GEOLOGICAL AND GEOCHEMICAL ASPECTS OF THE LOCH LOYAL ALKALINE COMPLEX, SUTHERLAND

a thesis
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by
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ABSTRACT

The object of this investigation was to categorize all geological and geochemical parameters applicable to the Loch Loyal syenites and to relate these both to processes operating there and to the broader problems of alkaline rock genesis. Whole rock and trace element contents have been determined for the Loyal syenites and compared with other alkaline intrusions in Scotland and both pegmatite chemistry and mineralogy have been detailed.

Loch Loyal syenites consist of three separate bodies, Ben Loyal, Beinn Stumanadh, and Cnoc nan Cùilean each intrusive into grey flaggy psammitic Moinian granulites. They are best described as quartz-nordmarkites. Emplacement of the magma resulted in the formation of a feldspar flow lamination in the outer parts of the Loyal mass and to deformation of the surrounding country rocks. Core rocks crystallized as a one-feldspar type and outer laminated syenites as a two-feldspar assemblage. A pegmatitic phase was succeeded by low-temperature hydrothermal mineralisation and considerable deuteric activity in which strontium and barium carbonates, hematite and rare-earth elements were deposited either in veins or druses and, at a temperature close to 250°C, a type of lead metasomatism formed green amazonitic feldspar.

The intermediate nature of the Loyal nordmarkite has been established, it straddles the sodaclase-granite/nordmarkite division of Johannsen, is close to sphene-orthite type granitoids but contains a mineral with monazite structure, and the tantalo-niobate mineral polycrase occurs within the pegmatites contrary to a suggestion by

Pavlenko et. al. that such minerals are absent from sphene-orthite type granitoids.

The other alkaline intrusions in Sutherland, Loch Ailsh and Loch Borralan, were found to differ in trace-element chemistry from each other and from the Loch Loyal syenites. Even so a general alkaline petrographic province is postulated for the N.W. Highlands which persisted from early Caledonian times and included the metamorphosed syenite of Glen Dessarry, part of the Glenelg-Ratagain complex and scattered areas of soda-metasomatism. Compared with other rocks of the Scottish "Newer Igneous" suite Loyal syenites are markedly enriched in Pb,Ba,Nb, and the rare-earth elements and very greatly deficient in calcium.

Anomalous radioactivity associated with the Loyal intrusions is due chiefly to the thorium content of allanite.

Within the pegmatites of Sgòr Chaonasaid at the northern extremity of the Loyal range a zonation between galena and silicate minerals exists in which silver and copper form complex sulphides such as stromeyerite.

The origin of the Loyal syenites is not thought to be connected with the hypothesis of limestone assimilation for alkaline rock genesis as envisaged by Daly and Shand nor to the specialised stable tectonic conditions considered important by Harker, but to anatexis at depth and subsequent extreme differentiation, connected with faulting, which resulted in an increased sodium content and a 'reworking' of surrounding sediments and/or granitic rocks, with consequent enhancement of U,Th,Nb,RE's,Ba and Sr over that usual for granitic rocks.

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CHAPTER ONE

INTRODUCTION

Location

The Ben Loyal igneous complex lies approximately 10 km. to the south of Tongue village in Sutherland. Three separate syenites, Ben Loyal, Beinn Stumanadh and Cnoc nan Cùilean occupy areas of 16.8 square km, 5 square km, and 2.5 square km, respectively; nordmarkite forming the bulk of the rocks.

Each of the intrusions share characteristics although Cnoc nan Cùilean presents features not seen in the other two bodies namely development of a basic marginal zone and prominent contact phenomena. The syenites are emplaced within Moine granulites which are contact altered by the intrusions. In addition the strike of the Moine sediments is sharply deflected, sometimes at distances of up to three kilometres from the contact, to encircle the Loyal and Cùilean intrusions; unusually dips are inward towards the centre of the masses in both cases. On approaching the syenite contact the dip of the Moine metasediments increases from 20-30 degrees to about 45-60 degrees. Locally, and particularly surrounding the northern edge of Beinn Stumanadh the Moinian rocks are highly crumpled and in some cases gleitbretter shear folds are developed. Normally however, contacts are not much disturbed. Several large xenolithic rafts, one up to 500 m in length, occur more especially within the Ben Loyal mass and this together with the feldspar lamination in the outer parts must be explained in any theory of origin.

