THE PSEUDOLEUCITE BOROLANITES AND ASSOCIATED ROCKS OF THE SOUTH-EASTERN TRACT OF THE BORRALAN COMPLEX, SCOTLAND

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BY

ALAN ROBERT WOOLLEY

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SYNOPSIS

The contact of the rocks at the southeastern end of the Complex with the later syenites is an intrusive one. The South-eastern Tract comprises an upper pseudoleucite suite and an earlier, underlying lower suite. Within the pseudoleucite suite are three units: at the top are potassic feldspar–muscovite rocks, beneath these are potassic feldspar–biotite–magnetite rocks, beneath which are borolanites (potassic feldspar–melanite–biotite $\pm$ nepheline).

Pseudoleucites are present throughout, but no intrusive junction has been recognized within the sequence. The potassic feldspars change from orthoclase in the borolanites through to microcline in the muscovite group. The lower suite has been encountered in boreholes down to 151 feet (46·02 m) in the Quarry, and the upper part outcrops in the Gorge at Aultivullin. It consists of an upper series of pyroxene–biotite and andradite–biotite syenites (the pyroxene group), which includes the rock vullinite ; a middle group of pseudoleucite-free borolanites, and a lower group of hornblende, hornblende–pyroxene and andradite–biotite syenites (the hornblende group). Xenoliths in the pseudoleucite borolanites derive from the pyroxene group.

Twenty-one new whole rock analyses, nineteen analyses of rocks for alkalis only, together with an andradite, three pseudoleucites, two nephelines and two feldspar analyses are presented. There is an upward increase in the pseudoleucite suite in silica, alumina and potash, while iron, lime, titania and soda decrease upwards. The muscovite group shows exceptional enrichment in potash with values generally greater than 14 per cent and soda less than 0·5 per cent. The observed chemistry and mineralogy are referred to crystallization from the bottom upwards of soda-leucite and gravitational settling of melanite and pyroxene. The pyroxene and hornblende groups of the lower suite are richer in soda than the pseudoleucite suite and comparable with the ledmorites. They are intruded and metasomatized by the borolanites and by the later syenites, the former causing potash enrichment and the growth of melanite, the latter an increase in silica, the ' hornblendization ' of pyroxene and the replacement of pyroxene and hornblende by andradite and biotite. The pseudoleucite suite, the lower suite, and the ledmorites are probably derived from a common parent, the pseudoleucite suite representing upward concentration in soda-leucite crystals, and the lower suite and ledmorites produced by enrichment by gravitational settling of pyroxene. This gravitational differentiation took place prior to emplacement.

I. INTRODUCTION

Recent drilling by the Robertson Research Company at the eastern end of the Borralan Intrusion encountered a series of rocks the majority of which are not exposed at the surface. A re-examination of the rocks from the exposed part of the Complex at its eastern end, both in the field and in the laboratory, has revealed that there is much greater diversity among the described rocks than has been realized hitherto, and has led to the recognition of rock types not described before from the Complex. The purpose of the present paper is, therefore, to present an account of this suite of rocks, and to give detailed descriptions of the new rock types discovered by drilling. The exposed rocks are re-described with particular reference to their variations and inter-relationships. The only published chemical data on the rocks at the eastern end of the Borralan Intrusion are five borolanite analyses. Some 29 new rock and mineral analyses and a number of partial analyses are presented here and these, together with the field and petrographic data, have led to a re-appraisal of the petrogenesis of these rocks.

II. PREVIOUS WORK

It was in the middle years of the nineteenth century that mention was first made in the literature of the rocks of the Loch Borralan area, although this was largely incidental to the interest and controversies that were developing over the structure of the North-west Highlands. The first specific account was by Horne and Teall (1892) who described, figured and named the rock borolanite. In a later paper

Teall (1900) described a number of other Borralan rocks. The first map was produced as a result of the systematic sheet mapping by the officers of the Geological Survey (1 inch to 1 mile sheets 101, 1892; 102, 1925; special Assynt Sheet, 1923); the related account is contained in the Memoir (Peach *et al.* 1907). It is, however, in the various papers of Shand (1906, 1909, 1910, 1939) that the most detailed descriptions of the Complex and its constituent rocks are given. A short paper on borolanite was published by Smith (1909), while certain aspects of petrogenesis were dealt with by Bowen (1928), based on Shand's descriptions, and Phemister (1930) described a carbonated ultrabasic rock. A general account of the area is given in the geological excursion guide to the Assynt District and Sutherland (Macgregor & Phemister 1937). Further contributions were made by Sabine (1953), Tilley (1958) and Woolley (1970). Unpublished work is contained in theses by Phemister (1929) and Woolley (1965).

Several of the minerals of the Borralan Complex have aroused interest including sulphatic cancrinite and analcime (Stewart 1941), soda-pyroxene (Sabine 1950), nepheline (Tilley 1956) and opaque minerals (Stumpfl 1961).

Shand (1910) suggested that the nature and concentric distribution of the Borralan rocks could be accounted for by mechanisms of limestone assimilation and gravitational differentiation in place, resulting in lower more basic layers grading upwards into syenites and quartz syenites. The rocks at the eastern end of the complex, designated the South-eastern Tract by Shand (1910, p. 381), were thought to have been thrust such that these relatively basic rocks were juxtaposed with syenites and quartz syenites of a higher level (*op. cit.* p. 381). He recognized three 'belts' of rocks in the South-eastern Tract: a belt of schistose rocks (the vullinite exposures), a belt of 'spotted and unspotted borolanites' running from the Gorge to the Knolls (Text-fig. 2), and a belt of 'granulites' overlying the borolanites. Although Shand recognized spotted rocks free of garnet among the granulites, he considered that the granulites were the product of granulation and hydrothermal alteration of borolanite (Shand 1910, p. 412; 1939, p. 415).

The rocks of the Borralan Complex can be divided into an earlier and later series separated by an intrusive junction (Text-fig. 1). The later rocks are syenites and perthosites grading into quartz syenites. The earlier series comprises pseudoleucite types, including the well-known borolanite, ledmorites, nepheline syenites and various ultramafic rocks.

III. FIELD RELATIONSHIPS

The South-eastern Tract is limited to the east by eastward dipping marbles, to the south by thrust quartzites of the Assynt Nappe (Sabine 1953, p. 152), and to the west by an intrusion of syenite (Text-fig. 2). Mapping suggests that the eastern contact, although nowhere exposed, is probably conformable with the marbles and dips gently eastwards. A small outcrop of marble 500 m west of the limestone boundary (Text-fig. 2) may represent a xenolith, or part of a roof pendant. The southern contact is also unexposed but indirect evidence, in the form of a series of alkaline dykes cutting the thrust quartzite and exposed in the

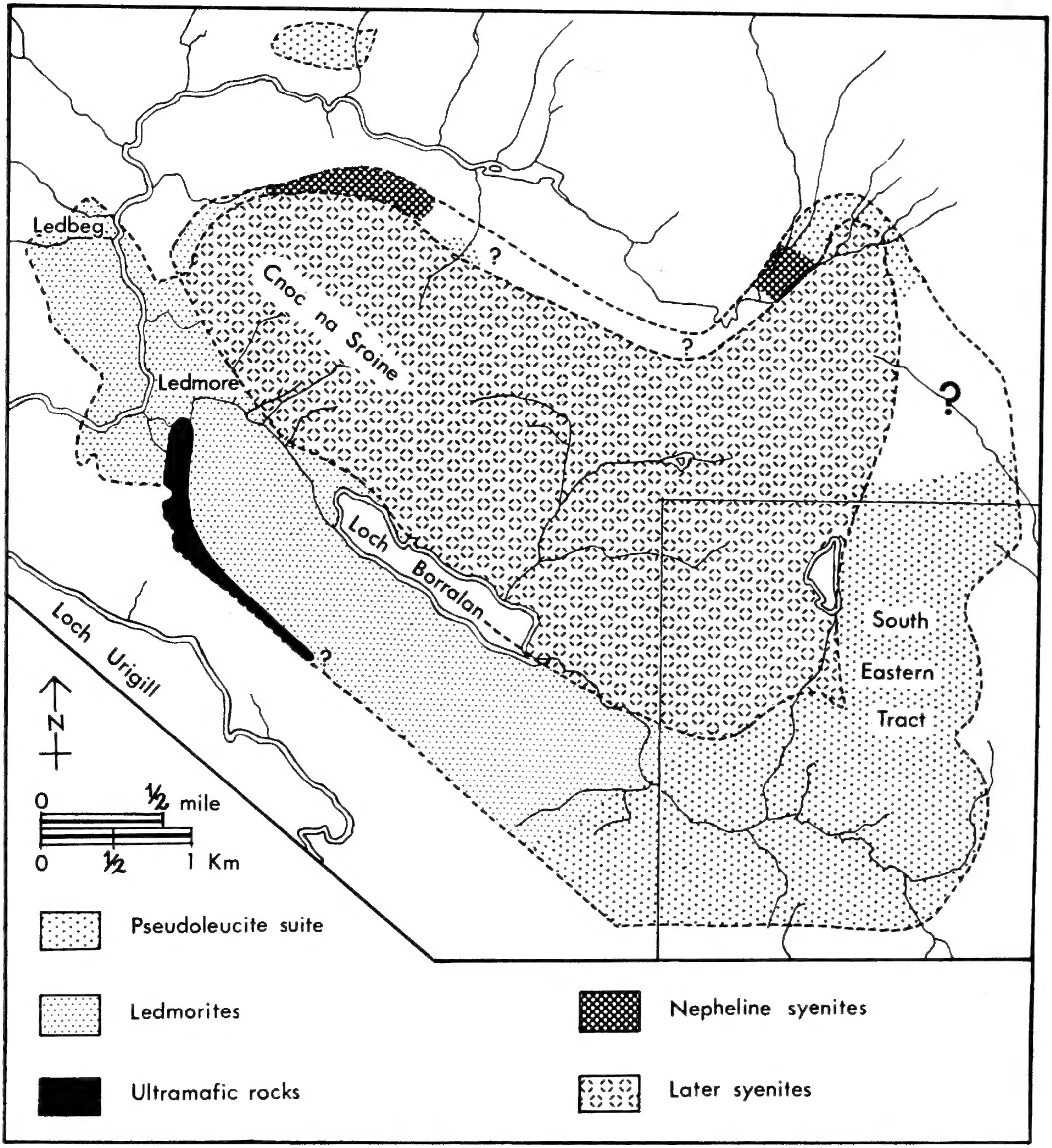

FIG. 1. The general geology of the Borralan Complex. The location of Text-fig. 2 is indicated.

streams flowing northwards off Glas Choille, together with the presence of metasomatized quartzites, also at Glas Choille, suggests the emplacement of the igneous rocks after the main period of thrusting. The intrusive contact with syenite is exposed at the southern end of the syenite apophysis south-south-east of Loch a'Mheallain (Text-fig. 2). The porphyritic syenite is somewhat finer grained close

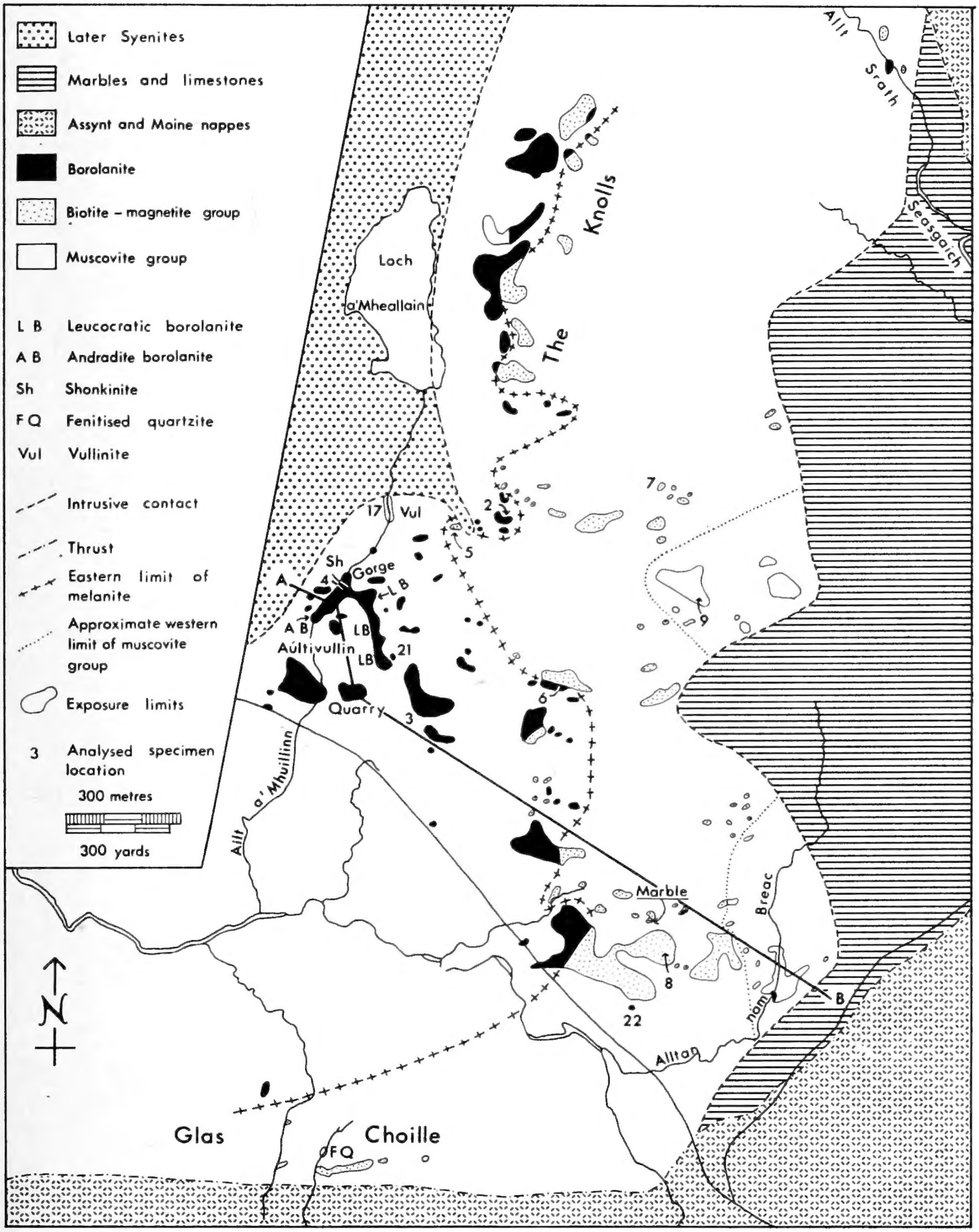

FIG. 2. The geology of the South-eastern Tract. Line of section (Text-fig. 3) is indicated.

to the contact and cuts sharply across rocks containing distorted pseudoleucites. This contact was mapped as a thrust by Shand (1910, p. 381) and a fault is shown along part of the contact on the published one-inch map. Veins of syenitic composition are abundant in the Quarry (see Text-fig. 2), the Gorge and cutting the rock designated as vullinite on Text-fig. 2.

Recognizable pseudoleucites are abundant over the whole of the South-eastern Tract, though they are commonly distorted. Among the rocks of the Knolls and in a north–south trending belt in the central part of the Tract, dark, eastward-dipping, platy rocks appear to represent an extreme stage of deformation in which the pseudoleucites have been obliterated. It is, however, common to find quite undistorted pseudoleucites next to strongly sheared rocks.

It is possible to map a line across the South-eastern Tract separating garnet-bearing rocks (borolanites) to the west from garnet-free rocks to the east (Text-fig. 2). A few patches of each type lie on the ' wrong ' side of the line, but generally this boundary could be mapped with confidence because of the easy recognition of garnet in hand specimen. A consideration of the trend of this boundary in relation to the topography suggests that it is fairly planar and dips eastwards at an angle which is just greater than the slope of the ground (Text-fig. 3). No evidence has been found to suggest that this boundary is an intrusive one, nor are the rocks on one side of it more deformed than on the other, and pseudoleucites are equally abundant on either side. Another boundary (Text-fig. 2) separating a muscovite group from a biotite–magnetite group of pseudoleucite rocks is based mainly on a study of thin sections, although these rocks also have distinctive features in the field.

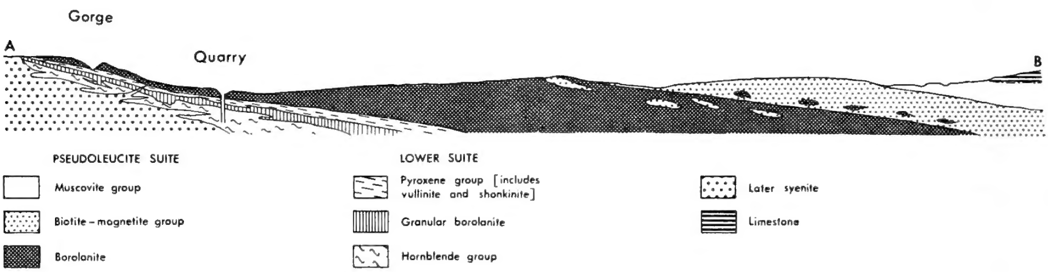

FIG. 3. Section across the South-eastern Tract. Line of section indicated on Text-fig. 2. The position of the Aultivullin Quarry boreholes are indicated.

Rocks beneath the pseudoleucite suite are exposed in the steep walls of the Gorge at Aultivullin. In the eastern bank of the northern (upper) end of the Gorge the lower limit of the pseudoleucite rocks can be distinguished ; it is fairly sharp, although there is considerable shearing which has obscured the real nature of the boundary. Below this contact are eastward dipping foliated rocks consisting of a deeply weathered shonkinite and a pseudoleucite-free borolanite. The borolanite and shonkinite form interleaving layers and pods of variable thickness, the shonkinite becoming thinner to the north. To the south both rock types are lost beneath scree. The southern (lower) half of the Gorge exposes massive andradite-bearing borolanites which probably lie beneath the shonkinite–borolanite group. The few outcrops immediately west of the Gorge are of pseudoleucite borolanites, and these are of a distinctive pink colour in contrast to the usual grey. The pseudoleucite-free rocks along the Gorge were considered by Shand (1910, p. 409) to result from shearing of pseudoleucite borolanites.

