fact develop conspicuous aegirine-augite and hastigsitic amphibole in a narrow zone near the contact.

(c) Alkali metasomatism of a highly sheared metagabbro or metadolerite sheet, associated with the emplacement of the rocks of the carbonatite group.

The last-named explanation is favoured since in many places relict slivers of hornblende schist occur in the pyroxenite. In these cases aegirine-augite or hastigsitic amphibole is seen as rims around green-brown common hornblende. The relict hornblende schists consist generally of a brown or green-brown hornblende, plagioclase (An_{6-8}), biotite, sphene and epidote. In many examples highly corroded more basic plagioclase is found, and often the albitic plagioclase occurs in patches with pale green (p.p.1) epidote. In the centres of lenses or slivers of hornblende schist the plagioclase is usually around An_{30} with a second later generation around An_8. In two localities patches of massive amphibolite occur in the centres of large lenses of hornblende schist. These were found to be of gabbroamphibolite with a brown hornblende after pyroxene (in one of the examples a few relict grains of augite were observed), highly saussuritized labradoritic plagioclase, sphene and magnetite preserving a relict ophitic texture. A second generation of plagioclase, around An_9, is present as small grains around the margins of the highly corroded labradorite crystals. The aegirine-augite pyroxenite thus appears to have originated as the result of fenitisation, marginal to the rocks of the carbonatite complex, of a thin gabbro sheet. The gabbro sheet is sensibly concordant to the schistosity of the country rocks and was strongly sheared presumably during F1 to produce a hornblende schist. It is apparent that the sheet was affected by this shearing and by almandine amphibolite facies metamorphism prior to fenitisation. Dolerites showing evidence of fenitization have been recently described by Garson (1962) from the Tundulu Complex in Nyasaland.

Basic dykes which are apparently not affected by the alkali metasomatism cut the aegirine-augite pyroxenite and syenite sheets and are relatively little sheared. These dykes bear evidence of upper green schist facies metamorphism and contain the typical assemblage green hornblende, biotite, plagioclase (An_{6-10}) and epidote. They also contain frequent highly saussuritized relicts of a labradoritic plagioclase and retain a subophitic texture.

The sequence of events can be conveniently summarized as follows:—

(a) Intrusion of gabbro sheet.
(b) Strong shearing (late F1).
(c) Basic dyke intrusion.
(d) Almandine amphibolite facies metamorphism.
(e) Folding and shearing (F2).
(f) Fenitisation, accompanied by the intrusion of syenite sheets, and alkali-feldspar net-veins.
(g) Intrusion of basic dykes.
(h) Shearing.
(i) Upper green schist facies metamorphism.
(j) Intrusion of carbonatite breccias with associated carbonate metasomatism and zeolitization.
(k) Emplacement of late coarse calcite veins.

(2) *Fenites in Metasediments.*

Fenites are developed in the metasedimentary psammites and semi-pelitic schists, though they are generally restricted to a narrow zone, only some 4 or 5 metres in width, against the contact of the aegirine-augite pyroxenite and other rocks of the carbonatite association. The fenites consist of mainly alkali feldspar (usually microperthitic), plagioclase (An_{8-10}), and hastingsitic amphibole. Accessory minerals include sphene, zircon, apatite, biotite, allanite, magnetite, pyrite, melanite (only observed in one thin section), and occasional small grains of pyrochlore. Small amounts of quartz are present in some of the rocks, but this depends upon the extent of fenitization. Secondary minerals include calcite and zeolite.

The parent rocks from which the fenites have arisen are psammites and semi-pelitic schists of the Klubben Quartzite formation. The general mineralogy of these rocks is quartz, plagioclase (An_{25-34}), alkali feldspar (usually microcline), biotite and magnetite with accessory zircon. Many of the semi-pelitic schists also contain almandine garnet. As the narrow zone of fenitization is approached the reduction in the amounts of quartz and biotite and the alteration of plagioclase (An_{25-34}) are noted. Such changes are accompanied by the development of perthitic alkali feldspar and of albite/oligoclase as the contact with the rocks of the carbonatite association is approached. Also significant is the development of aegirine-augite (Table 20), particularly

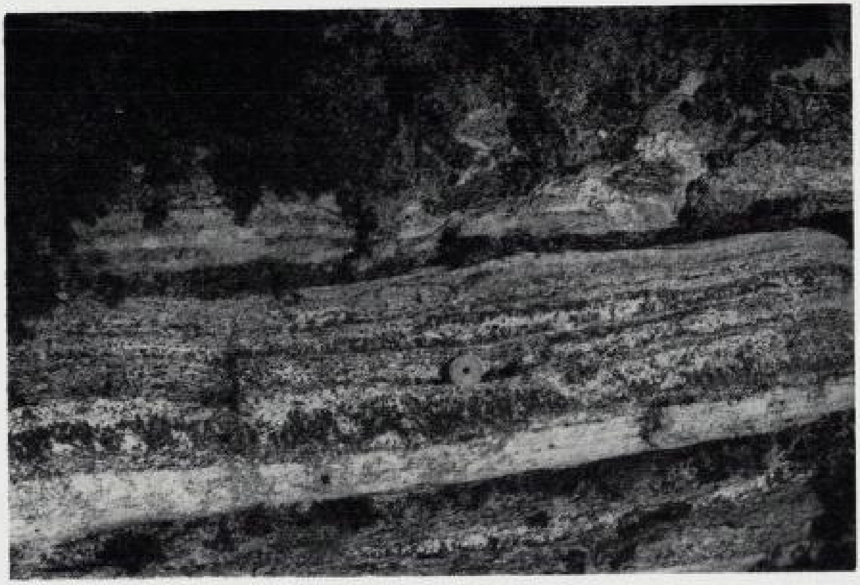

Fig. 36. Fenites developed in semi-pelitic schists and psammite. Note how the aegirine-augite crystals grow with random orientation across the banding. Roadside exposure south of football ground, Breivikbotn.

along pelite bands, at the expence of biotite. Near the contact with the aegirine-augite pyroxenite there is an increase in the amount of aegirine-augite, often growing as large bladed porphyroblasts up to 2.5 cm. in length. These porphyroblasts cut indiscriminately across the schistosity (Fig. 36), and in some cases the mineral may form the dominant constituent of the fenites (Table 4). Even in such examples where the fenites shows evidence of basification there can be no doubt of the original metasedimentary nature of the parent material. One of the most marked features of the fenitization is the development of a microperthitic alkali feldspar at the expense of an apparently homogenous variety. This phenomenon is also commented upon in descriptions of fenites from Alnö by Von Eckerman (1948) and from Fen by Saether (1957). Similar mineralogical and textural changes may be observed in the inclusions of metasedimentary country rocks contained in the syenites associated with the carbonatite.

(3) *Syenites.*

Associated with the carbonatites is a group of syenites of variable composition. These can be considered under two broad headings: (a) melanocratic syenites approaching shonkinite in composition and (b) coarse grained leucocratic syenites. These appear to be sheet-like bodies and to have been intruded in the order shonkinite—leucocratic syenite. Frequent examples of the leucocratic syenites net-veining and intruding the shonkinites as cross-cutting sheets are to be observed (Fig. 37). Both types are intruded by rare later sheets of syenite aplite, and by basic dykes.

(a) *The Shonkinites.*

On the shore section at Haraldseng (Fig. 34) a group of variable syenites which approach shonkinite in composition (Table 17) occur above the aegirine—augite pyroxenite. These syenites are separated from the pyroxenite by a carbonatite breccia which contains abundant fragments of both rock types. The shonkinites are fairly coarse grained rocks and consist essentially of varying proportions of the minerals

Fig. 37. Shonkinite net-veined by leucocratic syenites. Haraldseng.

Fig. 38. Shonkinite showing streaky banding. Haraldseng.

alkali—feldspar, albite/oligoclase, zeolite (after feldspar), aegirine—augite,[1] hastingsitic amphibole,[1] melanite, and calcite. The numerous accessory minerals include sphene, apatite, allanite and pyrite which are almost ubiquitous; and less frequently zircon, biotite, phlogopite, magnetite, ilmenite, analcite, and rarely pyrochlore (Table 5). The shonkinitic syenites are rocks of very striking appearance and are often banded with alternating melanocratic and leucocratic bands, the chalky-white zeolites making very strong contrast with the black amphiboles, garnets and pyroxenes (Fig. 38). The banded appearance of the shonkinites is partly due to the presence of thin sheets of leucocratic syenite, though it can be demonstrated to be mainly related to the strong shearing that the syenitic rocks have undergone and to be a tectonic structure. The shonkinites have suffered extensively from hydrothermal alteration and carbonate metasomatism.

It appears that the shonkinites originally consisted of varying proportions of plagioclase (An_{5-11}), alkali feldspar, aegirine—augite and hastingsitic amphibole, with accessory sphene, allanite, apatite, iron ore, zircon, and pyrochlore (occasionally found as inclusions within alkali

[1] Detailed studies of the individual minerals have not yet been undertaken.

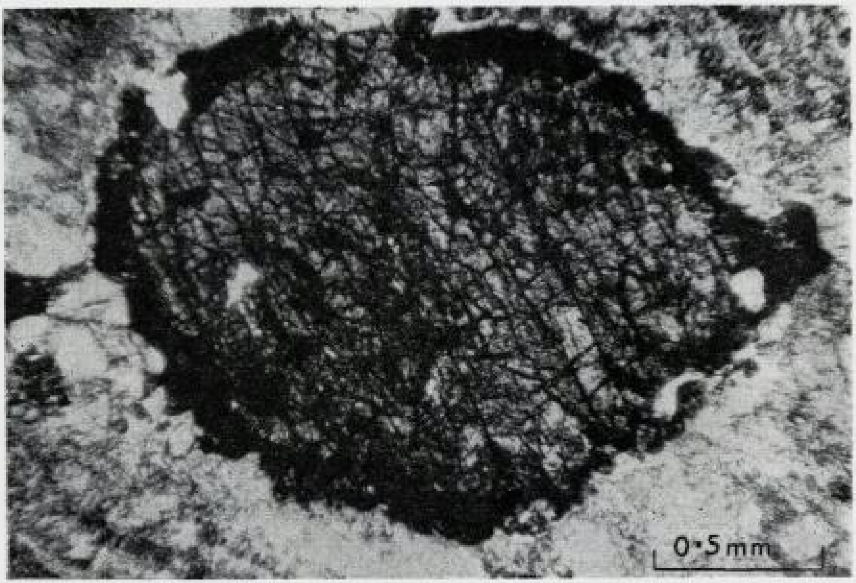

Fig. 39. Aegirine-augite crystal rimmed by ferro-hastingsite in shonkinite. Plane polarized light. (Slide no. SB.91.)

Fig. 40. Aegirine-augite crystal rimmed by hastingsite, but also containing inclusions of hastingsite of different orientation. Note the partial zeolitization of the groundmass feldspar mozaic. Shonkinite. Plane polarized light. (Slide no. SB.5.)

feldspar). The feldspars occur either as a fairly even grained polygonal groundmass mosaic or as larger phenocrysts of alkali feldspar up to 2 cm. in length. The alkali feldspars vary from microcline to orthoclase and are usually perthitic. In many cases the hastingsitic amphibole forms irregular rims around crystals of aegirine–augite (Fig. 39), however, many examples of both intergrowths of amphibole within pyroxene and of pyroxene in amphibole occur (Fig. 40); indicating that at least some of the amphibole crystallised with the pyroxene. Garnet has always developed subsequently to the crystallisation of the amphiboles and the pyroxenes. The garnets are very irregular in their distribution, and in some rocks large irregular garnet grains may account for a considerable part of the volume of the rock (Table 5). The garnet crystals are usually zoned from a central dark reddish brown core (p/p light) to a pale yellow margin, other examples have alternating zones of these colours. The larger garnet crystals often contain inclusions of pyroxene and amphibole. They also have numerous inclusions of sphene which often have their long axes concentric with the zonal structure of the garnet. Concentrations of garnets are sometimes found to follow shear zones in the shonkinites. This feature along with the evidence of late crystallisation and their generally patchy occurrence indicate that the garnets do not form part of the original mineral assemblage of the shonkinites, and that they probably are the result of the metamorphism of the syenite. The metamorphism of the syenite is also indicated by the fact that basic dykes intruded into both shonkinites and the leucocratic syenites are now in the condition of albite-epidote amphibolites.

The shonkinites and leucocratic syenites have been very strongly deformed along irregularly spaced shear-planes. The deformation also affects the basic dykes, intruded into these rocks, which in some instances are folded into 'gleitbretter' folds (Figs. 41 a and b) with a steep plunge. Other dykes are shredded out into lenses whose long axes are aligned parallel to the shear planes in the syenites (Fig. 42). The banded structure observed in the shonkinites and the leucocratic syenites can be demonstrated to be mainly of tectonic origin, and consists of relatively more melanocratic and more leucocratic bands parallel to the shear planes. In detail this banding is parallel to the axial planes of the 'gleitbretter' folds (Figs. 41 a and b). An examination of thin sections of the syenites reveals that the mafic minerals have been mechanically broken down along the shear planes. A second generation of apatite and sphene has, however, developed after the shearing movements ceased, and long

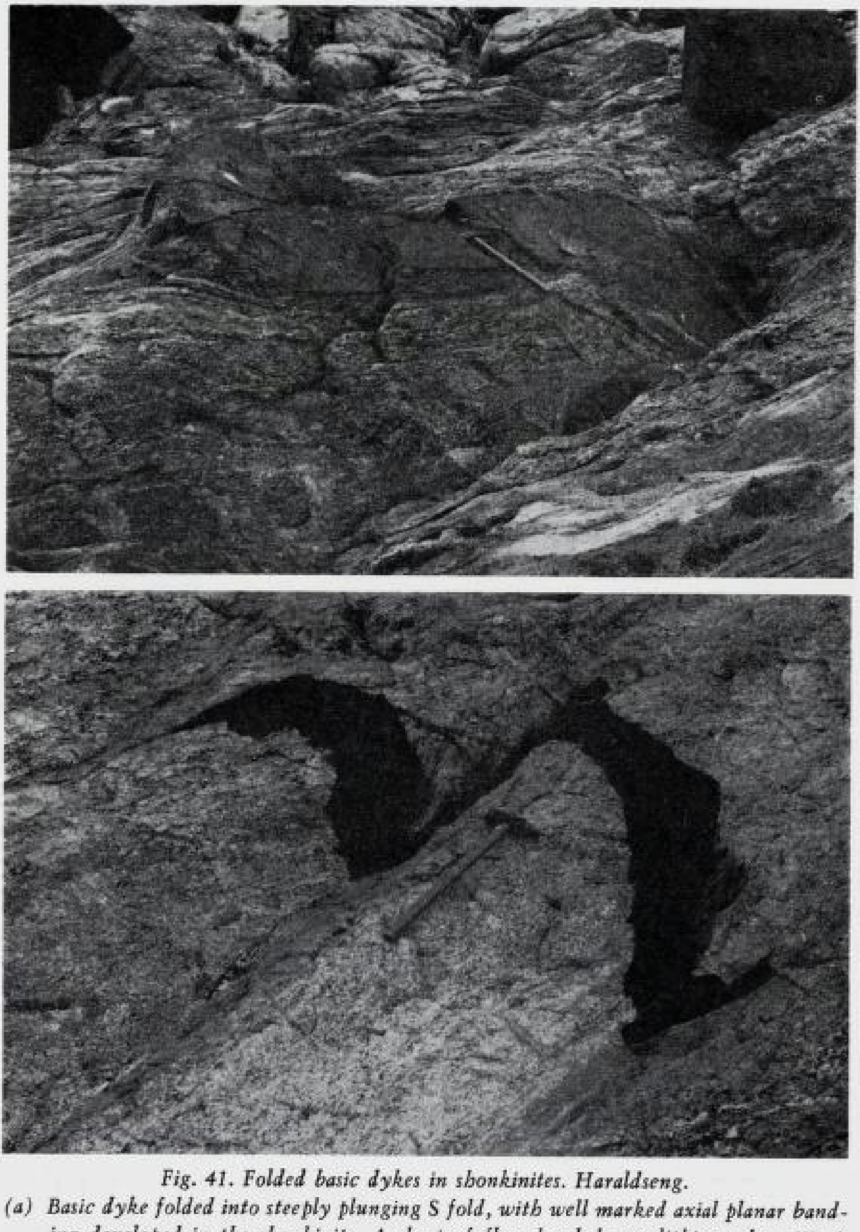

Fig. 41. Folded basic dykes in shonkinites. Haraldseng.

(a) Basic dyke folded into steeply plunging S fold, with well marked axial planar banding developed in the shonkinite. A sheet of flow-banded xenolithic carbonatite is intruded parallel to this banding and is seen in the foreground.

(b) Basic dyke folded into 'Gleitbretter' folds. Thin sheets of undeformed carbonatite are intruded along the axial planar shear zones.

Fig. 42. Highly deformed basic dyke material in shonkinite. Baarvik.

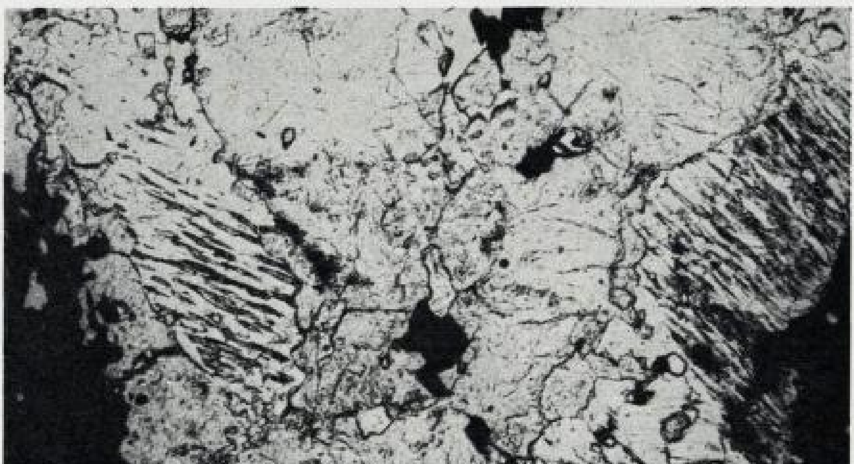

Fig. 43. Zeolitization of leucocratic syenite showing preferential alteration of lamellae in large perthite phenocrysts. Plane polarized light. (Slide no. SB.72.)

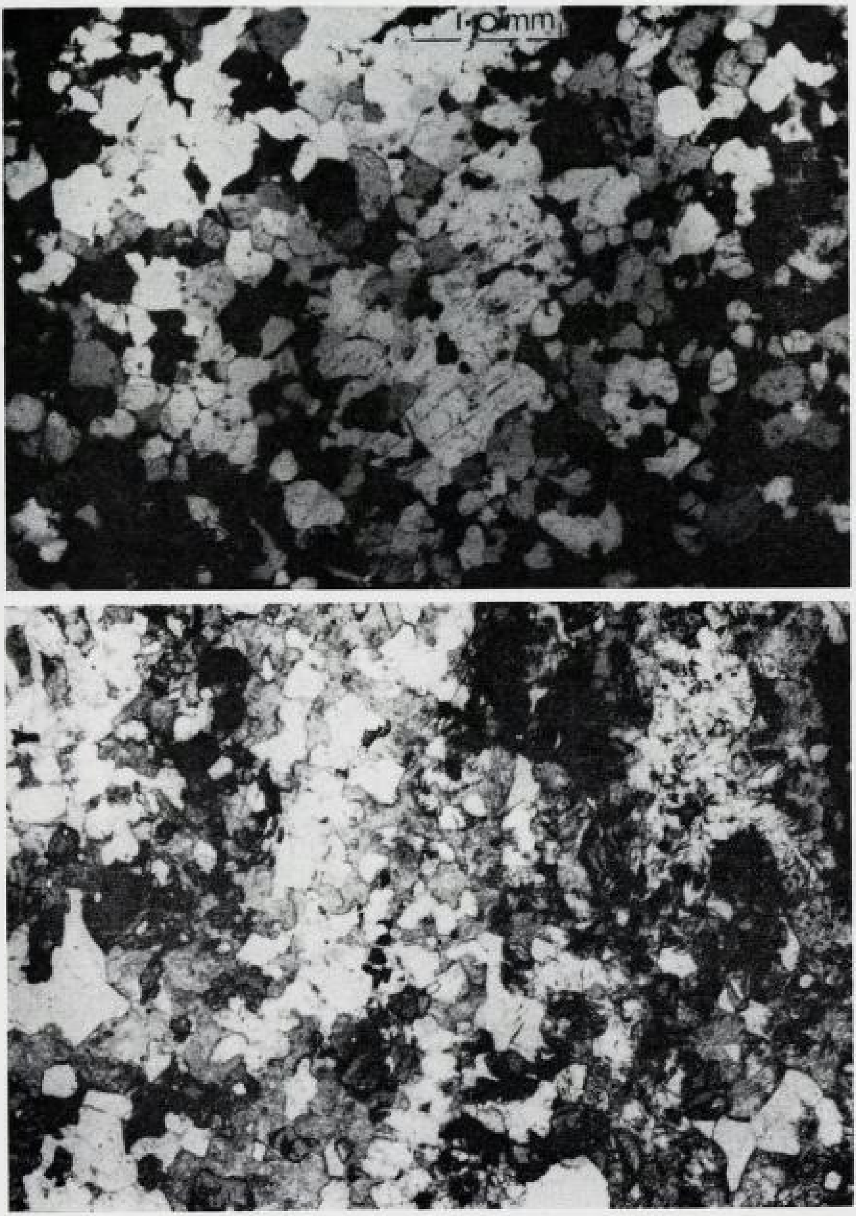

Fig. 44. Zeolitization of shonkinites.

(a) Unaltered shonkinite showing feldspar grain boundary pattern. X-polarized light. (Slide no. SB.262.)

(b) Partially zeolitized shonkinite. (Slide no. SB.5.) Same scale as 44 (a).

tapering euhedral crystals of these minerals occur in syenites that contain highly fractured aegirine-augite, amphibole and melanite.

The shonkinites have also been strongly affected by a phase of fairly intense hydrothermal alteration mainly producing zeolite at the expense of feldspar. The hydrothermal alteration is most marked in the zones of strongest shearing, and is found to selectively follow shear planes. In some instances the zeolitization is pervasive and the shonkinites become chalky-white rocks studded with black melanocratic minerals. From the examination of a large number of thin sections of these rocks the zeolite can be shown to be secondary after feldspar, and series of specimens can be collected which demonstrate the progressive alteration of alkali feldspar phenocrysts. In the least affected rocks the zeolitization has taken place at the margins of feldspar grains and along cracks in the feldspars. In rocks which contain large perthitic alkali feldspar phenocrysts it is possible to observe, in some cases, how the perthite lamellae have been selectively altered into zeolite (Fig. 43). As indicated earlier the groundmass feldspar usually forms a polygonal grain mosaic, and even in the most completely zeolitized rocks the polygonal grain mosaic pattern is preserved as a relict structure by minute dusty inclusions within the zeolite fibres, (Figs. 44 & 45). The zeolites generally have a fibrous habit and have a tendency to be grouped into sheaves or rosettes. Zeolite with a more tabular habit has sometimes crystallised in cracks within the melanocratic minerals. No systematic study of the zeolites has yet been undertaken but they appear to be mainly natrolite and thomsonite.[1]

The shonkinites have also been much affected by a late phase of carbonate metasomatism, associated with the emplacement of carbonatite. The secondary carbonatization follows preferentially along the strong shear zones in the shonkinites as indeed do sheets of carbonatite which show no signs of subsequent deformation. The carbonate, which is almost entirely calcite, forms irregular areas and patches in the syenites and is invariably a secondary mineral (Fig. 46). The order of crystallisation between zeolite and calcite is difficult to establish in many instances, though calcite does generally appear to be the later mineral. Many of the melanocratic minerals in the shonkinite, especially in the most deformed portions are cracked and fractured, and the cracks are now infilled with either calcite or zeolite. In some cases, particularly well shown on the Haraldseng shore section, the amount of secondary

[1] Determinations by Dr. G. P. L. Walker of Imperial College, London.

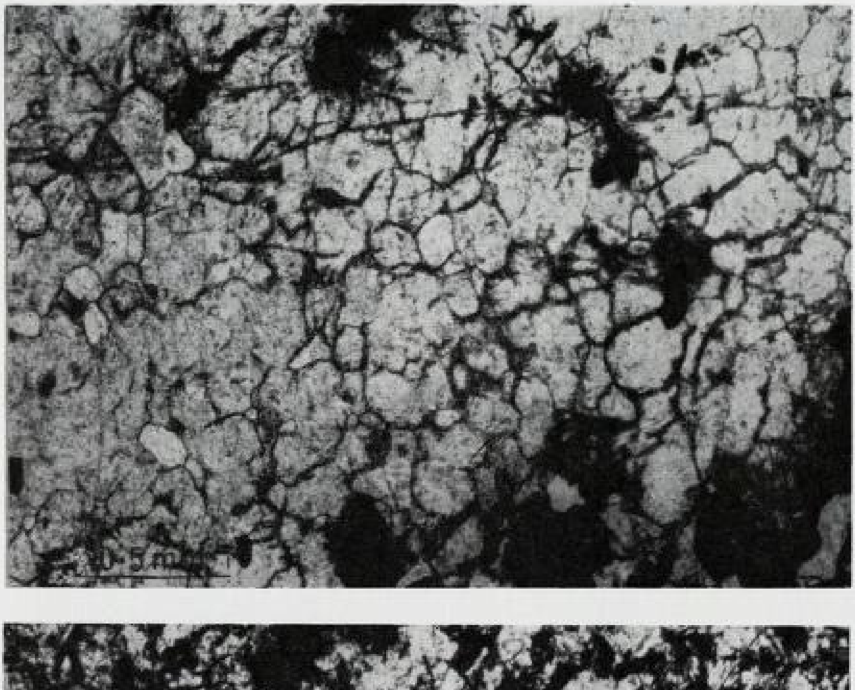

Fig. 45. Relict grain boundary pattern (feldspar) preserved in completely zeolitized shonkinite. (Slide no. SB.64.)
(a) Plane polarized light.
(b) X-polarized light.