Mineralogically the syenites are composed of potash feldspar, albite and perthite mixtures, sodic pyroxene and/or sodic hornblende quartz, sphene, allanite, zircon and iron oxides. The commonest feldspar is a beautifully perthitic cloudy anorthoclase in which the potash is less than the soda and is therefore antiperthitic. Supplementary to this antiperthite, albite crystals occur, and potash feldspar in small shapeless grains is often cross-hatched and twinned on the Carlsbad law. Checker-type twinning is often seen in the independent albites. A bluish-green hornblende replaces stout, subhedral, prismatic crystals of pyroxene throughout most of the intrusions and only in Cnoc nan Cùilean is pyroxene the dominant constituent. Quartz is found on occasions marginal to the Loyal intrusion. Sphene occurs in all three bodies and allanite in zoned crystals is common. Many of the syenites peripheral to the Loyal mass have small miarolytic cavities filled with a canary yellow mineral which Von Knorring and Dearnley (1960) have considered to be a new hydrated species of monazite structure. The rocks can be assigned to a nordmarkitic suite.

The mineralogy in the complex is diverse and Heddle early in the 1880's demonstrated its unusual nature; reflecting this, trace element content, and radioactivity show anomalous concentrations and values. Pegmatitic minerals from Sgòr Chaonasaid at the northern end of the Loyal range are particularly interesting.

Historical review

Since the preliminary survey of Sutherland by Cunningham (1841) several authors have made reference to the Tongue district; however, few of these papers have as their central theme the Loyal intrusions and with the exception of King (1942) and Parsons (1971 & 1972) most observers have mentioned the syenites only briefly. Robertson and

Quartz-nordmarkite showing yellow rare-earth mineral in druses, Lettermore Quarry, Ben Loyal

Parsons have in preparation a paper on the major chemistry of the Loyal rocks which is to be published early in 1974. The following list is a chronological review of previous work relating to the Tongue area:-

1841	CUNNINGHAM, R.J.H.,	Geognostical account of the county of Sutherland.
1868	TAIT, L.,	The shell mounds of Sutherland.
1877	HEDDLE, M.F.,	Rare minerals in the north of Scotland.
1879	------------,	Chapters on the mineralogy of Scotland.

1881 ----------, A geological and mineralogical map of Sutherland.

1883 ----------, On the geognosy and mineralogy of Sutherland.

1886 CADELL, H.M., The geology and scenery of Sutherland.

1888 GEIKIE, A., Report on the recent work of the Geological Survey in the North-West Highlands of Scotland.

1893 PEACH, B,N. & HORNE, J., Notes on a shell mound at Tongue Ferry Sutherland.

1901 HEDDLE, M.F., The mineralogy of Scotland.

1907 PEACH, B.N. et al., The geological structure of the North-West Highlands of Scotland.

1928 MACKIE, W., The heavier accessory minerals in the granites of Scotland.

1930 PEACH, B.N. & HORNE, J., Chapters on the geology of Scotland.

1931 READ, H.H., The geology of Central Sutherland.

1936 PHEMISTER, J., Scotland: The Northern Highlands.

1942 CHENG, Y.C., A hornblendic complex, including appinitic types, in the migmatite area of north Sutherland, Scotland.

1942 KING, B.C., The Cnoc nan Cuilean area of the Ben Loyal igneous complex.

1943 CHENG, Y.C., The migmatite area around Bettyhill, Sutherland.

1952 WILSON, G., A quartz vein system in the Moine Series near Melness A'Mhoine, North Sutherland, and its tectonic significance.