The rock termed ' vullinite ' by Shand (1910, p. 407) crops out along the Allt a'Mhuilinn to the north of the Gorge. It forms eastward dipping slabs which are veined and eventually cut out by the syenite intrusion. The spatial relationship of the vullinite to the pseudoleucite rocks is nowhere apparent, but it is noteworthy that the vullinite is on the same strike as the similarly dipping foliated rocks beneath the pseudoleucite borolanite of the Gorge.

Three boreholes put down in the Quarry by the Robertson Research Company have brought to light a completely new group of rocks, and helped in understanding the equivocal relationships at the Gorge, and the probable role of vullinite in the geological setting of the South-eastern Tract. The holes were drilled within a few metres of each other and reached 159, 151 and 90 feet (48·46, 46·02 and 27·43 m) respectively. A detailed petrographic account of these rocks is given later, but the principal rock groups encountered can be summarized as follows :

0–20 feet (0–6·10 m)	Pseudoleucite borolanite
20–50 feet (6·10–15·24 m)	Mixed pyroxene-bearing group, includes andradite–pyroxene syenites, and vullinite
50–90 feet (15·24–27·43 m)	Pseudoleucite-free borolanites
90–156 feet (27·43–47·55 m)	Mixed hornblende-bearing group

A very noticeable reddening is apparent in the two longer cores, particularly in the bottom 10–15 feet (3·05–4·57 m) where it is associated with red syenite veins, but it first becomes noticeable at depths of about 120 feet (36·58 m). This effect is very similar to contact phenomena at the margin of the later syenite in the Ledmore area of the Complex (Woolley 1970, p. 177), and suggests that a contact with syenite occurs close to the bottom of the two deeper holes, as has been assumed in Text-fig. 3. The same process undoubtedly caused the reddening of borolanites west of the Gorge.

The contact between the pseudoleucite borolanite and the underlying rocks in the boreholes is comparatively sharp, but, as in the Gorge, is obscured by shearing. The boreholes show that the rocks lying below the pseudoleucite borolanite in the Gorge, together with the vullinite, extend eastwards beneath the main outcrop of pseudoleucite rocks (Text-fig. 3). How far eastwards they extend cannot be determined without further drilling.

The cliffs to the north-north-east of the Quarry are of a leucocratic borolanite free of pseudoleucite (Text-fig. 2) and at the northern end of the cliffs there is a sharp contact with pseudoleucite borolanite. The leucocratic borolanite appears to vein the other, while the vague outlines of a large raft-like mass of the pseudoleucite borolanite can be traced within the leucocratic type.

In the vicinity of Glas Choille (Text-fig. 2) a small mass of metasomatized quartzite (Woolley *et al.* 1972) probably represents a quartzite from the Assynt Nappe, but lack of exposure obscures the relationship of this rock to pseudoleucite rocks of the South-eastern Tract.

IV. PETROGRAPHY

For descriptive purposes the South-eastern Tract rocks are divided into a 'pseudoleucite suite', and a 'lower suite' which comprises the rocks lying structurally below the pseudoleucite borolanites in the Gorge and the boreholes. A number of rocks cannot be accommodated in either category and are treated separately.

(1) Pseudoleucite suite

The pseudoleucite suite is subdivided into three groups in which the feldspar is exclusively, or overwhelmingly, potassic. The mafic minerals define the following assemblages :

muscovite (magnetite)	(Muscovite group)
biotite – muscovite – magnetite	(Biotite–magnetite group)
melanite – biotite	(Borolanite)

These assemblages occur in this order from east to west across the Tract (Text-fig. 2), and they are described accordingly.

(*a*) *Muscovite group*

The rocks of the muscovite group are usually pale grey or pink. Rare patches and streaks of mafic minerals, together with muscovite, sometimes define vague pseudoleucites which may be enhanced on weathered surfaces to form rounded, wart-like knobs up to 2 cm in diameter. Potassic feldspar and muscovite, sometimes with the addition of carbonate, usually constitute about 99 per cent modally. One specimen is outstanding in containing some 80 per cent of muscovite [1972, P8 (249)][1]. The potassic feldspars are rather variable in size but usually build either large anhedral plates, up to 2 cm in diameter, or a much finer-grained mosaic which is patchily developed and sometimes included within the large plates. Small grains commonly show microcline cross-hatching but large ones rarely so. Muscovite forms coarse and fine-grained aggregates up to a centimetre across, and ragged isolated flakes which may be interstitial to, or enclosed by, feldspar (Pl. 16, 3) ; it also fills narrow veinlets. Biotite, pleochroic from yellow or greenish-yellow to apple-green or deep khaki-green, occurs as ragged individual flakes and clusters up to 7 or 8 mm across, which are usually included and replaced by feldspar. An association of biotite and ore is often evident and biotite sometimes appears to be altering to muscovite. Magnetite euhedra, up to 1 mm across, partially or wholly altered to hematite (martite), are common, while veins and aggregates of carbonate are abundant in the Alltan nam Breac vicinity (Text-fig. 2). Oligoclase has been identified in one section [1972, P8 (131)] and apatite and sphene, enclosed in feldspar, are also found.

[1] Numbers in brackets are British Museum (Natural History) rock collection specimen numbers.

The leucite pseudomorphs are difficult to distinguish in thin section as they have textures identical with the matrix. They are also similar mineralogically being composed essentially of aggregates of potassic feldspar and muscovite, while biotite, ore and apatite are confined to the matrix.

(*b*) *Biotite–magnetite group*

The pseudoleucites in these rocks vary considerably in size from a maximum of about 2 cm in diameter to 1 mm or less ; they may be angular, rounded, lenticular or vague ; approximately equal in size, or variable within one hand specimen ; and they may be rare or abundant. The colour is also variable from pinks to greys or white. The lenticular pseudomorphs have been formed by shearing and flattening, and they become vague as these rocks grade eastwards into the muscovite group. A more rare type of pseudomorph, suggestive of prismatic sections of amphibole or pyroxene, is black, up to 4 mm in diameter and sometimes rectangular (Pl. 16, 1 & 2).

Rocks of the biotite–magnetite group contrast with the muscovite group in being finer grained, for the feldspars, biotite and ore diameters of between 0·01 and 0·1 mm are usual, though towards the muscovite-rich rocks a slight coarsening is sometimes evident. Both the pseudoleucites and groundmass are finely granular, though the pseudoleucites are usually slightly coarser.

Pseudoleucites can be distinguished in thin section by their freedom from biotite and ore, and sometimes by their slightly coarser texture. The edges of the pseudomorphs are commonly very sharp and the occasional concentration of ore along the boundary enhances the contrast. They are composed of potassic feldspar, muscovite and a little carbonate. The muscovite content varies from 10 to 100 per cent, and tends to be inversely proportional to the size of the pseudomorph. The fine-grained but undistorted nature of many of the pseudomorphs indicates that the fine grain size is not a product of shearing.

The potassic feldspar of the matrix forms an equigranular mosaic which is sometimes modified in the more easterly rocks, by the development of larger individuals. In some sheared rocks the feldspars develop a dimensionally orientated texture in which they have sometimes been noted to ‘ flow ’ around the pseudomorphs as if these had acted as resistant augen. Occasionally grains of oligoclase are present and these are especially abundant in the vicinity of the tongue of syenite which encroaches into the South-eastern Tract to the northeast of Aultivullin.

Biotite has two quite distinct habits. Westwards towards the borolanite biotite is abundantly present as innumerable tiny, fresh, euhedral, green flakes, which often appear to be developing at the expense of muscovite. Eastwards, however, towards the outer contact of the Complex, biotite decreases in amount and is present as large, often ragged, grains and clusters which show alteration to muscovite and replacement by feldspar. Some of these clusters of coarse biotite correspond to the black pseudomorphs sometimes apparent in hand specimens. The magnetite is also of two types ; to the west the ore forms tiny, euhedral to subhedral grains which are evenly distributed, but on the eastern side of the Tract it occurs dominantly, as irregular masses and aggregates in rocks in which it is often modally more abundant than biotite. Carbonate may comprise as much as 7 per cent of the rock, in the form of veins, aggregates, large isolated plates and as a fine peppering in the feldspars. Deep blue to colourless fluorite is found in both pseudomorphs and matrix of some rocks near to the borolanites. Sphene also is restricted to the area near to the borolanite junction, as tiny pale-yellow grains, often within biotite. Apatite, epidote and pyrite also occur.

Some members of this group lack pseudoleucites, and these rocks closely resemble the matrix of the pseudoleucite-bearing rocks. The dearth of pseudomorphs seems often to be due to their obliteration by recrystallization, which is sometimes demonstrably associated with shearing, but usually there is little trace of textures which are obviously diagnostic of deformation. There is no doubt that some of these rocks were deformed before and some after recrystallization and development of the newer biotite and magnetite.

(*c*) *Borolanite*

The pseudoleucite borolanites are grey rocks speckled with white, and sometimes pink, pseudoleucites up to 2·5 cm in diameter. Black, often euhedral, garnets as much as 0·5 cm across are studded through the matrix but do not occur within the pseudomorphs. The pseudoleucites are megascopically identical to those of the biotite–magnetite group rocks and show all stages of deformation to thin white streaks though in some instances the associated garnets are apparently unaffected by the movements. However, other borolanites with deformed spots contain strongly sheared garnets. Unlike the biotite–magnetite group, sharply defined angular pseudomorphs are rather rare among the borolanites. The borolanites contain melanite, nepheline, cancrinite and zeolite, all of which are absent from the biotite–magnetite and muscovite group rocks, while magnetite is relatively rare and muscovite reduced in importance. Garnet, magnetite and biotite rarely occur within the pseudoleucites but the other minerals occur indiscriminately in pseudomorphs and matrix.

The feldspar of the borolanites is an orthoclase, though some degree to triclinicity is often manifest (see section V). It forms large anhedral plates which poikilitically enclose the other minerals (Pl. 17, 1 & 2), but towards the contact with the biotite–magnetite group it builds a fine-grained mosaic (Pl. 16, 4). The fine, granular feldspar is identical to that of the biotite–magnetite group and in some specimens the finer-grained feldspar is restricted to patches which are interstitial to, and sometimes enclosed by, the more usual poikilitic plates [1972, P8 (121), (123) & (285)], and the large crystals appear to have overgrown and replaced the finer grained feldspar. These rocks represent the transition from textural types typical of the biotite–magnetite group to those typical of the borolanites. The larger feldspar plates as well as poikilitically including biotite and garnet, overgrow the pseudoleucites (Pl. 17, 1 & 2). Plagioclase is uncommon in the borolanites but oligoclase is found in the western part of the South-eastern Tract, close to the syenite contact.

Melanite, the second ubiquitous mineral of the borolanites, forms between 20 and 30 per cent of the matrix. It shows all degrees of idiomorphism and varies in size up to about 0·5 cm. The colour ranges from honey-yellow to dark brown, and simple zoning, from dark core to pale rim, or multiple zoning may be developed. Analyses indicate about 4 per cent of TiO_2 for these garnets (Table I). The garnet occurs either as large euhedral to subhedral grains, which are frequently patchily altered to sphene, and include or cut across biotite, or as myriads of small yellow grains which may be embedded in feldspar but more usually form wormy growths in biotite (Pl. 17, 3) and sometimes in pyroxene and amphibole. The alteration of melanite to sphene may result in an even distribution of hundreds of small sphenes through the garnet, or in the patchy development of only a few sphene individuals.

Table I

Chemical analyses of melanites and andradite

	A	B	1		A	B	1
				(metal ions on the basis of 24 oxygens)			
SiO_2	33·58	33·94	37·04	Si	5·717	5·64	6·076
TiO_2	3·96	3·88	1·57	Ti	0·283	–	–
Al_2O_3	2·61	3·89	8·13	Al	–	0·36	–
Fe_2O_3	24·63	23·02	15·88	Ti	0·244	0·48	0·194
FeO	1·67	1·23	2·63	Al	0·524	0·40	1·572
MnO	0·69	0·53	–	Fe^{3+}	3·156	2·88	1·960
MgO	0·84	0·24	2·00	ΣY	3·904	3·76	3·726
CaO	30·04	32·99	32·50	Fe^{2+}	0·238	0·18	0·360
Na_2O	–	0·49	–	Mn	0·099	0·08	–
K_2O	–	0·21	–	Mg	0·213	0·06	0·488
H_2O^+	–	0·11	–	Ca	5·481	5·88	5·312
H_2O^-	–	0·00	–	Na	–	0·16	–
P_2O_5	–	tr.	–	K	–	0·04	–
Total	98·02	100·53	99·75	ΣX	6·031	6·40	6·160

A. Melanite, from nepheline syenite pegmatite, Aultivullin Quarry (Howie & Woolley 1968, Table 1, no. 4)
B. Melanite from pseudoleucite borolanite, Borralan Complex (Miyashiro 1959, Table 1)
1. Andradite from an andradite syenite in borehole 1A at depth of 36 feet (10·97 m), Aultivullin Quarry [1969, P17 (5)]. Analyst: C. J. Elliott

Biotite forms euhedral to anhedral flakes up to 3 mm in length; it is pleochroic with α medium to pale yellow to pale yellow-green, and $\beta = \gamma$ apple-green to deep khaki-green. Rarely reddish-brown streaks and patches occur in the biotite and brown halos are always found around included apatites; 2V(−) is very small. Biotite together with intergrown garnet sometimes defines rectangular areas [1972, P8 (344) & (356)] which are probably pseudomorphs after pyroxene (Pl. 17, 4). Muscovite forms occasional clusters in the matrix or the pseudomorphs, and a little sericite is sometimes evident.

Nepheline may be present as discrete grains or as a complicated intergrowth with feldspar, referred to as dactylotypic texture by Shand (1906, p. 429 & Plate

XVI). The first type of nepheline is invariably ragged in form, usually included by feldspar, and occasionally displays a textural relationship with feldspar which suggests replacement, though the direction of this replacement is difficult to interpret (Pl. 18, 3). The dactylotypic texture consists of very fine cylindroidal threads which lie within feldspar and have an average diameter of about 0·01 mm and lengths up to 0·2 mm. They form either radiating or subparallel bundles (Pl. 18, 1). The feldspar may be completely or only partly permeated by this structure, and there is some dependence of the development of dactylotypic nepheline on the boundaries between the feldspar grains (Pl. 18, 2). The dactylotypic nepheline is usually sericitized and occurs indiscriminately in pseudoleucites and matrix, but there is some evidence from modes that there is a greater proportion of nepheline, of both textural types, within the pseudomorphs. Cancrinite tends to be associated with nepheline, often as an alteration product, but also occurs as a late primary mineral in nepheline-free rocks. Nepheline and cancrinite are restricted to the borolanites of the Aultivullin area and immediately to the east of Aultivullin.

Replacement of feldspar by zeolite, tentatively identified as mesolite and thomsonite, is widespread in the area of the Gorge and Quarry. Pyroxene is rare in the pseudoleucite borolanites. It forms discrete, subhedral grass-green grains seldom more than 0·05 mm in length ; it is an aegirine-augite. Hornblende has been found in the rocks of the Gorge and is common in the small exposures west of it [1972, P8 (106–108)] where it develops sturdy, sieved prisms up to 1·5 mm long which have the pleochroic scheme α pale-khaki, β green and γ deep blue-green ; $\gamma : c$ 31°. Apatite is abundant, but ore is very minor except in the finer-grained borolanite near to the biotite–magnetite group. Carbonate, fluorite, epidote and andradite garnet have also been identified in the pseudoleucite borolanites.

The pseudoleucites of many of the borolanites display a greater or lesser degree of ellipticity, but they seldom show in thin section any sign of the deformation to which they have been subjected. From this it must be concluded that recrystallization of the constituent minerals took place after, or simultaneously with, the deformation as suggested by Horne and Teall (1892, p. 176). That the shearing movements outlasted the main mineralogical reconstitution, however, is shown by the brittle deformation of some rocks of the South-eastern Tract. Moderate deformation leads to bent micas, broken garnets and fractured feldspars, but in more extreme cases the feldspar is completely comminuted to a fine ' paste ' and garnet is streaked out and broken down to ore and carbonate. Such rocks acquire a distinctly platy appearance.

(*d*) *Xenoliths*

The pseudoleucite borolanites of the Aultivullin vicinity contain xenoliths which are particularly noticeable in the north wall of the Quarry. Their presence was first recorded by Macgregor & Phemister (1937, p. 45), who ascribed them to an early intrusion, or intrusions, of mesocratic melanite–pyroxene–biotite–syenite. Xenoliths have not been recognized in other members of the pseudoleucite suite.

The xenoliths vary in diameter from 0·5 to 50 cm. They are rounded in outline (Pl. 19, 1), sharply bounded, and sometimes have a faint planar structure that is enhanced by weathering. There are two types; the more abundant are dark-green in colour, homogeneous, pyroxene-rich rocks, while the others are essentially melanocratic borolanite, free of pseudoleucite.

The pyroxene-bearing xenoliths [1972, P8 (173), (277) & (340)] are equigranular rocks of subhedral, sometimes zoned, aegirine-augite of composition Di. 53, Hd. 13·6, Ac. 33·3 (Tyler & King 1967, analysis Bo 270), and finely twinned microcline grains between 0·05 and 0·2 mm (Pl. 19, 2). In a few samples the feldspar is more variable in size, while the pyroxene is concentrated into clots and streaks and varies greatly in its degree of idiomorphism; it is also more aegirine-rich. Ragged biotite when present is pleochroic with α bright-orange and $\beta = \gamma$ olive-orange. Apatite, pleochroic foxy-brown sphene, carbonate and fluorite are accessory. One xenolith has been found which is rich in alkali amphibole [1972, P8 (345)]. The amphibole builds prisms up to 0·2 mm in length and is often intergrown with deep-green aegirine-augite. The 2V is negative; birefringence about 0·012 and a high dispersion which often prevents complete extinction; the polarization colours are anomalous; $\gamma : c$ 39°, α pale yellow-green, β pale blue-green and γ very pale blue-green. It is probably a magnesioarfvedsonite (Deer *et al.* 1963a, p. 370). Biotite is restricted to a zone about a centimetre broad against the enclosing borolanite. Within the xenolith it is pleochroic from orange to olive-green but changes gradually towards the borolanite until it is straw-yellow to dark-green.