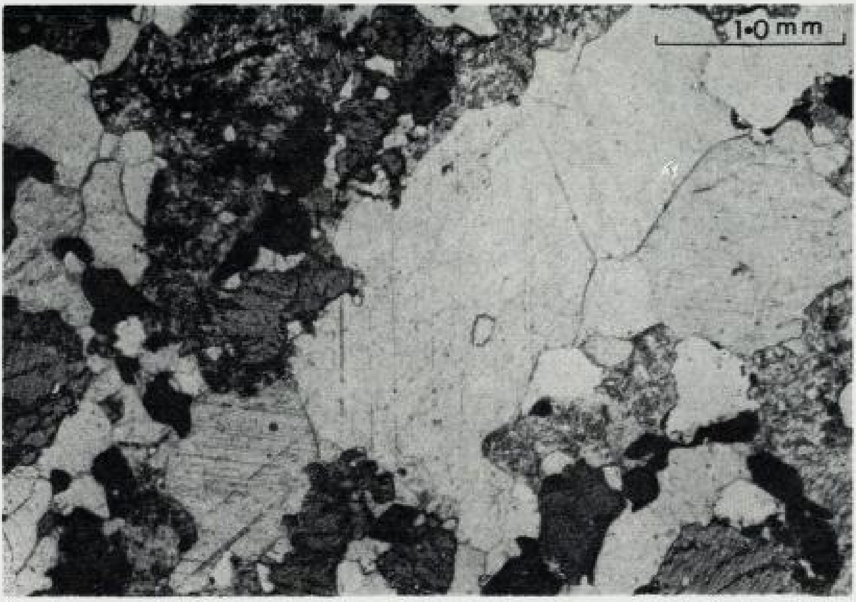

Fig. 46. Secondary calcite developed in zeolitized shonkinite. X-polarized light. (Slide no. SB.5.)

calcite developed is so great that it becomes difficult to distinguish such rocks from carbonatite in hand specimen. Accompanying the carbonate metasomatism of the shonkinites has been the formation of segregations and veins of coarse granular calcite, garnet and pyroxene. The pyroxenes in such segregations form perfectly euhedral crystals and may be up to 2 cm. in length. The black lustrous garnets may be up to 5 cm. in diameter and are perfectly euhedral. The analyses of a garnet and a pyroxene crystal from one such segregation are presented in Table 20. These veins and segregations are undeformed and later than the strong shearing movements which have affected the shonkinites.

The contacts between the shonkinites and the adjacent rock types are poorly displayed, due in part to the fact that they are margined by carbonatite breccias, on the shore section at Haraldseng. However, the aegirine-augite pyroxenite is cut in places by thin sheets of highly sheared shonkinitic syenite. At Baarvik the contact between syenites and metasediments (Klubben Quartzite) occurs and the highly schistose syenites are observed to have a slightly cross-cutting relationship to the structures in the metasediments. In one locality near Haraldseng part of the original contact between shonkinite and metasediments is preserved, and is markedly transgressive (Fig. 52). The contact is sub-parallel to the axial plane of a large F2 antiform. The shonkinitic syenites are cut, in many places, by sheets and net-veins of leucocratic syenite, and abundant blocks of both shonkinitic and leucocratic syenites occur in the carbonatite breccias. On the shore-section at Baarvik several large rafts of semi-pelitic metasediment are included in the shonkinites. These metasedimentary inclusions have been extensively fenitized and are now syenite gneisses, though many relicts of their metasedimentary parentage are present. The rocks of the inclusions are often folded by F2 minor folds, of similar style to those occurring in the country metasediments, with fold axes plunging at about 8° towards 354° and axial planes dipping 62° towards the west with a 186° strike. Thin sheets of carbonatite breccia occur sub-parallel to the axial planes of some of these minor folds.

(b) *The Leucocratic Syenites.*

The leucocratic syenites at Haraldseng are always later than the shonkinites. They often show slight variations in mineral content from outcrop to outcrop, but because of the very poor inland exposures it has proved impossible to sub-divide them in terms of the field mapping. Generally they consist of alkali-feldspar, biotite, sphene, with accessory allanite. They also contain varying amounts of the minerals aegirine-augite, hastingsitic amphibole, muscovite, pyrite, magnetite, plagioclase (around An_8), apatite and zircon (Table 6). Zeolite is often present as a secondary mineral after feldspar, and also varying amounts of secondary calcite. Where the leucocratic syenites contain a considerable amount of secondary calcite they have a very rotten weathered appearance in the field.

The most typical variety of the leucocratic syenites north of Haraldseng is a highly feldspathic syenite which is frequently pegmatitic, containing feldspars up to 15 cm. in length though feldspars up to 30 cm. long have been recorded. These syenites have also been affected by the late shearing movements and are sometimes highly schistose, and large feldspar grains are much shattered (Fig. 47). The feldspars in the coarser leucocratic syenites always have two habits (a) as small clear polygonal grains of alkali feldspar and occasionally albite forming a groundmass mosaic, and (b) as large phenocrysts of alkali feldspar

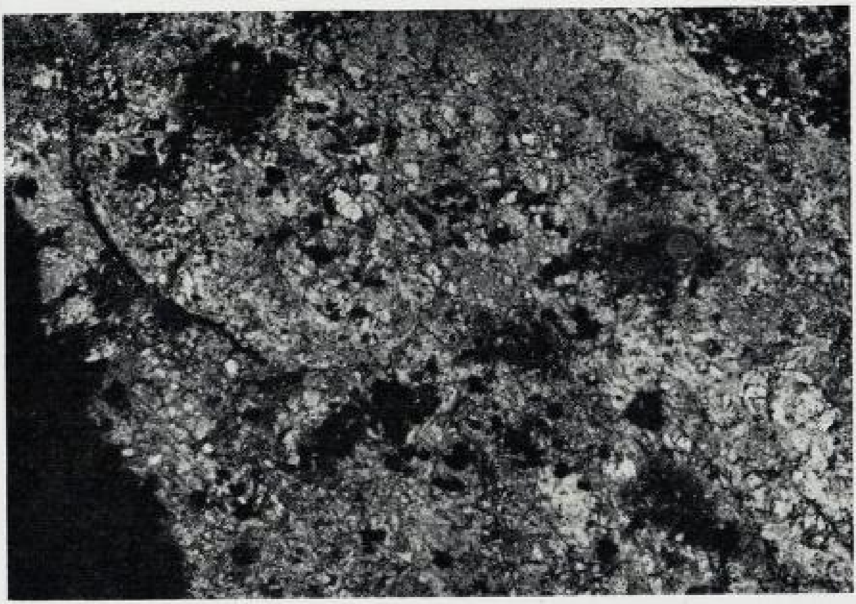

Fig. 47. Coarse leucocratic syenite showing fracturing of feldspar phenocrysts. 1 km. north of Haraldseng.

which in some rocks are nonperthitic and in others have a well developed perthitic structure. The types of perthite vary from very fine hair-like microperthite to coarse vein and patch types, which may all occur in the same thin section. The coarse vein and patch types often have the appearance of metamorphic porphyroblasts and have extremely irregular grain boundaries. The hair-perthite phenocrysts contain many dark near opaque needle shaped inclusions that are probably rutile. The leucocratic syenites north of Haraldseng are generally nonschistose and massive except where they have been sheared.

Sheets and net-veins of the leucocratic syenite have been described cutting the shonkinites (p. 60), and at one locality about 1 km. north of Haraldseng a large lens of shonkinite some 100 m. in length is included in the leucocratic syenites. Thin sheets of the syenite also occasionally cut the aegirine-augite pyroxenite. The contact of the leucocratic syenites with the country metasediments is unfortunately not exposed. Along the small road leading to the settlement of Haraldseng, however, a dyke of pegmatitic leucocratic syenite intrudes the metasediments and cuts certain of the basic dykes within these rocks. This pegmatite is very similar to the syenites described above and is composed of perthitic alkali feldspar, with minor amounts of hastingsitic amphibole, biotite and sphene also secondary pyrite and calcite. Magnetite also occurs in this pegmatite as conspicuous well-developed octahedra up to 5 cm. in diameter. The pegmatite is cut by basic dykes similar to those cutting the syenites of the main outcrop. Another such pegmatite, at the top of the gully leading down to the shore-section at Haraldseng, cuts both shonkinite and the fenitised metasedimentary country rocks, and is itself intruded by carbonatite breccia. The pegmatite contains prominent crystals of hastingsitic amphibole up to 17 cm. in length (Fig. 48). The effects of the late shearing are well shown in the pegmatite and the large amphibole crystals are often cut by shear planes which divide them up into sectors with differing orientation, and in some cases the amphibole has been granulated along the shear planes. The feldspars also exhibit strain shadowing, bent twin lamellae and granulation. A later crystallisation of amphibole is shown by an example of slender amphibole crystals which have grown with a radial habit coating a joint surface.

To the south of Baarvik the leucocratic syenites are of somewhat finer grain, though occasional examples of more pegmatitic varieties do oc-

Fig. 48. Pegmatitic leucocratic syenite with large hastingsite crystals. Haraldseng.

cur. Exposures in this southern area are, however, extremely poor. Aegirine-augite is present in most of the syenites of the southern outcrop generally as irregular clusters of quite small grains, though occasional sub-hedral crystals up to 1 cm. in length have been observed. In the poorly exposed southern belt most of the exposures encountered are of leucocratic syenite, though it would appear from changes in the vegetation that considerable quantities of carbonatite are probably present beneath the surface. Traverses with a protonmagnetometer, in areas of good exposure, show that the syenites and carbonatite are readily distinguishable in terms of their magnetic effects. The carbonatite always produces a large magnetic anomaly (often several thousand gammas) owing to its fairly high magnetite content. Preliminary traverses in the southern belt of poor exposure revealed the presence of anomalies of the same order indicating the presence of carbonatite beneath the cover of superficial deposits (Dr. M. Brooks personal communication). It is intended to carry out a detailed magnetic survey of the belt to enable the limits between syenite and carbonatite to be mapped with confidence.

(c) *Syenite—Aplites.*

Fine grained cross-cutting sheets of syenite aplite are of rare occurrence in rocks of the carbonatite association, though two irregular sheets are found on the Baarvik shore-section. One of these, about a metre in thickness, intrudes the marginal metasediments and cuts through into the aegirine-augite pyroxenite. This sheet of syenite-aplite is in turn truncated by carbonatite and blocks of it have been found in the latter. A second sheet of syenite-aplite cuts coarse-grained leucocratic syenite. The syenite-aplites at Baarvik have a hypidiomorphic texture and are practically pure feldspar rocks (Table 6, no. 8). The feldspar are albite (An_{3-5}) and microcline. The syenite-aplites also contain rather ragged grains of aegirine-augite, interstitial calcite and apatite.

A further example of a syenite-aplite sheet cuts the aegirine-augite pyroxenite at the Haraldseng shore-section. This rock has a fine-grained granular groundmass of albite (An_6) and alkali feldspar with sporadic irregular phenocrysts of perthitic alkali feldspar and clusters of aegirine-augite grains. Accessory minerals are biotite, sphene (often euhedral), apatite, magnetite with secondary pyrite and calcite. The syenite-aplite sheet is schistose, the schistosity being defined by the alignment of the melanocratic minerals. It is impossible, at this exposure to see the relationships between the syenite aplite and either the shonkinites or the leucocratic syenites as it is abruptly truncated by carbonatite breccias.

(d) *Basic dykes intrusive into the syenites and their metamorphism.*

A series of diabase dykes intruded the shonkinites and leucocratic syenites before the late shearing movements (Fig. 41, 42). Blocks of the basic dyke materials occur in the carbonatite breccias. The rocks of the basic dykes have been strongly metamorphosed and develop the typical assemblages plagioclase (An_{6-12}), green-brown hornblende, and biotite with accessory sphene, epidote and magnetite. In some instances relict augite crystals can be observed which are incompletely altered into hornblende. Patches persist, particularly in the centres of the dykes, of highly saussuritised basic plagioclase (too altered to determine composition) associated with sub-rectangular areas of granular albite/oligoclase and pale green epidote (after basic plagioclase). These preserve a relict sub-ophitic texture with the mafic minerals. The mineral assemblage developed is characteristic of the upper part of the Green Schist Facies (Fyfe, Turner and Verhoogen 1958), and indicates the minimum grade of metamorphism that has affected the shonkinites and the leucocratic syenites. Diabase dykes that develop a similar metamorphic assemblage are intrusive into the nepheline syenites of the area (p. 15 & 40). The authors have also observed basic dykes, of similar type and grade, intruded into the nepheline syenite mass at Nabberen on Stjernöy. In the mine-addit at Lillebugt, on Stjernöy, carbonatite breccia is intrusive along the contact of the nepheline syenite body and is observed to contain blocks of the diabase dyke material. These features imply a major phase of basic dyke intrusion in the region after the emplacement of most of the alkaline rocks but earlier than that of the carbonatites.

On the shore-section at Haraldseng the diabase dykes occasionally develop some aegirine-augite and hastingsitic amphibole, in their marginal zones, at the expense of hornblende. In one example small irregular veinlets of albite/oligoclase and aegirine-augite are developed in a diabase dyke. Such features imply a limited migration of constituents across the contacts of the dykes and the enclosing syenites during their metamorphism.

A basic dyke of unusual type is intruded into the shonkinites on the shore-section at Baarvik; this has a very fine-grained texture with sub-hedral to euhedral crystals of melanite, aegirine-augite, hastingsitic amphibole, sphene and apatite set in a groundmass of calcite and zeolite. There is no evidence which would indicate that this rock was ever a diabase and it is perhaps best considered as a minor intrusion associated with the carbonatites.

(4) *The Carbonatites.*

Intrusive and metasomatic carbonatitic rocks are to be found at several localities near Breivikbotn. The principal occurrences are associated with the belt of syenitic rocks and fenites described above. Carbonatites are abundantly associated with these rocks and their relations are best displayed on the shore-sections at Baarvik and at Haraldseng. The exposures to the north of the Haraldseng shore-section are generally rather poor in carbonatite, though well-developed carbonatite breccias occur to the east of Kölevann. To the south-east of Baarvik the exposures are extremely poor and relatively little carbonatite is to be encountered at the surface. It appears, however, from the preliminary magnetic profiles (p. 73) that considerable quantities of carbonatite are now obscured by drift.

The carbonatites of the main belt occur as an earlier series of sheets and as a later of coarse calcite net-veins. Intrusive and metasomatic carbonatitic rocks also occur on the coast section about ½ km. south of Baarvik and about 1 km. east of Sörvaer.

(a) *Carbonatite Sheets.*

The principal occurrences of carbonatite are of a sheet-like form and they vary from breccias through xenolithic carbonatite to non-xenolithic sheets. The carbonatites have somewhat variable compositions as is shown by Tables 7 and 19. They generally consist of calcite, aegirine-augite, amphibole, sphene, and apatite with minor amounts of allanite and ore minerals (principally magnetite and pyrite). Melanite garnet is present in some samples and small amounts of biotite in others. At Baarvik, on the shore-section, a distinctive variety of carbonatite occurs and contains irregular pseudo-hexagonal books of biotite up to 8 cm. in diameter. These outcrops are, however, very badly weathered and it proved impossible to collect adequate samples for analysis. Some of the carbonatite specimens contain considerable amounts of feldspar (Table 7 nos. 5 and 6). These samples, however, are of carbonatite breccias which contain many fragments of syenitic rocks; they are also the only specimens examined which are completely free of pyroxene. Other minerals found in the carbonatite are zeolite (probably after feldspar), and in one sample zircon.

The pyroxene is generally an aegirine-augite, though in one case (SB 595) it is nearer diopside-hedenbergite. The amphibole is usually a hastingsite or ferro-hastingsite. The mafic minerals do not normally show good crystal shapes, and particularly in the breccias they are much fractured and broken in a matrix of calcite that forms a polygonal grain mosaic with stable triple-point junctions. In some cases, even in the breccias, occasional small amphibole and pyroxene crystals show sub-hedral to euhedral shapes. In the non-xenolithic carbonatite sheets the smaller amphibole crystals are often sub-hedral or euhedral and pyroxene crystals subhedral. It is difficult to be certain of order of crystallisation of pyroxene and amphibole in the carbonatites, though generally amphibole is later than pyroxene and forms irregular rims around the latter mineral. Some examples are however observed of small oriented inclusions of amphibole in the pyroxene, which may indicate that the crystallisation of amphibole and pyroxene to some extent overlapped. It will be recalled that a similar situation exists in other rocks of this assosiation. Both minerals contain inclusions of calcite and small sphene crystals which are often euhedral. Melanite garnet where it occurs either forms semi-continuous rims around pyroxene and amphibole crystals or forms clusters of minute grains around these minerals.

Sphene is a prominent accessory mineral in the carbonatites (Table 7), and occurs as inclusions of small often euhedral crystals in pyroxene, amphibole, and garnet, and as fractured, broken and sometimes rounded grains in the groundmass particularly of the breccias. It also occurs as slender tapering euhedral crystals up to 3 cm long, particularly in the non-xenolithic sheets of the shore-section at Haraldseng. In some examples reddish-brown sphene occurs in sheaves. Apatite has a similar manner of occurrence to that of sphene. In some of the carbonatite sheets on the Haraldseng shore-section long pale green apatite crystals up to 5 cm. in length have been collected. These are invariably euhedral and have well developed crystal faces. It will be noted from Table 7 that the highest concentrations of apatite in the carbonatites (7.7 %) are very similar to values listed by Strand (1951) for the biotite-sövites of Stjernöy.

The carbonatites contain abundant magnetite which varies from small grains to large lensoid segregations (the largest found was 48.5 × 19 × 13 cm.). The bigger segregations usually have euhedral crystals of sphene around their margins. The presence of considerable quantities of magnetitein the carbonatites is reflected by magnetic anomalies with intensities of several thousand gammas. It is of interest to observe in this context that a large number of what appear to be hold shallow trial diggings occur in the unexposed ground south-east of Baarvik, and the preliminary magnetic survey indicates the magnetic anomaly to be high at such places. At the southern extension of the carbonatite/syenite belt there occur three large old pits, called the 'Russene Gruve' and the indications are that these represent ancient iron workings.

On the shore-sections of Haraldseng and Baarvik there occur carbonatite breccias and sheets of highly xenolithic carbonatite along with sheets of carbonatite that only contain occasional xenoliths. The carbonatites are intrusive into the surrounding rocks and cut sharply across the banding of the marginal metasediments. The carbonatite breccias and highly xenolithic carbonatite sheets at Haraldseng are intruded along the margins of the syenitic rocks. A sheet of carbonatite breccia some 5 m. thick is intruded along the contact between shonkinites and the aegirine-augite pyroxenite. This breccia contains fragments of shonkinite, leucocratic syenite, syenite pegmatites, aegirine-augite pyroxenite, various metasediment types, basic dyke material, hornblende schist, and also a fine-grained syenite consisting of albite (An_6), alkali feldspar, aegirine- augite and melanite which forms small interstitial grains (often euhedral). This last named rock type has not been discovered *in situ* in the area, though several blocks of similar material have been discovered in other exposures of carbonatite breccias. The blocks in the breccias vary from angular to fairly rounded and show considerable variation in size. They usually show signs of strong deformation, being often spindle shaped or lensed, and slivers of basic dyke material have been strongly flayed out or folded (Figs. 49 and 50). The breccias thus have the appearance of tectonic breccias. Within the breccias the melanocratic minerals have been broken and fractured and there has been subsequent recrystallisation of the calcite into a polygonal grain mosaic and growth of euhedral crystals of apatite and sphene. The temperatures presumably not being high enough to initiate the recrystallisation of the pyroxenes, amphiboles and garnets.

The carbonatite breccias above the syenites at Haraldseng have a

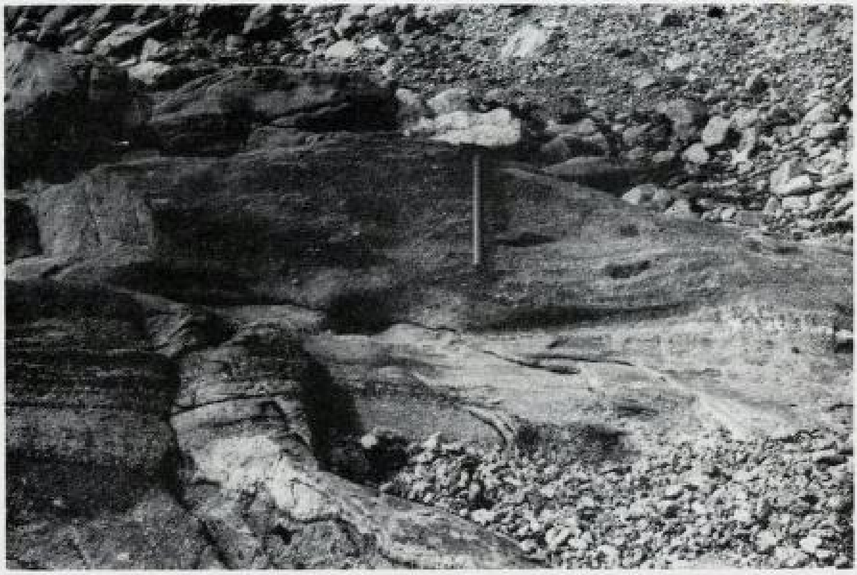

Fig. 49. Carbonatite breccias with spindle shaped inclusions. Haraldseng.

Fig. 50. Carbonatite breccias with angular fragments of leucocratic syenite, intruded into leucocratic syenite.

conspicuous banding of light and dark minerals. This is apparently a flow banding and is observed to swirl around xenoliths. The long axes of the fractured prismatic minerals lie parallel to this banding. The carbonatite breccias have an intrusive contact with the marginal metasedimentary schists (Figs. 51 and 52), which have been variably fenitised. The country rocks, at this locality, have a dip of 67° towards the east and a strike of 177°, and lie on the steep eastern limb of an F2 antiform. The banding in the carbonatite breccias is markedly oblique to this and has a dip of 36° towards the west with a strike of 025°. Slivers of both shonkinitic and leucocratic syenites are cut off by the carbonatite breccias along their contact with the metasediments (Fig. 52). Both of the syenitic rocks have fairly gently westward dipping contacts which sharply transgress the structures in the metasedimentary country rocks. Irregular sheets and dykes of carbonatite stem from the banded breccias and penetrate the metasediments along prominent joints. The breccias here contain many fragments of shonkinite, leucocratic syenite, aegirine-augite pyroxenite, basic dyke material, and fenitised metasediment. The banding in the carbonatite breccias is sensibly parallel to the axial plane of the large F2 fold mentioned

Fig. 51. Intrusive contact of carbonatite into sheeply dipping metasedimentary country rocks. Haraldseng.

Fig. 52. Detail of Fig. 51. This illustration shows an intrusive contact of shonkinite into metasediment (above hammer) sliced through by flow-banded carbonatite. Note how flow-banding swirls around xenoliths.

above, and the authors consider that the carbonatite breccias have been emplaced into their present position during the late stages of the F2 movements. A syn-kinematic emplacement of the breccias would of course account for the strong deformation seen in the fragments. The carbonatite material of the breccias is thought to have crystallised at some distance from their present position, and to have been mobilised under stress. It is considered that the carbonatite breccias were emplaced in the solid state, movement taking place by plastic flow. The calcite and some of the sphene and apatite has obviously recrystallised after emplacement to give the polygonal grain mosaic texture, whilst the mafic minerals of the carbonatite were much broken, fractured and milled down during the movements.

At Baarvik the main carbonatite is much more massive and is not markedly banded. It is a compact brownish weathering rock with a large number of angular, subangular and rounded xenoliths of various syenites, aegirine-augite pyroxenite, metasediments, basic dykes, and in one case a fragment of granite gneiss (Fig. 53). The mafic minerals are often broken and fractured, though in some rocks well-developed

Fig. 53. Massive carbonatite with many rounded xenoliths of varied composition, including one of granite gneiss (to right of hammer handle). Baarvik shore-section.

Fig. 54. Intrusion of xenolithic carbonatite into folded shonkinite. Baarvik shore-section.

pseudo-hexagonal books of dark mica up to 8 cm. in diameter are quite frequent in occurrence. These rocks also usually contain euhedral crystals of amphibole and pyroxene. At places on the shore section at Baarvik the carbonatite is sharply intrusive into the shonkinites and leucocratic syenites (Fig. 54). The carbonatite in such instances frequently contains a profusion of fragments of the banded syenitic rocks, which are usually elongated parallel to the walls of the carbonatite sheets giving them a banded appearance. Large rafts of metasedimentary material have been described (p. 70) as occurring in the syenites at this locality. Within these, narrow veins and dykes of carbonatite breccia follow the axial planes of F2 folds. Small segregations of calcite and garnet also occur parallel to the *ac*—joints of the folds.

Many of the rocks associated with the carbonatites become strongly carbonatised with the introduction of considerable quantities of calcite. This is particularly marked in the field, in the case of the aegirine-augite pyroxenite where there is a considerable colour contrast between the black pyroxenite and the brownish-white secondary calcite (Fig. 55). As the pyroxenite is traced northwards from the Haraldseng shore section there is a progressive increase in the amount of introduced calcite, until east of Kölevann it passes into flow-banded carbonatite breccia which forms a sheet up to 10 m. thick. This contains abundant fragments of aegirine-augite pyroxenite (most common), shonkinitic and leucocratic syenites, basic dyke and hornblende schist fragments and assorted metasedimentary rocks most of which show signs of fenitization (Fig. 56). At its northern extremity the carbonatite thins and fingers out along the schistosity of the country rocks, where it is involved in a number of asymmetrical folds which plunge approximately 25° towards 225°.

On the shore-section at Haraldseng thin sheets of carbonatite are intruded into the shonkinitic syenites. The thickness of these sheets does not exceed 4 m. and is often much less. The carbonatite sheets only contain sporadic xenoliths of syenite and basic dyke material of local derivation. The carbonatite is banded, the banding being the result of differences in the relative proportions of light and dark minerals. This banding is observed to swirl around xenoliths and is considered to be a flow banding. The carbonatite in these sheets is a very handsome rock and fresh, blasted specimens show euhedral red-brown crystals of sphene up to 5 cm. in length and euhedral pale-green apatite up to 7 cm. long. Segregations of magnetite are fairly abundant. The amphi-

Fig. 55. Carbonatite breccia with xenoliths of aegirine-augite pyroxenite. 200 m. E. of Kölevann.