1956 McINTYRE, D.B. et al., On the conglomerates of supposed Old Red Sandstone age near Tongue Sutherland.

1959 FERREIRA, R.E.C., Scottish mountain vegetation in relation to geology.

1960 BARBER, M.J., The petrology and structural petrology of the Tongue district, North Sutherland.

1960 VON KNORRING, O. & DEARNLEY, R., A note on a nordmarkite and an associated rare-earth mineral from the Ben Loyal syenite complex, Sutherlandshire.

1963 KING, C.A.M. & WHEELER, P.T.. The raised beaches of the north coast of Sutherland, Scotland.

1965 BROWN, P.E. et al., Potassium-argon ages of some Dalradian, Moine and related Scottish rocks.

1968 BROWN, P.E. et al., Isotopic ages of late Caledonian granitic intrusions in the British Isles.

1970 BOWIE, S.H.U. et al., Uranium reconnaissance in northern Scotland.

1971 GALLAGHER, M.J. et al., New evidence of uranium and other mineralisation in Scotland.

1971 PARSONS, I. & BOYD, R., Distribution of potassium feldspar polymorphs in intrusive sequences.

1972 PARSONS, I., Comparative petrology of the leucocratic syenites of the Northwest Highlands of Scotland.

1973 LEAKE, R.C. & AUCOTT, J.W., Geochemical mapping and prospecting by use of rapid automatic X-ray fluorescence analysis of panned concentrates.

1974 ROBERTSON, R.C.R. & PARSONS, I., The Loch Loyal syenites.

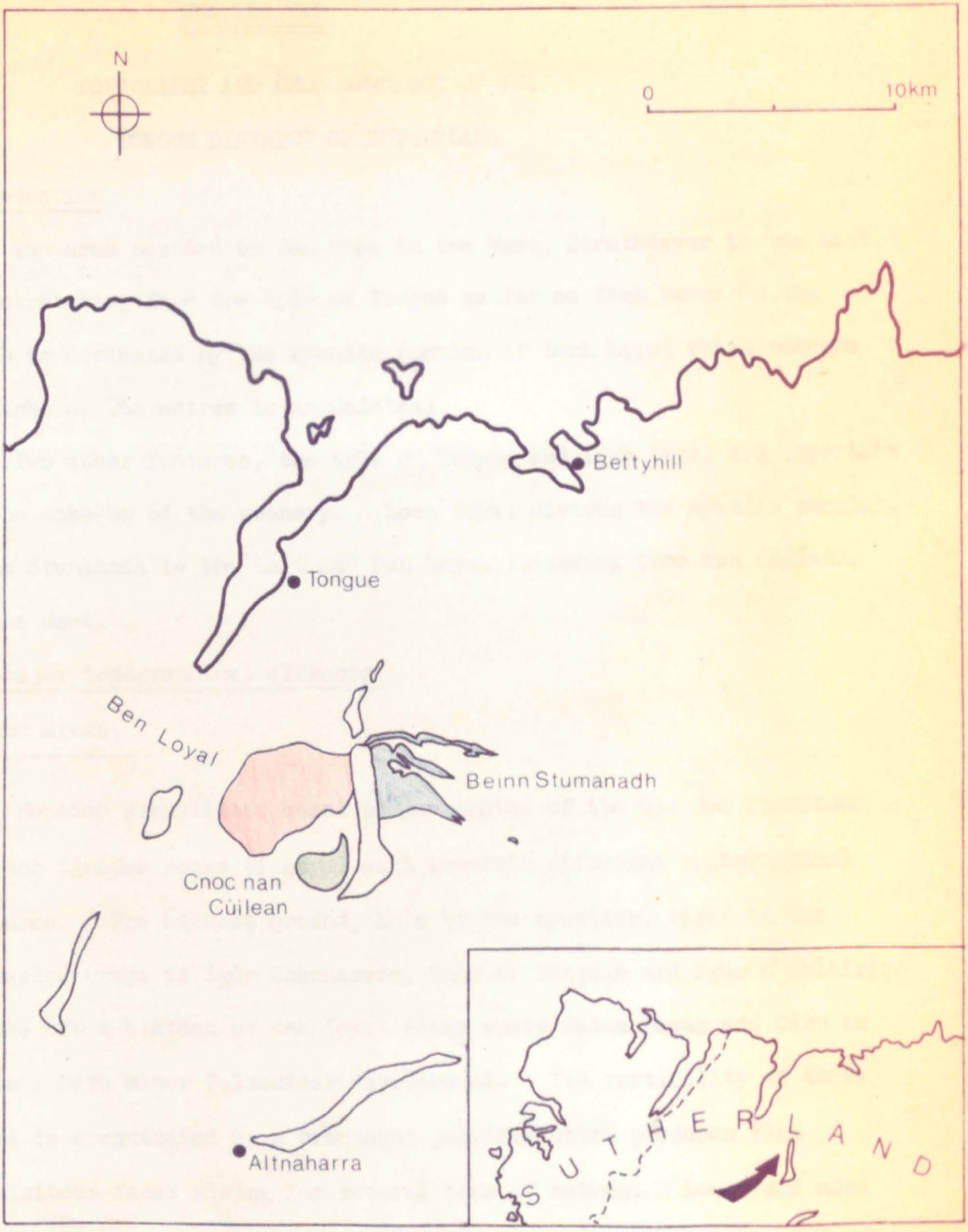
The present study.