The melanocratic borolanite xenoliths are differentiated from the enclosing borolanite by the lack of pseudoleucites and the higher colour index. They contain large and small garnets, extensively altered to sphene, biotite, irregular and prismatic grains of aegirine-augite and apatites which are enclosed poikilitically by clear, untwinned plates of potassic feldspar. Dactylotypic intergrowths of nepheline and feldspar are widespread, while some zeolitization of the feldspar and sericitization of the nepheline has occurred.

(*e*) *Summary*

The principal mineralogical and textural features of the pseudoleucite rocks can be summarized as follows:

	Borolanites	*Biotite–magnetite group*	*Muscovite group*
Colour index	30–45	5–40	<5
Grain size	coarse in west; coarse/fine in east	fine	coarse and coarse/medium
Muscovite	<10%	5–40%	20–80%
Biotite	5–15%	0–20%	<3%
Ore	0–2%	3–8%	<3%
Melanite	15–25%	absent	absent
Pyroxene/hornblende	sometimes present	absent	absent
Zeolite	0–15%	absent	absent
Nepheline	0–25%	absent	absent
Cancrinite	0–8%	absent	absent

(2) Lower suite : the Aultivullin Quarry boreholes

The outcrop of the lower suite is confined to the Allt a'Mhuilinn, but it comprises the bulk of the rocks encountered in the Aultivullin Quarry boreholes. Of these rocks only the vullinite (Shand 1910, p. 406 ; Macgregor & Phemister 1937) and granular borolanite of the Gorge Section (Shand 1910, p. 409) have been described previously.

The Robertson Research Company kindly gave slices taken at roughly 5 feet (1·52 m) intervals, from all three boreholes. (These rocks have the British Museum (Natural History) number 1969, P17.) Text-fig. 4 is based on sections made from these slices and shows, schematically, the vertical range of pseudoleucite, and the presence, or absence, of pyroxene, hornblende, andradite and melanite with depth.

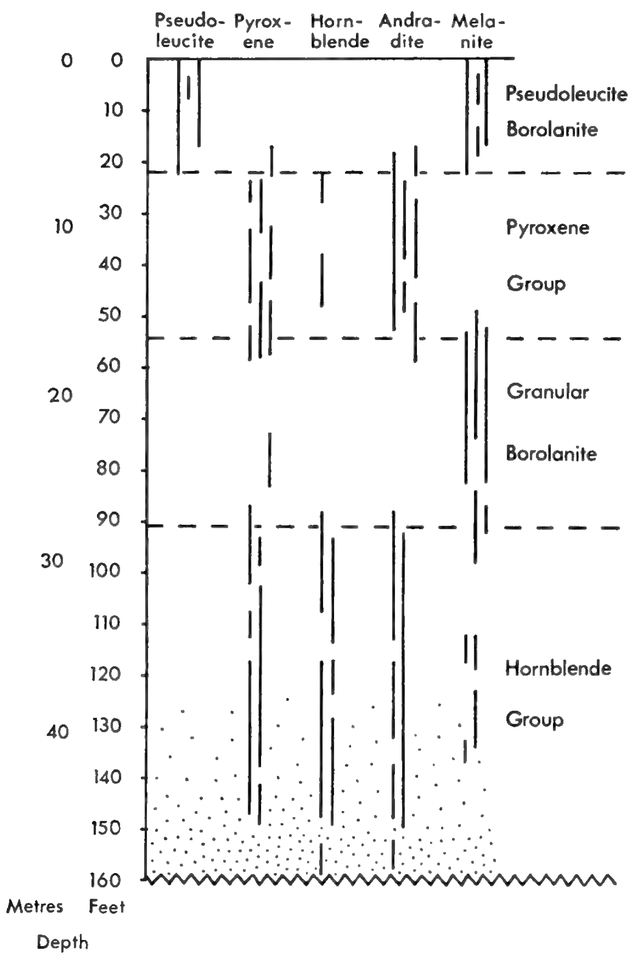

FIG. 4. The vertical range of pseudoleucite and the principal mafic minerals encountered in the Aultivullin Quarry boreholes. The four major rock divisions are indicated. Stippling shows range of feldspathization.

The subdivisions which have been erected, according to the changes of mineralogy, are shown also on Text-fig. 4. The stippling at deeper levels indicates the range of pink syenite veins and a general reddening of the rocks. The pseudoleucite rocks, which extend to a depth of 20 feet (6·1 m), are not described in the following section as the account of the pseudoleucite rocks already given applies equally to those of the boreholes.

(a) *Pyroxene group*

This group is somewhat variable in texture and mineralogy. Two extreme types can be identified which grade into each other, and which are usually represented in each thin section. One rock is a pyroxene–biotite syenite showing simple grain boundaries, fluidal panidimorphic textures and with homogeneous, or slightly perthitic, alkali feldspar. The other is an andradite–biotite syenite characterized by very ragged intergrowths of biotite and garnet, and two distinct feldspar phases which also develop complicated interlocking non-equilibrium textures. The development of the andradite-bearing rock from the pyroxene–biotite syenite can be followed in thin section. Neither type persists for more than one or two centimetres before grading into the other.

The pyroxene–biotite syenites are mesocratic rocks in which the alkali feldspar may be optically homogeneous, or a perthite of string–bead type. It varies from euhedral to anhedral in form, and may be Carlsbad twinned ; a linear texture is sometimes evident and boundaries may be simple, meeting at 120° triple junctions, or amoeboid. It is variably turbid and encloses the other minerals poikilitically. The pyroxene is a diopside with $c : \gamma$ 41–45° and a very pale-green colour, sometimes slightly pleochroic to a pale yellow-green. Deeper green rims of diopsidic aegirine-augite are sometimes present. It forms euhedral to subhedral prisms up to 2 mm long, and much smaller anhedral ' granules ' which commonly build clusters in association with magnetite and biotite. The prismatic and granular forms occur together in most sections. Biotite with α yellow, $\beta = \gamma$ very dark green is less abundant than pyroxene and ranges from euhedra to completely ragged flakes. It is commonly intergrown with pyroxene and may be replacing it in part. Hornblende has been found in three specimens of the pyroxene group. It builds poikilitic crystals of an open type in which segments are often apparently isolated, though optically continuous (Pl. 21, 4). Feldspar is included in this way, but the overgrowth of granular pyroxene clusters appears to be replacive (Pl. 20, 2), as are hornblende rims to individual pyroxenes. Large numbers of small, brown grains of sphene included by the hornblende may be a product of replacement of pyroxene, as they are rare in the rest of the rock. Pleochroism of the hornblende is α yellow, β very dark greenish-brown, γ blue-green ; $\gamma : c$ 32°.

Accessory minerals include short, stout euhedra of apatite as much as 1 mm in length, euhedral to anhedral magnetite and brown pleochroic lozenges of sphene.

The andradite–biotite syenites show stronger signs of deformation than the pyroxene–biotite syenites in the form of a streaky development of mafic minerals, a ' flaky ' and finer-grained texture of the feldspars and distorted mica cleavages.

A high proportion of the feldspar is oligoclase as independent anhedral grains, and irregular patchy intergrowths in perthite. In some places the oligoclase forms subhedral phenocrysts up to 2 mm long with inclusions of biotite, which are very similar to those in the rock vullinite. Biotite and andradite are intimately intergrown and form irregular clusters and streaks, and sometimes pseudomorph pyroxene (Pl. 21, 1). The development of biotite and andradite at the expense of pyroxene can be followed in thin section. The biotite is pleochroic from apple-green to pale-yellow, but develops brown halos around apatite and some sphene crystals, while the andradite varies from colourless to pale-brown and occasionally contains cores of deeper-brown melanite. The andradite is invariably anhedral and is anisotropic showing complex sector twinning. The differences in composition of the andradite and melanites from pseudoleucite borolanite are apparent from Table I.

The same accessory minerals are found as in the pyroxene–biotite syenites, but with the addition of some carbonate and muscovite. It must be stressed that the andradite–biotite syenite is formed from the pyroxene-bearing syenite and that the two are intimately mixed on a small scale according to the alteration relationship :

$$\text{pyroxene} + \text{alkali feldspar} + (\text{ore}) \rightarrow \text{biotite} + \text{andradite} + \text{oligoclase} + (\text{alkali feldspar})$$

(*b*) *Granular borolanite*

Apart from the absence of pseudoleucite, the granular borolanites are mineralogically very similar to the pseudoleucite borolanites except that nepheline has not been identified. There are, however, textural differences. The alkali feldspar builds a granular mosaic of simply bounded crystals, not the large poikilitic plates of the pseudoleucite borolanites. Oligoclase is patchily distributed, often in vein-like areas, and forms complexly intergrown masses in the vicinity of which the alkali feldspar becomes very turbid and perthitic textures are evident. Zeolitization of the feldspar is extensive, but unevenly distributed, and cross-cutting, very narrow veins of thomsonite occur. Rare angular patches of zeolite, sericite and sometimes cancrinite, are possibly after nepheline.

Green biotite and yellow to brown melanite form very complicated intergrowths in which either one may be included in the other. However, the textural evidence suggests replacement of biotite by melanite, and nucleation of melanite in biotite. Biotite also displays cuspated margins towards feldspar. Melanite is commonly moulded around feldspar (Pl. 20, 3) and apatite, and is rarely euhedral, but forms very ragged or amoeboid crystals, in striking contrast to its euhedral habit in the pseudoleucite borolanites. Alteration to sphene is sometimes evident, and myriads of small brown sphenes are occasionally found in biotite.

Green diopside occurs in the top few feet of the granular borolanites and, together with hornblende, in the bottom few feet. Minor carbonate, muscovite and cancrinite are found in some sections, while apatite, which causes brown halos in juxtaposed biotite, and ore are invariable accessories. There is often evidence of shearing.

(*c*) *Hornblende group*

These rocks, lying beneath the borolanites, and with further thin layers of borolanite developed within them, are characterized by the presence of hornblende, which is invariably in greater abundance than pyroxene. As in the pyroxene group there are essentially two main rock types interleaved, in this case a hornblende–pyroxene syenite and an andradite–biotite syenite, of which the latter has formed at the expense of the former.

The hornblende–pyroxene syenites are medium grained with a variable colour index up to 50 and either a linear fabric defined by aligned feldspar, hornblende and biotite or, more commonly, a granular texture. A layered structure is sometimes defined by variations of grain size and mineral proportions. Simple inter-feldspar grain boundaries and triple junctions are well developed. The feldspar is an optically homogeneous alkali feldspar with only rare oligoclase crystals. Zeolitization of feldspar is occasionally quite extensive, and dactylotypic intergrowths in feldspar of sericite have been found in two specimens, and are very probably after nepheline. Hornblende, with $\gamma : c$ 30° and α yellow, β very dark-green and γ bluish-green, forms stout subhedral crystals and complex sieved grains which include and are moulded around feldspar. Cores of pyroxene in hornblende occur in most specimens (Pl. 21, 3) and this texture, together with the rimming of clusters of pyroxene grains by hornblende and insinuation of hornblende between the pyroxenes, indicates some degree of alteration and replacement. There is a complete gradation from rocks in which the evidence suggests that all the hornblende has grown at the expense of pyroxene to rocks in which a clean feldspar–hornblende fabric with only occasional pyroxene cores suggests primary crystallization of hornblende.

The pyroxene is a pale-green diopside indistinguishable from that of the pyroxene–biotite syenites, while the euhedral to subhedral biotite, pleochroic with α yellow, $\beta = \gamma$ very dark-green, almost opaque, is also the same. Accessory minerals include apatite, sphene and magnetite.

As with the pyroxene group these rocks are affected by a change whereby hornblende and pyroxene alter to andradite and biotite (Pl. 21, 2), with a concomitant increase in the proportion of oligoclase and perthite. These changes may be restricted to small patches, follow very narrow zones, or pervade several centimetres of rock. The feldspar, dominantly oligoclase, is very variable in size, but of a finer grain than in the andradite-free parts, and with complex grain boundaries. The original alkali feldspar becomes turbid and usually displays exsolution of a sodic phase. All degrees of alteration of pyroxene and hornblende to andradite and biotite occur, the final product being an andradite–biotite syenite. The andradite is invariably anhedral as ragged clusters and streaks, and is usually anistropic and sector twinned. Larger grains occasionally have pale-brown cores. This relationship is particularly noticeable in the borolanites, which occur intermittently among the hornblende group (Text-fig. 4), in which brown melanite and colourless andradite are intergrown. The secondary biotite, which is intergrown with andradite, is of a slightly paler colour than the primary biotite, and is pleochroic from pale-yellow to apple-green. Accessory minerals are apatite, sphene, sericite, magnetite and carbonate which is probably partly a product of the alteration of pyroxene.

Although there is an increase in the turbidity of the feldspar in the andradite–biotite syenites, there is also an alteration of the feldspar related to the reddening which is apparent in hand specimen, and which increases with depth. The feldspars in the bottom 10 feet (3·05 m) of the two deepest boreholes are almost opaque in places. The only mafic mineral is a green, very fine-grained biotite, with some admixed magnetite. However, a section from the lowest level of the deepest borehole [1969, P17 (73)] contains unaltered hornblende together with andradite and biotite, although the feldspar is very turbid indeed.

As in the pyroxene group shearing is shown by broken and bent crystals, in more extreme cases by mortar structure and ultimately by a very fine-grained, streaky rock.

(3) Lower suite : the Allt a'Mhuilinn section

(*a*) *Vullinite*

In hand specimen vullinite is a rather fine-grained, sometimes foliated, dark-grey rock speckled with feldspar tablets up to 3 mm long. It is built of a mosaic of potash feldspar, albite–oligoclase and biotite in which are set larger grains and clusters of pyroxene and plagioclase ; hornblende is occasionally important and ore, sphene and apatite are plentiful. The potassic feldspar is sometimes perthitic and is confined to the groundmass. The albite–oligoclase of the groundmass may develop amoeboid grains or a simpler granular fabric, while the phenocrysts have sutured margins. Albite, Pericline and Carlsbad twins are present but are usually obscured by alteration, which is confined to the cores of grains while the rims are quite fresh and untwinned. Euhedral to subhedral biotites are included by the plagioclase phenocrysts in which they appear to have grown (Pl. 20, 1). Biotite is noticeably less abundant in the hornblende-bearing varieties. It forms stout books up to 0·5 mm long, which are pleochroic with α yellow and $\beta = \gamma$ deep-green, and sometimes defines a strong foliation. Large plagioclases cut across the biotite foliation but there is also some deflection of the biotites around them (Pl. 20, 1). The larger pyroxenes, up to 1·5 mm long, tend to be prismatic, but smaller aggregated grains are invariably anhedral. They are zoned from a very pale-green or colourless core to a pale-green rim ; $\gamma : c\ 45°$, but lower at the rim. Sphene, ore and biotite are sometimes included by the pyroxene but may also be moulded around it. Hornblende is pleochroic with α yellow, β deep olive-green and γ deep bluish-green ; $2V(-)$ is moderate and $\gamma : c\ 35°$. It is poikilitic towards feldspar and occasionally to sphene, ore, apatite, biotite and pyroxene, and is only found in the vicinity of aplite veins. Anhedral magnetite is included by biotite, pyroxene and hornblende but more often is moulded around these minerals, and penetrates them along cleavages and cracks. The abundant anhedral sphene is pleochroic from yellow to reddish-brown and often rims ore. Apatites are anhedral, except in tiny crystals, while epidote is secondary after plagioclase and also forms thin, discontinuous veins.

Shand (1910, p. 407; 1938, p. 416) considered vullinite to be a metamorphic rock, as did Phemister (Macgregor & Phemister 1937). There is no doubt that its textures resemble those of some hornfelses.

(*b*) *Shonkinite*

This rock is restricted to a layer some 12–15 m long by 3–4 m thick on the eastern side of the middle part of the Gorge. It has a well-defined layered structure [1972, P8 (289) & (399)] parallel to which are lenses and pods of borolanite which are more resistant to weathering. Hand specimens are dark-green in colour and have a pronounced foliation picked out by more melanocratic and leucocratic layers. Modal analyses give pyroxene 50–60 per cent, zeolite 22–28 per cent, alkali feldspar 13–17 per cent, sphene 1–2 per cent, melanite 1 per cent, biotite 0·3 per cent and minor magnetite. The equidimensional pyroxenes have a characteristic sugary texture, which is very similar to some of the xenoliths in the pseudoleucite borolanites (Pl. 19, 3). They vary between 0·05 and 0·1 mm in diameter, are slightly pleochroic with α green, β slightly paler-green, γ greenish-yellow, and 2V(+) 61°. The potassic feldspar occasionally displays microcline cross-hatching or Carlsbad twinning. It is extensively zeolitized to fibrous, stellate, straight extinguishing clusters (probably thomsonite). Cross-cutting feldspathic veins are quite unaffected by the zeolitization. Andradite, melanite and sphene are patchily distributed along the foliation, and the melanite is commonly moulded around pyroxene and feldspar and forms wormy growths through the rare biotite.

(*c*) *Borolanite*

Borolanites of the lower suite occur along the full length of the Gorge, but they are variable in type. In none of them is pseudoleucite to be found, the pseudoleucite borolanites being confined to levels above the shonkinite. In the upper part of the Gorge borolanite forms layers within the shonkinite and the shonkinite grades laterally into borolanite. These borolanites are granular rocks, occasionally with a dimensionally orientated fabric of prismatic feldspars or elongated clusters of mafic minerals, and invariably with a greater or lesser proportion of a diopsidic pyroxene. The pyroxene is pale-green, often with deeper green rims, and may form tiny, fresh grains or larger prisms, up to 1 mm, with rims of biotite and melanite. Clusters of green biotite with intergrown melanite often contain remnant cores of pyroxene. The biotite–melanite clusters typically have the melanite forming worm-like growths through the biotite, and undoubtedly these two minerals have replaced earlier pyroxene. The feldspar is dominantly an optically homogeneous alkali feldspar, but it may be perthitic. Oligoclase is present in widely varying amounts. There is some zeolite present, and sphene, apatite and ore are accessories.

Similar borolanites occur in the middle and lower sections of the Gorge, but pyroxene is a rare constituent of these, though the biotite–melanite clusters are present. Andradite, which is rarely found in the upper part of the Gorge, is commonly intergrown with melanite in the lower Gorge rocks.