Fig. 56. Carbonatite with large xenolith of psammite. The inclination of the banding in the xenolith is shown by the hammer handle; the normal dip of "in situ" metasediments is seen at the top of the picture. 200 m. E. of Kölevann.

bole in these rocks is usually either euhedral or sub-hedral except where it forms irregular rims around aegerine-augite grains. The calcite again forms a polygonal grain mosaic with stable grain boundaries. Signs of deformation of the mafic minerals, so conspicuous in the carbonatite breccias, are practically absent in these rocks. The carbonatite sheets, at this locality follow the strong shear-banding in the shonkinites; this being particularly well marked where the sheets are intruded along the axial planes of folded basic dykes in the shonkinites (Figs. 41 & 42). These sheets of carbonatite are undeformed.

(b) *Late calcite veins.*

The final phase of carbonatite activity in the area was the emplacement of coarse dominantly calcite-bearing veins, which frequently follow conspicuous *ac*—joints to F2 folds. In other instances they form net-veins (Fig. 57), cutting all the surrounding rock types including the carbonatite sheets and breccias, and in some cases continue for short distances into the marginal metasediments. They are mainly composed of coarsely crystalline calcite which usually occurs as well-

Fig. 57. Late calcite net-veins cutting aegirine-augite pyroxenite. Haraldseng.

developed rhombohedra and scalenohedra. Associated with these veins are small segregations of pyrite occurring both as cubes and pyritohedra. In some instances the composition of the veins is found to be more complex and they tend to have a central zone of patchily textured material consisting essentially of calcite, zeolite, biotite and sphene, with fragmental aegirine-augite, hastingsitic amphibole and apatite having the appearance of a fine grained breccia. The large calcite crystals in the veins show little or no signs of deformation.

(c) *Other occurrences of intrusive and metasomatic carbonate rocks.*

These are to be found at two localities, the one about 150 m. to the south of the main Baarvik shore-section, and the other on a small peninsula about 1.5 kilometres east of the village of Sorvaer.

In the first of these occurrences carbonatitic rocks are found on one large shore exposure, and in a few outcrops a short distance inland. The carbonate rocks occur as a series of thin un-foliated sheets which are never more than 0.4 m. in thickness. The sheets are intruded into metasedimentary psammites and semipelitic schists and follow the axial planes of F2 minor folds (Figs. 58 a and b). The minor intrusive activity accompanying this phase of folding was fairly complicated and a number of basic and granitic sheets are also intruded along the axial planes of the F2 folds (Fig. 58 a). Many of these sheets are sheared,

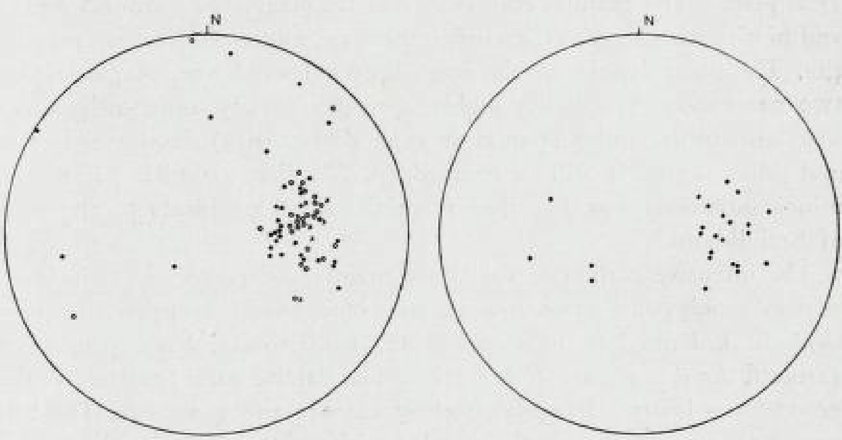

Fig. 58. Relationships of minor intrusions to F2-folding south of Baarvik.
(a) Poles to margins of carbonatite sheets (crosses); granite sheets (open circles) and basic sheets (solid dots).
(b) Poles to axial planes of F2-folds.

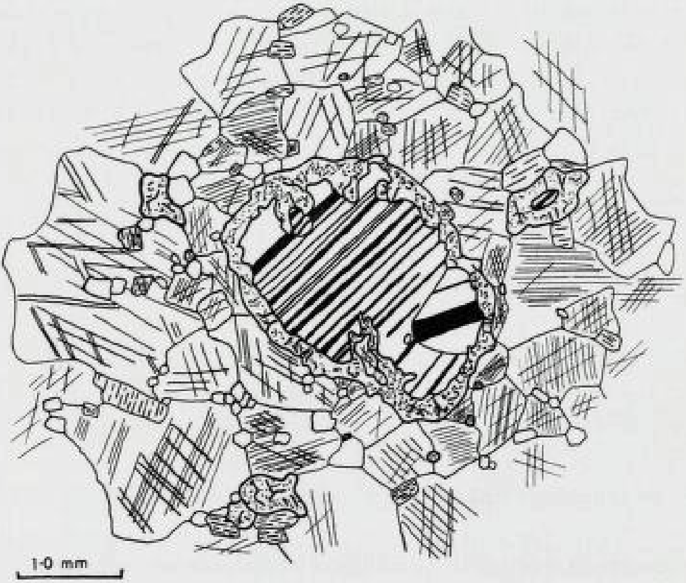

Fig. 59. Thin section of intrusive carbonate rock, showing andradite corona about plagioclase (bytownite). The ground mass is mainly calcite with some apatite and hedenbergite. Slide no. SB710.

with a schistosity developed parallel to their margins and the F2 fold axial planes. The granites consist of quartz, plagioclase (around An_{15}) and biotite with accessory garnet, muscovite, zircon, pyrite and magnetite. The basic dykes contain green-brown hornblende, plagioclase of two generations (an earlier highly corroded variety apparently andesine/labradorite, and a later clear type about An_{12}), iron ore, biotite and relict augite. It will be recalled (p. 27) that a similar pattern of minor intrusions was described from the small peninsula to the west of Breivikbotn.

The intrusive carbonate sheets are mainly composed of calcite usually in a polygonal grain mosaic, pyroxene which is apparently very close to hedenbergite in composition, wollastonite, basic plagioclase (around An_{60}), garnet and apatite. The calcite grain mosaic of the groundmass is often irregular both in texture and grain-size. The calcite of the mosaic is typically mottled with small rounded inclusions of quartz, pyroxene, garnet and apatite. The inclusions may also be minute euhedra of these minerals. The pyroxene in these rocks is generally subhedral. Garnet has two principal modes of occurrence, firstly as minute grains (often euhedra) enclosed within calcite or as interstitial grains, and secondly as conspicuous coronas rimming grains of plagioclase (Fig. 59). The mineralogy of these intrusive carbonate rocks is very different from that of the carbonatites of the main belt, and the typical minerals aegerine-augite, hastingsitic amphibole, alkali feldspar, melanite, allanite, etc. of the main belt carbonatites were not found in any of the specimens examined. The sheets have more the mineralogy of a typical skarn, and may even represent tectonically mobilised limestone skarns although there are no beds of limestone in the immediate vicinity with which they can be equated.

The other small, isolated occurrence of intrusive carbonate rocks well removed from the main centres of Carbonatite emplacement, can be found on a small peninsula 1.5 km. east of Sorvaer. The carbonate rocks occur as two thin sheets, near concordant with the layering in an interbanded sequence of flaggy psammites and thin semi-pelitic schists of the Klubben Quartzite close to the junction with the overlying Storelv group. The lower and thicker sheet varies between 10 cm. and 2 m. while the upper is more discontinuous with a maximum thickness of 0.5 m.

The sheets have been affected by F2 movements and are folded with the metasediments into a symmetrical syncline and anticline with a wave-length of 100 m. In the crest of the anticline where the rocks are strongly plicated the calcite of the lower sheets displays a rodding parallel to the fold axes.

The carbonate rocks are truncated on the landward side by a small fault trending N8OE. Coarse-grained granular calcite forms the matrix of the thin brecciated zone and infiles associated splinter fractures.

Where they are thinly developed the carbonate rocks occur as irregular strings and thin sheets of granular calcite penetrating along the schistosity. With increased development these strings coalesce into one sheet in which xenoliths of garnetiferous psammite occur preserving their original orientation. In the calcite bands the calcite has a coarse granoblastic texture enclosing sporadic rounded inclusions of quartz and garnet. At the margins of the bands calcite penetrates along grain boundaries of the host rock, develops as small isolated spots at quartz-quartz interfaces or penetrates into host grains.

A feature of the psammites in the xenoliths and in several places at the marginal contact with the carbonatite is their glassy appearance. In the psammite of the contact areas garnet is prominent as isolated porphyroblasts, knots of porphyroblasts up to several centimetres across or in conspicuous thin red veins parallel to the layering. In thin-section these veins are seen to be solid garnet streaks or trains of coalescing porphyroblasts associated with biotite flakes and heavily altered feldspar containing granules of clinozoisite. In some bands the garnet is associated entirely with coarse granoblastic clinozoisite. There are two generations of garnet present in some rocks, an earlier grey coloured variety invariably poikiloblastic and a later pink, idioblastic, inclusion-free variety occurring in veins or clusters of individual porphyroblasts at the margins of the calcite layer.

The upper carbonatite sheet is involved with a thin but extensive metabasalt sill. The contact between the two rock types may be sharp and unmodified though locally the metabasalt is largely reconstituted to an assemblage of calc-silicate minerals, plagioclase, hornblende, clinozoisite, scapolite and sphene. The texture of the metabasalt varies from randomly disposed hornblendes with intergranular feldspars to strongly schistose biotite-hornblende schist. Scapolite occurs as granules within sericitised plagioclase or it may be the only felsic mineral present. Calcite is the last formed mineral penetrating between and into all the other minerals. The basalt sheet is extensively boudinaged with calcite and calc-silicate minerals sometimes developed in the neck area of the boudins.

IV. The geochemistry and petrogenesis of the alkaline rocks

A. *The Nepheline Syenite Association.*

(1) *Major Elements.*

Chemical and normative compositions of a number of representative samples from the Breivikbotn area are presented in Table 8. The nepheline syenites are highly sodic and belong to the miaskitic group of alkaline rocks having an excess of alumina and a deficiency in silica (Sörensen 1960). The analyses are too few for more than tentative conclusions to be drawn regarding the influence of host rock compositions, but the analysed nepheline syenite gneisses which occur in the metagabbro have higher iron, lime and titania allied with lower alumina and alkalies than either the pegmatite or the nepheline syenite gneiss

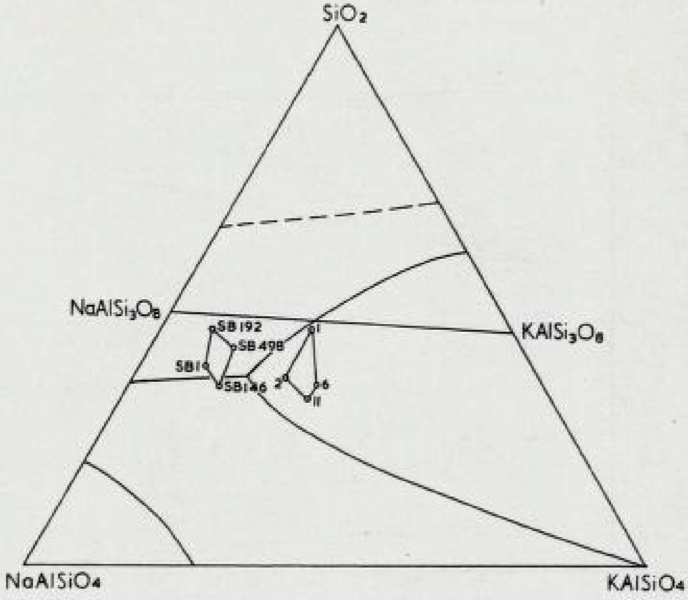

Fig. 60. Position of the analysed nepheline syenites in the system $NaAlSiO_4$—$KAlSiO_4$—S_iO_2. Söröy analyses SB.1, SB.146, SB.192 and SB.498. Stjernöy analyses 1, 2, 6 and 11 (taken from Heier 1961).

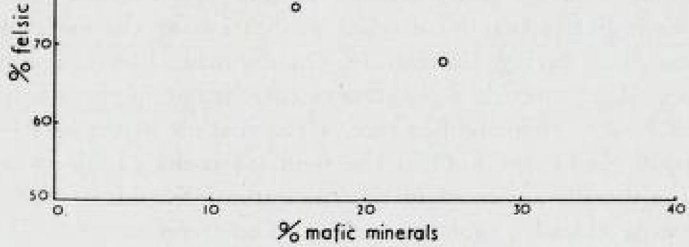

Fig. 61. Modal analyses of fenitized metasediments and nepheline syenite gneisses, showing how nepheline enters into the paragenesis as the felsic index increases.

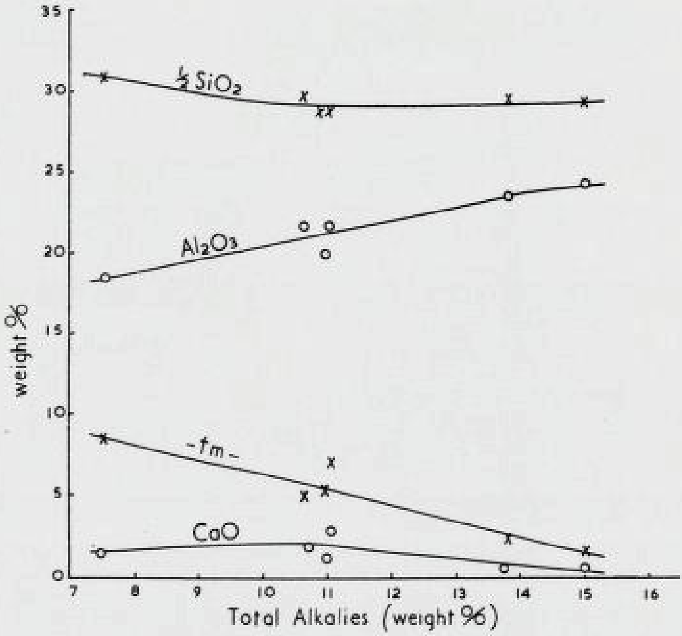

Fig. 62. Chemical trends of nephelinization, of metasediments, shown by the plot of analyses of a semi-pelitic schist, three fenitized semi-pelitic schists and the nepheline syenite gneisses from Hvitness. (fm = total iron as Fe_2O_3 + MgO.)

occurring in the metasediments. The position of the analysed specimens in the system $NaAlSiO_4$–$KAlSiO_4$–SiO_2 is given in Fig. 60.

The nepheline syenite gneisses occurring in the metasediments represent the end stage of a process of fenitisation of the latter. The sequence of mineralogical changes is illustrated in Fig. 61. The fenitisation sequence from semi-pelitic schist to nepheline-free alkali syenite gneisses shows only a small decrease in the percentage of SiO_2 (Fig. 62). This indicates that no marked desilication of the metasediments has taken place during fenitization. On the other hand a conspicuous trend is evident towards a progressive enrichment in the alkalies particularly Na_2O. There is, however, a fluctuation in the relative proportions of Na_2O and K_2O in the fenitised rocks (Tables 8 and 9), which is naturally reflected in the amounts of K-feldspar and albite/oligoclase developed (Tables 1 and 2). The trend towards alkali enrichment is mirrored in the pregressive rise in values for Al_2O_3 with fenitization (Fig. 62). Also marked are the progressive decrease in the

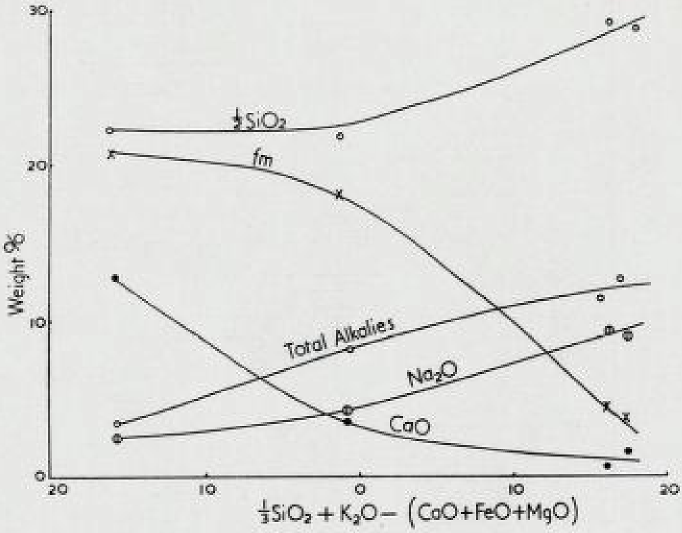

Fig. 63. Chemical trends of nephelinization of metagabbro shear zones, shown by the plot of analyses of average gabbro (from Stumpfl and Sturt 1964), biotite schist, and two nepheline syenite gneisses. (Plotted on Larsen-type diagram.)

contents of FeO, Fe_2O_3, MgO and in a rather more erratic manner of CaO.

Only one analysis is available of a nepheline-free syenite gneiss in the metagabbro shear zone. The trends of fenitization and eventual nephelinization are, however, fairly well shown in Fig. 63. This is seen to involve enrichment in SiO_2, Al_2O_3 and the alkalies particularly Na_2O. Allied to this trend is the progressive loss of Fe_2O_3, FeO, MgO and CaO.

(2) *Trace Elements.*

Determinations (X-Ray Fluorescent) of trace elements, for representative rocks of the nepheline syenite association, are presented in order of increasing atomic number in Tables 11 and 12.

Titanium.

The more extensive series of spectographic determinations (Table 11) show average values for the nepheline syenite gneisses in the metagabbro of 3,265 p.p.m. and in the metasediments of 867 p.p.m. The

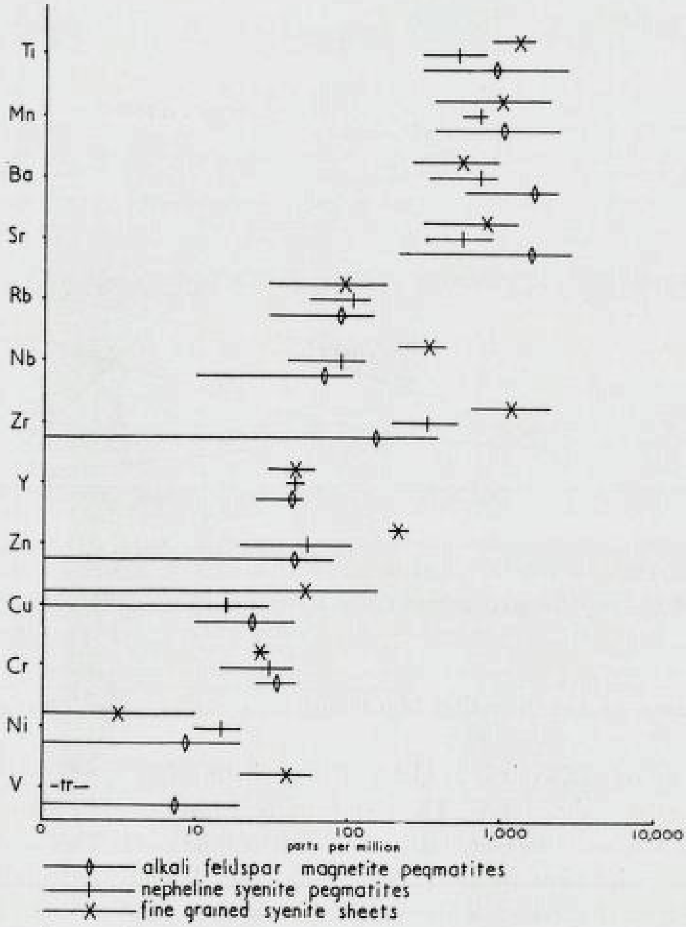

Fig. 64. Trace element distribution in intrusive phases of the Nepheline Syenite Association. The range and average values are given in parts per million.

nepheline syenite pegmatites have a rather lower average value (520 p.p.m.), which is in contrast to the higher figure of 1,900 p.p.m. for the alkali feldspar-magnetite pegmatites (Fig. 64).

Manganese.

The nepheline syenite gneisses all have very similar values for Mn. Those in the metagabbro have an average value of 1,192 p.p.m. and those in the metasediments 1,327 p.p.m. (Fig. 65). Both sets of values are higher than those given for the nepheline syenite pegmatites (Av.

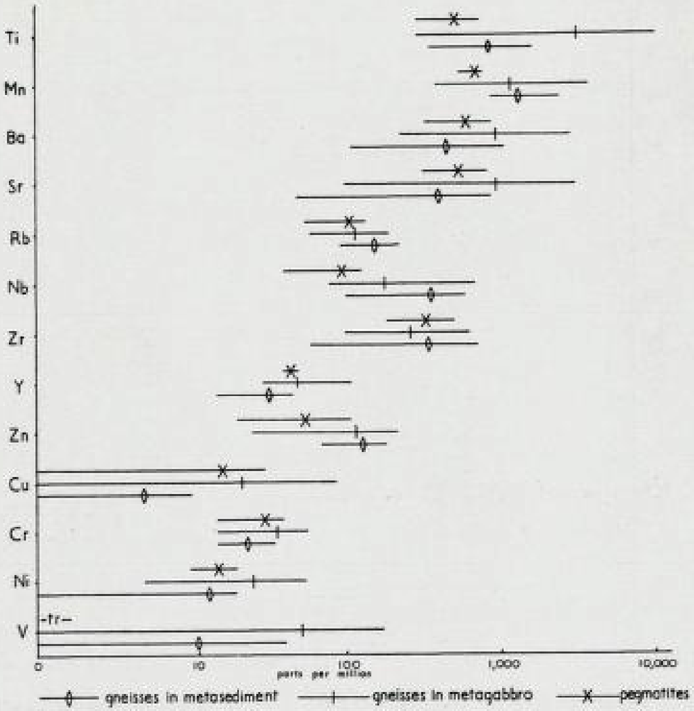

Fig. 65. Trace element distribution in nepheline syenite gneisses and pegmatite. The range an d average values are given in parts per million.

709 p.p.m.). The alkali-feldspar-magnetite pegmatites have an average value of 1012 p.p.m. The nepheline syenite gneisses in the metagabbro have very similar values to those of the latter (1,192 respec. 1,312 p.p.m.), though the range in values is very much greater (Fig. 66). The Mn content of the nepheline syenite gneisses in the metasediments is observed to be somewhat lower than that of the associated alkali gneisses (Table 12).

Vanadium.

The vanadium content of the nepheline syenite gneisses occurring in the metagabbro (Av. 50 p.p.m.), is significantly higher than that of the gneisses occurring in the metasediments (11 p.p.m.) The V content of the former is, however, considerably lower than that of the host metagabbro (Av. 280 p.p.m.), though the ranging values are observed to overlap (Fig. 66). The alkali gneisses developed in the meta-

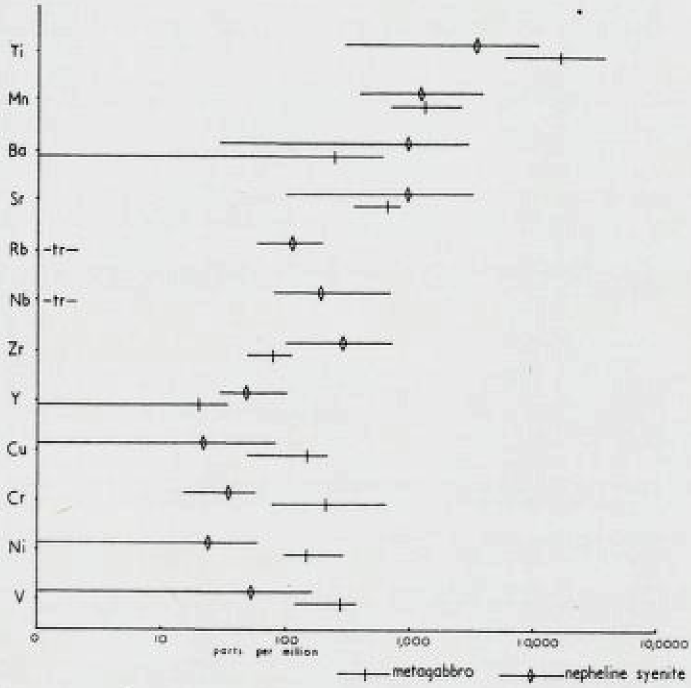

Fig. 66. Comparison between trace element distribution in the Breivikbotn gabbro (from Stumpfl and Sturt 1964) and nepheline syenite gneisses developed in shear zones within the gabbro. The range and average values are given in parts per million.

sediments (Table 12) also have a considerably higher V content than the associated nepheline bearing varieties. The nepheline syenite pegmatites only contain a trace of V as do the alkali-feldspar magnetite pegmatites (Av 7.5 p.p.m.); rather higher values (Av 41 p.p.m.) are found in the fine-grained intrusive syenites (Fig. 64).

Chromium.

There is again a tendency for the nepheline syenite gneisses in the metagabbro (av. 36 p.p.m.) to have higher values than those occurring in the metasediments (av. 23 p.p.m.); and the range of the former is observed to be very much greater (Fig. 65). The comparative figure for the metagabbro is 210 p.p.m. The nepheline-free alkaline gneisses developed in the metasediments are also seen to be richer in Cr (Table 12) than the associated nepheline bearing varieties. The intrusive phases all appear to have rather similar Cr. contents and range of values (Fig. 64).

Nickel.

The nepheline syenite gneisses in the metagabbro have the highest Ni content (av. 24 p.p.m.). This compares with an avearge of 13 p.p.m. for the nepheline syenite gneisses in the metasediments and a rather similar value for the pegmatites (av. 15 p.p.m.). The comparative figure for the metagabbro is 150 p.p.m. The fenites developed in the metasediments have slightly higher Ni contents than the associated nepheline gneisses (Table 12). The intrusive phases are all seen to have low Ni contents (Fig. 64).

Copper.

The Cu content in the rocks of the nepheline syenite association is uniformly rather low (Figs. 64 and 65).

Zinc.