This research was prompted by the radioactivity and occurrence of a rare-earth mineral reported by Von Knorring and Dearnley (1960) from Lettermore quarry in the marginal part of the Ben Loyal syenite.

Syenites, pegmatites, and minerals found in the igneous complex have been collected and whole rock chemistry together with trace element contents have been determined and compared with rocks from the two other alkaline intrusions in northern Scotland, Loch Borralan and Loch Ailsh.

Several minerals have been separated from the syenites and analysed. A radiometric traverse has been undertaken and a revised outcrop pattern determined for the Beinn Stumanadh massif. A series of soil samples have been analysed by X-Ray spectrometry to determine the mobility of trace elements. Electron probe micro-analysis has revealed some details of pegmatite chemistry. A petrogenetic model is proposed to account for all the features displayed by the intrusions.

Area location map



CHAPTER TWO

TOPOGRAPHY AND GEOMORPHOLOGY OF THE TONGUE DISTRICT OF SUTHERLAND

Introduction

The area bounded by Ben Hope in the West, Strathnaver to the East, and stretching from the Kyle of Tongue as far as Loch Naver in the South is dominated by the syenite complex of Loch Loyal which reaches a height of 764 metres in An Caisteal.

Two other features, the Kyle of Tongue and Loch Loyal are important in the make-up of the scenery. Loch Loyal divides the syenite complex, Beinn Stumanadh to the East and Ben Loyal including Cnoc nan Cùilean, in the West.

The major topographical elements.

Upland areas.

Moinian granulites, basal conglomerates of the Old Red Sandstone and the igneous rocks of Loyal each generate different topographical features. The highest ground, held by the syenites, rises in the pinnacled crags of Sgòr Chaonasaid, Sgòr a' Bhatain and Sgòr a' Chléirich to the 670 m plateau of the Loyal range where Beinn Bheag and Càrn an Tionail have minor felsenmeer development. The verticality of these crags is accentuated by a prominent jointing which produces flat precipitous faces rising for several tens of metres. Lower and more rounded expression of these syenites represented in the hills of Cnoc nan Cùilean, Ben Hiel and Beinn Stumanadh reach heights of 526 m.

Smooth slopes caused by the Moine rocks are punctuated by occasional sheer cliffs such as those at Creag an Dherue and Creag an Achaidh Mhoir.

Garbh Chnoc and An Garbh-chnoc to the west of Tongue village are minor manifestations of more resistant Moine rocks standing above the general topographic level.

Rounded knolls lying astride the Lairg - Tongue road including Cnoc Craggie, Beinn Bhreac and Cnoc an Fhreiceadain represent outliers of basal conglomerate to the west of the main Old Red Sandstone outcrops of Caithness.