(*d*) *Andradite–biotite syenites*

The rocks in the lower part of the Gorge are dominantly syenites with andradite and biotite as the principal mafic minerals. They have mineralogical and textural features in common with some members of the pyroxene group from the boreholes. The feldspar varies from a homogeneous granular mosaic of potassic feldspar and lesser amounts of oligoclase to a porphyritic texture of heavily exsolved perthites up to 2 mm across in a matrix of oligoclase and potassic feldspar averaging some 0·1 mm diameter. The andradite is invariably anhedral, often quite ragged, while the biotite, though usually green, is brown in patches and commonly has brown halos against orthite or sphene crystals. One specimen [1972, P8 (403)] contains 2–3 per cent of hornblende and pyroxene which are being replaced by andradite and biotite. Sphene, apatite, orthite and epidote are accessory, and cubes of pyrite are very abundant in some specimens.

(4) Other rock types

(*a*) *Leucocratic borolanite*

These borolanites, restricted to a line of cliffs north of the Quarry, are light-grey, massive rocks in which mafic minerals form only occasional clots and streaks up to a centimetre across. The junction with the pseudoleucite borolanites is clear cut against the matrix of the pseudoleucite rocks but indistinguishable against the pseudoleucites. The leucocratic borolanites are of two types: a group rich in nepheline and a group of potassic feldspar–muscovite rocks broadly similar to those along the eastern margin of the South-eastern Tract.

The muscovite-rich rocks consist of unevenly extinguishing potassic feldspar plates up to 6 mm in diameter, which are sometimes slightly perthitic and usually turbid and untwinned, and include and replace clusters and individual flakes of muscovite. Relatively rare biotite is partly altered to muscovite and sporadic melanite is much altered to sphene and ore. Cancrinite is common and some carbonate is present. The feldspar poikilitically encloses all the other minerals. These muscovite-rich borolanites lie adjacent to the pseudoleucite borolanites and the contact, as seen under the microscope, merely defines a sudden change in the abundance of the mafic minerals. Biotite alters to muscovite at the contact.

The nepheline-bearing leucocratic borolanites are composed dominantly of untwinned potassic feldspar plates up to 8 mm across through which nepheline, of the dactylotypic and coarser types, is riddled. The frequent continuity of the dactylotypic canals with large, easily recognizable, nepheline grains shows clearly that the mineral in the canals is nepheline. Cancrinite forms small veins, patches and individual flakes in the nepheline and feldspar, and there is some development of zeolite. Biotite and garnet are sparsely distributed, usually in aggregates up to a centimetre across, and the larger garnets show the usual alteration to sphene. Apatite, ore and very rare aegirine-augite have also been recognized.

(*b*) *Aegirine–nepheline–analcime borolanite*

An unusual borolanite forms the southernmost of the exposures to the west of the Alltan nam Breac [1972, P8 (334)]. Its contact relationships cannot be seen.

It is a homogeneous, grey rock consisting of a fine-grained mosaic of potassic feldspar, fresh nepheline and melanite ranging from 0·05 to 0·2 mm in diameter, in which are set potassic feldspar porphyroblasts up to 5 mm across and smaller ragged biotites and aegirines. The porphyroblastic nature of the feldspar is indicated by numerous inclusions of all the other minerals and intricately interdigitating boundaries (Pl. 18, 4). Between the feldspar and the nepheline there is invariably an even, thin, isotropic layer which is probably analcime. The biotite is pleochroic with α yellow, $\beta = \gamma$ very dark-green. The aegirine forms stubby subhedral prisms and ragged grains which include and are moulded around feldspar; the pleochroism is from yellow to a deep emerald-green; $\alpha : c$ is very small.

A similar rock has been found in an isolated exposure just to the north of the road one-third of a mile (540 m) east of Aultivullin [1972, P8 (365)]. This rock is abundantly endowed with nepheline and contains considerable pyroxene and analcime. The subhedral to anhedral pyroxene is a green, unzoned aegirine-augite with $\alpha : c$ 58°, and the texture is similar to that of a pseudoleucite borolanite. Melanite is zoned from brown to honey-yellow, and the nepheline, which forms nearly a quarter of the rock, has a narrow zone of analcime between it and the feldspar.

(*c*) *Dykes and veins*

Veins are plentiful in the borolanites of the Quarry and among the rocks of the Gorge, but are relatively rare over the rest of the South-eastern Tract. They comprise an earlier suite of potassic feldspar–nepheline pegmatites, and pegmatites rich respectively in melanite, biotite, cancrinite or analcime. These veins are cut by a later suite of microcline-microperthite veins and aegirine aplites which are comagmatic with the later syenites of the Complex.

The potassic feldspar–nepheline pegmatites may be sharply cross-cutting or form segregations which grade into the adjacent rock. Nepheline is often quite fresh, but may be altered or replaced, wholly or partially, by sericite or cancrinite. There is invariably a uniformly narrow 'corona' of analcime between nepheline and feldspar. Cancrinite, magnetite, melanite, biotite, albitic plagioclase, sphene and orthite are accessory. Zeolitization is often extensive.

In the Quarry, pegmatites with books of biotite up to 10 cm across are common, while masses of melanite garnet as much as 5 cm across also occur. The garnet is often concentrated as broad selvages to veins. Cancrinite and analcime pegmatites from the Quarry have been described and analysed by Stewart (1941) and the exceptional richness in SO_3^- radical of the cancrinite led to its classification by Deer *et al.* (1963b, p. 313) as carbonate vishnevite. The melanite analysis given in Table I (anal. A) is from one of these pegmatites.

The later veins and dykes include a suite of microcline-microperthite veins with accessory biotite, albitic plagioclase, magnetite, carbonate, aegirine and andradite (probably xenocrystal). Aplitic dykes, which are finely granular rocks but occasionally porphyritic, may be composed dominantly of microcline-microperthite or a mixture of microcline-microperthite and sodic plagioclase. Aegirine, quartz and sphene are present. The presence of microcline twinning and the complete absence of zeolitization, together with the cross-cutting relationships, serve to distinguish this group from the earlier veins.

V. ALKALI FELDSPARS

The potassic feldspars of the muscovite group rocks commonly display microcline cross-hatching, which is never found in the borolanite feldspars, although these do have uneven extinction patterns. Miyashiro (1957, p. 392) described feldspar from borolanite in which the 2V ranged from 52° to 76°, and the obliquity was variable. Feldspars have been separated from 40 pseudoleucite rocks of the South-eastern Tract and they have been investigated by X-ray diffraction, while the weight percentages of Na_2O and K_2O have been determined by wet chemical methods on 30 of these (Table II).

Table II

Structure and composition of South-eastern Tract feldspars

Borolanites

No.	Feldspar structural type‡	Obliquity	Wt. % Na_2O	Wt. % K_2O	% Or
50	1		2·0	14·4	83
56	2		1·7	13·5	84
61	2	0·65	–	–	–
84	2		0·9	14·7	91
90	1		0·87	14·5	91
114	1		1·7	13·6	84
116	1		1·2	14·9	89
123	2		2·2	13·1	80
285	2		0·32	15·4	97
290	1		1·45	13·4	86
329	2		0·48	15·3	95
344	2		0·24	16·0	98
355	2		0·48	15·9	96
356	3	0·75	0·67	15·6	94
363	1		0·16	16·1	98
378	2		0·12	15·9	99
†1912, 700	2		0·43	15·4	97
*7585	1		0·18	16·0	98

Biotite–magnetite group

No.	Feldspar structural type	Obliquity	Wt. % Na_2O	Wt. % K_2O	% Or
161	3		0·79	14·9	92
323	2		1·3	13·1	87
325	2		0·48	14·7	95
342	3	0·63	–	–	–
350	2	0·46	0·35	15·9	97
351	4	0·74	1·15	15·2	89
362	2	0·49	2·2	12·4	79

Muscovite group

No.	Feldspar structural type	Obliquity	Wt. % Na_2O	Wt. % K_2O	% Or
129	4	0·79	0·35	15·8	97
130	3	0·73	0·33	15·8	97
131	4	0·81	0·36	16·0	96
142	3	0·46	0·58	15·3	94
145	3	0·69	–	–	–
159	3		0·32	15·4	97
160	4	0·83	0·52	15·2	95
352	4	0·74	–	–	–
388	4	0·64	0·64	15·0	94

Alkali analyses by C. J. Elliott

* Specimen given by Professor Tilley (see Tilley 1958, Table 1, no. 1).
† British Museum (Natural History) specimen. Described and analysed by Campbell Smith (1909).
‡ See text.

The 131–$1\bar{3}1$ reflections in the 2θ range 29–30½° indicate that there is a complete transition from orthoclase to microcline. It has proved practicable to divide the feldspars, according to their 131–$1\bar{3}1$ reflections, into four groups which are illustrated in Text-fig. 5. The grouping has not been made on a quantitative basis

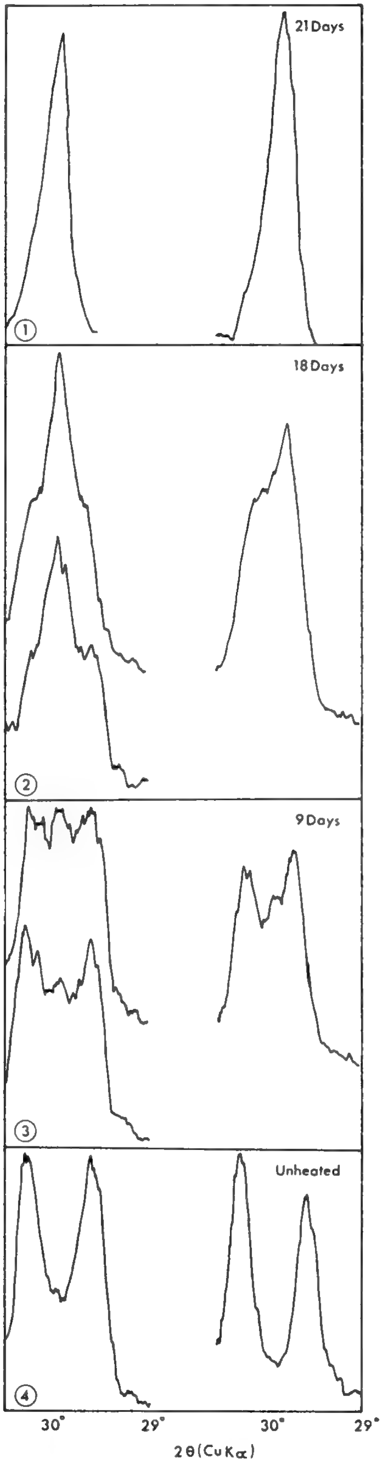

FIG. 5. Diffractometer traces of feldspars from pseudoleucite rocks (left) and traces of heat-treated Madagascar microcline (right). For explanation of groups 1 to 4 see text.

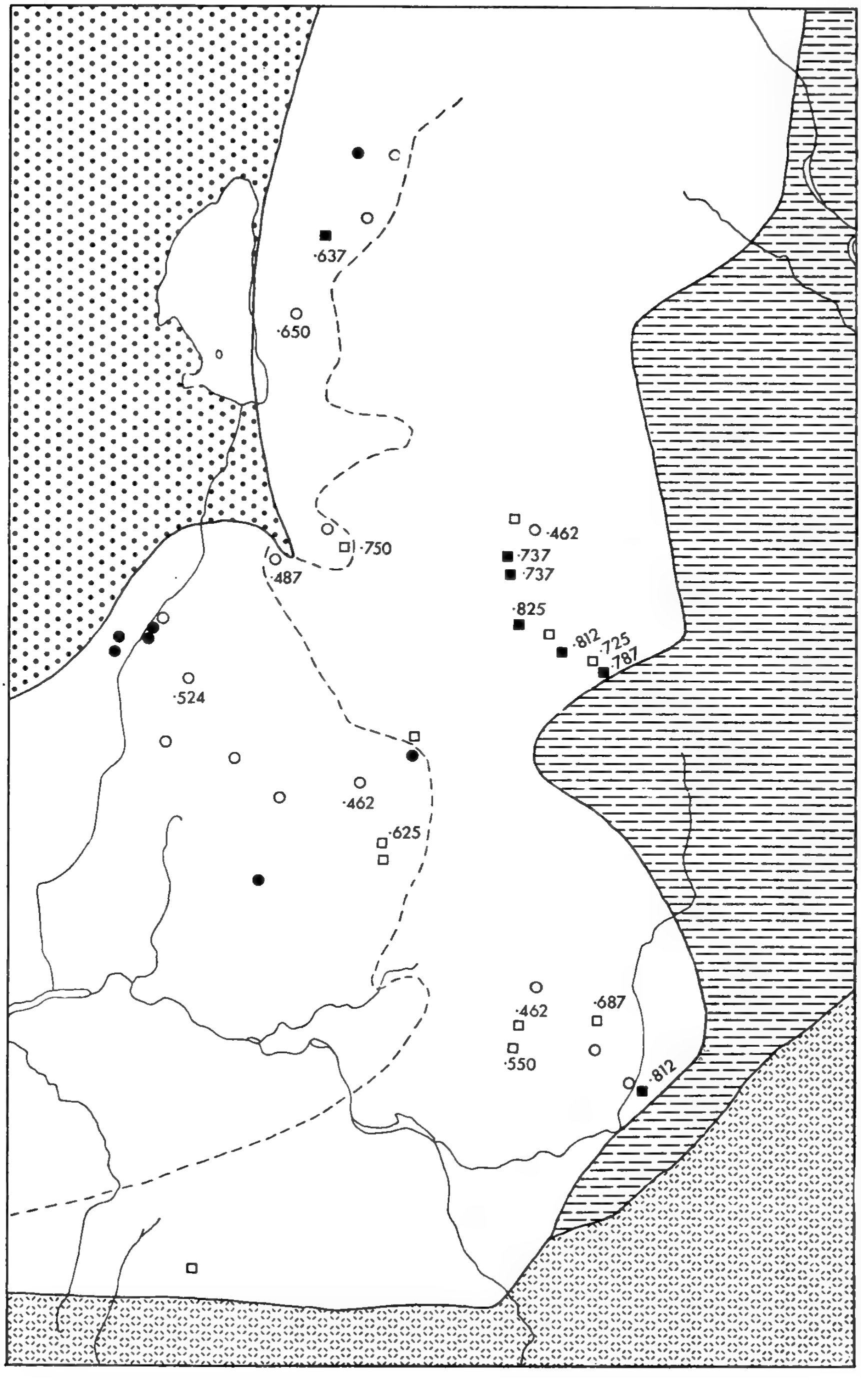

FIG. 6. Areal distribution of feldspars groups 1 to 4 over the South-eastern Tract, and obliquity values. Filled circles, group 1 ; open circles, group 2 ; open squares, group 3 ; filled squares, group 4.

but a rough estimate of the proportions of orthoclase and microcline can be made by comparison with the curves given by Steiger and Hart (1967, Fig. 3) for artificial mixtures. Group 1 feldspars have orthoclase > 80 per cent; group 2, 80–40 per cent orthoclase; group 3, 40–20 per cent orthoclase; group 4, < 20 per cent orthoclase. Also shown on Text-fig. 5 for comparison are diffractometer traces following the transformation of Madagascar microcline to a monoclinic form as a result of heating the powdered material in a furnace at 1040 °C for up to 21 days.

The areal distribution of the four structural groups illustrated in Text-fig. 5 are plotted in Text-fig. 6 together with obliquity values. There is an overall variation from the borolanites containing a feldspar of dominantly orthoclase type in the west to the muscovite group rocks which contain microcline with high obliquity values and little or no orthoclase component in the east. There appears to be a decrease in obliquity values concomitant with an increase in the proportion of monoclinic feldspar.

It is apparent from Table II and Text-fig. 7 that although borolanite feldspars are essentially of structural types 1 and 2 and the muscovite group feldspars of types 3 and 4, there is little or no chemical difference which can be correlated with structural type.

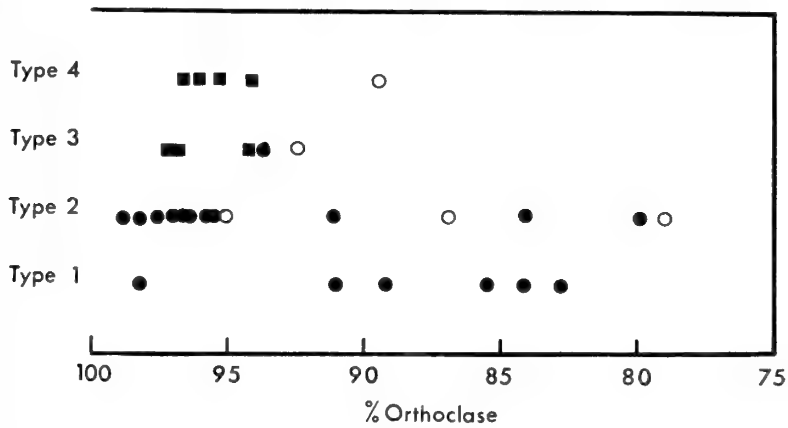

FIG. 7. Variation of feldspar structural types 1 to 4 with percentage of orthoclase component. Filled circles, borolanites; open circles, biotite–magnetite group; filled squares, muscovite group.

Possible mechanisms to explain the variable obliquities of the South-eastern Tract feldspars are: (*a*) variations in the stress field, (*b*) differences of composition of the host rocks, (*c*) primary cooling patterns, (*d*) re-heating by a later intrusion.

The first two mechanisms appear to be unlikely: the second two more probable. The conversion of microcline to orthoclase in aureoles around intrusive stocks has been described by several workers (Doe & Hart 1963; Hart 1964; Steiger & Hart 1967; Wright 1967; Tilling 1968). The intrusion of the later syenites at Borralan could have re-heated the South-eastern Tract rocks converting the feldspars, particularly in the rocks closer to the contact, to orthoclase. In contrast, the coincidence in the variation of feldspar type with rock type might suggest that the borolanites crystallized at relatively elevated temperatures with the production of the high-temperature polymorph orthoclase, while the lower-temperature polymorph microcline, was produced in the more easterly rocks of the South-eastern Tract by crystallization at lower temperatures. However, the wide variation in rock type, the unevenness of the results, and the relatively poor exposure over the South-eastern Tract suggest that any interpretation must be approached with caution.