The values for Zn in the nepheline syenite gneisses tend to be rather similar (Fig. 65), though the pegmatite phases have somewhat lower Zn content (nepheline syenite pegmatites av. 55 p.p.m., alkali feldspar-magnetite pegmatites av. 45 p.p.m.). The highest values of Zn are observed in the fine-grained intrusive syenites (av 220 p.p.m.). The alkali gneisses in the metasediments have considerably higher Zn contents than the associated nepheline gneisses. No comparative data is available on the zinc content of the metagabbro.

Rubidium.

The Rb contents of the nepheline syenites and associated rocks are all rather low. The nepheline syenite gneisses developed in the metasediments (av. 156 p.p.m.) have a higher Rb content than those in the metagabbro (av. 116 p.p.m.). The content of the former is lower than in the associated fenites (Table 12), on the other hand the metagabbro (Fig. 66) only contains a trace of Rb indicating an accession of Rb during the metasomatic metamorphism. The intrusive phases all have rather similar Rb contents (Fig. 63).

The rubidium content of the nepheline syenites and their associated rocks is much lower than the average value for nepheline syenites (455 p.p.m.) given by Goldschmidt (1954). A similar pattern of Rb depletion was noted on Stjernöy by Heier (1964 b). Comparative figures for nepheline syenite gneisses of the Haliburton-Bancroft area, Canada, are provided by Appleyard (1963). He gives average values of 177 p.p.m. for igneous nepheline syenites, and 274 p.p.m. for metasomatic nepheline bearing gneisses.

Strontium.

The nepheline syenite gneisses in the metagabbro (av. 961 p.p.m.) have a higher Sr content than the nepheline syenite gneisses in the metasediments (av. 412 p.p.m.). This difference would appear to be partly a function of the strontium levels of the respective host-rocks. The average for the metagabbro is 660 p.p.m., and that for the fenites and metasediments (ignoring one erratically high value) is 203 p.p.m. Thus there would appear in both cases to be an enrichment of minor amounts of Sr during the development of the nepheline syenite gneisses. The alkali feldspar-magnetite pegmatites (av. 1,584 p.p.m.) have notably higher values for Sr than the nepheline syenite pegmatites (av. 545 p.p.m.).

The values of Sr for the nepheline syenites of the Breivikbotn area are somewhat low in relation to the average value of 1,400 p.p.m. given by Goldschmidt (op. cit.) for nepheline syenites. The average values given by Appleyard (op. cit.) for the Haliburton-Bancroft area are perhaps more comparable at 395 p.p.m. for igneous types and 1,260 p.p.m. for metasomatic nepheline syenite gneisses.

Zirconium.

The nepheline syenite gneisses in the metasediments (av. 351 p.p.m.) have somewhat higher values for Zr than those in the metagabbro (av. 268 p.p.m.). This is in part a reflection of the Zr contents of the respective host rocks. The low Zr content of the metagabbro (av. 80 p.p.m.) implies an influx of Zr during the fenitization. The alkali-feldspar magnetite pegmatites (av. 151 p.p.m.) have notably lower Zr than the nepheline syenite pegmatites (av. 330 p.p.m.) The highest concentrations of Zr (av. 1,197 p.p.m.) are found in the fine-grained intrusive syenites.

Comparative data from the Haliburton-Bancroft area are 22.5 p.p.m. for igneous and 143 p.p.m. for metasomatic nepheline syenites.

Miyashiro and Miyashiro (1956) provide data on the Zr content from nepheline syenites of the Fukushin-zan district of Korea. They give average values of 1,926 p.p.m. for metasomatic nepheline syenite gneisses.

Barium.

The Ba content of the nepheline syenite gneisses in the metagabbro (av. 950 p.p.m.) tends to be higher than that of those in the metasediments (av. 462 p.p.m.). The comparative value for Ba in the metagabbro is 245 p.p.m. The fenites in the metasediments tend to have higher values than the associated nepheline syenite gneisses (Table 12). The alkali feldspar-magnetite pegmatites (av. 1,615 p.p.m.) are relatively enriched in Ba compared with the nepheline syenite pegmatites (av. 709 p.p.m.). The general coherence of Ba with K demonstrated by Goldschmidt (1954) and by Heier (1960) is followed in the Breivikbotn rocks.

A figure of 580 p.p.m. is given by Goldschmidt as an average value of Ba for nepheline syenites and phonolites, and compares quite well with the Breivikbotn data. Comparative average data from the Haliburton-Bancroft area are 1,500 p.p.m. for igneous and 1,062 p.p.m. for metasomatic types. Miyashiro and Miyashiro (op. cit.) give values of 964 p.p.m. for igneous and 643 p.p.m. for metasomatic nepheline syenites.

Yttrium.

Values for Y tend to be very similar and to show little variation. The metagabbro apparently has a lower Y content than the contained nepheline syenite gneisses, and the fenites in the metasediments tend to have higher values of Y than the associated nepheline syenite gneisses.

(3) *Discussion of Trace Element Data.*

The nepheline syenite gneisses occurring in the metagabbro are found to be richer in Ni, Cr, V and Ti relative to the nepheline syenite gneisses in the metasediments. These are all elements which have high values in the metagabbro (Table 22). The nepheline syenite gneisses in the metagabbro are also relatively enriched in Sr and Ba. On the other hand the nepheline gneisses occurring in the metasediments are richer in Zr, Zn, Nb, Rb, and Mn, all of which are elements that are more concentrated in the metasediments and fenites. The pattern of migration of minor elements during the metasomatic metamorphism of the shear zones in the metagabbro is shown in Fig. 66. This indicates an enrichment in Y, Zr, Nb, Rb, Sr, and Ba during fenitization coupled with the depletion in Ti, Cu, Cr, Ni and V. Only Mn remains relatively passive during the nepheline syenite formation. The pattern of impoverishment in Ti, V, Cr and Ni is particularly well illustrated in Table 11 (analyses 12—16) which are of specimens showing progressive nephelinization. It is difficult to comment in detail on the pattern of minor element migration during the fenitization of the metasediments as only one analysis of unaffected semi-pelitic schist is available.

The alkali feldspar-magnetite pegmatites, which represent the earliest of the intrusive phases, are notably richer than the nepheline syenite pegmatites in Sr, Ba and Ti, whereas the latter rocks are relatively richer in Zr and Nb. The highest values for Zr and Nb are to be found in the fine-grained intrusive syenites.

(4) *Comparison with the Nepheline Syenites of Stjernöy.*

On the neighbouring island of Stjernöy nepheline syenites occur both as nepheline-biotite-albite pegmatites, in the form of dykes, which often fill fractures following a general N—S trend, and as a larger body of perthite bearing nepheline syenite forming the mountain of Nabberen, south of Lillebugt where it is at present being mined by Nordkapp Nefelin A/S (Heier 1961, 1964, Heier and Taylor 1964, Oosteroom 1963). Heier (1961) states that the Nabberen nepheline syenite is 'stock-like' and concludes (Heier and Taylor 1964) that the intrusion has crystallised from a magma characterized by high Ba and Sr allied to low Rb and Cs contents. In his 1961 paper Heier emphasises the sodic character of the pegmatite dykes as indicated by their feldspars. He quotes the experimental work of Burnham and Tuttle (1960) who demonstrated that the aqueous phase coexisting with liquids that approach the granitic composition will tend to have higher Na_2O/K_2O ratios (and lower $Al_2O_3/Na_2O + K_2O + SiO_2$ ratios) than those of the coexisting liquids. Heier infers from this that the high Na_2O/K_2O ratio in the pegmatites and the low values for this ratio at the Nabberen occurrence is in harmony with the findings of Burnham and Tuttle. The pegmatites, according to Heier, represent the aqueous phase derived from the syenitic liquid, the latter crystallising to give the Nabberen nepheline syenite intrusion. Heier in his series of papers presents a considerable volume of valuable geochemical data on the mdain nepheline syenite mass at Nabberen (1961 table 9, 1964 table 5), but regretably no information concerning either the major or minor element distributions is provided for the nepheline-biotite-albite pegmatites.

There are a number of significant differences, in terms of major elements, between the Breivikbotn nepheline syenites and those of the Nabberen occurrence (Table 8 and Heier 1961 table 9). One of the most striking features is the lower content of silica of the Nabberen nepheline syenites (av. 53.26 % SiO_2) compared with those at Breivikbotn (av. 58.33 % SiO_2), whereas the contents of Al_2O_3 are virtually identical at the two occurrences (Nabberen av. 21.95 %; Breivikbotn av. 23.11 %). This points to the more strongly miaskitic character of the Nabberen material. The analyses from Nabberen also show consistently higher lime and titania (av. CaO 3.53 %; TiO_2 1.02 %) than those from Breivikbotn (av. CaO 0.90 %; TiO_2 0.20 %). The nepheline syenites have very similar amounts of total iron at the two localities, but there is a considerable difference in their respective oxidation states (Table 13). The Fe_2O_3 : FeO ratio of the Nabberen nepheline syenite (av. value 1.19) is consistently and notably higher than the values for this ratio in the Breivikbotn rocks (av. value 0.35). At the present stage of the investigation sufficient data is not yet available to give a reasoned explanation of this feature. It is of interest to note, however, that the values for the Nabberen mass are very similar to those given for magmatic nepheline syenites by Goldschmidt (1954, table VIII, p. 35) from the Oslo district.

Probably the most significant difference between the two occurrences is between the highly sodic nature of the Breivikbotn nepheline syenites and the more potassic character of the Nabberen rocks. The contrast is well seen by comparison of the ratios of Na_2O : K_2O for the two types (Table 14). The values of this ratio at Breivikbotn (av. value 3.19) are much higher than those at Nabberen (av. value 0.99). In this respect, then, it would appear that the Breivikbotn nepheline syenites bear more resemblance to the nepheline-biotite-albite pegmatites on Stjernöy than to the nepheline syenite of the main intrusion at Nabberen. This is of considerable interest in view of the relationships between the two types envisaged by Heier (1961) and outlined above, where the pegmatites were regarded as an aqueous phase derived from a nepheline syenite magma, the latter crystallising to give the

Nabberen intrusion. The authors consider that in the Breivikbotn area many of the nepheline syenite gneisses and some of the pegmatites are metasomatic. The majority of the pegmatites, however, are intrusive and are taken to represent the crystallisation of a highly fluid nepheline syenite magma in a system of fractures. Fluids and emanations associated with this magma are envisaged as following paths of easy access in the surrounding country rocks, such as structurally determined planes or zones of weakness, along which the metasomatic conversion of schistose rocks into nepheline syenite gneisses took place.

The differences in the major element compositions of the Breivikbotn and Nabberen occurrences are depicted in Fig. 60. This illustrates how the nepheline syenites of the two areas occupy distingtly different fields in the system $NaAlSiO_4-KAlSiO_4-SiO_2$. The further implication of this diagram is that the nepheline syenites of the Breivikbotn area probably crystallised at lower temperatures than did the nepheline syenites of the Nabberen intrusion.

Significant differences in the concentrations of certain of the minor elements are also seen in a comparison of the two syenite localities (Fig. 67). The distribution of the minor elements in the two localities show two main features:

(i) Differences in the levels of individual elements.

(ii) The very much greater range in values in the nepheline syenites of the Breivikbotn area.

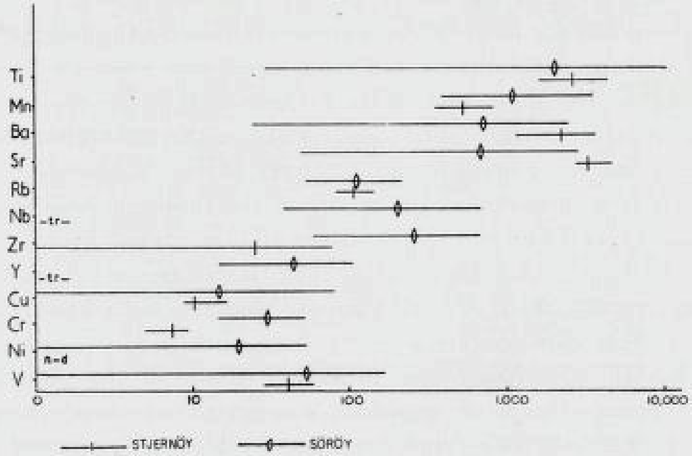

Fig. 67. Comparison between the trace element distribution in the nepheline syenites of Stjernöy (data from Heier 1964) and Söröy.

Generally (Fig. 67) it can be shown that the Breivikbotn nepheline syenites are richer in V, Ni, Cr, Y, Mn, Zr and Nb relative to those at Nabberen. The latter occurrence, however, shows a very significantly greater concentration of Ba and Sr. The level of Rb is virtually the same in the two localities, though the range in values for the Breivikbotn area is much greater. The depletion of the Nabberen magma in Rb has been commented upon by Heier (1964). Heier also discusses the exceptionally high contents of Sr and Ba in the Nabberen rocks and speculates as to whether this implies a deep-seated origin for the magma. The values for Sr (av. 3,500 p.p.m.) and Ba (av. 2,400 p.p.m.) in the Nabberen nepheline syenites are very substantially higher than those in the Breivikbotn nepheline syenites (Sr av. 711 p.p.m.; Ba av. 750 p.p.m.). Furthermore the values of minor elements in the Nabberen rocks have a comparatively small range in relation to the extended range of values at Breivikbotn (Fig. 67). Perhaps the most significant enrichments of the Breivikbotn nepheline syenites are in Zr, Nb, and Y, which are all elements typically concentrated in late residual magmas (Goldscdhmidt 1954).

(5) *The Origin of the Nepheline Syenites in the Breivikbotn Area.*

Nephelinization has been described from a wide variety of areas, though perhaps particular mention should be made of the Haliburton-Bancroft area of Canada, described in detail in the classic account of Adams and Barlow (1910), because of its many resemblances to the area under description. A considerable number of areas originally mapped by Adams and Barlow have been subsequently re-investigated and most workers have arrived at the conclusion that many of the nepheline-bearing rocks have originated as the result of a process of metasomatic metamorphism. One of the most detailed accounts was by Gummer and Burr (1946) who ascribed the origin of nepheline bearing gneisses in the Bancroft area to a process of nephelinization of a varied series of Grenville paragneisses. They are, however, somewhat vague concerning the origin of the metasomatizing fluids and emanations and put them down to "granitic or syenitic magmas of uncertain nature and origin." Moyd (1949) considers that the nepheline gneisses, in south-eastern Ontario, were due to emanations derived from a granitic magma that had been desilicated by passage through dolomitic marbles. Osborne (1930) in an examination of the nepheline syenites from the Egan Chute area, suggests that they are partly magmatic and partly metasomatic in origin. Osborne considers the nepheline syenites seen at the surface as being related to larger bodies of intrusive nepheline syenite at depth. A similar conclusion is rarived at by Tilley (1958) who moreover draws attention to "genuine feldspathoid intrusives of magmatic origin" in the region. Tilley considers that the solutions and emanations responsible for the nephelinization were nepheline bearing and were related to a magmatic source in depth. These ideas have been confirmed by the work of Gittins (1961) and by Appleyard (1963). Nepheline syenites which are partly magmatic and partly metasomatic in origin have also been described from a regional metamorphic terrane in the Fukushin-zan area of Korea by Miyashiro and Miyashiro (1956). This area again has many features in common with the Breivikbotn area.

Fenitization and nephelinization related to carbonatite emplacement have been described by many authors (Von Eckermann 1948, Saether

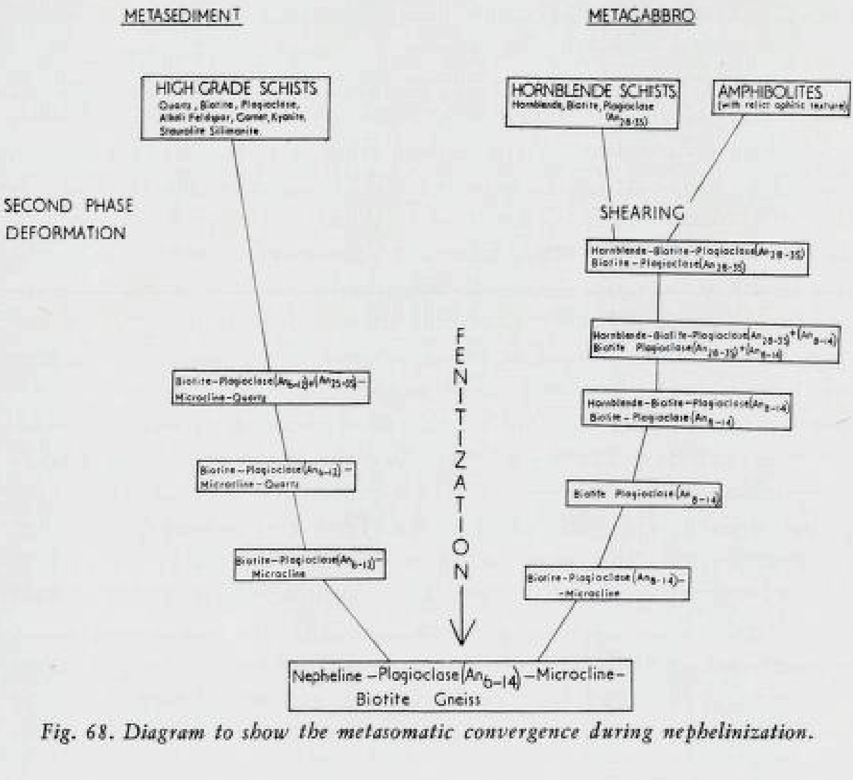

Fig. 68. Diagram to show the metasomatic convergence during nephelinization.

1957, King and Sutheland 1960, King 1965, and Garson 1962). Their accounts show how the country rocks, surrounding central alkaline intrusions, are subjected to extensive alkaline metasomatism producing fenites and eventually nepheline syenites. In the Breivikbotn area, however, although carbonatites with associated fenites occur in the same general area as nepheline syenites, no association in detail between these groups of rocks is to be observed. Furthermore, the fenites adjacent to the carbonatite and its associated syenites never develop nepheline.

The trends of nephelinization have been described from both the metasediments and in shear-zones within the metagabbro, in terms of their field relationships, petrography and geochemistry. As the result of this process it is possible to trace a convergence from the two basically differents hosts into very similar nepheline bearing gneisses (Fig. 68). The solutions and emanations responsible for the fenitization and nephelinization are concluded to be related to a source of nepheline syenite magma at depth. Intrusive nepheline syenites are present in the Breivikbotn area as pegmatites, and on Stjernöy both the nepheline-biotite-albite pegmatites and the main Nabberen nepheline syenite body appear to have intrusive relationships with the surrounding country rocks. The ultimate source of this nepheline syenite magma is, however, not clear.

B. *The Carbonatite Association.*

(1) *The Aegirine-Augite Pyroxenite.*

It has been shown (p. 47) that the aegirine-augite pyroxenite was probably produced as the result of the fenitization of a highly sheared gabbro sheet. Field and petrographic evidence were given in support of this conclusion. Analytical data of major and minor elements is given for one specimen of the aegirine-augite pyroxenite in Table 15. The average composition of the Breivikbotn gabbro (Stumpfl and Sturt, 1964) is also quoted for purposes of comparison. Possibly the most significant differences, in terms of the major elements, are the decidedly lower value of Al_2O_3 and the higher value of Fe_2O_3 of the aegirine-augite pyroxenite relative to the average metagabbro. The values for the other major constituents are very similar in the two rock types, and those of the aegirine-augite pyroxenite fall well into the range of compositional variation of the metagabbro (Stumpfl and Sturt 1964, Table 2). The trace elements concentrations in the aegirine-augite pyroxenite and the metagabbro also show a number of significant differences, particularly in terms of the higher concentrations of Mn, Y, Zr and Nb in the former. The last three of these elements, it will be shown below, are all characteristically enriched in the fenites. The main changes in composition during the formation of the aegirine-augite pyroxenite would then appear to be loss of Al and enrichment in Fe^{3+}, Mn, Y, Zr and Nb. The alkalies are now occurring in aegirine-augite and hastingsitic amphibole instead of in feldspars.

(2) *The Fenites.*

An analysis of a typical fenite developed in the semi-pelitic schists adjacent to the rocks of the carbonatite association is given in Table 16, together with an analysis of one of the semi-pelitic schist. Two features are immediately apparent, i.e. the depletion in Al_2O_3 and enrichment in Fe_2O_3 of the fenite relative to the semi-pelitic schist. It will be recalled that this was a marked feature in the comparison of the aegirine-augite pyroxenite with the metagabbro. The fenite also shows enrichment in CaO and the alkalies (particularly in potash). A study of the respective trace element concentrations indicates higher values of V, Mn, Zr, and Nb (Table 21) in the fenites.

Garson (1964 Table VI) summarizes the metasomatic changes during fenitization, associated with the emplacement of carbonatites, from a number of areas. This table of Garson's is of considerable interest as it demonstrates that different patterns of element transfer were operative in different areas. Saether (1957) in his description of the fenites, from the type area of Fen, Norway, shows that during fenitization Al_2O_3,Cao, Na_2O, K_2O and CO_2 were added along with small quantities of BaO, whilst SiO_2 was removed. The fenites at Breivikbotn, however, show more resemblance to those at Tundulu (Garson 1963), Dorowa (Johnson 1959) and Alnö (Von Eckermann 1948) in that there is an enrichment in Fe_2O_3, K_2O, CaO and on the small scale in Na_2O and P_2O_5. This is allied to a marked reduction in the Al_2O_3 content. There is no evidence of any marked degree of desilication of the Breivikbotn fenites. King and Sutherland (1960) also draw attention to a number of alkaline complexes where the addition of alumina during fenitization is prominent. King and Sutherland emphasize that fenitization frequently produces rocks of a more melanocratic nature than the starting material. This generalisation is seen to apply also to the fenites under consideration.

The fenites associated with the carbonatite group of rocks at Breivikbotn never become sufficiently desilicated to develop nepheline or other feldspathoidal minerals. This feature deserves comment as the production of nepheline in zones of fenitization appears to be a relatively common feature in alkaline complexes containing carbonatite, and frequent appeal is made to the desilicating effects of the incoming carbonatite. It has been mentioned previously (p. 101) that metasomatic nepheline bearing gneisses have developed in the area as the end-stage of a process which involves fenitization. Thus two types of fenitization occur, in the Breivikbotn district, which have distinctly different characteristics. In the case of the carbonatite associated fenitization the main chemical changes are manifested in a marked alumina depletion allied with an enrichment in potash, lime and iron (mainly ferric). On the other hand, the fenitization resulting in the ultimate production of nepheline-bearing gneisses is characterised by a marked depletion in iron and an enrichment in alumina and soda. The Breivikbotn occurrence is of further interest as although the two types are broadly coeval in their time of formation they are geographically separate, and contacts between them are not observed. This indicates that although the magmas from which the carbonatite (and its associated syenites) and the nepheline syenite pegmatites crystallised may have been derived ultimately from a common parent, they became separated at a fairly early stage and have followed independent development. The alkaline complex of the Breivikbotn area is obviously not of the central type, but is influenced in its form by the developing tectonic structures of the area. This indicates a structural control over the channelling of the respective magmas, and hence the emplacement of the varied rock types.

(3) *The Syenites.*

As indicated in the appropriate sections the syenitic rocks associated with the carbonatites form a group of varying composition from shonkinite to leucocratic syenite and syenite aplite. A number of analyses of typical shonkinites and leucocratic syenites are presented but no data is yet available for the syenite aplites.

Analyses in terms of major element oxides, together with norm calculations are presented in Tables 17 & 18. It has been shown (p. 34) that the shonkinites and associated syenitic rocks have been extensively affected by carbonate metasomatism consequent upon the intrusion of carbonatite. The main effect of this metasomatism was in the development of variable amounts of secondary calcite in the rocks affected. This is well illustrated by Table 5 which shows the modal content of calcite in the shonkinites to range from 0—25.8 %; and is of necessity reflected in higher than normal contents of CaO and CO_2 in the rock analyses. Allied to the carbonate metasomatism affecting the syenites was the extensive zeolitization of the rocks. This is mainly expressed in the replacement of feldspar to form zeolite (p. 67), and is illustrated by considerable range in modal contents of feldspar and zeolite in the rocks (Table 5). The main effect on the composition is reflected in higher than normal water contents. Thus it is apparent that the analysed cdomposition of the shonkinites will show differences as a result of the subsequent alterations described. Hence, the authors have recalculated the analyses by removing the constituents of the calcite in the norm, the H_2O^+, and adjusting the remaining values. The authors are conscious that this is not an exact procedure, and are aware that there may be other migrations of elements associated with these processes, but are nonetheless confident that the re-calculated analyses provide a more reasonable estimate of the original composition of the shonkinites.

The shonkinites of the Breivikbotn area are to be regarded as peralkaline types (Shand 1950) owing to the presence of sodic pyroxenes and amphiboles. When the analyses of the Breivikbotn shonkinites are compared with those of the type shonkites from Shonkin Sag, Montana (Weed and Pirsson 1901, Osborne and Roberts 1931), they are seen to be similar in most respects but to be richer in Al_2O_3 and poorer in MgO. They are also seen to have a dominance of Na_2O over K_2O which is a trend observed at the Fen occurrences (Saether 1959, Table 5 a). The Breivikbotn shonkinites also have a close resemblance, in composition, to the shonkinite porphyry listed by Guimaeres (1960 p. 333) from Sao Paulo, Brazil. The shonkinite at the latter occurrence is, however, seen to have somewhat lower Al_2O_3 and higher K_2O than at Breivikbotn.