Sgòr Chaonasaid (708 m) and Sgòr a' Bhatain (704m), the Ben Loyal range. The junctions between the Moinian metasediments and the syenite is indicated by the broken line.

The summit of Ben Loyal looking towards An Caisteal (764 m) showing a felsenmeer field in the middle background.

Lowland areas

Areas of low elevation to the north of Ben Loyal owe their character to the influence of glacial drift. Surrounding and parallel with the slopes of Sgòr Chaonasaid are linear features representing the moraines of a local ice dispersal point probably centered on the Ben Loyal range. Tectonic control governs the north-east to south-west trend of several valleys and hollows in the neighbourhood of Ribigill farm.

Prominent jointing at Sgòr a' Chléirich

Drainage

Consequent streams were supposed to have been initiated on a cover of Cenomanian rocks which formed a foundational high plateau surface, remnants of which exist in the isolated summits of Ben Hope and Ben Loyal. Deep incision of present day valleys has resulted from a rejuvenation brought about by emergence in response to isostatic readjustment following the melting of the Pleistocene ice-sheets. The simple consequent drainage has been radically transfigured by diversion and capture by subsequent streams aided by facility of erosion along belts of weakness, which in the Tongue district are aligned north to south. Four rivers drain the area to find exit on the north coast. From west to east these are Kinloch River, Rhian Burn, River Borgie and the River Naver. Youthful, dendritic drainage is seen throughout the district, meanders being few and far between and restricted to low peat covered drift areas notably at the mouth of Kinloch River and in Allt Lon Malmsgaig. An exception to this usual dendritic drainage is the incipient development of a trellised pattern by Allt Lon Malmsgaig along the northern flanks of Sgòr Chaonasaid. Here, facilitated by ease of erosion along the strike of less resistant hornblendic Moinian metasediments, the stream has eroded back at right angles to the Rhian Burn and in so doing has captured rivulets draining Coille na Cuile which formerly discharged into the Kinloch River via Clach na h'Armaichd.

Structural control of drainage is best seen on and to the east of Beinn Stumanadh where the headwaters of Allt a'Phuill, Allt Ach' nan Tot and streams issuing from Loch Meleag have prominent north-north-west to south-south-east trends related to weaknesses created by faulting in this direction. Streams between Loch Coulside and the River Mudale have north-east to south-west oriented drainage coincident with a reversion of Moinian strike direction to its normal direction before being influenced by the Loyal intrusion. Streams flowing to the Rhian Burn have cut steep gullies through the lowland moraines.