VI. CHEMISTRY

Twenty-one new rock analyses, together with two analyses taken from the literature, of South-eastern Tract rocks are given in Tables III, V, and VI. The localities from which the specimens were collected are indicated on Text-fig. 2.

Table III

Chemical analyses, norms and modes of rocks of the pseudoleucite suite

	2	C	3	D	4	5	6	7	8	9
SiO_2	47·16	48·19	48·52	48·86	49·05	50·46	52·27	54·35	54·90	57·40
TiO_2	1·58	1·75	0·68	0·96	1·57	0·61	0·55	0·51	0·47	0·20
Al_2O_3	15·94	18·52	20·16	19·50	16·50	20·60	18·50	20·85	20·82	22·88
Fe_2O_3	5·34	4·51	2·13	5·01	6·61	1·68	2·22	2·09	2·60	1·36
FeO	2·60	1·68	2·20	2·14	2·01	3·15	2·62	1·79	1·25	0·36
MnO	0·19	–	0·12	0·17	0·21	0·18	0·13	0·09	0·09	0·01
MgO	1·33	1·12	0·54	0·95	1·39	1·07	0·87	0·35	0·25	0·09
CaO	10·05	10·29	3·65	6·33	10·22	4·97	4·05	1·93	2·09	0·03
Na_2O	3·04	3·44	5·48	3·65	2·43	1·60	3·18	0·52	0·51	0·47
K_2O	8·95	8·05	10·10	9·56	7·77	10·75	10·72	13·65	13·26	14·66
H_2O^+	1·58	3·00	1·90	1·38	2·03	1·13	1·31	1·32	1·41	1·55
H_2O^-	0·03	0·45	0·09	0·06	0·05	0·07	0·12	0·09	0·01	0·03
P_2O_5	0·31	–	0·17	0·12	0·34	0·26	0·21	0·07	0·06	0·06
CO_2	2·18	–	2·27	0·16	0·11	3·05	2·06	1·53	1·71	0·28
BaO	0·19	–	0·31	0·34	0·25	0·36	0·28	0·25	0·27	0·19
SrO	0·18	–	0·31	–	0·37	–	0·30	0·18	0·15	0·03
S	0·28	–	0·50	–	0·04	0·01	0·19	–	–	–
SO_3	–	–	–	0·72	–	–	–	–	–	–
Cl	–	–	–	0·14	–	–	–	–	–	–
NiO	–	–	–	–	–	0·03	–	–	–	–
	100·93	101·00	99·13	100·05	100·95	99·98	99·58	99·57	99·85	99·60
O ≡ S, Cl	0·14		0·25	0·03	0·02	0·005	0·09			
	100·79		98·88	100·02	100·93	99·97	99·49			

TABLE III (*cont.*)

Norms

	2	C	3	D	4	5	6	7	8	9
Q	0·0	0·0	0·0	0·0	0·0	0·0	0·6	0·0	0·98	0·0
C	0·0	0·0	0·0	0·0	0·0	4·98	0·0	5·22	5·63	6·24
Or	38·68	27·03	48·56	35·76	44·95	63·54	63·36	80·68	78·37	86·65
Ab	0·0	0·0	0·0	0·0	0·0	6·49	3·40	1·50	4·31	0·81
An	3·42	11·32	0·58	8·59	11·17	3·68	4·55	0·0	0·0	0·0
Lc	11·15	16·11	8·73	16·27	0·76	0·0	0·0	0·0	0·0	0·0
Ne	13·93	15·77	25·12	16·73	11·14	3·82	12·73	1·57	0·0	1·72
Di	7·14	6·02	1·71	5·10	7·47	0·0	0·96	0·0	0·0	0·0
Wo	8·96	13·36	0·0	6·04	11·29	0·0	0·0	0·0	0·0	0·0
Hy	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·32	0·0
Ol	0·0	0·0	1·38	0·0	0·0	4·74	2·95	1·15	0·0	0·0
Mt	4·42	0·34	3·09	4·67	2·61	2·43	3·22	3·03	2·96	0·0
Hm	2·29	4·27	0·0	1·79	4·81	0·0	0·0	0·0	0·56	1·36
Il	3·00	3·32	1·29	1·82	2·98	1·16	1·04	0·97	0·89	0·38
Ap	0·73	0·0	0·40	0·28	0·80	0·61	0·49	0·16	0·14	0·14
Cc	4·96	0·0	5·16	0·36	0·25	6·94	4·68	3·28	3·59	0·09
H_2O^+	1·57	3·00	1·89	1·37	2·02	1·12	1·30	1·32	1·41	1·55
H_2O^-	0·03	0·45	0·09	0·06	0·05	0·07	0·12	0·09	0·01	0·03
Others	0·65	0·0	1·12	1·20	0·66	0·40	0·77	0·43	0·42	0·81
Total	100·93	101·00	99·13	100·05	100·95	99·98	99·58	99·57	99·85	99·60

Modes

	3	D	4	6	7	8	9
K-feldspar	–	39	37·4	55·4	52·8	52·0	60·8
K-feld + nepheline	55·1		–	–	–	–	–
Nepheline	–	19	–	--	–	–	–
Dactylotypic nepheline + feldspar	–	16*	15·4	–	–	–	–
Plagioclase	–		–	0·3	–	–	0·1
Melanite	–	15	18·3	5·5	–	–	–
Biotite	17·6	11	11·6	27·9	10·1	1·1	–
Muscovite	9·2		2·3	P	27·5	37·1	38·7
Zeolite	–		12·3	–	–	–	–
Carbonate	6·5		–	7·0	3·0	4·8	–
Sphene	5·8		2·4	2·7	–	P	–
Apatite	P		0·3	0·2	–	–	–
Fluorite	0·9		–	0·8	–	–	–
Ore	4·9		–	0·2	6·5	5·0	0·1

* Includes cancrinite (Tilley 1958, p. 158).

2. Pseudoleucite borolanite [1972, P8 (356)]
C. Pseudoleucite borolanite (Campbell Smith 1909, p. 154)
3. Pseudoleucite borolanite [1972, P8 (370)]
D. Pseudoleucite borolanite (Tilley 1958, p. 157)
4. Pseudoleucite borolanite [1972, P8 (290)]
5. Pseudoleucite biotite–magnetite rock [1972, P8 (362)]
6. Pseudoleucite biotite–magnetite rock [1972, P8 (364)]
7. Pseudoleucite biotite–magnetite rock [1972, P8 (350)]
8. Pseudoleucite biotite–magnetite rock [1972, P8 (331)]
9. Pseudoleucite muscovite rock [1972, P8 (131)]

For localities of analysed rocks see Text-fig. 2.

Analyst: C. J. Elliott

TABLE IV

Alkali analyses for rocks of the pseudoleucite suite

Borolanites				Biotite–magnetite group				Muscovite group			
No.	K_2O	Na_2O	$\frac{100K_2O}{K_2O + Na_2O}$	No.	K_2O	Na_2O	$\frac{100K_2O}{K_2O + Na_2O}$	No.	K_2O	Na_2O	$\frac{100K_2O}{K_2O + Na_2O}$
370	10·10	5·48	64·8	364	10·72	3·18	77·1	142	13·89	0·59	95·9
*	8·05	3·44	70·1	342	9·97	2·78	78·2	131	14·66	0·47	96·9
†	9·56	3·65	72·4	323	9·84	2·13	82·2	145	12·70	0·39	97·0
114	9·76	3·63	72·9	362	10·75	1·60	87·0	159	14·66	0·39	97·4
344	9·09	3·16	74·2	325	11·56	1·59	87·9	129	14·06	0·34	97·6
356	8·95	3·04	74·6	351	13·40	0·88	93·8	130	14·32	0·34	97·7
116	8·47	2·74	75·6	161	13·73	0·70	95·1	322	12·77	0·26	98·0
285	8·23	2·60	76·0	352	13·05	0·66	95·2				
290	7·77	2·43	76·2	331	13·26	0·51	96·3				
339	9·09	2·52	78·3	350	13·65	0·52	96·3				
123	8·28	2·10	79·8								
355	8·45	1·09	88·6								
Average values	8·82	3·03	75·3		11·99	1·45	88·9		13·87	0·40	97·2

Analyst: V. K. Din

* Campbell Smith (1909, p. 154).
† Tilley (1958, p. 157).

TABLE V

Chemical analyses and norms of Aultivullin Quarry borehole rocks

	10	11	12	13	14	15	16
SiO_2	54·59	51·56	48·36	48·96	54·40	51·27	50·84
TiO_2	0·68	0·68	0·87	0·89	0·78	0·96	0·21
Al_2O_3	17·04	16·07	17·82	15·80	17·60	15·81	20·43
Fe_2O_3	2·80	3·95	4·97	5·12	2·39	3·06	2·19
FeO	3·49	2·56	2·46	3·06	4·12	5·24	6·05
MnO	0·14	0·17	0·23	0·31	0·13	0·14	0·07
MgO	3·53	3·82	2·36	2·89	2·48	3·54	2·09
CaO	5·70	8·08	7·92	7·85	6·03	6·69	1·33
Na_2O	5·3	4·1	3·1	2·1	4·7	3·0	1·0
K_2O	4·0	5·7	7·7	8·6	4·7	6·3	9·9
H_2O^+	1·05	1·79	1·84	2·32	1·02	0·74	3·20
H_2O^-	0·28	0·32	0·52	0·43	0·16	0·24	0·50
P_2O_5	0·39	0·45	0·60	0·63	0·53	0·78	0·09
CO_2	0·78	0·86	0·58	0·71	0·61	1·10	1·55
BaO	0·26	0·30	0·29	0·26	0·23	0·26	0·22
SrO	0·32	0·36	0·54	0·50	0·33	0·26	0·13
Total	100·35	100·77	100·16	100·43	100·21	99·39	99·80
				Norms			
Q	0·0	0·0	0·0	0·0	0·0	0·0	0·69
C	0·0	0·0	0·0	0·0	0·0	0·0	8·07
Or	23·64	33·69	45·15	46·62	27·78	37·24	58·51
Ab	38·67	16·58	0·0	0·0	34·22	20·38	8·46
An	10·90	8·61	11·97	8·29	13·05	11·07	0·0
Lc	0·0	0·0	0·28	3·30	0·0	0·0	0·0
Ne	3·37	9·81	14·21	9·62	3·01	2·71	0·0
Di	7·95	18·11	12·68	16·46	7·82	8·22	0·0
Wo	0·0	0·0	1·44	0·45	0·0	0·0	0·0
Hy	0·0	0·0	0·0	0·0	0·0	0·0	12·92
Ol	5·91	1·19	0·0	0·0	5·04	7·71	0·0
Mt	4·06	5·73	6·16	7·42	3·47	4·44	3·18
Hm	0·0	0·0	0·72	0·0	0·0	0·0	0·0
Il	1·29	1·29	1·65	1·69	1·48	1·82	0·40
Ap	0·92	1·06	1·42	1·49	1·25	1·84	0·21
Cc	1·77	1·96	1·32	1·62	1·39	2·50	2·16
H_2O^+	1·03	1·77	1·82	2·30	1·00	0·71	3·20
H_2O^-	0·28	0·32	0·52	0·43	0·16	0·24	0·50
Others	0·72	0·81	0·98	1·04	0·74	0·67	1·56
Total	100·49	100·92	100·31	100·71	100·39	99·54	99·86

10. Pyroxene–biotite–andradite syenite (pyroxene group) [1969, P17 (48)]. Borehole 1, at depth 25 feet (7·62 m)
11. Pyroxene–biotite–andradite syenite (pyroxene group) [1969, P17 (35)]. Borehole 2, at depth 40 feet (12·19 m)
12. Granular borolanite [1969, P17 (39)]. Borehole 2, at depth 65 feet (19·81 m)
13. Granular borolanite [1969, P17 (59)]. Borehole 1, at depth 80 feet (24·38 m)
14. Hornblende–pyroxene syenite (hornblende group) [1969, P17 (66)]. Borehole 1, at depth 120 feet (36·57 m)
15. Hornblende–pyroxene syenite (hornblende group) [1969, P17 (24)]. Borehole 1A, at depth 136 feet (41·45 m)
16. Biotite syenite (hornblende group) [1969, P17 (72)]. Borehole 1, at depth 151 feet (46·02 m)

Analyst: V. K. Din

TABLE VI

Chemical analyses, modes and norms of vullinite, shonkinite, a pyroxene–microcline xenolith, andradite borolanite, leucocratic borolanite and aegirine–nepheline–analcime borolanite

	17	18	19	20	21	22
SiO_2	55·10	48·38	58·61	53·60	52·07	50·70
TiO_2	0·77	0·64	0·65	0·71	0·30	0·53
Al_2O_3	16·66	13·71	11·26	18·14	23·79	22·69
Fe_2O_3	4·50	1·79	2·90	4·52	0·90	3·16
FeO	3·29	3·23	2·73	1·08	1·01	1·50
MnO	0·17	0·18	0·10	0·12	0·20	0·07
MgO	2·50	6·37	4·11	1·01	0·00	0·00
CaO	7·08	17·23	8·20	4·35	2·13	3·97
Na_2O	5·09	2·00	1·65	2·0	5·69	4·74
K_2O	3·99	2·10	9·00	10·0	11·11	9·85
H_2O^+	0·68	3·67	0·22	1·47	1·95	2·01
H_2O^-	0·07	0·34	0·08	0·37	0·13	0·22
P_2O_5	0·69	0·16	0·17	0·23	0·16	0·29
CO_2	0·09	0·08	0·10	1·15	0·40	0·20
S	–	0·04	–	–	–	–
BaO	–	0·45	0·02	0·54	–	–
SrO	–	–	–	0·40	–	–
NiO	–	0·04	0·08	0·09	–	–
	100·68	100·41	99·88	99·78	99·84	99·93
O ≡ S		0·02				
		100·39				

Norms

	17	18	19	20	21	22
C	0·0	0·0	0·0	0·0	0·0	0·0
Or	23·58	12·41	53·19	59·10	43·94	47·74
Ab	36·83	5·11	7·68	11·68	0·0	0·0
An	10·83	22·23	0·0	10·99	6·56	11·55
Lc	0·0	0·0	0·0	0·0	17·04	8·21
Ne	3·38	6·40	0·07	2·84	26·08	21·72
Ac	0·0	0·0	5·42	0·0	0·0	0·0
Di	15·27	41·23	28·24	1·42	0·38	0·0
Wo	0·0	4·12	1·53	0·0	0·0	2·08
Ol	0·25	0·0	0·0	1·30	0·60	0·0
Mt	6·52	2·60	1·49	1·81	1·30	3·53
Hm	0·0	0·0	0·0	3·27	0·0	0·73
Il	1·46	1·22	1·23	1·35	0·57	1·01
Ap	1·63	0·38	0·40	0·54	0·38	0·68
Cc	0·20	0·18	0·23	2·61	0·91	0·45
H_2O^+	0·65	3·66	0·21	1·46	1·94	2·00
H_2O^-	0·07	0·34	0·08	0·37	0·13	0·22
Others	0·0	0·53	0·10	1·03	0·0	0·0
Total	100·68	100·41	99·88	99·78	99·84	99·93

TABLE VI (*cont.*)

Modes

	17	18	19	20	21	22
Alkali feldspar	27·4	13·9	59·4	66·3	49·3	57·1
Plagioclase	29·0	–	–	1·7	–	P
Zeolite	–	22·3	–	4·5	14·4	P
Nepheline	–	–	–	–	8·4	22·8
Nepheline (dactylotypic)	–	–	–	–	12·1	–
Cancrinite	–	–	–	–	3·0	–
Analcime	–	–	–	–	–	1·8
Melanite	–	1·3	–	13·1*	4·6	8·4
Biotite	22·6	0·4	–	7·9	3·5	4·8
Pyroxene	15·6	60·0	39·2	0·1	P	1·5
Muscovite	0·6	–	–	–	3·3	P
Sphene	1·6	1·0	0·9	1·2	0·8	0·1
Apatite	0·9	–	0·5	P	0·1	–
Ore	2·3	1·1	–	4·6	0·4	3·5
Carbonate	–	–	–	0·1	0·1	–
Fluorite	–	–	–	–	–	P

17. Vullinite [1972, P8 (67)]
18. Shonkinite [1972, P8 (399)]
19. Pyroxene–microcline xenolith from pseudoleucite borolanite in Quarry [1972, P8 (277)]
20. Andradite borolanite [1972, P8 (400)]
21. Leucocratic borolanite [1972, P8 (378)]
22. Aegirine–nepheline–analcime borolanite [1972, P8 (334)]

For location of specimens see Text-fig. 2

Analyses 17, 21 and 22 by Mrs J. Banham ; 18 and 19 by C. J. Elliott ; 20 by V. K. Din

* Includes approximately an equal amount of andradite.

The pseudoleucite series is characterized by very high potash to soda ratios – commonly greater than 10 to 1, and often greater than 20 to 1 – while magnesia is extremely low, usually less than titania. The values for silica increase from the borolanites through the biotite–magnetite group to the muscovite group so that Harker diagrams prove useful in reflecting chemical changes with height in the layered complex. Upwards there is an increase in silica, alumina and potash while iron, lime, titania and soda increase downwards. It is noteworthy that in terms of a Harker plot (Text-fig. 8) the biotite–magnetite and muscovite group rocks define relatively smooth trends, but that the borolanites show much more scatter. The lower suite, however, has a totally different distribution from the pseudoleucite rocks in terms of a Harker plot and is not shown on Text-fig. 8.