Chemical analyses and norm calculations of the leucocratic syenites are given in table. These syenites have also been extensively affected by

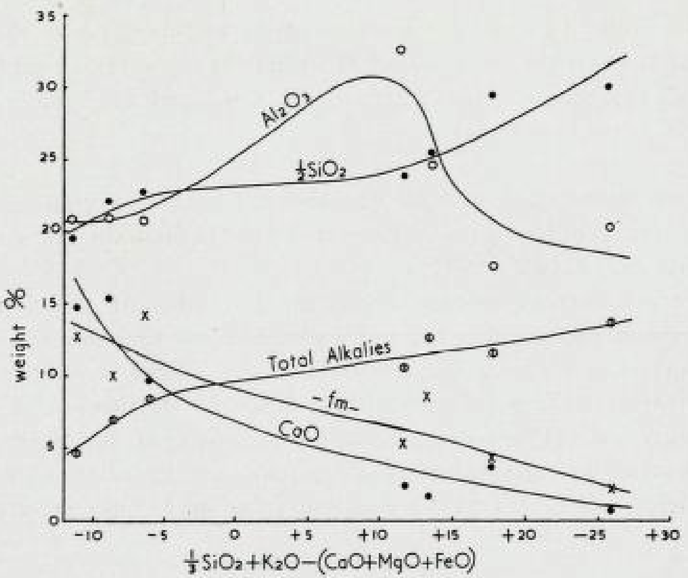

Fig. 69. Differentiation trends of the syenitic rocks of the Carbonatite Association. Plotted on standard Larsen type diagram. (fm = total iron as Fe_2O_3 + MgO.)

carbonate metasomatism and zeolitization, as described above in the case of the shonkinites. These effects are only seen in two of the analysed rocks (SB 63 and SB 236). Similar recalculations of the analyses, to those outlined for the shonkinites, have been made for these rocks in order to give a more realistic picture of their original composition. The most striking comparisons with the shonkinites are seen in the higher SiO_2 and K_2O contents of the leucocratic syenites, and their markedly lower concentrations of FeO, Fe_3O_3 and CaO. The recalculated analyses of the shonkinites and the leucocratic syenites have been plotted on a standard Larsen-type variation diagram (Fig. 69), and this diagram shows the general differentiation trends of these related groups of rocks. The more marked features are:

(i) The progressive enrichment in SiO_2.

(ii) The progressive rise in the total alkalies. This, however, is found to be more complex in detail. Firstly Na_2O is seen to rise sharply in the shonkinites and to gradually tail off in the leucocratic syenites. The opposite effect is shown by K_2O which is observed to fall in the shonkinites and then to make a steady and progressive rise in the leucocratic syenites.

(iii) The similarity in Al_2O_3 contents of the end-members of the series and the marked culmination in values for the middle members.
(iv) The progressive impoverishment in CaO and in –fm– (Total iron as FeO + MgO).

The differentiation trends outlined above, for the Breivikbotn rocks, are thus very similar to those postulated for the Shonkin Sag intrusion (Osborne and Roberts 1931).

The trace element concentrations for a number of rocks of both groups are given in Table 21, and a plot to show the comparative values is given in Fig. 70. The Breivikbotn shonkinites are seen to have trace element concentrations fairly similar to shonkinites described from other areas. The average value for vanadium of 167 p.p.m. compares withan average value of 86 p.p.m. for Brazilian shonkinites (Guimaeres and Dutra 1959) and one value of 268 p.p.m. given by

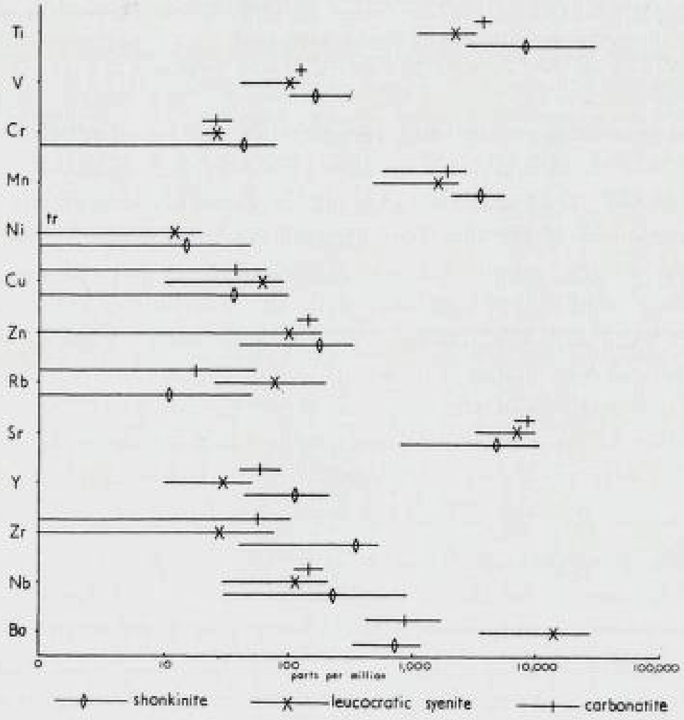

Fig. 70. Trace element distribution in rocks of the Carbonatite Association. The range and average values are given in parts per million.

Osborne and Roberts from the Shonkin Sag. Nickel with an average value of 15 p.p.m. compares with an average of 14 p.p.m. for the Brazilian rocks, and chromium at 43 p.p.m. compares with 23 p.p.m. for the Brazilian rocks and one value of 240 p.p.m. for the Shonkin Sag. Guimaeres and Dutra (op. cit) give values of 231 p.p.m. for Zr (Breivikbotn 350 p.p.m.), 78 p.p.m. for Nb (Breivikbotn 230 p.p.m.), and 83 p.p.m. for Y (Breivikbotn 116 p.p.m.). Two values for Zr are listed by Saether, from the Fen shonkinites, at 484 and 370 p.p.m. There is perhaps rather more disparity in terms of Barium concentrations, for example the Brazilian average is given at 9,407 p.p.m. (Breivikbotn 728 p.p.m.). The levels of Ba quoted by Osborne and Roberts from the Shonkin Sag are at 2330 p.p.m. and 4120 p.p.m., while Saether gives values at 358 and 537 p.p.m. from Fen. The Breivikbotn shonkinites have fairly high Sr contents, the average value being 4934 p.p.m. This contrasts with an average figure of 698 p.p.m. for the Brazilian shonkinites, and two values given for the Shonkin Sag at 1100 and 1230 p.p.m.

Certain differences in the levels of trace element concentration emerge between the shonkinites and the leucocratic syenites. The shonkinites are observed (Fig. 70) to be richer in Ti, V, Cr, Ni and Mn all of which elements are a reflection of the more melanocratic nature of the shonkinites. The levels of Zr, Nb, and Y are also, perhaps surprisingly, higher in the shonkinites than in the leucocratic syenites. The leucocratic syenites on the other hand have a higher content of rubidium (77 p.p.m., respect. 11 p.p.m.), and are strikingly enriched in Ba relative to the shonkinites (av. 14,258 p.p.m. respect. 728 p.p.m.). The leucocratic syenites also have a tendency towards enrichment in Sr (av. 7069 p.p.m. respect. 4394 p.p.m.). The trend towards barium enrichment with differentiation is commented upon by Osborne and Roberts (op. cit.) in relation to the Shonkin Sag intrusion. Semi-quantitative determintaions of rare earths show values in the order of 150 p.p.m. for lanthanum and 250 p.p.m. for cerium in one of the shonkinite specimens (SB 5).

(4) *The Carbonatites.*

Analyses in terms of major element oxides are given in Table 19, and trace elements in Table 21. Three of the analyses contain (Table 19) varying amounts of xenolithic material, mainly syenite, and this accounts for their fairly high values of Al_2O_3 and SiO_2. Two analyses of carbonatites from Stjernöy (Strand 1951) are also presented (Table 19). An interesting point of comparison between the Stjernöy and Söröy carbonatites is in the considerably higher $K_2O : Na_2O$ ratio of the former. It will be recalled that this was one of the most contrasting features in the compositions of nepheline syenites from the two localities (p. 99).

The carbonatites appear to have certain group features, in terms of trace element concentrations, relative to the associated syenitic rocks (Fig. 70). The Breivikbotn carbonatites have trace element concentrations which bear many features of comparison with other carbonatite localities. Strontium which averages 8,260 p.p.m. at Breivikbotn compares with 75 p.p.m. in carbonatites on Alnö island (Von Eckermann 1952), 1130 p.p.m. in sövites and 11,300 p.p.m. in Bastnaesite-carbonatites at Tundulu (Garson 1962). The carbonatite sheets occurring in the Songwe Scarp area of Tanganyika (Brown 1964), have many similarities in their mode of occurrence to the Breivikbotn examples, and two values for Sr are given at 2,100 and 2,800 p.p.m. (Deans and Hamilton 1964). No values have yet been obtained for the Sr^{87}/Sr^{86} ratio of the Breivikbotn carbonatites, but one value of this ratio is given, by Powell and Hurley (1963), for a carbonatite sample from Stjernöy. This sample shows a value of the ratio identical to normal carbonatites and different from metasedimentary limestones. Barium with an average value of 888 p.p.m. at Breivikbotn, compares with average values of 435 p.p.m. at Fen, 1185 p.p.m. at Alnö island, 2,040 p.p.m. in sövites and 4,590 p.p.m. in bastnaesite-carbonatites from Tundulu, and two values of 540 and 1000 p.p.m. at Songwe Scarp. The Breivikbotn carbonatites are rather low in their niobium contents (av. 141 p.p.m.) compared with most of these localities. The average of values quoted by Saether at Fen is 5,430 p.p.m., and at Tundulu values of 1,312 p.p.m. for sövites and 2,000 p.p.m. for bastnaesite-carbonatites are quoted by Garson. The values given by Deans and Hamilton for the Songwe Scarp area, however, are much closer at 70 and 320 p.p.m. The zirconium content of the Breivikbotn carbonatite also appears to be rather low in comparison with the average value of 220 p.p.m. given for the sövites of the Fen area. Determinations of trace element concentrations of one specimen of carbonatite from Stjernöy (kindly provided by Dr. H. Björlykke), and one specimen of a typical metamorphic limestone from Breivik are also given for purposes of comparison (Table 21).

The carbonatites at Breivikbotn are intrusive into the country rocks, as described in the section on field relationships, and they are also a part of an intrusion sequence. Furthermore their trace element concentrations are very similar to those of other described carbonatite occurences, and the carbonatites of the nearby island of Stjernöy have Sr^{87}/Sr^{86} ratios identical with those of normally accepted magmatic carbonatites. Thus it would appear that the Breivikbotn carbonatites have crystallised from a carbonatite magma, the ultimate source of which is as yet not clear. The genetic relationships with the shonkinites and leucocratic syenites are also obscure, but these rock types are always intimately associated in the field. Oosteroom (1963) is of the opinion that most of the carbonatites on the island of Stjernöy are products of metasomatism often in structurally determined zones. At Breivikbotn, however, although the rocks in contact with the carbonatites are often extensively affected by carbonate metasomatism and by hydrothermal alteration, the carbonatites themselves always have intrusive contacts with the surrounding rocks.

V. Conclusions and general petrogenetic considerations

The alkaline rocks of the Breivikbotn area have been shown to fall into two quite distinctive groups: nepheline syenites and associated rocks, and carbonatites with associated syenites of variable composition. It has been demonstrated furthermore that the two groups of alkaline rocks are broadly coeval in their emplacement during the protracted second (F2) major deformation phase. It is impossible, however, to discuss details of the relative ages of the two groups as they have not yet been found in contact with each other. Heier (1961, p. 150), however, considers the nepheline syenites of Stjernöy to be later than the carbonatites of that island, owing to the occurence of "nepheline lenses in the latter." This relationship is perhaps somewhat ambiguous for the carbonatite on Stjernöy has, according to Heier (op. cit.) and Oosteroom (1963), been strongly deformed, and many of the nepheline bearing lenses within the carbonatite are obviously of tectonic derivation. In the adit of the Nordkapp Nefelin A/S mine at Lillebugt the margin of the nepheline syenite mass can be observed to be cut by a carbonatite breccia which contains fragments of the syenite and also apparently of basic dykes intrusive into the latter. In spite of the general lack of detailed field relationships of rocks of the two groups it would appear that the various rocks of the complex, broadly coeval in emplacement, are probably genetically related and derived from the same ultimate parent material at greater depth.

The rocks of the nepheline syenite association at Breivikbotn, are mainly metasomatic in origin, though their production is considered to be related to the influx of a highly fluid nepheline syenite magma. There appear to have been two major periods of intrusion in this association. Firstly the intrusion of a pegmatite magma which crystallised to give alkali feldspar-biotite-magnetite pegmatites and secondly the intrusion of a nepheline syenite pegmatite magma. The latter was introduced mainly along a series of vertical and near-vertical fractures trending generally between N–S and N.N.E.–S.S.W. The nephelinization resulting in the ultimate production of nepheline syenite gneisses and occasional pegmatite bodies is regarded as the end-stage in a process of fenitization associated with the emplacement of the intrusive nepheline syenite pegmatites. Thus the process is considered to be the result of the metasomatising action of a highly fluid nepheline syenite pegmatite magma, particularly along structurally determined zones. It is further considered that this pegmatite magma was related to considerably larger bodies of nepheline syenite magma in depth. The intrusion of nepheline syenite at Nabberen on the adjacent island of Stjernöy is of course an example of a pluton of not inconsiderable dimensions. The hypothesis regarding the immediate origin of the nepheline-bearing rocks of the Breivikbotn area has many features in common with the modes of origin postulated for similar rock types in the Haliburton-Bancroft area of Canada (Osborne 1931 and Tilley 1958) and in the Fukushin-zan district of Korea (Miyashiro and Miyashiro 1956).

The rocks of the carbonatite association, however, present somewhat different problems. These are rock types not normally found in orogenically active zones. Indeed many descriptions (e.g. Pecora 1956, Garson and Campbell-Smith 1960, Garson 1962) stress the restriction of carbonatite-bearing alkaline complexes to fairly stable shield areas in contradistinction to tectonically active orogenic zones. The rocks at Breivikbotn, however, form an integral part of the complex sequence of tectonic, metamorphic and intrusive events involved in the development of this particular part of the Caledonian orogenic belt. The rocks of this association occur in one fairly narrow strip and form a series of intrusive sheets. The earliest event concerned the intrusion of melanocratic syenite (shonkinite) which was later invaded by more leucocratic syenite types (Fig. 71). These rocks have been demonstrated to represent members of a distinctive differentiation sequence which bears many resemblances to the sequence and trends of differentiation described for the rocks of the Shonkin Sag intrusion, Montana (Osborn and Roberts 1931). The rock types on the shore-section at Haraldseng are observed to follow the axial plane of an F2 fold structure, thus implying a tectonic channelling of the differentiated sub-magmas. The carbonatites are also intruded along the same tectonic zone and have cross-cutting relationships with both the metasedimentary country rocks and the various syenitic types. In the Breivikbotn occurrence the fenitization of country metasediments and basic rocks marginal to the rocks of the carbonatite association is seen to be a contact effect of the intrusion of the shonkinitic and various more leucocratic syenite types. Inclusions both of the various syenites and of fenitised country rocks are abundant in the carbonatite breccias. The fenites adjacent to rocks of the carbonatite association never develop nepheline.

The carbonatites of the Breivikbotn area have been shown to have the typical pattern of trace element enrichment normally associated with igneous carbonatites (Higazy 1954, Garson 1962), and furthermore carbonatites on Stjernöy have Sr^{87}/Sr^{86} ratios identical with those from carbonatites of proven magmatic origin. The field relationships and the geochemical properties of the Breivikbotn carbonatites thus point to a magmatic source for these rocks. Recent work on carbonate melts (Wyllie and Tuttle 1960 a, 1960 b and 1962) have shown that low-temperature carbonate melts are quite possible under the appropriate conditions. They indicate that for the system $CaO-H_2O-CO_2$ complete liquification will occur when water forms at least 13 % of the total (1,000 bars total pressure and 683° C). The presence of considerable quantities of water in the carbonatite melt which produced the Breivikbotn carbonatites is certainly indicated. It will be recalled that accompanying or preceding the emplacement of the carbonatite the invaded syenites were very extensively affected by carbonate metasomatism and by the zeolitization of the feldspars. This implies the action of hydrous emanations rich in dissolved $CaCO_3$ representing a hydrothermal front to the advancing carbonatite melt. If the carbonatites did in fact crystallise from such a melt, slight differences must

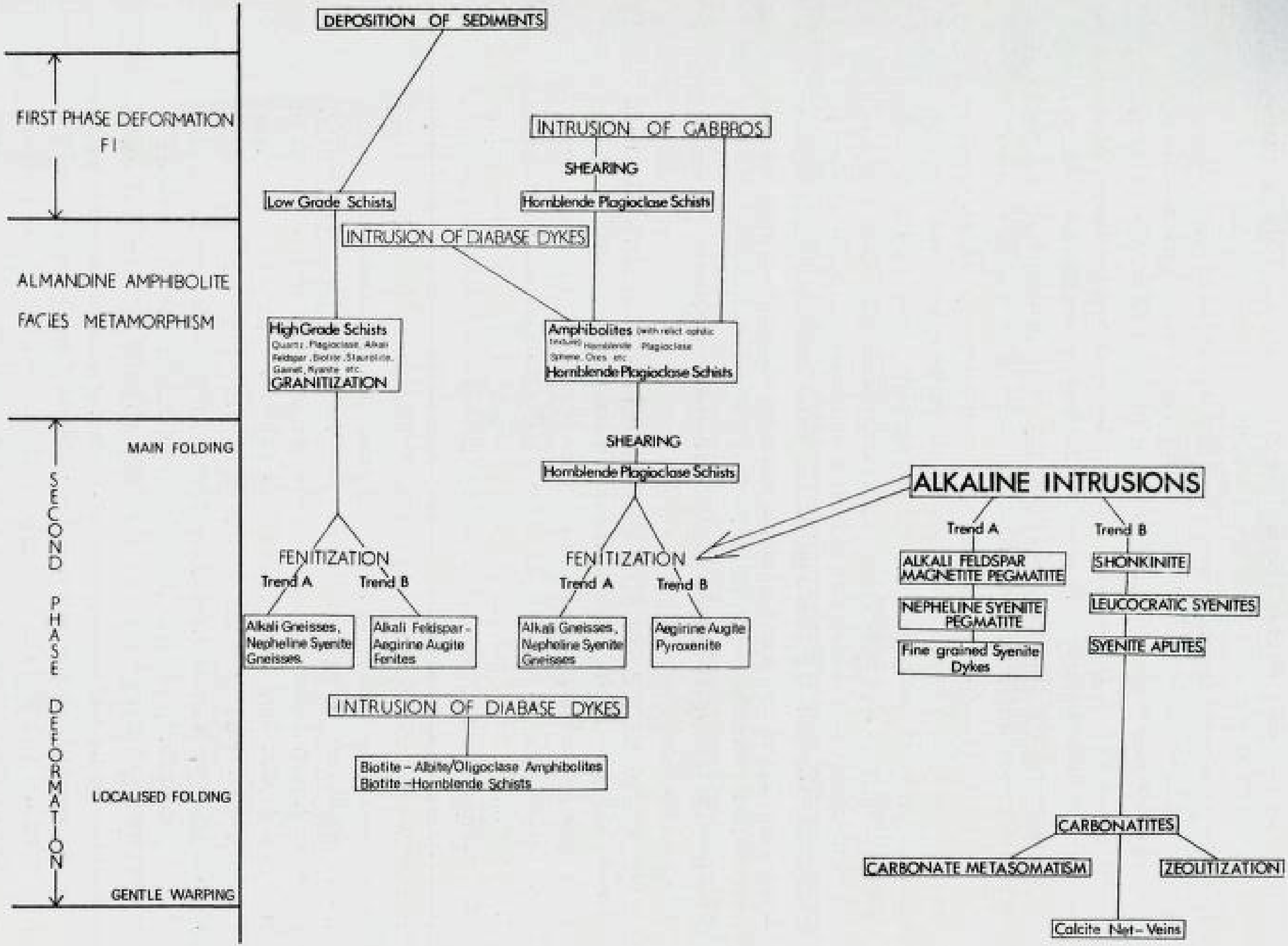

Fig. 71. Flow-diagram to illustrate the history, development and relationships of Breivikbotn Alkaline Complex.

be sought in the composition of the respective local magmas responsible for the Breivikbotn and Stjernöy carbonatites. Such differences are principally expressed in the respective Na_2O/K_2O ratios. The carbonatite breccias contain a great variety of fragments of varying shapes and sizes and have generally cataclastic textures. Many of the breccias have the appearance of tectonic breccias being very highly sheared and stretched. If the carbonatites represent rocks crystallised from an original carbonatite magma the breccias must be regarded as having been tectonically remobilized.

King (1965 p. 30) gives reasons why the carbonatites in most complexes appear to have been generated and emplaced at relatively low temperatures. He draws attention to the fact that "their appearance at late stages in the sequences, and their high content of minor constituents, are only reconciled easily with their representing derivative magmas." The intimate field relationships, and the general similarity in mineralogy of the carbonatites and the shonkinites at Breivikbotn, along with the very obvious "family relationship" in the trace element distributions in the rocks of the carbonatite association, indicate that a carbonatite melt could well be considered as a derivative from the same general parent magma as the various syenitic types.

King and Sutherland (1960 b) describe the common rock associations of the alkaline complexes of eastern and southern Africa. They relate the plutonic alkaline types in the following manner:—

ALKALI PERIDOTITE — MELTEIGITE — IJOLITE — URTITE
or — MALIGNITE — NEPHELINE SYENITE
PYROXENITE — SHONKINITE — SYENITE

They show all the major plutonic alkaline types thus to be related to an alkali peridotite or pyroxenite. In a subsequent account (1960 c) the same authors appeal to a carbonated alkali peridotite as the common source magma from which is derived the ijolite series and carbonatites. The nepheline syenites and other syenitic types are considered to be the products of a widespread (at depth) process of fenitization. Intrusive rocks of such compositions are regarded as being mobilized fenites, which latter have extrusive equivalents as phonolites and trachytes. These ideas are reiterated and expanded by King (1965) who considers the immediate parent magma to be one of melteigite—melanephelinite composition and being itself, probably, derived from an alkali peridotite. The plutonic series are considered, in this latest account, to have developed both by a process of crystallisation differentiation, from the envisaged parent magma, and by extensive fenitization produced by waves of emanations accompanying the emplacement of the intrusive alkaline types.

The origin of carbonatite and associated syenitic rocks have received a variety of explanations in other Scandinavian occurrences. Von Eckermann (1948), in his classic account of the alkaline complex of Alnö island in Sweden, when discussing the origin of the rocks of the complex appealed to a primary carbonatite magma in the form of a carbonated alkaline melt. The various alkaline silicate rocks are regarded by Von Eckermann as having been produced from country rock gneisses by a process of fenitization effected by emanations from the carbonatite melt. In many instances he envisaged the products of this process of fenitization as having been mobilized and being now represented as intrusive types. In his description of the Fen area in Southern Norway, Saether (1957) considered that the source magma was kimberlitic and that the various alkaline rocks of the area were produced by a combination of the processes of crystallisation differentiation and metasomatism. A very similar petrogenetic scheme is envisaged by Garson (1962) in his account of the origin of the Tundulu alkaline complex in Nyasaland.

The alkaline rocks of the Breivikbotn area are seen to fit well into the general scheme of plutonic alkaline rock associations worked out by King and Sutherland (1960 b) for eastern and southern Africa, and to follow two diverging trends of independent evolution. If the alkaline rocks of the area have a general genetic relationship the separation of the sub-magmas, from which these two divergent trends of differentiation have evolved, must have occurred at depths considerably below those now exposed at the surface. This implies a common parent probably at a very deep level in the crust. The nature of this common parent magma must remain somewhat of a mystery as rocks of suitable composition to represent such a magma i.e. alkali peridotite or kimberlite are not exposed at the surface anywhere in the region. The possibility of ultimately an ultrabasic source magma can, however, certainly not be excluded. The results of a preliminary gravity survey of the area are consistent with this view, for they reveal a regional gravity anomaly in the order of $^{+}90$ milligals centred over the SW part of the island. This anomaly may be interpreted as being caused by a large volume of high density, probably ultrabasic rocks occurring in depth beneath the area (M. Brooks personal communication).

Thus the alkaline rocks of the Breivikbotn area are considered to have been derived from a common parent deep in the earth's crust. Sub-magmas have been derived from this common parent and have followed separate and independent lines of crystallisation differentiation. The effects of tectonic stresses in facilitating the separation and channelling of the derived sub-magmas cannot be calculated, but are considered by the authors to be of prime importance in controlling the pattern of evolution of the alkaline complex. Extensive metasomatism accompanied the intrusion of the various alkaline rock types producing fenites and nepheline syenite gneisses. The ultimate source magma is postulated as a deep-seated ultrabasic magma, possibly alkali peridotite, though comments as to the detailed nature of this material are obviously very much in the field of speculation.

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Table 1.

Modal Composition of Nepheline Syenite Gneisses, Breivikbotn, Söröy.

	1	2	3	4	5	6	7	8	9
	SB1	SB52	SB101	SB105	SB109	SB139	SB158	SB179	SB185
K-feldspar	7.4	19.7	28.1	16.8	41.7	8.5	1.5	6.1	1.4
Plagioclase	66.1	51.1	46.3	50.8	24.6	66.3	72.0	79.8	70.1
Nepheline	18.0	25.7	20.4	27.3	29.4	23.8	18.5	6.5	21.7
Biotite	8.2	1.5	3.4	3.3	3.8	0.5	4.9	6.0	4.7
Amphibole	—	—	—	—	—	—	—	—	—
Calcite	—	1.6	×	—	—	—	—	—	—
Sodalite	—	—	—	—	—	—	0.3	—	—
Cancrinite	—	×	0.2	—	×	—	0.2	—	0.2
Muscovite	0.3	×	1.5	1.5	0.4	0.5	2.6	1.6	1.8
Zeolite	—	—	—	—	0.2	—	—	—	—
Apatite	—	0.1	—	—	—	—	—	—	—
Zircon	×	—	0.2	0.3	×	×	—	×	0.2
Pyrochlore	×	—	×	×	—	×	—	—	—
Sphene	—	—	—	—	—	—	—	—	—
Iron Ore	—	0.3	×	×	—	—	×	—	—
Scapolite	—	—	—	—	—	—	—	—	—
Corundum	—	—	—	—	—	—	—	—	—

* No. 12 contains also minor amounts of epidote and allanite

	1	2	3	4	5	6	7	8	9
Plagioclase composition % An	An_{11}		An_{12}		An_{9}		An_{10}		An_{8}

1—12 Nepheline Syenite Gneisses occurring in metasediments

10	11	12*	13	14	15	16	17*	18	19	20	21
SB197	SB502	SB522	SB17	SB44	SB46	SB481	SB482	SB495	SB497	SB499	DMS1
29.5	2.8	19.9	12.4	17.8	7.8	13.0	34.4	1.2	2.7	12.7	24.7
50.4	69.1	63.2	33.5	50.7	65.5	55.4	35.5	55.1	75.0	59.3	25.5
12.9	23.0	5.1	31.4	22.9	15.2	7.9	19.4	1.4	4.5	24.7	6.9
2.3	4.1	5.0	0.7	5.1	1.3	×	3.9	12.8	15.0	2.2	0.2
—	—	4.3	—	—	×	—	—	21.2	×	—	—
3.6	1.0	—	×	—	0.2	—	—	0.8	1.6	—	0.3
—	—	—	8.0	×	6.8	16.3	×	—	×	×	21.5
×	—	—	3.7	0.6	0.6	1.1	×	×	×	×	2.1
0.7	—	—	10.0	1.6	2.4	5.2	1.0	×	—	—	18.6
—	—	—	—	×	—	×	×	2.2	×	—	—
—	×	×	—	0.2	—	—	×	0.5	0.4	×	×
—	×	×	×	—	0.1	×	—	—	×	×	×
—	×	×	×	—	—	×	—	—	—	×	×
—	—	1.0	—	—	—	—	—	1.4	0.8	—	×
0.6	×	×	0.3	0.2	0.1	×	4.8	×	×	1.1	0.2
—	—	1.0	—	—	—	—	1.0	—	—	—	—
—	—	—	×	—	—	1.1	×	—	—	—	—

* No. 17 contains a few grains of spinel

An_{12}			An_{10}		An_{8}	An_{10}				An_{8}	

13—21 Nepheline Syenite Gneisses occurring in metagabbro
× Present in very small amounts
— Absent
All feldspar determinations on U-Stage (Turner method).