The Lochs

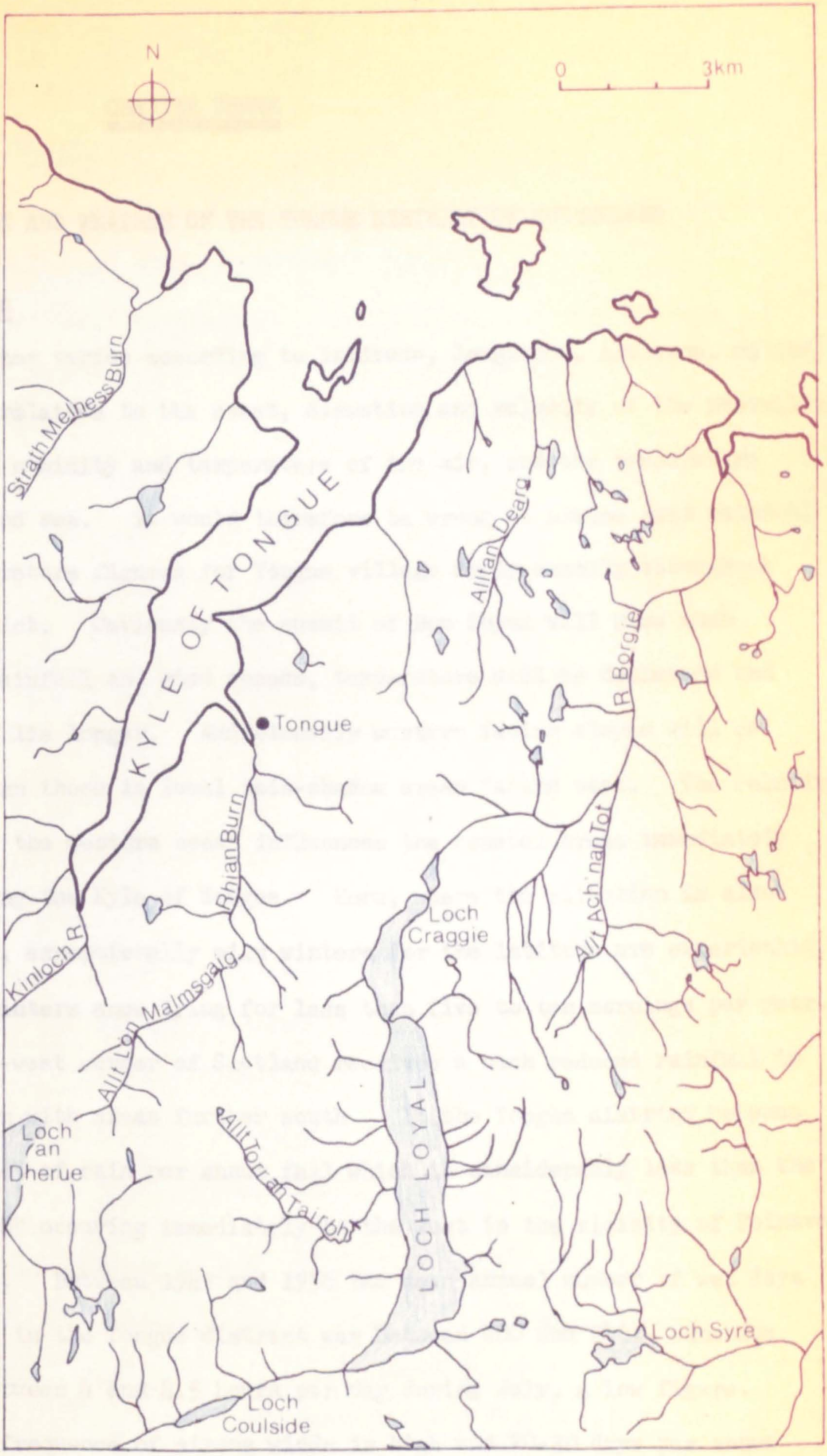
Lakes, habitually a sign of youth or immaturity in a river system, are numerous. Three distinct types occur. Large lochs occupying glacially scoured valleys including Loch Naver, Loch Loyal, Loch Craggie, Loch Meadie and Loch an Dherue, typically have regular linear edges and depths of 30 to 60 metres. Calbhach Coire, Loch na Creige Riabhaich and Loch Fhionnaich are all excellent examples of ice-generated corrie lochs. In lowland areas small irregular peat controlled lochs typified by Loch Eileanach, Loch a'Phriosain and Loch Syre, abound.

A combination of structural and topographical controls is evident in the common north-south trend of lochs; this is especially the case to the south-west of Ben Loyal, where Loch Meadie and Loch an Dherue occupy a glacially scoured valley along the general Moinian structural trend. This trend is even more convincingly seen to the south of Loch Haluim in Loch nan Ealachan and An Coal-loch, the latter following the strike between hornblende-schists and granulites of the Moine Series. Loch Fhionnaich is tectonically controlled lying parallel to a fault trending north-north-west to south-south-east.

Waterfalls.

Several waterfalls occur in the Tongue district the largest having a fall of 12 metres, at map reference NC 611472 on Allt Tòrr an Tairbh. Each may represent a knickpoint acting as a temporary base-level, to which the cycle of erosion is working as a result of rejuvenation. A complex response to attainment of equilibrium is indicated by the variable altitudes at which these waterfalls are found.