In addition to the whole rock analyses alkali determinations only have been made on a further 19 pseudoleucite rocks (Table IV). Although there is some variation, particularly in the intermediate biotite–magnetite group, the changes in the content of K_2O and Na_2O and the ratio of these two oxides varies consistently through the series culminating in the average values of 13·8 per cent K_2O and 0·40 per cent Na_2O in the muscovite group. These very high potash to soda ratios

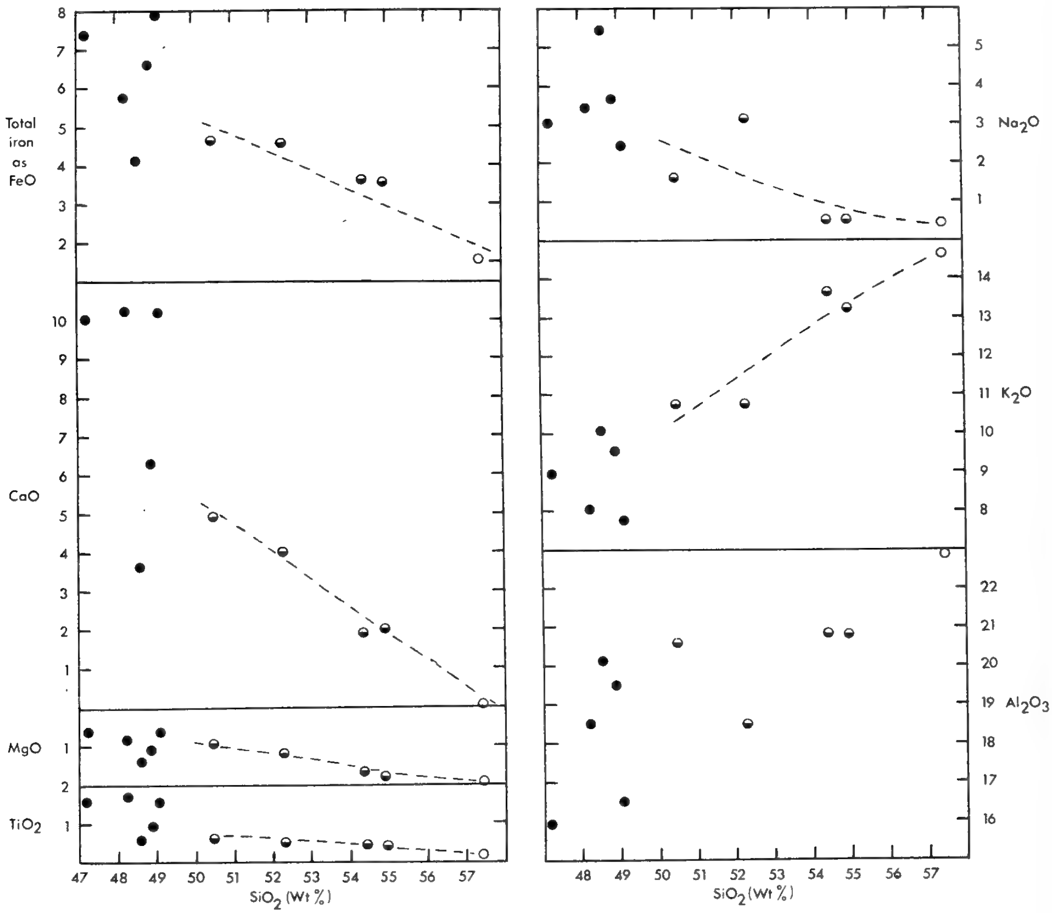

FIG. 8. Harker diagram of South-eastern Tract pseudoleucite rocks. Filled circles, borolanites; half-filled circles, biotite–magnetite group; open circle, muscovite group.

are extremely rare, and comparable rocks usually have much higher magnesia values, in contrast to the extremely low magnesia values of the Borralan suite. The volcanics of the Leucite Hills, Wyoming (Carmichael 1967), range up to 12·66 per cent K_2O and 0·94 per cent Na_2O, but MgO is usually in excess of 6 per cent. Similarly the South-west Uganda volcanics (Holmes & Harwood 1937) have higher MgO values, as do the lavas of the Roman alkaline province (Washington 1906), the Kimberley province of Australia (Wade & Prider 1940; Prider 1960), and the leucite suite of Java (Iddings & Morley 1915). The pseudoleucite tinguaite of Tzu Chin Shan, China (Yagi 1954), contains 12·64 per cent K_2O, 5·43 per cent Na_2O and 0·03 per cent MgO, which is comparable to the muscovite group and some of the biotite–magnetite group rocks, though rather higher in Na_2O. The borolanites with their less extreme compositions can be matched from a number of localities.

Text-fig. 9 emphasizes the strong reciprocal relationship of soda and potash in South-eastern Tract rocks. Coombs and Wilkinson (1969, Figs. 8 & 9) on similar diagrams give the trends for some 20 provinces and separate intrusions and in all of these soda and potash rise sympathetically, though the Shonkin Sag intrusion, over part of its range, shows some decrease of soda against potash. Even highly potassic provinces such as the Roman Comagmatic region, South-west Uganda and Java show ' normal ' trends (Text.-fig. 9, inset diagram), the only exception encountered being the Kimberley province, Australia (Wade & Prider 1940; Prider 1960). The mechanism which determined the well-defined Borralan trend is not, therefore, usually operative in the majority of igneous provinces.

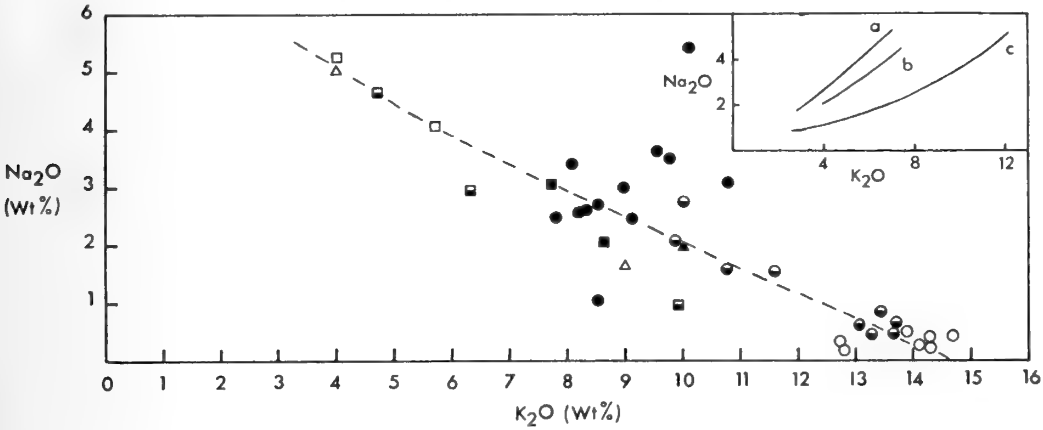

FIG. 9. Plot of soda against potash for pseudoleucite and lower suite rocks. Filled circles, pseudoleucite borolanites; half-filled circles, biotite–magnetite group; open circles, muscovite group; open squares, pyroxene group; half-filled squares, hornblende group; filled squares, borolanites of lower suite; open triangles, vullinite and pyroxene–microcline xenolith; filled triangles, andradite borolanite. Inset diagram shows trends of soda against potash for (*a*) southwest Uganda volcanic province, (*b*) Java volcanic province and (*c*) Roman comagmatic region.

In Text-fig. 10 the pseudoleucite rocks are shown plotted according to their normative Qz – Ne – Ks, normative anorthite being relatively small in these rocks. They lie along a path between potassic feldspar and the nepheline compositions defined by Morozewicz (1930) and Buerger *et al.* (1947). Also plotted are the nepheline syenite and its constituent nepheline and feldspar from near Loyne at the northwest end of the Borralan Complex, described by Tilley (1956, p. 409, Table 4), and comprising his ' juvet type ', the most potassic of the low temperature nepheline syenite assemblages.

Analyses were made of pseudoleucites hand picked from three of the analysed rocks and these, together with an analysis of a borolanite pseudoleucite given by Shand (1906), are given in Table VIII. The compositions were determined of two nephelines (Table VII) taken from a leucocratic borolanite and an aegirine–augite–analcime borolanite which crop out among the pseudoleucite rocks. The pseudoleucite rocks themselves were not chosen, because of difficulty in separating the nepheline. Partial analyses of feldspars, obtained by electron probe, are given in Table IX, and alkali determinations only of feldspars in Table II. The nephelines and pseudoleucites are plotted in Text-fig. 10, and in Text-fig. 11 in part of the Qz – Ne – Ks system pseudoleucites and feldspars are joined by tie lines to their respective rocks. The variation in composition of pseudoleucites and feldspars in sympathy with changes in rock composition is apparent. The pseudoleucites are invariably more sodic than their host rocks. Pseudoleucite number 27 (Text-fig. 11) appears to be unique among analysed pseudoleucites in the combination of high potash and low soda, and its position in the Qz – Ne – Ks system close to the orthoclase point.

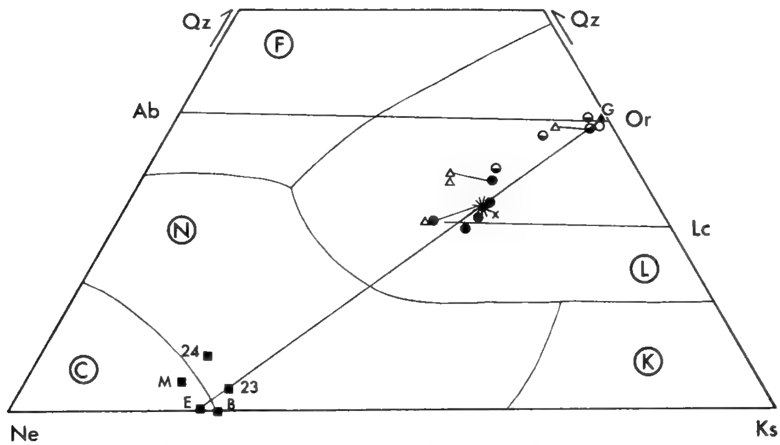

FIG. 10. Plot of pseudoleucite rocks, pseudoleucites and nephelines in the system SiO_2 (Qz)–$NaAlSiO_4$ (Ne)–$KAlSiO_4$ (Ks). Filled circles, borolanites; half-filled circles, biotite–magnetite group rocks; open circles, muscovite group rocks; open triangles, pseudoleucites; filled squares, nephelines. E–*–G, nepheline–rock–feldspar of a Borralan nepheline syenite described by Tilley (1956, Table 4). Nephelines M and B are the compositions of Morozewicz (1930) and Buerger *et al.* (1947) respectively. Tie lines join pseudoleucites to their host rocks. Field boundaries in the dry system are taken from Schairer (1957). Extent of soda-leucite solid solution indicated (Fudali 1963). Stability fields of leucite (L), feldspar (F), nepheline (N), carnegeite (C) and kalsilite (K) are shown.

Text-fig. 12 is part of a von Wolff diagram which illustrates the generally greater enrichment in the 'M' components (MgO, CaO, FeO, MnO) of the borolanites compared with the biotite–magnetite and muscovite groups. In terms of this diagram there is a trend in the borolanites away from the leucite point, while the biotite–magnetite and muscovite group rocks define another trend towards the feldspar point.

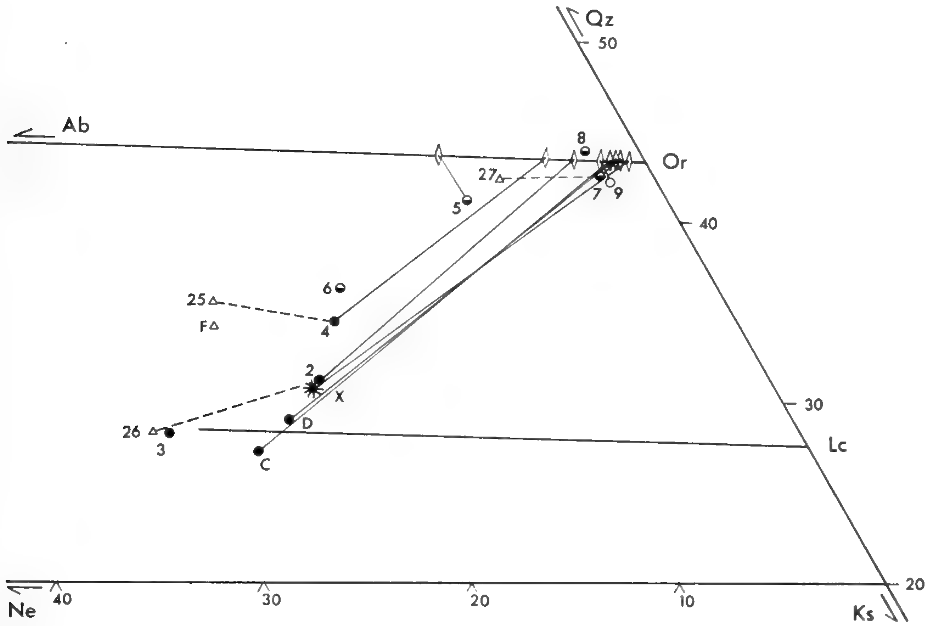

FIG. 11. Part of the system Qz – Ne – Ks showing distribution of the pseudoleucite suite, and coexisting pseudoleucites and feldspars. Symbols for rocks and pseudoleucites as for Text-fig. 10. Lozenges, feldspar compositions. *, nepheline syenite (Tilley 1956) as on Text-fig. 10. Numbers and letters refer to analyses in Tables 2, 3, 8 and 9.

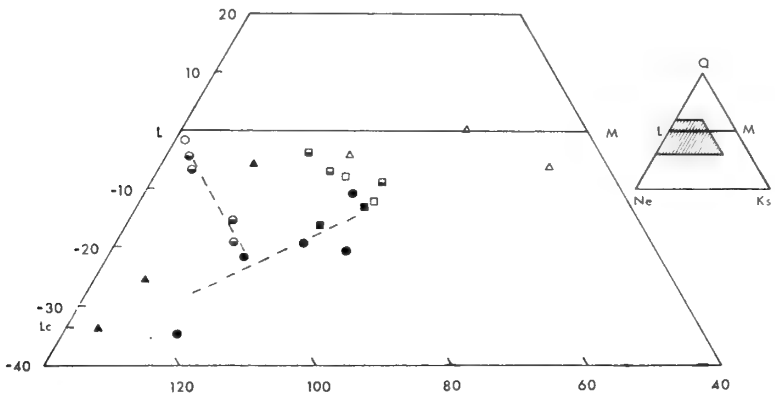

FIG. 12. von Wolff diagram including all analysed South-eastern Tract rocks. Filled circles, pseudoleucite borolanites; half-filled circles, biotite–magnetite group; open circle, muscovite group; open squares, pyroxene group; half-filled squares, hornblende group; filled squares, borolanites; open triangles, vullinite, shonkinite, and pyroxene–microcline xenolith; filled triangles, andradite, leucocratic, and nepheline–aegirine–analcime borolanites.

Table VII

Partial analyses of nephelines

	23	24	E
SiO_2	41·07	43·71	41·06
TiO_2	< 0·03	< 0·03	nil
Al_2O_3	36·20	33·98	33·93
Fe_2O_3	0·20	0·37	0·83
MnO	–	–	nil
MgO	–	–	nil
CaO	–	–	0·19
Na_2O	14·46	14·50	15·92
K_2O	7·65	6·16	7·14
H_2O^+	–	1·30 (with H_2O^-)	0·74
H_2O^-	–		nil
Total	99·58	100·02	99·81

	23	24	E
Qz	3·4	8·2	0·7
Ne	69·6	70·0	73·8
Kp	27·0	21·8	24·4
An	–	–	1·1

23. Nepheline from leucocratic borolanite, cliffs north of Quarry at Aultivullin (B227). Analyst: C. J. Elliott
24. Nepheline from aegirine–augite–analcime borolanite, just north of road, ⅓ mile east of Aultivullin [1972, P8 (365)]. Analyst: C. J. Elliott
E. Nepheline from nepheline syenite, ½ mile southeast of Loyne–Borralan Complex (Tilley 1956, Table 4)

Table VIII

Chemical analyses of pseudoleucites

	25	26	F	27
SiO_2	55·67	51·25	56·26	55·83
TiO_2	0·18	0·23	–	0·05
Al_2O_3	26·00	22·82	21·93	25·00
Fe_2O_3	1·44	1·39	0·67	1·65
MgO	0·23	0·06	–	0·11
CaO	2·45	3·05	1·46	0·74
Na_2O	4·47	5·88	4·95	1·40
K_2O	9·68	10·40	10·63	12·42
H_2O (total)	–	2·73	4·16	2·89
CO_2	–	1·60	–	0·07
Total	100·12	99·41	100·06	100·16

	25	26	F	27
Qz	35·6	28·3	34·1	42·4
Ne	24·9	31·2	25·6	7·7
Kp	39·5	40·5	40·3	49·9

25. Pseudoleucite from pseudoleucite borolanite [1972, P8 (290)]
26. Pseudoleucite from pseudoleucite borolanite [1972, P8 (356)]
F. Pseudoleucite from pseudoleucite borolanite (Shand 1906, p. 441)
27. Pseudoleucite from pseudoleucite biotite–magnetite group rock [1972, P8 (350)].

Analyst: C. J. Elliott

TABLE IX

Analyses of alkali feldspars

	28	29	G
SiO_2	63·83	62·68	63·83
TiO_2	–	–	nil
Al_2O_3	18·24	18·78	18·72
Fe_2O_3	–	–	0·26
MnO	–	–	nil
MgO	–	–	nil
CaO	–	–	nil
Na_2O	0·56	1·45	0·20
K_2O	16·48	15·26	16·60
H_2O^+	–	–	0·07
H_2O^-	–	–	nil
P_2O_5	–	–	(0·11)
Total	99·11	98·17	99·79

28. Potassic feldspar [1972, P8 (356)]
29. Potassic feldspar [1972, P8 (290)]
G. Feldspar from nepheline syenite, ½ mile southeast of Loyne–Borralan Complex (Tilley 1956, Table 4)

Analyses 28 and 29 done on electron probe by R. F. Symes

The analyses of rocks from the boreholes (Table V) must be treated with some caution for two reasons. Firstly, these rocks are extremely heterogeneous so that it was not possible to separate pure pyroxene–biotite syenite from the replacing andradite-bearing syenite. Secondly, the slices available for crushing were small. The two borolanites from the boreholes (Table V, anals. 12 & 13) prove to be closely comparable with the pseudoleucite borolanites, the only significant difference being their higher magnesia values. The analyses of pyroxene and hornblende group rocks are rather different from those of the pseudoleucite suite, notably in the higher soda to potash ratios which result in normative albite varying from 8 per cent to 38 per cent, whereas it is negligible in the pseudoleucite suite. Somewhat higher magnesia and iron values tend to separate the borehole rocks from the pseudoleucite suite in terms of the von Wolff diagram (Text-fig. 12), while the borehole borolanites plot between the two. There is a very marked difference between the two suites in terms of a plot of MgO against (FeO + Fe_2O_3) (Text-fig. 14). The pseudoleucite suite defines a marked differentiation series low in magnesia, quite distinct from the more magnesia-rich lower suite.