Table 2.

Modal Composition of Fenites associated with nepheline syenites—Breivikbotn.

	1	2	3	4	5	6	7	8
	SB97	SB102	SB104	SB106	SB111	SB113	SB184	SB187
K-feldspar	57.3	0.7	46.0	23.7	2.7	12.7	59.1	4.0
Plagioclase	40.2	55.7	44.8	59.3	80.5	47.0	38.1	70.1
Biotite	—	33.7	5.9	—	12.6	10.1	1.5	15.1
Aegirine-augite	2.2	1.9	1.5	12.7	—	6.3	—	—
Amphibole	—	—	0.2	2.8	—	×	—	—
Calcite	—	1.8	1.4	×	—	1.1	—	8.7
Quartz	—	4.2	—	—	—	22.1	—	0.3
Apatite	×	0.7	0.2	0.5	0.3	0.3	×	0.5
Allanite	—	×	—	—	×	0.1	—	0.1
Zircon	—	0.2	×	×	×	×	1.1	0.2
Sphene	0.3	—	—	×	—	0.3	—	0.3
Muscovite	—	×	—	—	2.7	—	×	×
Ores	×	×	×	×	—	—	0.2	—
Epidote	—	×	—	—	—	×	—	0.3
Zeolite	—	—	—	—	—	—	—	0.5
Pyrochlore	—	×	—	—	—	—	—	×
Corundum	—	—	—	—	—	—	—	—
Scapolite	—	—	—	—	—	—	—	—
Spinel	—	—	—	—	—	—	—	—
Plagioclase Comp. % An.	An_{11}	An_{20}	An_{12}			An_{8}	An_{6}	

1— 9 Fenites developed in metasediments
10—17 Fenites developed in metagabbro shear zones
18 Syenite vein in metagabbro—Hvitness

9	10	11	12	13	14	15	16	17	18
SB501	SB126	SB164	SB250	SB252	SB279	SB286	SB480	SB496	SB48
8.5	24.3	—	28.5	27.2	1.8	6.6	4.2	3.9	26.3
70.0	62.8	62.7	57.3	63.4	68.7	85.4	72.9	65.9	69.6
19.7	12.3	30.2	4.4	2.7	25.7	6.8	1.8	24.1	0.6
—	—	—	—	—	—	—	—	—	—
—	—	×	9.2	2.7	2.6	—	—	×	—
1.6	×	4.8	—	0.5	—	0.7	—	5.3	—
—	—	—	—	—	—	—	—	—	—
0.2	0.6	0.2	0.4	—	1.2	×	×	0.5	×
—	×	—	0.2	×	×	0.3	0.2	—	—
×	×	×	—	—	×	0.2	×	×	×
×	×	0.2	—	×	×	×	—	×	—
—	—	×	—	—	—	—	×	—	—
—	×	×	0.1	×	×	×	×	×	3.5
—	—	1.6	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	×	—
—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	3.7	—	—
—	—	0.3	—	—	—	—	16.9	—	—
—	—	—	—	—	—	—	0.3	—	—
		An_{12}		An_{10}					An_7

× Present in very small amounts
— Absent

Table 3.

Modal Composition of Aegirine-Augite Pyroxenite.

	SB6	SB9	SB10	SB58	SB93	SB242	SB243	SB263
	1	2	3	4	5	6	7	8*
Aegirine-augite	78.3	43.6	45.4	71.3	40.9	42.8	56.9	38.9
Amphibole	6.3	28.6	4.3	15.5	10.4	10.6	19.7	41.5
Garnet	—	1.4	—	—	0.6	—	3.6	—
Sphene	7.9	5.5	16.6	6.1	3.3	2.7	3.0	4.4
Apatite	3.0	1.4	2.1	3.4	7.7	3.3	0.4	1.6
Allanite	—	—	0.2	—	0.4	0.3	×	×
Zeolite	0.3	15.9	12.4	—	—	9.8	0.5	—
Feldspar	—	—	—	—	—	—	—	6.9
Calcite	3.0	2.3	17.6	—	36.8	31.2	15.9	5.1
Iron Ores	1.2	2.5	1.4	3.7	×	×	×	1.6

* The feldspar is a plagioclase An_{10}

× Present in very small amounts

— Absent

Table 4.

Modal Compositions of Fenites in Carbonatite Association—Breivikbotn, Söröy.

	1	2	3	4	5	6
	SB69	SB78	SB95	SB246	SB264	SB309
K-feldspar	22.1	48.9	66.2	37.0	40.1	8.0
Plagioclase	27.2	7.8	16.8	40.0	15.1	56.1
Aegirine-augite	40.4	40.9	11.1	19.4	7.3	2.0
Amphibole	5.1	—	2.7	—	32.5	19.7
Biotite	—	—	0.6	—	—	×
Sphene	3.5	0.6	1.2	1.7	4.1	0.3
Calcite	—	—	—	0.6	—	12.3
Apatite	0.9	1.0	—	1.4	0.9	0.8
Allanite	0.1	—	—	—	—	0.6
Zircon	×	×	—	—	—	×
Pyrochlore	—	—	—	—	—	—
Iron ore	0.6	0.8	1.4	×	×	0.3
Melanite	—	—	×	—	—	—

× Present in very small amounts

— Absent

Table 5.

Modal Composition of Shonkinites.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	SB5	SB12	SB14	SB15	SB59	SB67	SB72	SB82	SB91	SB239	SB245	SB267	SB552	SB593
Feldspar	38.2	—	—	8.9	—	20.6	—	6.6	13.6	2.5	80.2	12.4	0.2	1.1
Zeolite	22.3	44.1	53.1	68.4	43.9	58.2	60.5	50.4	60.8	52.3	2.2	62.5	25.4	65.5
Biotite	—	—	0.1	—	—	0.1	—	—	—	×	—	—	—	×
Aegirine-augite	9.0	5.0	11.6	8.4	23.8	12.2	5.2	1.4	2.9	3.7	15.5	14.2	25.6	17.4
Amphibole	11.1	4.1	5.5	2.7	—	4.8	5.9	12.4	15.2	13.0	0.8	5.1	18.4	3.8
Garnet	—	28.0	17.7	9.6	—	—	2.7	22.4	3.6	×	—	—	2.2	0.4
Sphene	0.2	1.6	1.3	0.4	3.7	1.0	0.7	3.5	1.2	0.4	0.6	2.1	2.8	×
Apatite	1.6	1.1	1.6	0.7	1.4	0.7	1.8	0.9	1.5	1.7	0.5	1.0	1.7	8.7
Allanite	0.6	0.3	0.4	×	0.3	0.2	0.7	0.3	×	0.6	×	×	0.3	0.4
Calcite	15.5	14.8	8.4	0.5	13.6	2.2	21.3	1.4	1.2	25.8	—	2.3	20.8	2.3
Ores	1.5	1.0	0.3	×	0.2	0.1	1.3	0.5	×	×	0.2	0.4	2.6	0.3
Zircon	—	—	—	0.4	—	—	—	0.2	—	—	—	—	—	—

— Not present

× Present in very small quantities

Table 6.

Modal Composition of Leucocratic Syenites.

	1	2	3	4	5	6	7	8
	SB56	SB64	SB65	SB81	SB84	SB236	SB393	SB265
Feldspar	82.2	1.1	89.9	89.0	20.9	52.4	×	97.2
Zeolite	—	67.6	×	×	65.8	26.6	84.9	—
Biotite	1.5	0.7	6.1	0.2	6.4	7.4	—	—
Aegirine-augite	10.3	4.3	—	9.7	—	—	6.4	1.8
Amphibole	1.7	7.5	—	0.3	—	—	1.5	—
Garnet	—	—	×	×	—	—	2.0	—
Muscovite	—	—	×	—	2.3	—	—	—
Sphene	0.8	1.3	1.4	0.5	×	0.3	0.7	×
Apatite	0.2	0.8	×	0.3	0.3	×	2.7	0.7
Allanite	×	0.5	×	×	×	0.4	0.4	×
Calcite	2.2	14.3	2.1	—	3.9	10.2	1.3	0.3
Ores	1.1	2.1	0.5	×	0.4	2.7	×	×

— Not present
× Present in minor amount only
1—7 Coarse Leucocratic Syenites
8 (SB265) Syenite Aplite

Table 7.

Modal Composition of Carbonatites, Breivikbotn, Söröy.

	1	2	3	4	5*	6*	7	8	9	10	11
	SB240	SB242	SB265	SB266	SB310	SB311	SB504	SB505	SB548	SB595	SB/ES1
Calcite	61.3	31.2	60.5	48.1	31.2	24.2	43.9	48.3	56.9	57.6	56.4
Aegirine-augite	26.7	42.8	13.4	15.7	—	—	31.3	33.3	10.8	11.0	22.7
Amphibole	4.9	10.6	13.9	20.1	29.3	25.3	13.6	5.3	12.7	12.3	8.1
Garnet	0.2	—	1.4	5.5	—	—	0.4	—	1.4	3.2	0.3
Biotite	0.2	—	—	1.8	×	1.6	—	—	—	×	—
Sphene	1.6	2.7	1.9	3.5	5.8	8.1	3.6	2.7	2.2	2.4	1.8
Apatite	3.3	3.3	5.5	3.0	1.3	1.6	5.4	6.4	2.4	5.7	7.0
Allanite	0.4	0.3	0.2	0.6	×	1.3	0.8	0.9	1.0	0.9	0.5
Zircon	—	—	—	—	—	×	—	—	—	×	—
Plagioclase	—	—	—	—	28.2	34.5	—	—	—	—	—
Alkali feldspar	—	—	—	—	1.4	2.2	—	2.2	—	—	—
Zeolite	—	9.8	2.0	—	×	×	—	—	9.8	3.6	0.5
Iron ore	1.5	×	1.1	1.9	2.9	1.3	1.1	1.0	2.8	3.3	2.7

* Composition of Plagioclase SB310—An_{10}; SB311—An_{8}.

× Present in very small amounts

— Absent

Analyses 2, 3, 5, 6, 8, 9, 10 Carbonatite Breccias.

Table 8.

Chemical Analyses of Nepheline Syenites.

	1 SB1	2 SB146	3 SB192	4 SB498	5
SiO_2	58.97	57.43	59.37	57.53	53.26
TiO_2	0.11	0.12	0.19	0.36	1.02
Al_2O_3	23.58	24.13	22.99	21.74	23.90
Fe_2O_3	0.60	0.33	0.53	1.33	2.15
FeO	1.58	1.33	4.02	2.12	1.98
MnO	0.12	0.10	0.14	0.11	0.16
MgO	0.14	0.12	0.04	0.46	0.38
CaO	0.51	0.53	0.68	1.88	3.53
Na_2O	10.76	10.79	9.27	8.91	6.95
K_2O	3.00	4.21	2.20	3.73	7.09
H_2O-	0.07	0.10	0.08	0.13	0.05
H_2O+	0.50	0.68	0.78	0.75	0.32
CO_2	0.06	0.23	0.00	0.79	1.01
P_2O_5	0.00	0.04	0.01	0.12	0.16
Total	100.0	100.14	100.31	99.96	

CIPW Norms

	1	2	3	4
Or	17.79	25.02	12.79	21.68
Ab	54.49	41.92	65.50	51.87
An	0.25	1.39	3.34	4.45
Ne	19.60	26.70	6.82	12.21
Cor	1.73	1.22	4.08	1.63
Ol	2.32	1.91	5.44	2.54
Mg	0.93	0.46	0.70	1.86
Ilm	0.13	0.15	0.46	0.61
Ap	—	—	—	0.34
Cal	0.10	0.50	—	1.40

1 Nepheline Syenite Gneiss in Metasediment (Anal. R. Solli & G. Hofseth, N.G.U.)
2 Nepheline Syenite Pegmatite " " " " " " "
3, 4 Nepheline Syenite Gneisses in Metagabbro " " " " " " "
5 Average Nepheline Syenite—Stjernöy (taken from Heier 1961).

Table 9.

Chemical Analyses of Fenites associated with Nepheline Syenites.

	1 SB175	2 SB111	3 SB188	4 SB187	5 SB164
SiO_2	61.38	59.16	57.30	57.38	43.66
TiO_2	1.30	0.32	0.55	0.41	1.33
Al_2O_3	18.36	21.68	21.61	19.78	13.56
Fe_2O_3	0.47	1.16	0.99	0.82	1.36
FeO	5.94	3.51	5.64	3.97	8.03
MnO	0.07	0.32	0.36	0.39	0.27
MgO	2.14	0.20	0.82	0.58	8.95
CaO	1.23	1.84	0.95	2.90	3.27
Na_2O	2.82	3.07	7.82	8.31	3.27
K_2O	5.31	7.58	3.22	2.62	4.96
H_2O-	0.07	0.07	0.09	0.07	0.15
H_2O+	0.51	0.68	0.85	1.11	1.70
CO_2	—	0.05	—	1.69	3.96
P_2O_5	0.16	0.26	0.03	0.15	0.27
Total	100.06	100.17	100.23	100.18	99.95

1—3 Fenites marginal to nepheline syenite gneisses in metasediment
4 Inclusion of metasediment in nepheline syenite gneiss
5 Fenite developed in metagabbro shear-zone
Analysts R. Solli and G. Hofseth (N.G.U.)

Table 10.

Normative minerals in Breivikbotn Gabbro.

	1	2	3	4	5	6	7
	SD5	SB41	SB132	SB157	SB203	SB225	SB278
Q	—	—	—	1.14	—	—	—
Or	6.67	2.22	1.67	2.22	5.56	5.56	1.11
Ab	7.34	3.67	11.53	17.20	12.58	8.91	1.57
An	21.96	18.07	42.81	25.02	31.40	30.58	14.74
Ne	13.06	6.82	6.53	—	12.78	7.95	6.05
Cc	0.20	0.70	0.50	0.20	0.20	0.70	0.20
Di	25.56	46.21	7.85	27.85	21.10	29.90	28.05
Hyp	—	—	—	11.68	—	—	—
Ol	11.62	12.38	16.54	—	10.90	6.19	35.54
Mt	5.34	4.41	2.78	7.66	4.41	7.66	4.41
Il	6.66	3.86	7.75	3.45	1.82	3.34	2.58
Ap	0.34	0.34	—	0.34	0.34	0.67	0.34

1—6 Metagabbros
7 Peridotite
Data from Stumpfl and Sturt 1964 except for analysis 3 (SB132).

Table 11.

Trace-element concentrations in Nepheline Syenites—Breivikbotn, Söröy.

	1	2	3	4	5	6	7	8	9
	SB1	SB105	SB140	SB158	SB528	C177	SB17	SB46	SB51
Ti	900	480	720	1680	1080	360	540	300	1020
V	tr	tr	5	10	45	tr	10	tr	10
Cr	20	25	35	20	35	25	50	45	40
Mn	930	1080	880	2440	1010	1625	775	540	930
Ni	15	10	15	20	20	tr	tr	20	20
Cu	nd	nd	15	10	tr	tr	10	15	15
Zn	145	110	70	180	145	125	25	60	85
Rb	150	225	90	165	145	95	105	195	160
Sr	50	210	420	880	210	710	440	100	750
Y	25	15	40	45	35	40	40	110	15
Zr	300	700	420	60	80	550	100	630	40
Nb	230	295	100	145	550	590	85	700	100
Ba	280	110	310	1094	575	250	560	230	520

1— 6 Metasomatic Nepheline Syenite Gneisses in Metasediments.
7—16 „ „ „ „ „ Metagabbro.
17—19 Nepheline Syenite Pegmatites.

10	11	12	13	14	15	16	17	18	19
SB117	SB192	SB495	SB496	SB497	SB498	SB499	SB144	SB146	SB280
360	1020	10760	9470	5520	2520	1140	300	780	480
tr	10	175	115	90	20	10	tr	tr	tr
35	20	40	55	35	15	20	35	15	40
405	1085	1705	3850	1310	850	470	560	775	620
10	15	45	55	35	15	10	20	15	10
30	nd	85	nd	tr	30	25	20	tr	30
45	215	120	375	90	120	15	40	105	20
70	110	60	200	115	95	80	135	135	55
340	220	850	305	765	3140	2700	320	585	855
30	55	40	80	40	45	40	40	50	50
475	175	230	360	210	235	230	300	190	510
200	125	115	195	130	100	80	125	125	40
380	285	985	450	610	2990	2490	340	905	870

Table 12.

Trace-element Concentrations in Alkaline Rocks associated with Nepheline Syenites.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	SB141	SB142	SB147	SB281	SB111	SB184	SB188	SB501	SB530	SB175	SB164	SB177	SB121	SB553
Ti	1320	2700	300	1380	1920	600	3300	7440	7020	10550	8400	840	1380	1620
V	tr	20	tr	10	tr	tr	35	120	110	150	140	20	40	60
Cr	35	25	35	45	25	20	55	55	50	80	245	25	25	30
Mn	660	2400	370	620	2480	650	2790	2780	645	540	2090	485	355	2015
Ni	tr	20	15	tr	15	15	20	120	55	65	270	10	tr	nd
Cu	20	20	10	45	nd	nd	nd	nd	tr	nd	15	135	20	tr
Zn	70	80	tr	25	220	60	420	355	145	245	225	185	205	240
Rb	80	105	145	30	170	200	225	185	180	180	250	170	30	75
Sr	1500	1815	210	2810	1225	100	130	280	245	280	180	1250	750	310
Y	25	45	50	50	50	55	80	100	90	95	40	30	60	45
Zr	395	tr	210	nd	300	275	1365	405	215	395	185	650	850	2090
Nb	65	105	100	10	325	125	480	230	15	40	100	215	395	410
Ba	1860	1815	575	2210	1660	470	435	1080	1875	1355	240	950	380	260

All values expressed as ppm
tr present as trace
nd below limits of detection

1—4 Alkali-Feldspar/Magnetite Pegmatites
5—9 Fenites in semi-pelite adjacent to nepheline syenites
10 Quartz-biotite-garnet schist
11 Biotite-Plagioclase-Microline gneiss in shear-zone (Metagabbro)
12—14 Fine-grained syenite dykes along F2 axial planes.

Table 13.

Comparison of Fe_2O_3 : FeO ratios in nepheline syenites from Sørøy and Stjernøy.

	Sørøy Fe_2O_3 : FeO		*Stjernøy* Fe_2O_3 : FeO
SB1	0.38	No. 1	1.12
SB146	0.25	No. 2	1.20
SB192	0.13	No. 6	0.61
SB498	0.63	No. 11	1.82
Av values	0.35		1.19

Stjernøy values from Heier (1961)

Table 14.

Comparison of Na_2O : K_2O ratios in nepheline syenites from Sørøy and Stjernøy.

	Sørøy Na_2O : K_2O		*Stjernøy* Na_2O : K_2O
SB1	3.59	No. 1	1.00
SB146	2.56	No. 2	1.18
SB192	4.21	No. 6	0.83
SB498	2.39	No. 11	0.96
Av values	3.19		0.99

Stjernøy values from Heier (1961)

Table 15.

Analysis of Aegirine-Augite Pyroxenite.

	1	2		Trace elements 1	Trace elements 2
SiO_2	42.95	44.78	Ti	13,550	16,440
TiO_2	2.21	2.26	V	405	280
Al_2O_3	8.52	15.90	Cr	150	210
Fe_2O_3	10.45	4.01	Mn	6,660	1,312
FeO	8.22	7.77	Ni	20	150
MnO	0.82	0.14	Cu	10	150
MgO	6.40	8.28	Zn	355	—
CaO	14.47	12.67	Rb	tr	n.d.
Na_2O	3.56	2.95	Sr	405	660
K_2O	0.88	0.67	Y	85	20
H_2O-	0.12	0.07	Zr	350	80
H_2O+	0.99	0.61	Nb	375	n.d.
CO_2	0.13	0.20	Ba	90	245
P_2O_5	0.25	0.09			
Total	99.97				

	Norm 1		Mode 1
Or	5.56	Aeg.-Aug.	71.3
Alb	11.00	Amphibole	15.5
An	4.17	Sphene	6.1
Ne	10.51	Iron Ore	3.7
Di	42.25	Apatite	3.4
Woll	5.10		
Mag	15.31		
Ilm	4.26		
Ap	0.67		
Cal	0.30		

— Not analysed
n.d. Not detectable
tr Present in minor amounts

1 Aegirine-Augite Pyroxenite, Haraldseng (SB58) Analyst Per-Reidar Graff N.G.U.
2 Average metagabbro composition, Breivikbotn (From Stumpfl & Sturt 1964 + one new analysis).

Table 16.

Analysis of Fenite.

	SB245	SB175
SiO_2	60.70	61.68
TiO_2	0.89	1.30
Al_2O_3	12.00	18.36
Fe_2O_3	4.86	0.47
FeO	2.29	5.94
MnO	0.33	0.07
MgO	2.52	2.14
CaO	5.49	1.23
Na_2O	4.47	2.82
K_2O	7.00	5.31
H_2O^-	—	0.07
H_2O^+	—	0.51
CO_2	—	0.00
P_2O_5	0.24	0.16
Total	100.79	100.06

CIPW Norm	SB245
Q	0.42
Or	41.14
Ab	23.06
Ac	13.40
Di	19.12
Wo	1.04
Mt	0.46
Il	1.67
Ap	0.34

— Not determined

SB245 Fenite marginal to carbonatite (Analyst R. Tyler)

SB175 Metasedimentary semi-pelitic schist (Analysts R. Solli, and G. Hofseth, N.G.U).

Table 17.

Chemical Analyses of Shonkinites.

	1 SB5	2 SB10	3 SB15
SiO_2	33.28	35.49	41.20
TiO_2	0.63	6.83	1.33
Al_2O_3	15.16	19.05	19.44
Fe_2O_3	4.53	5.81	6.78
FeO	4.11	4.96	2.32
MnO	0.61	0.83	0.57
MgO	1.10	0.53	0.02
CaO	19.56	17.89	15.69
Na_2O	5.53	2.45	5.06
K_2O	0.56	1.79	1.45
H_2O-	0.22	0.12	0.17
H_2O+	3.76	0.46	5.20
CO_2	10.22	3.72	0.82
P_2O_5	0.30	0.27	0.05
Total	99.57	100.21	100.10

Normative Minerals	1 SB5	2 SB10	3 SB15
Or	3.34	10.56	8.90
Ab	15.72	4.19	10.48
An	15.01	35.58	23.35
Ne	16.76	9.09	17.24
Di	13.24	2.81	—
Wo	—	9.86	20.42
Mt	6.50	—	5.57
Hm	—	5.76	3.34
Il	1.22	12.16	2.43
Ap	0.67	0.67	0.34
Cc	23.20	8.40	1.80
Per	—	0.41	—

Re-calculated analyses.

	1 SB5	2 SB10	3 SB15
SiO_2	45.67	38.96	44.30
TiO_2	0.86	7.49	1.43
Al_2O_3	20.79	20.89	20.91
Fe_2O_3	6.21	6.38	7.29
FeO	5.62	5.45	2.50
MnO	0.84	0.98	0.61
MgO	1.51	0.58	0.02
CaO	9.00	14.46	15.80
Na_2O	7.59	2.69	5.44
K_2O	0.77	1.97	1.56
H_2O-	0.30	0.13	0.18
H_2O+			
CO_2			
P_2O_5	0.41	0.30	0.06
Total	99.57	100.21	100.10

Normative Minerals	1 SB5	2 SB10	3 SB15
Or	5.00	11.68	9.45
Ab	25.68	4.19	10.48
An	20.02	38.92	28.08
Ne	21.02	10.22	19.03
Di	17.88	3.24	0.22
Wo	0.23	10.79	20.53
Mt	9.05	—	5.80
Hm	—	6.46	3.36
Il	1.67	13.68	2.74
Ap	1.01	0.67	0.34
Per	—	0.54	—

Analyst Per-Reidar Graff (N.G.U.)

Table 18.

Chemical Analysis of Leucocratic Syenites.