TOPOGRAPHY OF THE TONGUE DISTRICT



DRAINAGE PATTERN OF THE TONGUE DISTRICT

CHAPTER THREE

CLIMATE AND WEATHER OF THE TONGUE DISTRICT OF SUTHERLAND

Discussion

Weather varies according to latitude, longitude, altitude, relief, position relative to the coast, direction and velocity of the prevailing wind, the humidity and temperature of the air, and the temperature of land and sea. It would therefore be wrong to assume that rainfall and temperature figures for Tongue village apply equally throughout the district. Obviously the summit of Ben Loyal will show much greater rainfall and wind speeds, temperature will be depressed and snow will lie longer. Additionally western facing slopes will be wetter than those in local rain-shadow areas facing east. The relative warmth of the western ocean influences the coastal areas immediately surrounding the Kyle of Tongue. Here, where the situation is also sheltered, exceptionally mild winters for the latitude are experienced, in many winters snow lying for less than five to ten mornings per year. The north-west corner of Scotland receives a much reduced rainfall in comparison with areas further south. In the Tongue district between 40" and 60" of rain per annum fall which is considerably less than the 80" to 120" occuring immediately to the west in the vicinity of Foinaven and Arkle. Between 1947 and 1956 the mean annual number of wet days ($>$ 0.04") in the Tongue district was between 200 and 210; sunshine totals between 4 and 4.5 hours per day during July, a low figure.

The frequence of strong winds is high and 20-30 days per annum have gales, in consequence of which fog is recorded on fewer than five days annually. Thunderstorms are scarce, less than three a year being usual.

Climatic tables.

The following climatic figures for Tongue have been abstracted from Bartholomews' Atlas of Scotland (1912) ;-

Station 45' O.D. Mean monthly and annual rainfall 1866-1890

Station 40' O.D. Mean monthly and annual temperature 1857-1880

RAINFALL			TEMPERATURE.	
ins.	mm.		°F	°C
3.80	965	January	37.7	3.2
3.36	853	February	38.5	3.6
2.92	742	March	39.7	4.3
2.03	516	April	44.3	6.8
1.70	432	May	49.0	9.4
2.02	513	June	54.5	12.5
2.55	648	July	56.0	13.3
2.80	711	August	56.0	13.3
3.54	899	September	52.6	11.4
4.42	1123	October	46.2	7.9
4.17	1059	November	40.6	4.8
4.40	1118	December	38.4	3.6
37.71	9579	TOTAL/YEARLY	46.1	7.8

The driest month is May, the wettest October, the warmest July and August, the coldest January. The two most equable months are May and June.

CHAPTER FOUR

VEGETATION PATTERNS OF THE TONGUE DISTRICT.

General observations

As a rule the vegetation of the Tongue district reflects greater response to prevailing climatic conditions than to underlying geology. However in two important and contrasting respects the chemistry of the syenite determines the type of plants found on the Loch Loyal complex. The low calcium content of the Loyal rocks is not conducive to good soil formation and an acidophilous environment is usual. Below the prominent jointing of the Ben Loyal summits there are occasional water seepages which are distinctly calcareous and these flushes generate calcicolous plant communities.

Vegetation in north Sutherland has sub-arctic affinities. Two climatic trends are at work governing plant distribution in these latitudes.

a) Increase in oceanity from east to west.

b) The gradual fall in temperature towards the north of the Highlands.

The first of these trends reflects the fact that rainfall and atmospheric humidity are the primary agents controlling most vegetational changes. Several distinct noda have been recognised as either typically 'oceanic' or 'continental', for example a fine development of Luzula sylvatica (Great Woodrush) grassland at 550 metres on Ben Loyal is distinctly western and oceanic and is particularly characteristic of hilltops about 460 m high along the Atlantic sea-board. Western noda have a more important low-level ombrogenous bog communities and an increasing number and extent of bryophyte dominated communities.