The close chemical coincidence of the higher level pyroxene group syenite (Table V, anal. 10) and the vullinite (Table VI, anal. 17) is apparent (Text-fig. 13), and confirms the correlation of these rocks made on petrographic grounds. While pyroxene syenite number 10 (Table V) is strongly altered to an andradite-rich syenite and contains an abundance of albite, which usually accompanies this alteration, the other analysed member of the pyroxene group (Table V, anal. 11) is more undersaturated, which is confirmed by the occurrence of altered nepheline

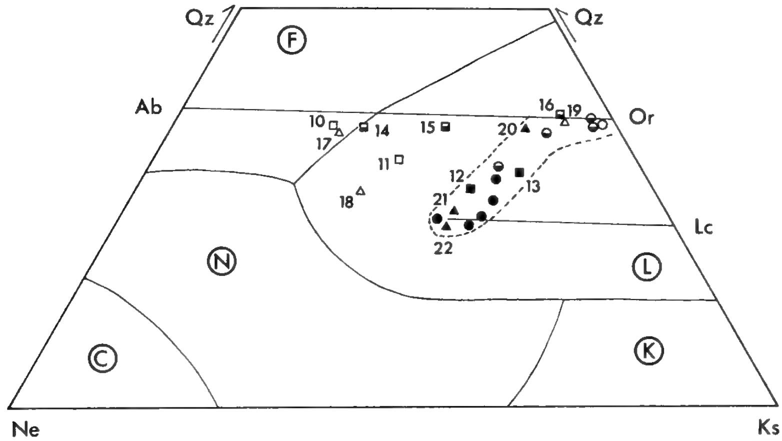

FIG. 13. Plot of all South-eastern Tract rocks in the system Qz – Ne – Ks. Symbols as on Text-fig. 12. Numbers refer to analyses of Tables 5 and 6. Field of pseudoleucite suite outlined. Field of leucite (L) etc. as on Text-fig. 10.

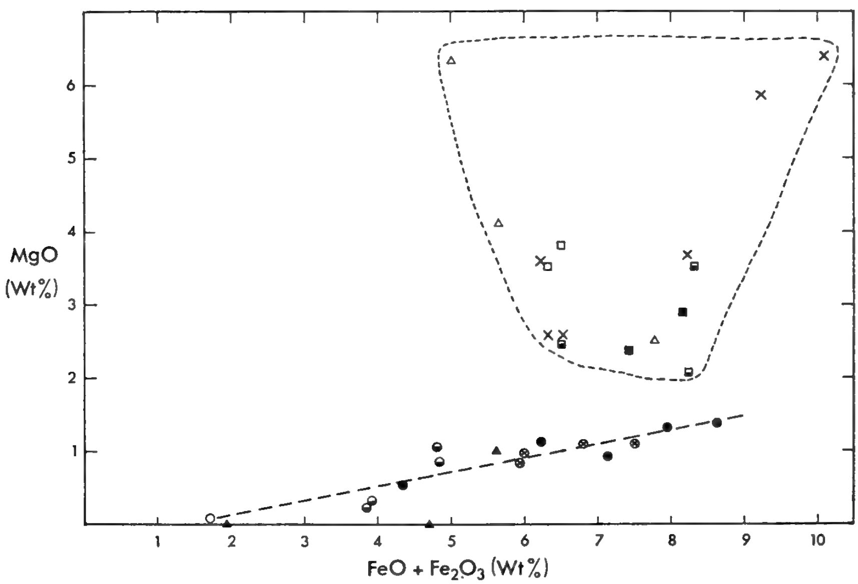

FIG. 14. Plot of MgO against ($FeO + Fe_2O_3$) (weight per cent) for all South-eastern Tract rocks together with ledmorites of the Borralan Complex, and ledmorite dykes of the Assynt area. Symbols as on Text-fig. 12; ledmorites, crosses.

in thin section, and is only slightly changed towards an andradite syenite. The three analysed rocks representative of the hornblende group (Table V, anals. 14–16) show little variation in terms of silica saturation, but considerable variation in the ratio of soda to potash (Text-fig. 13). They do not differ significantly from the pyroxene group in terms of lime, magnesia and iron (Text-fig. 12).

The pyroxene–microcline xenolith (Table VI, anal. 19) has a high potash to soda ratio, which is to be expected as it was enclosed in borolanite, and hence lies amongst the pseudoleucite series in terms of Text-fig. 13. The shonkinite (Table VI, anal. 18) because of its high colour index is low in alkalis but, significantly, contains nearly as much soda as potash. These two rocks are the most mafic encountered in the South-eastern Tract and hence are enriched in ' M ' components in terms of Text-fig. 12. The leucocratic borolanite and aegirine–nepheline–analcime borolanite (Table VI, anals. 21 & 22) prove chemically to be very similar to the pseudoleucite borolanites (Text-fig. 13), although the leucocratic rock is inevitably lower in total iron, lime and magnesia.

Very high strontium and barium values have been found in all South-eastern Tract rocks (Tables III, V and VI).

VII. DISCUSSION

There is strong evidence that the pseudoleucite suite of rocks was emplaced after the lower suite. This conclusion is drawn from the presence of xenoliths within the pseudoleucite borolanites which can be matched with the shonkinites of the lower suite; the layers of borolanite within the shonkinite, which are interpreted on textural grounds as being metasomatic; and the similar replacement features revealed by thin sections of the borolanites from the boreholes. The contact between the two suites as seen in the Gorge is apparently sharp, but obscured to some extent by shearing. However, there is no sign at all of chilling, which suggests intrusion of the pseudoleucite magma into rocks which were already at relatively elevated temperatures.

There are three principal problems posed by these rocks: firstly, what mechanism was responsible for the variation within the pseudoleucite suite; secondly, how were the rocks of the lower suite generated, and how are they related genetically to the pseudoleucite suite; and thirdly, how do these rocks relate to the igneous history of the Borralan Complex as a whole?

(1) The pseudoleucite suite

No intrusive contacts have been recognized among the pseudoleucite rocks, and this, together with the gradual, yet consistent, mineralogical and chemical changes across the South-eastern Tract suggest that *in situ* differentiation was the principal mechanism of rock diversification. The marked concentration of iron, calcium, titanium and magnesium at lower levels is consistent with the sinking of melanite and to some extent of pyroxene crystals. Consideration of the distribution of alkalis and silica through the suite is more difficult of explanation. The uppermost rocks contain the most silica and a remarkable concentration of potash such that potash to soda ratios are of the order of 50 : 1. Soda increases at lower levels in spite of the fall off in silica. The trend which is defined on a Qz – Ne – Ks diagram (Text-fig. 10) could not have been produced by the crystallization and removal from the melt of potash-leucite.

The pseudoleucites in the borolanites consist of potassic feldspar and nepheline–feldspar intergrowths of vermiform type, while in the higher rocks they consist of an alkali feldspar and, to a greater or lesser extent, muscovite. Chemically the pseudoleucites are more sodic than their host rocks, and they change in composition sympathetically with the rocks. The problem, therefore, is to decide what was the original composition of the pseudoleucites and, if different from the present composition, by what mechanism was the change achieved. Of the various theories put forward to solve the pseudoleucite problem two are paramount. Knight (1906) postulated the unmixing on cooling of a soda-rich leucite, while Bowen (1928) considered that reaction between leucite crystals and melt is responsible for pseudoleucite formation. Fudali (1963) has shown that in the system quartz – nepheline – kalsilite – water as much as 40 per cent of soda-leucite can be held in leucite solid solution, depending on the water vapour pressure, and he has demonstrated that pseudoleucites from the Bearpaw Mountains, Montana, are derived from the breakdown of soda-leucites. On Text-fig. 11 the maximum extent of leucite solid solution determined by Fudali is shown, and one of the analysed borolanite pseudoleucites lies close to the extreme soda-leucite composition. However, there is no evidence, so far, for extensive, indeed any, solid solution between soda-leucite and potash feldspar. Subsolidus breakdown will not, therefore, explain the compositions of the other three Borralan pseudoleucites. Some change in their bulk composition must have taken place.

As already pointed out, the change in composition of the pseudoleucite suite cannot be attributed to separation of potash-leucite because the later fractions would be enriched in soda, not potash, while if it were postulated either that leucite floated to the top of the magma chamber, or that crystallization proceeded from the top downwards, then the observed trend in terms of Qz – Ne – Ks would not result. Crystallization of soda-leucite, on the other hand, is a reasonable mechanism. As the ultra-potassic pseudoleucite rocks are much less voluminous than the borolanites an acceptable primary magma would be a borolanite such as number 2 on Text-fig. 11. Separation of leucite containing 30–40 per cent soda-leucite molecule from such a magma would enrich the melt in potash and silica, driving it towards the orthoclase end of the feldspar join. If the pseudoleucite reaction now became operative, reaction of soda-leucite crystals with the melt would produce a mixture of alkali feldspar and nepheline, resulting in the addition of further sodium to the leucites and enriching the melt still further in potassium. Because of the depletion of the melt in sodium the primary crystallizing leucite phase probably became increasingly potassic, and this together with the increase of silica in the melt would gradually change the pseudoleucite reaction from one producing feldspar + nepheline to one producing feldspar only. If there was an increase in the water vapour pressure during the differentiation, as seems probable, then this would also cause a decrease in the sodium content of the primary leucite, as shown by the work of Fudali (1963). This hypothesis therefore requires both the production of a soda-leucite, as originally suggested by Knight (1906), and Bowen's (1928) pseudoleucite reaction to proceed from the bottom of the magma chamber and to work its way through to the top.

Bowen (1928, p. 256) interpreted the layered structure of the Borralan Complex as described and illustrated by Shand (1910, Fig. 2) in terms of the gravitational settling of leucite, plus the pseudoleucite reaction, resulting in an ultrabasic zone at the bottom grading through to a quartz syenite zone at the top. The pseudoleucite suite is in fact intruded by the later syenites (Woolley 1970) and the ultrabasic rocks probably do not form a basal layer to the Complex (Parsons 1965, p. 57), but Bowen's mechanism, with modifications, is applicable to one group of rocks of the intrusion.

The leucocratic and aegirine–nepheline–analcime borolanites are chemically very close to the pseudoleucite borolanites, though free from pseudoleucite. Rocks of such compositions would crystallize leucite initially, but the subsequent pseudoleucite reaction and complete recrystallization has destroyed the pseudomorphs. It is envisaged that these rocks represent batches of magma which were somehow separated from the main mass of borolanite magma, were presumably subjected to different physical conditions and were intruded late. The dearth of mafic minerals in the leucocratic borolanite suggests their separation by gravitational settling, either *in situ* or prior to intrusion.

(2) The lower suite

A number of late mineralogical and textural changes have been described from the lower suite. The rocks which are least affected by these changes are the patches of pyroxene–biotite syenite, which occasionally carry nepheline, and the shonkinite, and these are considered to be remnants of the primary rocks of the lower suite. Although Shand (1910, p. 407; 1939, p. 416) suggested that the vullinite might be a metamorphosed calcareous sediment, or an igneous rock, Phemister interpreted it as 'a metamorphosed igneous rock, probably a mesocratic pyroxene–biotite–syenite or porphyrite' (Macgregor & Phemister 1937, p. 45). It is noteworthy that Phemister's suggested precursor to vullinite coincides exactly with the primary rock of the lower suite indicated by the present work.

Four principal secondary effects are recognizable among the lower suite rocks:

(a) 'Borolanitization.' This involves the formation of titanium garnet in rocks adjacent to borolanite sheets in the Gorge and boreholes, and the metasomatic introduction of garnet along certain layers in the Gorge outcrops.
(b) The alteration of pyroxene to hornblende.
(c) The alteration of pyroxene and hornblende to biotite and andradite, with the concomitant development of a sodic plagioclase.
(d) Zeolitization of the feldspar.

Because of the widespread development of these secondary changes it has proved difficult to determine the chemical composition of the primary magma of the lower suite. Two analyses, however, seem to be close to it; the shonkinite (Table VI, anal. 18), and the lesser altered of the borehole pyroxene–biotite–andradite syenites (Table V, anal. 11) in which nepheline is still recognizable. These two rocks are the most undersaturated of the lower suite (Text-fig. 13) and it is apparent from Text-figs. 14 and 15 that they are a close match chemically with the group of rocks of the Borralan Complex called ledmorites by Shand (1910, p. 384), for which there are six chemical analyses available (Shand 1910; Tilley 1958; Woolley 1965). The ledmorites are essentially malignites and shonkinites very similar to the lower group pyroxene–biotite syenites. Although there is some variation in the limited chemical data on the ledmorites, and although the pyroxene–biotite syenite has undoubtedly undergone some chemical change, the mineralogical and chemical match is good enough to demonstrate convincingly that the lower suite of rocks of the South-eastern Tract are comagmatic with the ledmorites. However, the majority of rocks of the lower suite have undergone chemical changes as can be seen from Text-fig. 15. Apart from rocks 11 and 18 (Text-fig. 15) all the lower suite are only slightly undersaturated, in marked contrast to the highly undersaturated ledmorites. Two rocks, the pyroxene microcline xenolith (Table VI, anal. 19) and the biotite syenite (Table V, anal. 16), are highly potassic. The xenolith was enclosed in pseudoleucite borolanite and would be expected to be enriched in potash, while it must be assumed that the biotite syenite was similarly metasomatized by a nearby vein of pseudoleucite magma type. The increase in silica in the other lower suite rocks is undoubtedly related to the alterations involving the development of hornblende and biotite + andradite.

Microscopic examination of the borehole rocks shows that hornblende replaces pyroxene, and even in the purest hornblende types some pyroxene can still be found in the cores of crystals. In the vullinite it can be shown that hornblende growth is related to the proximity of syenite veins, and these veins comprise part of the later suite of syenites and quartz syenites. It is also noteworthy that late, spongy hornblende crystals have been found in the pseudoleucite borolanite outcrops west of the Gorge, close to the intrusive contact with the later syenites. It must be concluded, therefore, that the development of hornblende is a contact effect associated with the intrusion of the later syenites.

The alteration of hornblende and pyroxene to biotite + andradite may be a further stage of this contact metamorphism. A similar effect has been found among the ledmorites at the west and southwest ends of the Complex (Woolley 1965), in which the replacement of the pyroxene by biotite + melanite and/or andradite garnet can be followed in thin section. This alteration increases towards the intrusive contact with the later syenites, and in a zone 100–150 m wide along the contact very little fresh pyroxene can be found. The striking parallel between this mineral transformation and that found in the lower suite of the South-eastern Tract indicates a similar cause, and it is concluded that this is also a contact metamorphic effect of the intrusion of the later syenites, but that it is later than the ‘hornblendization’.

Returning to the problem of the increase in the degree of silica saturation shown by the altered lower suite rocks, the mineralogical evidence indicates the influence of the later syenites, and it is, therefore, concluded that the silica increase is part of the same contact effect. In Text-fig. 15 the area occupied by the later syenites and quartz syenites is shown, and the interpretation of the more silica-rich lower suite rocks as reaction between ledmorite type rocks and the later syenites seems a reasonable one in terms of this figure.

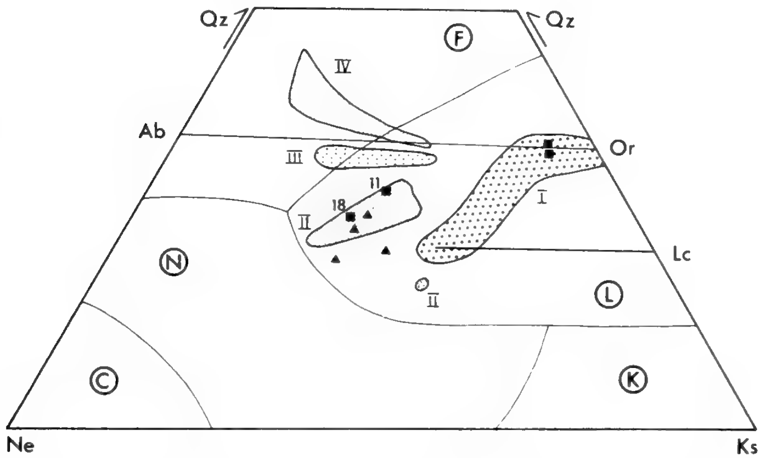

FIG. 15. The distribution of the major rock types of the Borralan Complex in the system Qz – Ne – Ks. I, pseudoleucite suite ; II, ledmorites ; III, hybrid rocks of the lower suite, South-eastern Tract ; IV, later syenites and quartz syenites – based on data of Parsons (1972). The squares are the least hybridized pyroxene group rocks (11 and 18), which plot in the ledmorite field, and the biotite syenite (hornblende group) and pyroxene–microcline xenolith which have undergone potash metasomatism. The triangles are ledmorite dykes of the Assynt area. Field of leucite (L) etc. as on Text-fig. 10.

(3) The relationship to the ledmorites

The four principal groups of rocks which comprise the Borralan intrusion, excluding certain ultramafic rocks, are defined in Text-fig. 15 in terms of Qz – Ne – Ks. The nepheline syenites of the complex have been shown by Tilley (1958) to include two types, a foyaite type and a juvite (juvet) type, and these plot in Text-fig. 15 in the ledmorite and pseudoleucite suite fields respectively. In a similar plot to Text-fig. 15 Tilley (1958, Fig. 1), combining the data then available for the Borralan and nearby Loch Ailsh complexes, together with data for the minor intrusions of the Assynt region, defined four groups, which correspond in Text-fig. 15 to the borolanite part of group I, group II and group IV which Tilley subdivided into two separate groups. No data corresponding to group III were then available. He concluded that ' Consideration of this analytical plot raises many problems relating to the differentiation and evolution of alkali complexes of the Assynt type '. A mechanism for the production of group III rocks involving hybridization between II and IV has been outlined above, but the direct genetic relationship between the later syenites and the highly undersaturated groups I and II, a problem which arises in many syenite complexes, cannot be considered here. However, it is believed that the relationship between the ledmorites and the pseudoleucite suite can be deduced.