	1 SB63	2 SB81	3 SB236	4 SB553
SiO_2	35.58	59.95	37.44	59.97
TiO_2	0.58	0.50	0.52	0.21
Al_2O_3	24.64	17.05	16.38	20.45
Fe_2O_3	2.03	2.87	3.98	0.02
FeO	2.05	1.71	3.31	0.84
MnO	0.15	0.37	0.41	0.12
MgO	tr	0.76	0.28	1.59
CaO	12.71	3.99	14.93	0.85
Na_2O	5.21	4.81	3.91	4.45
K_2O	2.60	6.88	5.58	9.22
H_2O-	0.99	0.02	0.26	0.01
H_2O+	5.50	0.45	1.15	1.14
CO_2	8.80	0.04	10.80	0.19
P_2O_5	0.02	0.07	0.03	0.01
Total	100.66	99.45	98.98	99.07

Normative Minerals	1	2	3	4
Or	14.69	40.59	33.36	54.49
Ab	25.68	38.77	11.00	28.82
An	7.51	5.00	5.84	3.06
Ne	9.94	0.85	11.93	5.11
C	10.40	—	1.73	1.94
Di	—	5.59	—	—
Wo	—	2.78	—	—
Ol	1.16	—	2.60	3.82
Mt	3.02	4.18	5.80	—
Hm	—	—	—	—
Il	1.22	0.91	0.91	0.46
Cc	20.00	0.10	24.60	0.50
Ap	—	0.34	—	—

Analysts: J. Bartle (SB63); Per-Reidar Graff, N.G.U. (SB81; SB236; SB553).

Re-calculated Analyses.

	1	3
SiO_2	47.74	50.66
TiO_2	0.77	0.69
Al_2O_3	32.99	22.14
Fe_2O_3	2.72	5.37
FeO	2.74	4.47
MnO	0.18	0.55
MgO	—	0.32
CaO	2.01	1.62
Na_2O	6.97	5.29
K_2O	3.49	7.54
H_2O-	1.03	0.29
H_2O+		
CO_2		
P_2O_5	0.02	0.04
Total	100.66	98.98

Normative Minerals	1	3
Or	20.57	44.48
Ab	35.11	15.72
An	10.01	8.06
Ne	13.06	15.62
C	13.97	2.35
Di	—	—
Wo	—	—
Ol	1.57	3.42
Mt	3.94	7.89
Hm	—	—
Il	1.60	1.37
Cc	—	—
Ap	—	—

Table 19.

Chemical Analyses of Carbonatites.

	1 SB E/S	2 SB266	3 SB548	4 SB595	5 BR240	6	7
SiO_2	12.40	17.78	19.34	14.73	4.58	18.43	13.49
TiO_2	0.98	1.64	0.96	1.02	nd	2.76	2.19
Al_2O_3	1.75	8.10	9.51	6.47	3.61	8.81	5.84
Fe_2O_3	4.36	6.13	4.15	5.02	0.16	3.37	3.00
FeO	2.33	4.99	4.81	4.55	0.35	13.67	7.15
MnO	0.58	0.50	0.57	0.48	nd	0.32	0.16
MgO	2.26	0.44	1.92	1.93	nd	4.05	4.46
CaO	43.40	35.00	33.83	37.89	50.97	22.47	32.78
Na_2O	1.62	2.25	2.91	1.59	0.57	0.44	0.54
K_2O	0.25	0.61	0.49	0.37	0.30	4.54	3.03
H_2O-	0.03	—	0.17	0.05	0.02	0.23	0.12
H_2O+	0.13	0.30	0.46	0.43	0.30	1.24	0.88
CO_2	27.58	22.20	20.45	23.99	39.33	16.27	21.52
P_2O_5	1.51	0.20	0.48	0.48	0.01	1.91	4.60
S	0.85	—	—	—	—	0.25	0.18
BaO	—	—	—	—	—	0.60	0.27
F	—	—	—	—	—	0.12	—
Total	100.53	100.14	100.11	99.50	100.20	99.98	100.21

1—4 Carbonatites—Breivikbotn area (Analysts (1) R. Thomas, (2) J. Bartle, (3) and (4) Per-Reidar Graff N.G.U.)

5 Metasedimentary Limestone—Breivik (Analyst J. Bartle)

6 Average of 6 carbonatites—Stjernöy (Strand 1951)

7 Biotitt Søvitt—Stjernöy (Strand 1951).

Table 20.

Mineral Analyses from Alkaline Rocks—Breivikbotn.

	1	2	3	4	5
SiO_2	51.20	33.57	49.20	50.13	50.25
Al_2O_3	1.51	3.13	2.38	1.64	1.97
TiO_2	0.27	1.23	0.49	0.45	0.52
Fe_2O_3	6.10	24.02	8.24	13.54	10.69
FeO	8.01	1.27	11.99	6.49	6.69
MnO	1.03	1.54	2.07	0.94	0.59
MgO	8.66	3.06	5.16	5.65	6.69
CaO	19.54	31.38	16.78	14.37	15.74
Na_2O	2.69	0.80	3.36	6.08	5.19
K_2O	0.78	0.16	0.87	1.03	1.14
P_2O_5	0.17	—	0.16	0.16	0.08
Total	99.96	100.16	100.70	100.48	99.75
R. I. α	1.716		1.728	1.735	1.720
γ	1.750		1.770	1.767	1.748
$A\Lambda C$	—		24.5°	24°	22°
S. G.	3.43		3.47	3.45	3.45
End members.					
Diopside	47.67		23.94	30.69	36.94
Hedenbergite	27.58		35.81	22.42	25.32
Acmite	22.96		30.21	43.99	38.30
Wollastonite	1.76		—	2.83	—

1 Aegirine Augite from Calcite-pyroxene garnet segregation in shonkinite (BAS 1)
2 Garnet from Calcite-pyroxene garnet segregation in shonkinite (BAS 2)
3 Aegirine-Augite from Fenite marginal to shonkinite (SB 78)
4 Aegirine-Augite from Fenite marginal to shonkinite (SB 245)
5 Aegirine-Augite from Nepheline Syenite (SB 190)

Analyses and mineral data by R. Tyler (see Tyler 1963)

Table 21.

Trace-Element Distribution in Rocks of Carbonatite Association.

	1	2	3	4	5	6	7	8	9	10	11
	SB5	SB10	SB15	SB72	SB91	SB275	SB56	SB63	SB81	SB236	SB553
Ti	2700	30630	4730	3480	6120	7500	2880	3360	1680	2760	1080
V	135	320	135	100	145	185	110	110	120	125	40
Cr	70	50	80	n.d.	30	25	25	20	20	30	30
Mn	3530	5460	3020	2090	3505	3795	2170	1160	2365	1960	465
Ni	20	50	5	tr	tr	15	10	5	15	tr	20
Cu	60	n.d.	30	100	15	25	55	90	40	85	30
Zn	200	315	60	40	295	170	85	105	140	180	tr
Rb	n.d.	50	15	n.d.	tr	tr	65	25	75	25	195
Sr	6980	840	3460	10800	3360	4180	4900	9055	3205	9770	8415
Y	210	135	75	50	45	180	10	15	50	40	35
Zr	50	385	405	40	630	570	40	tr	75	tr	30
Nb	105	930	60	30	165	105	210	70	210	45	30
Ba	810	335	1160	380	1195	475	3590	22230	7100	10650	27700

All values expressed as p.p.m.

1— 6 Shonkinitic Syenites
7—11 Leucocratic Syenites
12—13 Fenites
14 Aegirine-Augite Pyroxenite
15—17 Carbonatite
18 Stjernöy Carbonatite (specimen kindly provided by Dr. H. Bjorlykke)
19 Metamorphosed Limestone, Breivik

Gravimetric determinations of BaO for specimens SB63 and SB553 give 2.91 % and 2.87 % respectively (analyst, R. Tyler).

12	13	14	15	16	17	18	19
SB69	SB95	SB58	SB266	SB595	SB548	Stj 1948	BR240
10490	7490	13550	4560	3780	3220	10790	120
260	220	405	120	135	125	100	tr
50	30	150	35	20	25	20	10
5205	5240	6660	2720	565	2660	1625	90
15	10	20	10	tr	tr	10	n.d.
15	20	10	45	tr	65	15	tr
330	205	355	160	120	155	155	n.d.
40	40	tr	55	n.d.	n.d.	80	n.d.
1325	2650	405	9575	9480	6805	3400	2305
90	80	85	40	85	50	80	n.d.
420	760	350	70	tr	105	n.d.	n.d.
520	600	375	185	115	125	45	n.d.
1940	650	90	420	1605	640	870	140

tr — present as trace
n.d. — below limits of detection

Table 22.

Average values of trace element concentrations.

	1	2	3	4	5	6	7	8	9	10	11	12
Ti	2130	867	3265	520	2800	4056	3853	9230	2220	8990	16440	
V	29	11	50	tr	42	53	126	167	101	240	280	86
Cr	31	23	36	31	5-10	42	26	43	26	40	210	23
Mn	1160	1327	1192	709	550	1881	1982	3567	1604	5222	1312	
Ni	20	13	24	15	n.d.	45	tr-10	15	12	12	150	14
Cu	15	tr-10	21	16	11	n.d.	37	36	62	17	150	—
Zn	111	129	110	55	—	240	145	180	102	267	—	—
Rb	118	156	116	108	115	192	18	11	77	40	n.d.	—
Sr	711	412	961	545	3500	336	8620	4934	7069	1988	660	698
Y	46	32	48	45	tr	75	58	116	30	85	20	83
Zr	318	351	268	330	26	512	58	350	28	590	80	231
Nb	217	362	183	90	tr	233	141	230	113	560	n.d.	78
Ba	750	462	950	709	2400	1104	888	728	14258	1295	245	9407

All values expressed as p.p.m.
tr present as trace
n.d. below limits of detection
— not analysed

1 All Nepheline Syenites—Söröy
2 Metasomatic Nepheline Syenite Gneisses arising from metasediment—Söröy
3 Metasomatic Nepheline Syenite Gneisses arising from sheared metagabbro—Söröy
4 Nepheline Syenite Pegmatite—Söröy
5 Av. nepheline syenite—Stjernöy (data from Heier 1964)
6 Fenites associated with nepheline syenite—Söröy
7 Carbonatites—Söröy
8 Shonkinites—Söröy
9 Leuco-Syenite (ass. with shonkinite)—Söröy
10 Fenite associated with shonkinite—Söröy
11 Metagabbro, Breivikbotn (values from Stumpfl & Sturt 1964)
12 Average shonkinite in Brazil (Guimaraes & Dutra 1959)

PRELIMINARY DESCRIPTION OF THE GEOLOGY OF THE DØNNESFJORD AREA, SØRØY

By

EDWARD C. APPLEYARD

INTRODUCTION

The village of Dönnesfjord is located near the head of the south-western arm of the fjord of the same name on the north-west coast of Söröy (see inset map, fig. 1, locality D). The Dönnesfjord-Øen (as named on the AMS Series M711 map sheet 1836-III) actually consists of a tripartite peninsula linked to the mainland by a narrow isthmus, the three segments being named Vesteröy, Midteröy and Nordöy from west to east respectively. The area mapped embraces this peninsula, the islets of Rundholme and Sauöy, the westward-facing flank of the headland named Börfjordnaeringen and both sides of the northwest trending valley, locally called Dalen, which reaches the fjord southeast of Sauöy.

GEOLOGICAL SETTING

The general geological setting is of a mixed group of metasediments metamorphosed, as elsewhere in Söröy, under almandine-amphibolite facies conditions, intruded by two thick gabbro sheets, a thinner sheet of acid diorite, and a magmatic-metasomatic complex of nepheline-bearing alkaline rocks.

The metasediments are the oldest rocks in the area and appear to correlate with the upper part of the Klubben Quartzite Group (Ramsay and Sturt, 1963, p.413; Roberts, 1965). No primary sedimentary structures have been recognized but by analogy with the Breivikbotn area it appears that the beds become younger in a northerly direction. A number of lithological units are recognizable in the field which are listet in table I.

Two major periods of folding (F1 and F2) have been recognized in Söröy by Ramsay and Sturt (1963, p.414 (both of which are represented in the Dönnesfjord area. Here, the major structure consists of the northward-facing steep to overturned limb and the much flatter-lying upper limb of am ajor, F2, east-northeasterly plunging box fold. All the rocks exposed on the Dönnesfjord peninsula and on the northern tip of Börfjordnaeringen dip steeply, mainly towards the north, whilst the upper flat limb of the fold can be traced particularly well by the psammite 'T' and quartzite 'Q' contact as it extends southward along the ridge of Börfjordnaeringen. Structures developed during the earlier (F1) folding include tight isoclinal minor folds and the prominent schistosity of both the metasediments and the gabbros.

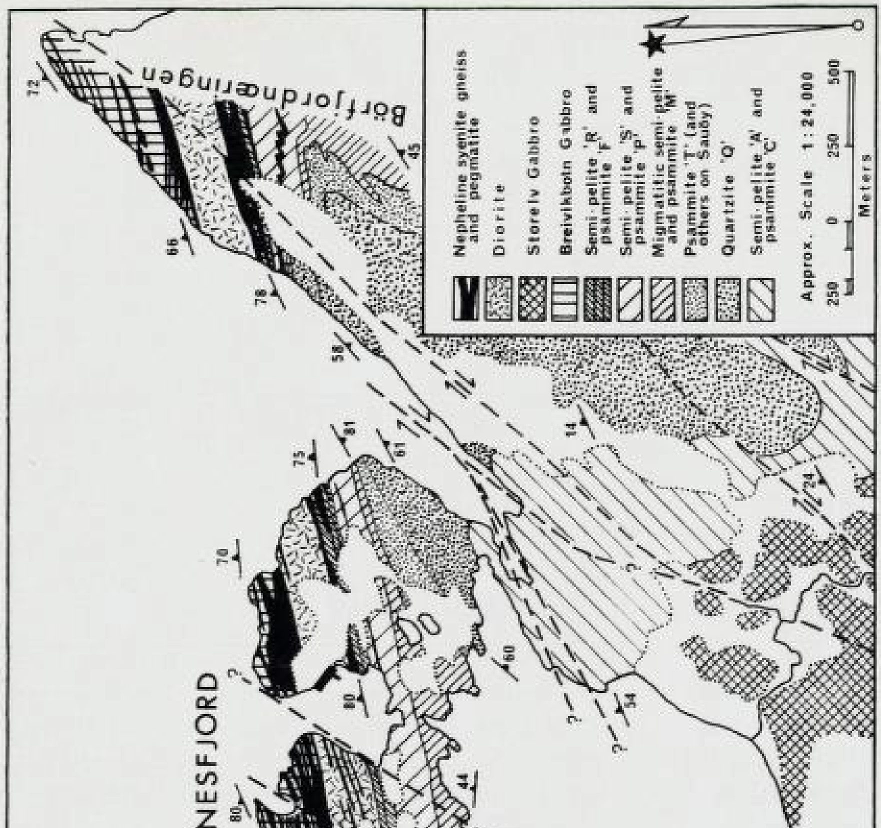

Figure 1. Generalized geological map of the Dönnesfjord area. On the inset map of Söröy are marked the areas where rocks of the nepheline-syenite suite have been mapped to date, viz. B—Breivikbotn area, D—Dönnesfjord area, S—Storelv area, and V—Vatna area.

Table 1

Metasedimentary Units Recognized in the Dönnesfjord Area

10)	Crystalline limestone and calc-silicate gneisses	'L'
9)	Rusty weathering sillimanite-rich semi-pelite	'R'
8)	Flaggy-foliated psammite gneiss	'F'
7)	Semi-pelite	'S'
6)	Psammite	'P'
5)	Migmatitic semi-pelite	'M'
4)	Regular banded psammite—semi-pelite	'T'
3)	Quartzite	'Q'
2)	Psammite	'C'
1)	Semi-pelite	'A'

STRATIGRAPHY

1) *Semi-pelite 'A'*—This semi-pelitic schist which is occasionally garnetiferous contains abundant intercalculations of psammitic gneiss which are usually less than 5 cm. in thickness but occur up to 15 cm. thick. Near the axial zone of the major fold the schist is intensely deformed; the normal foliation parallel to the lithological banding becomes indistinct or may be replaced by a new foliation approximately parallel to the axial plane of the fold. If numerous, the psammite layers usually maintain their coherence and outline complex minor folds, but when they comprise only a small proportion of the rock a tectonic breccia is commonly formed, the psammite fragments outlining disjunctive minor folds. The limbs of minor folds have often been completely sheared out along the axial plane foliation leaving only isolated closures defining a strong *b*-lineation. Diffuse veins and streaks of granitic matter and quartz are found sporadically throughout the outcrop of this unit usually lying in the axial plane foliation. Rarely, discrete dilational bodies of coarse-grained pink leucocratic muscovite granite cut across the foliation planes.

2) *Psammite 'C'*—The semi-pelite 'A' grades into a dominantly psammitic rock characterized by many thin folia of biotite-rich semi-pelite. An axial planar schistosity is often developed in these semi-pelitic partings especially in the axial region of the major fold. Tectonic breccias

are rare. Granite, granite pegmatite and quartz veins are concordant with the layering but also follow the secondary schistosity.

3) *Quartzite 'Q'*—Psammite 'C' passes fairly abruptly into buff-coloured, fairly massive quartzite with infrequent psammite and semi-pelite horizons. Minor folds in this unit are usually broad and open in style but where deformation has been intense they have largely been obliterated by a strong axial plane cleavage which also renders individual lithological horizons streaky and discontinuous. Boudinage structure sometimes occurs in quartzite bands when semi-pelitic partings are more numerous than usual.

The quartzite is usually partly granitized. This granitization is most intense on the upper flat limb of the fold where the foliation is almost obscured by pink disseminations, streaks and augen of potash-feldspar. Near the fold hinge the quartzite has often been brecciated and subsequently healed with an intensely granitized matrix. On the steep limb, however, the effects of the granitization are usually restricted to patches of pink feldspathized quartzite, often garnetiferous, or to discrete masses or veins of quartz, quartz-rich granite or granite pegmatite.

Thin, highly sheared, basic dykes occur parallel to the axial planes of folds. Pale brownish potash-feldspar is prominently developed along steeply dipping north-northwest joints related to the major F2 folds.

4) *Regular banded Psammite—semi-pelite 'T'*—The northern contact of the quartzite on Nordöy is strongly sheared and the succeeding unit of interbanded psammitic and semi-pelitic gneisses appears to truncate the 'Q' unit at a low angle. Near this contact the 'T' gneisses are often strongly disrupted and the layering obliterated by a complex of anastomosing shear planes. The unit is difficult to trace on the upper flat limb of the major fold due to the intensity of penetrative granitization which makes it barely distinguishable from the underlying granitized 'Q' unit. On Nordöy these gneisses often contain quartz veins and irregular masses of white, coarse-grained leucogranite up to 2 metres in diameter.

5) *Migmatitic Semi-pelite 'M'*—The 'T' lithological unit grades northward over a width of about one metre into a dominantly semi-pelitic unit which is characterized over much of its outcrop area by abundant lenses, streaks, veins and patches of leucocratic, coarse-grained quartzo-

feldspathic material. These commonly give the unit the appearance of a venitic migmatite. The palaeosome is usually a biotite-rich semi-pelitic gneiss often containing sporadic pink garnets not uncommonly forming knotty clusters up to 12 cm. in diameter. Some zones contain fairly abundant thin psammitic ribs but in general this lithology is subordinate in amount. The granitic neosome is usually completely leucocratic except for thin wisps and schlieren of biotite-rich schist. Mauve-pink garnets may be found in the granitic veins, as separate small euhedral grains and also as trains of small granules along the contact of the vein with the host rock. The amount of granitic material present varies considerably and often quite abruptly. At its maximum development it may comprise up to 50 per cent of the rock but the average content is closer to 10 to 15 per cent. Eastward the amount of granitic material diminishes and where the unit is exposed on Börfjordnaeringen it is essentially granite-free. Here, some pelitic horizons are sillimanitic. A less common manifestation of the granitization than the venitic facies is a more pervasive transformation of the schists into nebulitic quartz-feldspar-biotite-garnet gneiss with wispy biotite-rich streaks.

The foliation of the unit is largely a secondary schistosity axial planar to the major fold. It varies from well-developed and regular to discontinuous and erratic, depending on the degree of deformation. The unit is also strongly lineated. These lineations appear to comprise more than one set. East-northeast striking lineations, plunging gently in either direction, appear to be related to the major folds, while a north-west striking setw ith variable plunge is earlier. These lineations are marked by crumpled micaceous folia, aligned mica flakes on foliation surfaces, axes of ptygmatic quartz veins and of granitic rods and swollen portions of veins and by the axes of minor folds.

The unit is cut by basic dykes of at least two ages, one preceding and the other during or following the period of major folding.

6) and 7) *Psammite 'P' and Semi-pelite 'S'*—The 'M' semi-pelite is in sharp contact along its northern edge with flaggy, siliceous psammites of the 'P' unit. This unit passes upwards into a dominantly semi-pelitic unit, denoted the 'S' semi-pelite. In places the transition between these two units is abrupt but elsewhere the psammites grade imperceptibly into the dominantly semi-pelitic unit. Both units vary considerably in lithological character along the strike as well as across it.

Deformation is often intense but usually localized in extent. Minor folds of the F1 generation are prominent as well as the ubiquitous F2 folds.

These units contain two major intercalated sills of nepheline-syenite pegmatite/gneiss. One of these extends across all three "islands" and is found on the flanks of Börfjordnaeringen as well.

The units are not extensively granitized but locally streaks and veins of leucocratic, sometimes garnetiferous, granite become abundant. This is especially true near the contact with the 'M' unit to the south and near the isthmus between Vesteröy and Midteröy where discontinuous granitic sills up to 2 metres in thickness are found. Basic dykes older than the major folding have been found cutting the 'P' unit.

8) *Flaggy-foliated Psammite 'F'*—The 'F' psammite succeeds the 'S' semi-pelites northward across a sharp junction. This unit can be traced across all three "islands" and on the flank of Börfjordnaeringen forming a band up to 15 metres wide. It is instantly recognizable by its perfect, almost slaty cleavage which causes it to split into large thin sheets. Within these one can often discern tightly compressed hinge zones of sheared out folds. The unit is rather extensively veined with muscovite-biotite syenite which occurs in bands, elongate lenses, and diffuse streaks usually aligned within the foliation. On Börfjordnaeringen and the eastern coast of Nordöy the northern margin of the unit is largely replaced by massive gneissose feldspathic rocks which are variably syenitic, feldspathoidal or quartzose. Streaks and folia of schistose metasediment remain scattered throughout, preserving the banding an foliation of the country rocks.

9) *Rusty-weathering Sillimanite-rich Semi-pelite 'R'*—Sequentially northward is a pelitic/semi-pelitic unit characterized by the abundant presence of sillimanite. Near the base of the unit the dominant rock isa fine-grained quartzo-feldspathic-biotite schist containing prominent sheafs of fibres and euhedral single crystals of sillimanite up to 5.6 cm. by 2.3 cm. Northward the rock remains sillimanitic but the sillimanite takes on the fibrolite habit. Towards the top of the unit there are an increasing number of psammite ribs.

This horizon is exposed on all three islands but has been variably replaced by syenitic rocks of various types. On the west side of Midteröy and on Vesteröy the northern contact is transected at a low angle by the thick diorite sheet. On Börfjordnaeringen only sporadic patches of much altered sillimanite-rich schist remain as enclaves within nepheline-syenites.

This unit, like the other metasedimentary units, is cut by basic dykes and granite veins of both pre- and syn-F2 character as well as syn-F2 nepheline-syenites, syenites and quartz-syenites, and post-F2 quartz-rich granite veins and hydrothermal alteration products along joint surfaces.

10) *Crystalline Limestone and Calc-silicate Gneisses 'L'*—The most northerly recognizable metasedimentary unit consists of thinly bedded crystalline limestone with numerous fine-grained calc-silicate and micaceous (pelitic) horizons. Some harder psammitic bands also occur. Few of the layers are more than 10 cm. thick. The only large outcrop of this unit is found in the crags at sea level on the east side of Nordöy. Elsewhere, especially on the eastern and western sides of Midteröy, the unit is found as a disrupted screen within the intrusive diorite sheet. Disoriented xenoliths of the 'L' unit occur progressively farther from the southern margin of the diorite as one traces it westward until, on the west side of Vesteröy, limestone xenoliths can be found throughout the intrusive sheet. Commonly there is a hedenbergite-grossular-vesuvianite calc-silicate hornfels zone formed at the xenolith margin although the pure carbonate bands seem to have been altered very little except for being recrystallized. The diorite adjacent to the carbonate inclusions is altered to a chalky white contaminated facies characterized by grains of bright green pyroxene and occasionally by abundant brown garnet and black amphibole.

INTRUSIVE ROCKS

As noted previously, three major igneous intrusive bodies, each sheet-like in form, outcrop in the area. Intruded into the 'C' psammite and outcropping on the floor and walls of Dalen and on the southern part of Sauöy is a thick gabbro sheet correlated with the Storelv gabbro (Stumpfl and Sturt, 1965). Cutting across he northern half of the Dönnesfjord peninsula and the tip of Börfjordnaeringen is a second gabbro sheet correlated with the Breivikbotn gabbro (ibid.). Along the southern margin of the latter occurs a sheet of acid diorite.

Storelv Gabbro—Only the northern margin of the Storelv gabbro has yet been mapped in the Dönnesfjord area but a reconnaissance traverse indicates that the unit has a wide outcrop. The contact has been traced from the southeastern wall of Dalen across the valley floor, up to the valley mouth and is picked up again on the southern side of Sauöy. Throughout this section the gabbro is intrusive into semi-pelites and psammites of the 'A' unit. The contact is transgressive on a small scale but appears to be largely conformable over the breadth of the area mapped. It is usually sharp but there is a zone from one to several metres thick in which the basic rock is charged with abundant angular and usually disoriented blocks of the metasediments. Small metasedimentary xenoliths are not uncommon wherever the gabbro has been mapped; sometimes these remain discrete and angular but occasionally they appear to have been partly assimilated by the gabbro which may become garnetiferous in the immediate vicinity.

Over the area mapped, the Storelv gabbro now consists largely of schistose biotite-amphibolite. Stumpfl and Sturt have stated (1964) that it was intruded near the end of the first phase of folding and suffered recrystallization in a period of dynamic quiescence before the beginning of the second phase of folding. The mineralogy and texture of the gabbro in this area is largely due to subsequent recrystallization during the second phase of folding. Older textures may be preserved farther from the margins as on the south-west side of Dalen where the rock is a knotty amphibolite in which bundles of hornblende and granular plagioclase preserve a crude ophitic texture. Shear zones are sporadic in this area and biotite is not present except in the sheared facies.

During the dynamic deformation of F2 there appears to have been another phase of intrusion. Sheets of medium-grained, largely unfoliated xenolithic and garnetiferous grey diorite cut the biotite-amphibolite both on Sauöy and in outcrops near the mouth of Dalen. The xenoniths of this rock consist of schistose biotite-amphibolite, psammite, semi-pelite and of a coarse-grained metagabbro not thus-far encountered in the mapping. Some of these xenoliths must have been transported appreciable distances. A faint foliation is found parallel to the margins of the diorite bodies within which elongate xenoliths are aligned. In the centres, however, the rock is massive and the xenoliths show no preferred orientation. Garnet is irregular in its distribution, apparently occurring only where metasedimentary xenoliths are present. In the Sauöy occurrence garnet is most abundant in the foliated border zones of the diorite. Near the mouth of Dalen, the diorite netveins the gabbro.

The Storelv gabbro is characterized in this area, as well as at Storelv itself (Fig. 1, locality S on inset map) by being intensely but sporadically granitized. This alteration is most developed in the schistose border zone which has commonly been converted to a dioritic, monzonitic or granitic facies. The first sign of granitization is the presence of small yellowish-pink feldspar porphyroblasts in the biotite-amphibolite and a network of tiny quartz veins. As the rock becomes more feldspathic the porphyroblasts become both more numerous and larger (up to 5 cm. in length). They sometimes follow the foliation and may even define by their long axes a rather crude lineation but in other places they show no preferred orientation whatsoever. On a weathered surface it can readily be seen that the larger porphyroblasts consist of a pinkish core of microcline which is rimmed by a usually continuous border of chalky white plagioclase. This porphyroblastic variety of granitization is found in patches and streaks within intensely sheared portions of the gabbro. Some granitic masses containing up to 80 per cent feldspar, 5 per cent biotite and 15 per cent quartz became mobile for they transect the schistosity and engulf disoriented blocks of weakly granitized biotite-amphibolite and (occasionally) independently intrude the metasedimentary country rocks.

The other main variety of granitized gabbro is an agmatite consisting of a reticulate network of aplite veins cementing a chaotic breccia of gabbro blocks. These blocks may not appear to be feldspathized and may possess sharp contacts against the fine-grained aplite, but in other instances the aplite grades into the basic rock across a zone of decreasing porphyroblastesis.

The grey garnetiferous diorite dykes are themselves cut by aplite and are rarely replaced by the porphyroblastic type of alteration. An earlier basic dyke which was folded during F2 also suffered some granitization but was less affected than the adjacent gabbro.

It is inferred from the relationships between the two main types of granitization that the granitizing fluids were essentially aplitic in character and the ultimate product depended on the physical state of the gabbro when granitization commenced, the porphyroblastic variety developing only where the gabbro had been rendered into a schist which was effectively porous under the prevalent conditions and the agmatitic variety developing where brecciation had been the dominant mode of cataclasis.

Breivikbotn Gabbro—The northern portions of Vesteröy, Midteröy and Nordöy and the tip of Börfjordnaeringen are all comprised of altered basic rocks identified with the Breivikbotn gabbro. As can be seen in Fig. 1 this basic sheet is cut by myriads of ramifying sheets of nepheline gneisses and pegmatite, many of which are too thin and closely spaced to be illustrated on a map of this scale. These sheets, by persistent branching and coalescing, dissect the gabbro into a large number of lensoid or wedge-shaped portions which pinch out or neck down both laterally and vertically. The internal structure of the unit is the result of F1 and early F2 shearing which produced a strong schistosity in much of the rock and provided the channel ways for the subsequent introduction of the alkaline material and a later orthorhombic compression which stretched the more competent alkaline sheets creating boudins whose shapes are defined by sub-vertical and sub-horizontal axes. In detail then, the shapes of both the wedges of basic material and the alkaline sheets are complex. A description of the alkaline rocks themselves follows on page 156.

Mineralogically, the Breivikbotn gabbro is usually a dense black amphibolite characterized by extreme variability of texture and mineral content. Most of the exposed basic body displays the effects of the strong shearing to which it has been subjected, often being in the form of an amphibolite schist or a finely granular grey amphibolite cataclasite. Coarse to very coarse feldspathic pegmatoid facies occur in patches elongated parallel to the foliation but obviously preceding it in age. Glossy black amphibole crystals up to 8 cm. $\times$ 2 cm. are not unusual and are ophitically intergrown with purple-tinted scapolitized plagioclase. Pods of very dense melanocratic amphibolite are sometimes found within more feldspathic metagabbro.

The lenses of metagabbro typically grade outwards from a pegmatoid or coarse-grained gabbroic-textured rock into a fine-grained amphibolite schist which may become permeated towards the margins with thin veinlets of albite-microcline-nepheline or albite-microcline. The actual contact with nepheline-gneiss or pegmatite is usually, however, quite sharp, although this is due in many instances to later shearing being localized there.

The Breivikbotn gabbro has been considerably affected by hydrothermal alteration. Epidotized patches within the gabbro are common but the most intense effects are found adjacent to sub-vertical joints which are the late brittle expression of the major fold-producing movements. Epidote, zoisite, calcite, ankerite, biotite, muscovite, ferriferous potash feldspar, scapolite, prehnite, pyrite, haematite, magnetite, and several types of chlorites and zeolites occur in the altered gabbros and sometimes form beautiful subhedral encrustations on open joint surfaces. Sometimes quite large areas of the sheared facies of the gabbro have been altered to chlorite schist by the action of the hydrothermal fluids.

On the point of Börfjordnaeringen and in one or two small outcrops on the north side of Nordöy a gabbro breccia is found with blocks of the basic rock, usually as the fine-grained grey amphibolite cataclasite facies, lying chaotically distributed through a coarser, more feldspathic diorite. The diorite varies from a rather basic variety to an acidic quartz-diorite. In one outcrop three distinct phases were present: fine-grained, grey amphibolite cataclasite surrounding lens-shaped masses of coarse metagabbro, both of which are net-veined by diorite. These occurrences suggest a possible origin of the main diorite sheet outcropping along the southern margin of the gabbro.

Diorite Sheet—South of the Breivikbotn gabbro and always separating it from the metasediments occurs a sheet of acid diorite with an outcrop width of up to 180 metres. Like the gabbro this sheet is cut by a complex of nepheline-syenite sills and veins although these are less abundant than in the basic rocks. It maintains an approximately even width across the area. The contact with recognizable metagabbro is nearly always obscured by a thick sill of nepheline gneiss. The only place where the diorite is observed in contact with coarse metagabbro is in a small outcrop near the waterline on the east side of Vesteröy. Schlieren, wisps and xenoliths of the basic rock up to 36 cm. long are abundant near the contact and the diorite exhibits a basic contaminated phase. Veins of the diorite with greater amounts of mafic minerals than normal cut the metagabbro. Small patches of the basic rock appear to have been permeated by the diorite with the development of small rounded feldspar porphyroblasts. This contact clearly indicates the later age of the diorite.

At other localities in the area, notably on the northeast coasts of Nordöy and Vesteröy, the diorite is in contact on its northern side with fine-grained, non-banded, granular-textured grey amphibolite. This rock is often cut by veins and patches of pink feldspar and by diorite and can be observed in places to pass into diorite rick in grey amphibolite xenoliths. The origin of this grey rock is indicated by the breccias found in the Breivikbotn gabbro near the north tip of Börfjordnaeringen and described previously on page 154. Amphibolite granulites of this type are also found on the northern point of Midteröy where they also can be seen to have been produced by shearing and mylonitization of the gabbro.

The grey xenoliths are scattered irregularly throughout the diorite sill but in general they are most abundant near its northern and southern contacts. Some areas of the diorite remain xenolith-free. Where they occur they may amount to more than 50 per cent of the rock but are usually much less prevalent. They never display layering or banding within them so it is unlikely they could represent metasedimentary material. Sometimes their shape is rounded and roughly equidimensional but usually they are lenticular up to 30 cm. $\times$ 5 cm. in dimensions and are always oriented parallel to the foliation. Not uncommonly small porphyroblasts of feldspar can be seen extending into the grey amphibolite or veins of feldspar may extend from the diorite into the more basic rock. Rarely, pink garnets are found within the xenoliths.

Mineralogically, the diorite is a medium-grained, feldspathic rock containing biotite, amphibole and fairly abundant sphene. In general the foliation is better developed near the north and south margins of the sheet. The gross appearance of the rock depends on four factors:

1) the amount of mafic minerals present which, in turn, is usually a function of the prevalence of xenolithic material;

2) the degree to which a foliation has developed; (Many of the alkaline sheets occur in strongly sheared zones within the diorite. In general the foliation is best developed towards the north and south margins of the sheet and in addition there is an increase in the general development of the foliation from east to west.)

3) the grain size, which varies in a most irregular manner from coarse in the central part of the sheet to fine at the margins;

4) the colour of the feldspars. Four colour varieties can be recognized:

i) A greenish, fine-grained border facies occurring immediately at the north and south contacts.

ii) A chalky white border facies of the diorite where it is in contact with limestone which has already been described.

iii) A white to yellowish variety composed largely of white plagioclase feldspar, which probably represents most closely the unaltered diorite.

iv) A pink potash-feldspar rich variety which is also sometimes somewhat porphyroblastic. Sometimes the pink feldspar is homogenously developed through large volumes of the rock but in other outcrops it occurs in veins and localized patches. This pink feldspar is clearly epigenetic.

Almost continuous sections across the diorite are found at sea level on Börfjordnaeringen, the east coast of Nordöy, the west coast of Midteröy and on both sides of Vesteröy. In crossing each of these sections one can recognize a series of zones differing according to the various combinations of the four factors listed above. Most zones are gradational into one another across the strike and are also exceedingly irregular along the strike for these cross-sections can be correlated laterally only in the most general fashion. In particular, the zones of abundant xenoliths and of potash feldspathization are notably impersistent.

The diorite has been cut by basic dykes which roughly follow the foliation though they also cut across aligned xenoliths in places. These dykes are now very schistose with a strong mafic mineral lineation reflecting the F2 fold elements. These basic rocks are, in turn, cut by nepheline-syenite sills and have sometimes been pervasively nephelinized themselves. Many of the alkaline sills have subsequently been sheared and folded and affected by the same potash feldspathization as altered the diorite itself. Late dilational, salmon-pink, leucocratic syenite dykes have been found cutting feldspathized diorite. Brittle fractures, joints and some late shear zones cutting all the preceding rocks are the site of strong hydrothermal mineralization of the type described above, the development of epidote and lavender-blue scapolite being particularly notable.

THE ALKALINE ROCKS

As noted previously nepheline-bearing rocks in the form of sheets, sill-like bodies and veins occur in the Breivikbotn gabbro, the diorite and all the metasediments from the 'P' psammite to the 'L' crystalline limestone and calc-silicate gneiss. In the field these bodies fall into two fairly distinct groups, viz. well foliated nepheline-gneisses and more-or-less massive, unfoliated nepheline-syenite or pegmatite. Examples of these two types are, however, gradational one into the other in numerous places. In addition to this distinction, there are a number of mineralogical variants to be found and an interesting suite of alteration facies.

The massive nepheline-syenite/pegmatites are characteristically unfoliated though many possess a secondary foliation either along the centre of the sheet or at its margins. Many of these massively textured sheets transect the foliation of the country rocks and in such instances localized oblique shear zones cut the alkaline material. The nepheline-gneisses, on the other hand, always possess a strong foliation and where this has been folded into F2 minor folds a strong lineation is also present. Nepheline is commonly segregated into flattened lenticles defining the foliation which is also expressed by bands and folia of the mafic minerals. When deformed the nepheline often adopts a rodded texture such as has been described by Sturt (1961) from the Breivikbotn area. Some outcrops of the nepheline-gneisses possess a strikingly banded or layered structure superficially resembling supra-crystal layering. When traced laterally, however, these bands are impersistent and either fade out into a more massive facies or gradually pinch out to a protracted point or splay of points.

Some of the thicker alkaline sheets possess a texture which is in some respects intermediate between the two varieties described above. In this type the texture varies on a fine scale from pegmatoid and massive to fine-grained and gneissose. This imparts a streaky aspect to these outcrops. When examined closely it is evident that the foliated portions of the rock have two different origins. Fine-grained rather mafic patches of schistose texture are disrupted and replaced by coarse leucocratic pegmatite segregations. Sometimes trains of biotite flakes persist into the pegmatoid facies indicating the subsequent formation of the latter. This texture suggests metasomatism and pegmatitization of a pre-existing foliated rock. A later shear foliation affects both of these textures. An anastomosing pattern of shears produces lens-shaped patches of pegmatitic nepheline and feldspar separated by streaks and folia of biotite, muscovite and granulated felsic minerals. As noted previously these later shears may be confined to restricted zones such as the sheet margin of the core but in the thinner sheets they may locally pervade the entire thickness resulting in a nepheline-gneiss type of alkaline rock replacing a pegmatoid antecedent.

Mineralogically, the non-foliated nepheline-syenites are composed of albite, microcline and nepheline with mafic minerals only where they have been contaminated by permeating into sheared country rocks or by admixed, partly assimilated, xenoliths. In either case, but particularly the latter, the mafic contamination products are usually segregated into discrete patches of biotite and/or magnetic, single crystals of which may be 5 cm. or more in diameter. As in the Breivikbotn area there is a strong metasomatic convergence to a nepheline-syenite neosome with biotite and/or magnetite but a number of intermediate varieties between the palaeosome and the neosome are usually recognizable although these vary in type according to the host rock as will be described presently.

Late minor granitization and hydrothermal alteration had a marked effect on the nepheline rocks. The nepheline is pseudomorphed by muscovite, potash-feldspar is extensively developed throughout the rock imparting a strong pink colour to it and occasionally pink garnets are also developed in these muscovite-syeintes. All stages in the transformation can be followed in the field exposures. As a general rule the development of pink potash-feldspar and muscovite follows the sheared and foliated portions of the more massive sheets and leaves the more massive portions as unaltered relics. The other main locus of alteration is outward from steep joints of which there are several sets related to the F2 major folds. These joint surfaces are often also coated with epidote. Spectacular pegmatitic patches of nepheline-feldspar-biotite-epidote-scapolite-muscovite-chlorite-sodalite are developed in the dilational nodes between boudined fragments of nepheline-gneiss or nepheline-syenite sheets. Quartz-rich pink feldspar granite pegmatite veins cut altered nepheline-gneiss sheets in several places.

Nepheline-bearing Rocks in the Breivikbotn Gabbro—The strongly sheared and markedly schistose Breivikbotn gabbro forms the host for an intensive development of alkaline sheets up to 30 metres in thickness. Figure 1 suggests the pattern of intrusion and nephelinization but in many instances the sheets are too thin and numerous to be shown on such a scale. The original braided or anastomosing pattern of alkaline sheets has been complicated by local disruption and boudinage of the more competent leucocratic sheets, around the portions of which the schistose basic rocks have penetrated. The main sheets of gneiss split and coalesce around lens-shaped masses of basic rock from a few metres to one hundred or more metres in length. Xenoliths and schlieren of basic schist are abundant within them. They are very irregular in thickness and may pinch out suddenly, typically into a complex shear zone of crumpled biotite-rock, possibly containing isolated pods and veins of folded and sheared nepheline-syenite.

Contacts between the basic and feldspathoidal rocks are usually sharp but may consist of an intimate interlamination of the two lithologies. It can be recognized that in many instances shearing during the period of boudin formation was concentrated along the margins of the competent sheets thus obliterating all evidence of their primary character. On the other hand, some sharp contacts appear to be unsheared and must therefore represent a primary condition in which the limits of the alkaline neosome were sharply defined by an interface between zones of greatly differing permeability.

An exception to this situation is found on the north coast of Nordöy where a sheet of biotite syenite appears to have developed by a "soaking" metasomatism of the metagabbro. Instead of the usual sharp margins between the mafic and felsic rocks there is, on the northern margin, a gradational alteration of the basic rock into a rather mafic, sphene-rich biotite-syenite over a width of 2 to 3 metres. In the interior of the sheet there are several lens-shaped pods of nepheline-pegmatite containing coarse magnetite-ilmenite and biotite segregations. These are in sharp contact across a thin sheared margin with biotite-syenite characterized by a very irregular glomeroplasmatic texture with clots of biotite and sphene separated by a porphyroblastic, feldspathic matrix. This rock-type grades outward through a series of recognizable zones as follows: i) spotted glomeroplasmatic biotite-syenite with mafic clots, ii) streaked or foliated mafic biotite-amphibole-syenite characterized by large porphyroblastic feldspars and irregular wisps of sheared mafic rock, iii) coarse feldspathic gabbro pegmatite which overgrows the original foliation, iv) dense mafic amphibolite with occasional spots and veins of feldspathic material, and v) normal metagabbro. On the south side of the occurrence there is a fairly sharp contact between biotite-amphibole-syenite of zone ii) and ultramafic biotite-amphibolite of zone iv). In places these zones are obliterated by intense post-syenite shearing. When this occurrence of biotite-syenite is traced both east and west the amount of leucocratic nepheline-pegmatite increases considerably, the metasomatic zones along the margins are reduced and the sheet grades into a normal nepheline-gneiss sheet with relatively sharp contacts with the metagabbro.

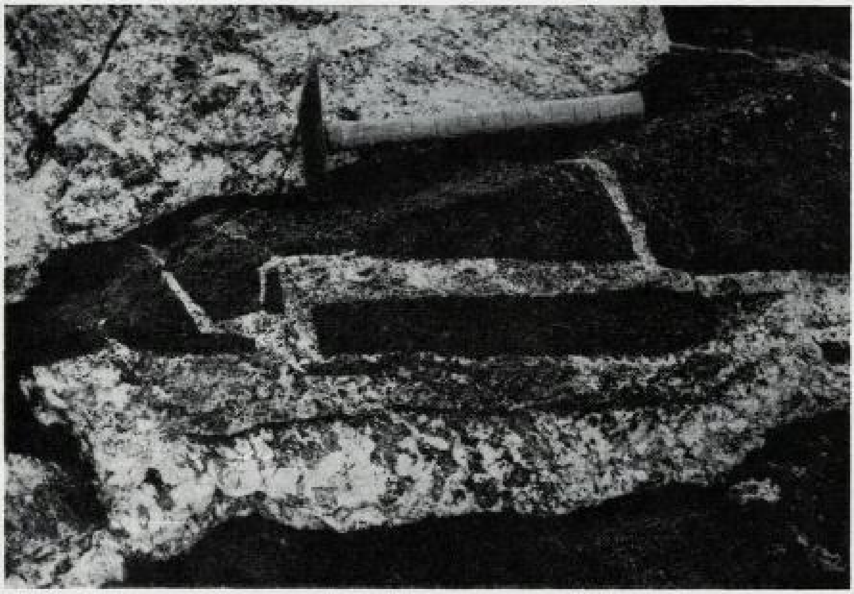

Figure 2. Pegmatitic nepheline-syenite cutting massive Breivikbotn gabbro.

Mafic folia and bands within the sheets are ultramafic in character consisting wholly of biotite-magnetite-sphene or amphibole-magnetite-sphene. Garnet is also found but is rather sporadic in its occurrence. Not uncommonly there is a selvage of glistening black amphibole along the contact between the sheets and the basic schists.

Most of the major alkaline sheets in the Breivikbotn gabbro are strongly sheared and often display a fine and well-defined banding which is nevertheless impersistent both along and across the strike. However, innumerable thin stringers and veins of massively textured nepheline-syenite extend from gneissic sheets into the bodies of basic rocks. Many of these are manifestly dialtional as illustrated in Figure 2.

Mineralogically, the alkaline rocks from the gabbro vary from mafic facies which are essentially impregnations of the gabbro to completely leucocratic nepheline-microcline-albite rocks. Not all of the intermediate lithological varieties contain nepheline but the more leucocratic the rock, the more likely will nepheline be present. The mafic mineral assemblages which have been recobnized are as follows: garnet-amphibole-epidote-sphene, amphibole alone, biotite-magnetite-sphene-calcite-muscovite, biotite-calcite, and biotite alone. There is a marked tendency for the garnet-amphibole-epidote facies to be restricted to the marginal zones of thick sheets. Biotite alone is typical of many of the very leucocratic dilational sheets.

Nepheline-bearing Rocks in the Diorite—As can be seen in Fig. 1 the contact between the Breivikbotn gabbro and the diorite to the south has been the locus of intense nephelinization. The diorite itself has been affected to a much lesser extent than the gabbro, a feature which must be linked with its considerably less sheared and foliated condition. The nepheline sheets in the diorite occur largely as discrete, parallel, sill-like bodies, seldom branching, and which in some instances are continuous enough to be traced from one "island" to the next. They tend to be rather thin, up to a maximum of 4 or 5 metres in thickness and to be of fairly uniform breadth. Thin veins, stringers and irregular patches of nepheline-syenite/pegmatite are fairly abundant where major sheets are also abundant.

There is a marked increase in the amount of alkaline material present towards the west along the strike. This is well illustrated on Vesteröy where the west coast exposures consist of interbanded nepheline-gneiss and foliated diorite sheets with the alkaline rocks exceeding the diorite in volume. On the east coast of the "island" however, only a few rather thin nepheline-syenite sheets occur. In the intervening ground occur outcrops of grey, nepheline-bearing gneiss which appears to be strongly foliated diorite nephelinized *in situ*. To the east, on Nordöy and on Börfjordnaeringen, the diorite is much more massive with relatively sporadic shear zones or strongly foliated facies except along the margins. Nepheline-bearing rocks are correspondingly diminished in volume although small sheets up to 1 metre in thickness and ramifying veins are still common in some zones.

The textural features found in the alkaline rocks within the diorite are very like those described above for the gabbro environment. Streaky-textured nepheline-syenite sheets with a relict foliation are common. Basic segregations are markedly fewer in number than those associated with alkaline rocks in the gabbros. In fact, it is possible to map a boundary separating nepheline-gneisses with abundant ultramafic bands and segregations to the north from similar gneisses lacking such basic associates to the south. This line also marks the southern limit of the occurrence of nepheline-gneisses with amphibole-garnet-epidote as mafic minerals. South of this line the nepheline-gneisses comprise the following primary mineral assemblages: biotite-amphibole-magnetite-calcite-sphene, amphibole-magnetite and biotite alone with nepheline-albite-microcline being essential in each case. This line is interpreted as being approximately the origin boundary between the gabbro and the diorite.

Nepheline-bearing Rocks in the Metasediments—Alkaline rocks rapidly decrease in abundance on passing southwards from the margin of the diorite. There is a complex zone of feldspathoidal, syenitic and granitic rocks of metasomatic origin immediately adjacent to the contact in which it is very difficult to recognize the identity of the palaeozome which may be calc-silicate gneiss, sillimaintic semi-pelitic schist, normal semi-pelitic schist, diorite or amphibolitized dolerite. Late granitization and hydrothermal alteration compound the complexity of this narrow zone.

In the 'F' unit, however, the picture is much less confused. Numerous thin veins, pods and streaks lie parallel to the main schistosity, often picking out isolated fold closures. Usually these cause no apparent disturbance of the perfect and finely-spaced foliation surfaces but occasionally some of the more leucocratic veins cause the foliation to bulge slightly around them (see Fig. 3). The alkaline metasomites comprise progressively more of the unit in a northward direction, culminating in a sheet about 9 metres thick along the northern contact of the unit composed essentially of nepheline- or muscovite-syenite with many strips of schistose material. The texture and mineral composition of this sheet, as in other examples already described, is greatly influenced by late shearing. Massive white, nepheline-syenite is largely confined to the central portion, the margins being granoblastic muscovite-biotite-gneiss. In remnant coarse-grained patches the nepheline is sometimes pseudomorphed by muscovite or irregularly replaced by sodalite or pink hydronepheline alteration products. The sheet is cut by granite veins rich in pink feldspar and milky quartz.

Alkaline sheets in the upper part of the 'S' semi-pelite are few in number but important by virtue of their thickness and continuity. Two main sheets cross Vesteröy and Midteröy, one of which also extends across Nordöy. A single important sheet is found on the flanks of Börfjordnaeringen. These sheets are thickest in the west where, on the west coast of Vesteröy, they each have a thickness of 10 to 12 metres. They thin progressively eastward and in places pinch out only

Figure 3. Nephelinization of the 'F' psammite. The lensoid sheet immediately below the hammer distorts the schistosity but also replaces adjacent metasedimentary laminae. Below this, note the relict fold closure marked by the white nepheline-feldspar segregation. The lighter coloured bands near the bottom and at the top of the photograph are partly feldspathized and nephelinized facies.

to reappear further along strike. In the west late shearing has been important in reducing them largely to a streaky gneissic texture; to the east the centres of the sheets are mainly pegmatitic with gneissic margins. Biotite is usually in greater than average abundance in the immediately adjacent metasediments and sometimes tiny quartz veins and segregations ramify through them. Thin veins of nepheline-gneiss or nepheline-free feldspathic material commonly strike parallel to the margins of the main sheets.

The only primary mineralogical varieties of these rocks noted in the metasedimentary environment are albite-microcline-biotite-nepheline-garnet. As elsewhere, there is much late microcline and muscovite in many places and pegmatitic granite veins cut through the sheets.

Origin of the Alkaline Rocks.

Field evidence indicates clearly that the essential difference between the foliated nepheline gneisses and the massive nepheline-syenite/pegmatites resides in the physical condition of the dilation zone into which the alkaline fluids were injected and the extent to which later deformation imposed a new foliation on the resultant rocks. It should be noted that, as at Breivikbotn, this activity was all coeval with the second major phase of dynamic deformation. Shears of F2, and possibly also of F1 age in some instances, were injected by a fluid whose initial composition was such that a completely leucocratic nepheline-syenite crystallized from it with a coarse pegmatoid texture. Where the shear was "tight," i.e. restricted essentially to a single plane, there was little contamination of the magma. Sheets of this character commonly show incontrovertible evidence of their dilational origin and many have formed at an oblique angle to the main foliation although these may become foliated where their strike swings into parallelism with it. Where the diastrophism produced a wide zone of cataclasis the invading fluids penetrated the whole width of the porous shear transforming it to a greater or lesser extent into a granoblastic alkaline gneiss.

Post-nepheline syenite shearing and recrystallization consequent on minor folding have led to the partial obliteration of the original textures but abundant examples remain to attest to the overall mode of origin of these rocks.

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