The extent of primary crystallization of leucite under anhydrous conditions in the system Qz – Ne – Ks as determined by Schairer (1957) is indicated in Text-fig. 15. The area of this field decreases with increasing water pressure but even at 1000 bars P_{H_2O} (Fudali 1963) all the pseudoleucite suite, and all but one of the ledmorites, lie within the leucite field. The primary ledmorites, that is those unaffected by the late replacement of pyroxene by biotite + garnet, contain little in the way of hydrous minerals. Modes on eleven of these rocks average less than four volume per cent biotite, and some of this is certainly of late development related to the contact metamorphism by the later syenites. The ledmorite magma was, therefore, essentially a dry one indicating that these rocks would lie well within the stability field of leucite. Although pseudoleucites do not occur in the ledmorites there is very extensive development of dactylotypic alkali feldspar–nepheline intergrowths, which are identical to those found in the borolanite pseudoleucites and in pseudoleucites at other localities, such as the Bearpaw Mountains, Montana (Fudali 1963, Plate 2, Figs. 3 & 4). Intergrowths identical to the Borralan ones occur in rocks at Kaminak Lake, Northwest Territories, Canada (Davidson 1970, Fig. 2), which do not contain pseudoleucites, but Davidson has shown convincingly that the feldspar–nepheline intergrowths developed by the breakdown of soda-leucite. It seems certain that leucite crystallized initially from the ledmorites. The work of Fudali (1963) indicates that the amount of $NaAlSi_2O_6$ that can be held in leucite-solid solution is increased at low water pressures so that it is assumed that soda-leucite separated from a magma of ledmorite type, then separation of such a crystal phase, perhaps by upward floating, would produce a fraction which, in terms of alkalis and silica, would be compositionally close to pseudoleucite borolanite (Text-fig. 15). The melt fraction would move to the leucite field boundary and eventually crystallize nepheline and alkali feldspar.

A plot of MgO against (FeO + Fe_2O_3) (Text-fig. 14) shows that apart from three rocks which are enriched in MgO there is a fair correlation of the ledmorites with the lower suite. They show, however, a totally different distribution from the pseudoleucite suite, which is very low in magnesia but shows a relatively smooth trend. The contrasting distributions are explicable in terms of the gravitational settling of pyroxene, a major mineral in the ledmorites and lower suite, but absent or very minor in the pseudoleucite suite. The sinking of pyroxene and the rising of soda-leucite is a mechanism which is adequate to explain the chemical differences between these two rock groups. It is believed that the differentiation took place before intrusion of the separate groups, although in the South-eastern Tract the relative positions of the rocks are consistent with an origin by gravitational differentiation *in situ*. This mechanism is close to the original suggestion of Shand (1910, p. 413) of gravitational settling of 'denser molecules', but Shand considered that the whole Borralan intrusion could be explained in terms of *in situ* differentiation of a single intruded body of magma.

There are in the Assynt region a number of dykes which are referred to as ledmorites by Sabine (1952), and which can be assigned to the Borralan magmatic episode. They extend up to 20 miles from the Complex. Four analyses are available (Horne & Teall 1892; Sabine 1952; Tilley 1958) and are plotted on Text-figs. 14 and 15. In terms of their alkali ratios and degree of silica undersaturation they are clearly comparable with the type ledmorites, but they have low MgO values similar to those of the pseudoleucite borolanites. The low MgO values of the dykes suggests some loss of pyroxene, probably by gravitational settling, during the lateral movement of this magma fraction away from the Borralan centre.

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PLATE 16

Fig. 1. Pseudoleucites and pseudomorphs after pyroxene (?) (black, towards top) in a potassic feldspar–biotite–magnetite rock. Ordinary light; scale line, 3 mm [1972, P8 (311)].

Fig. 2. A pseudomorph of biotite and magnetite after pyroxene (?), in a potassic feldspar–biotite–magnetite rock. Ordinary light; scale line, 0·5 mm [1972, P8 (311)].

Fig. 3. Sheaves of muscovite enclosed by a plate of potassic feldspar, in a potassic feldspar–muscovite rock. Crossed nicols; scale line, 0·5 mm [1972, P8 (131)].

Fig. 4. Fine-grained borolanite from close to contact with biotite–magnetite group. Black, magnetite; dark grey, high relief, melanite and sphene; medium grey, biotite; white, potassic feldspar. Ordinary light; scale line, 0·1 mm [1972, P8 (364)].

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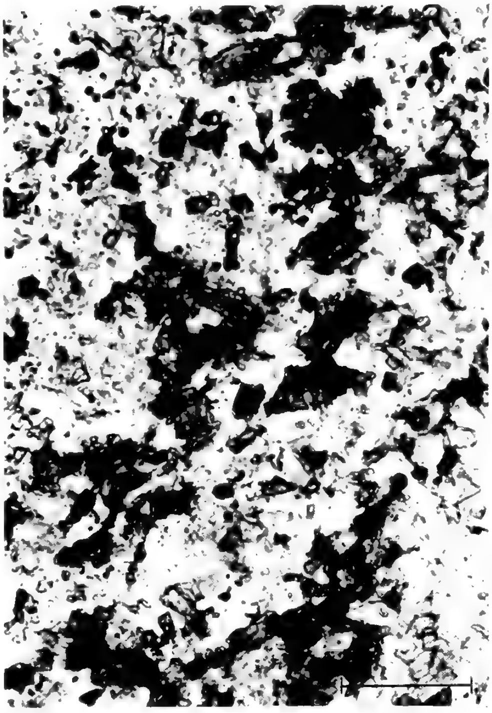

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PLATE 17

FIG. 1. A pseudoleucite in a borolanite has been overgrown by a large potassic feldspar crystal, but the original edge of the leucite is sharply defined by ' dust ', which is probably a remnant of the pre-recrystallization leucite porphyry. Biotite, dark grey. Crossed nicols; scale line, 0·05 mm [1972, P8 (344)].

FIG. 2. A large plate of potassic feldspar has overgrown a pseudoleucite (to the left) and matrix in a borolanite. Nepheline (grey, high relief) occurs in the pseudoleucite. Biotite, dark grey ; melanite, dark grey, high relief. Ordinary light ; scale line, 0·1 mm [1972, P8 (363)].

FIG. 3. Melanite (high relief) has grown within biotite (grey, low relief) in a pseudoleucite borolanite. Potassic feldspar is off white. Ordinary light ; scale line, 0·1 mm [1972, P8 (285)].

FIG. 4. Biotite (grey) and melanite (high relief) pseudomorph pyroxene and are poikilitically enclosed by potassic feldspar in a borolanite. Ordinary light ; scale line, 0·1 mm [1972, P8 (124)].

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PLATE 18

FIG. 1. Nepheline in dactylotypic intergrowth with potassic feldspar. Pseudoleucite borolanite. Crossed nicols ; scale line, 0·1 mm [1972, P8 (285)].

FIG. 2. Nepheline and potassic feldspar in dactylotypic intergrowth. Some feldspar grains (slightly strained) are free of nepheline, and there is a distinct tendency for nepheline to be concentrated at feldspar grain boundaries. Pseudoleucite borolanite. Crossed nicols ; scale line, 0·1 mm [1972, P8 (307)].

FIG. 3. Nepheline (dark grey) and potassic feldspar (grey) showing complex intergrowth. There is probably a replacement relationship, but the direction of this replacement is not readily apparent. The white flecks in the nepheline are cancrinite. Pseudoleucite borolanite. Crossed nicols ; scale line, 0·1 mm [1972, P8 (363)].

FIG. 4. Part of a Carlsbad twinned porphyroblast of potassic feldspar overgrowing a rock of feldspar, nepheline, aegirine, melanite, biotite and ore. All these minerals form inclusions in the porphyroblastic feldspar. Aegirine–nepheline–analcime borolanite. Crossed nicols ; scale line, 0·1 mm [1972, P8 (334)].

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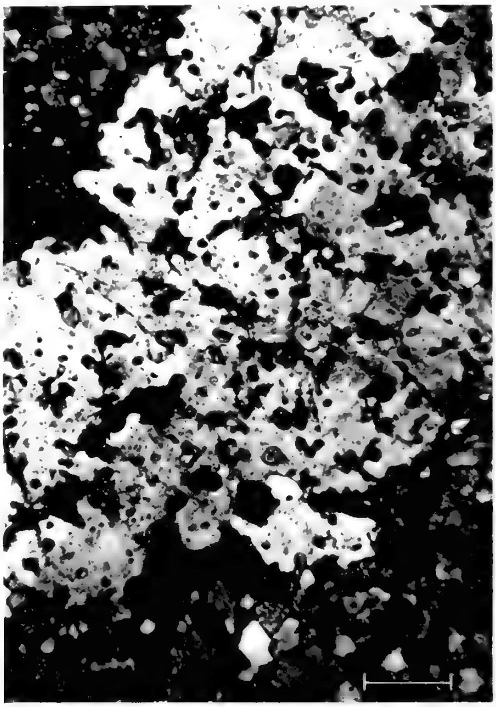

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PLATE 19

FIG. 1. Pyroxene–microcline xenoliths included in pseudoleucite borolanite. Aultivullin Quarry. The large xenolith is approximately 0·5 m in diameter.

FIG. 2. Pyroxene–microcline xenolith. From an inclusion in pseudoleucite borolanite, Aultivullin Quarry. Ordinary light ; scale line, 0·2 mm [1972, P8 (173)].

FIG. 3. Shonkinite, Aultivullin Gorge. Pyroxenes (medium grey) are set in a matrix of potassic feldspar and zeolite (pale grey to white). Ordinary light ; scale line, 0·2 mm [1972, P8 (399)].

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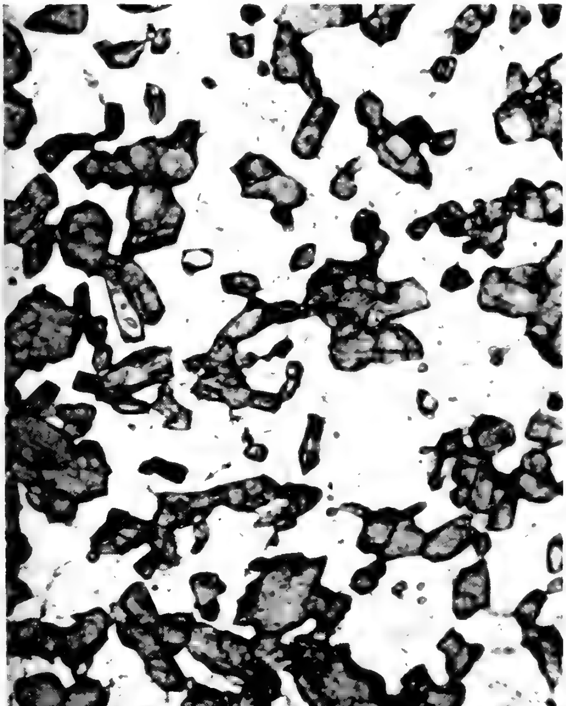

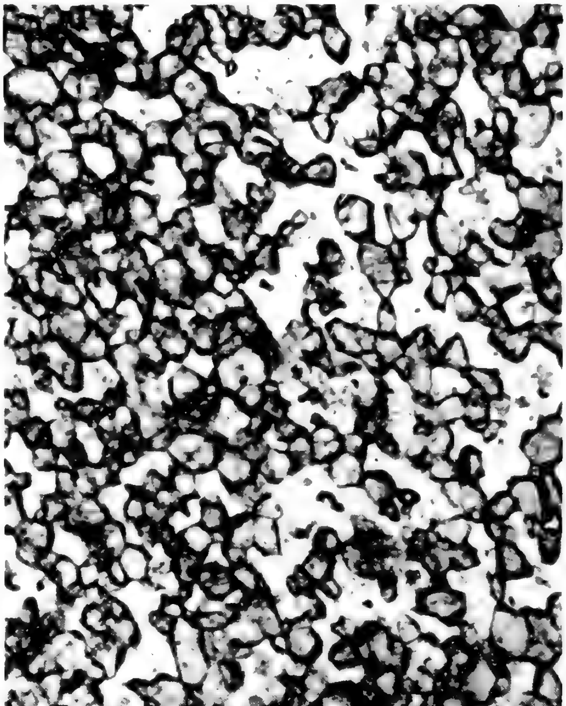

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PLATE 20

FIG. 1. Vullinite, Allt a'Mhuilinn. Aligned biotites (dark grey) are cut across by a crystal of plagioclase (dotted outline in ink) which has inclusions of biotite and pyroxene (high relief). Larger pyroxenes are also apparent. Feldspar, off white. Ordinary light; scale line, 0·1 mm [1972, P8 (68)].

FIG. 2. A cluster of small pyroxene grains (grey) is surrounded by a single large, ragged hornblende (dark grey to black) which is replacing them. Hornblende–pyroxene–andradite syenite. Borehole 1 at 40 feet (12·19 m), Aultivullin Quarry. Ordinary light; scale line, 0·2 mm [1969, P17 (51)].

FIG. 3. Melanite (dark grey, high relief) poikilitically encloses, and extends between, potassic feldspar grains (off white). Biotite, medium grey. Granular borolanite. Borehole 1A at 61 feet (18·59 m), Aultivullin Quarry. Ordinary light; scale line, 0·2 mm [1969, P17 (9)].

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PLATE 21

FIG. 1. Andradite–biotite syenite showing the typical 'ragged' texture. Rectangular shapes towards the top are pseudomorphs after pyroxene. Andradite, grey, high relief; biotite, grey, low relief; magnetite, black; feldspar, white to pale grey. Borehole 2 at 50 feet (15·24 m), Aultivullin Quarry. Ordinary light; scale line, 0·5 mm [1969, P17 (36)].

FIG. 2. Hornblende syenite, towards the top, is being altered to andradite–biotite syenite, towards the bottom. The relatively simple crystal boundaries of the hornblende (very dark grey) syenite contrast markedly with the ragged texture of the andradite–biotite syenite. Andradite, dark grey, high relief; biotite, grey, low relief; feldspar, white to pale grey. Borehole 1 at 90 feet (27·43 m), Aultivullin Quarry. Ordinary light; scale line, 0·2 mm [1969, P17 (60)].

FIG. 3. Hornblende–pyroxene syenite. Euhedral to sudhedral hornblendes, with occasional pyroxene cores (lower centre), and individual pyroxene grains. Hornblende, dark grey; pyroxene, grey, high relief; feldspar, white to pale grey. Borehole 1 at 145 feet (44·20 m), Aultivullin Quarry. Ordinary light; scale line, 0·2 mm [1969, P17 (71)].

FIG. 4. Hornblende–pyroxene syenite showing the complex, poikilitic forms of the hornblendes. Hornblende, dark grey; pyroxene, grey; ore, black; feldspar, white to pale grey. Borehole 1 at 45 feet (13·72 m), Aultivullin Quarry. Ordinary light; scale line, 0·2 mm [1969, P17 (52)].

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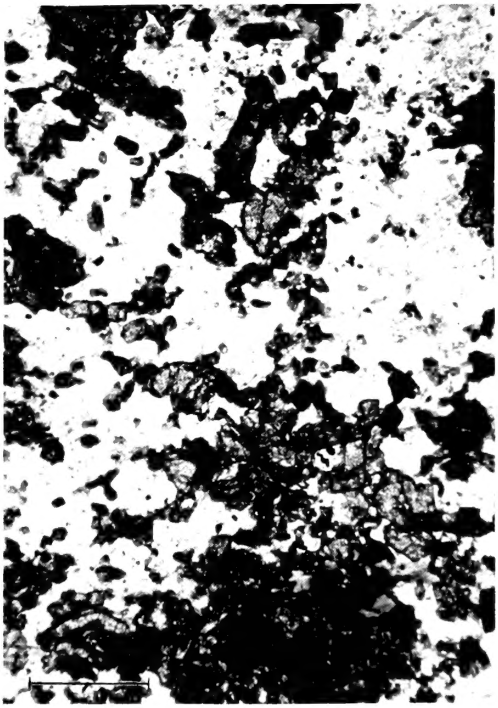

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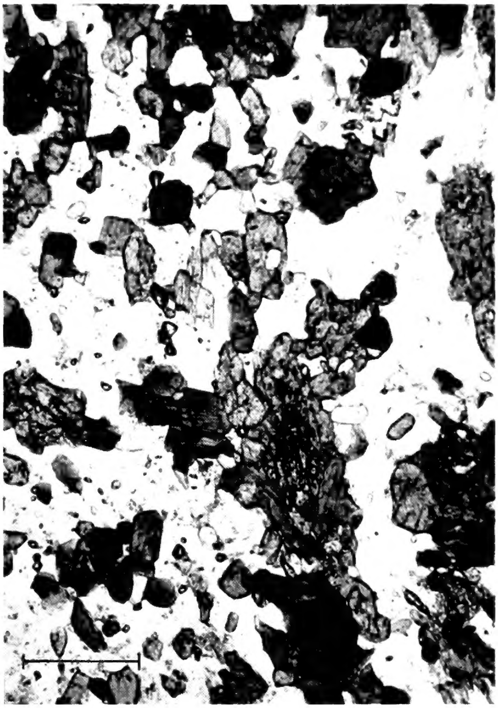

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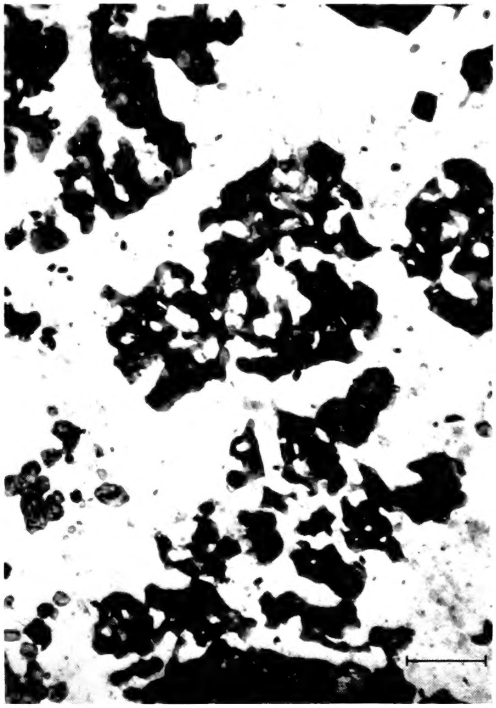

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