Replacement of the eastern Cladineto-Callunetum by Rhacomitreto-Callunetum in the west is a good example of this oceanity. The gradual fall in temperature towards the north is paralleled by the increasing development of communities rich in calcifuge or indifferent montane plant species and by the disappearance of those distinguished by the presence of thermophilous 'southern' species. However it is possible that while the greater abundance of some montane species such as Arctous alpina (Black Bearberry) and Betula nana (Dwarf birch) in the extreme Northern Highlands reflect the lower temperatures of the region, the factors governing their distribution could be connected with past migration unrelated to any present condition. Broadly four zones are discernible the Forest zone, Subalpine zone and the Low and Middle Alpine zones; within the Southern Highlands they occupy much higher altitudes than those obtaining in the Tongue area.

Zone	Southern Highlands	Tongue district
Middle Alpine		
	1065m	760m
Low Alpine		
	700m	275m
Sub Alpine		
	610m	90m
Forest		

It must be noted that on the most exposed coasts of the north-west mainland the forest and tall shrub zones vanish altogether and the principal vegetation at sea-level is dwarf shrub heath. In the Tongue district oak and pine, characteristic of the Southern Highlands have been replaced by birch forests such as Coille na Cuile and Coille na Leitire Bige these being an expression of increasing exposure as much as of falling temperatures.

In addition to the above two major factors it must be remembered that local climatic conditions can produce distinct plant communities on the east and west slopes of a massif respectively. North and east facing slopes tend to be wetter in atmosphere and soil, and have longer snow-lie than western and southern facing slopes, the latter in particular profoundly affecting the plant life displayed.

Sròn Ruadh, Beinn Stumanadh with downy birch forest in the foreground and sparse woodland of Coille na Leitire Bige surrounding the massif.

One other major controlling factor in the vegetation pattern is artificial grazing by sheep and Red deer. Close cropping by both animals has led to suppression of tree cover in particular birch forest. In areas which have not been grazed, such as the islands in Loch Syre, birch forest is well developed and some Juniperus nana occurs. All the birch woods surrounding the Loyal massif are in poor condition in that much rotting wood remains, the trees are gnarled and misformed, and new growth although prolific appears to have few regenerative powers because of overgrazing by deer. Rowan (Sorbus aucuparia) scattered within the birch forests appear to fare much better.

It has long been established that hard acid igneous rocks with their attendant acidophilous soils hold the least number of plant species and that grasses and dwarf shrubs are the dominant flora.

The plants of Ben Loyal

Conditions prevailing on Ben Loyal have been critically examined by Ferreira (1958) from which some of the following information has been abstracted.

Vegetation patterns on Loyal follow broadly altitudinal bands circumferential to the mountain. Often accentuated by solifluction, these zones encompass the Forest zone as far as the lowest horizons of the Middle Alpine zone at approximately 760m. Plateau communities occurring on the summit ridge are not well developed but conform to the Juncus trifidus (Scottish rush) -Salix herbacea (Least Willow) community, much of the flat ground being occupied by the rare plant Sibbaldia procumbens (Least Cinquefoil). Along the northern and eastern parts of the plateau where snow patches lie longest, Nardus snow patch communities are developed. At lower levels along the ridges the Black Bearberry and Wild Azalea make a show, below which wind-eroded communities diminish and sedge and mosses make up the Carex bigelowii - Rhacomitrium lanuginosum nodum. Slope communities reflect the different climatic conditions experienced on each side of the massif. On the west and south, which are influenced strongly by the warming effect of south-westerly winds Calluna-Vaccinium (Ling-Cowberry) and Calluna-Empetrum (Ling-Crowberry) communities predominate; in contrast along north and east facing slopes, where snow-lie is longer Vaccinium myrtillus (Bilberry) and Festuca vivipera (Viviparous fescue) with the mosses Rhytidiadelphus loreus and Hylocomium splendens are found. At the base of these slope communities the Forest zone is represented by the birch-rowan wood of Coille na Cuile.

Superimposed on this generalised pattern are communities surrounding and immediately below springs issuing from joint planes. In general these springs generate acidophilous communities although Ferreira (opcit) has discovered several calcareous flushes notably in Coire Fhionnaich, Calbach Coire and one at Glas-choire Mhor, which have a different and richer flora. Mosses have a large development in the non-calcareous springs and are usually associated with Blinks, Golden saxifrage, Thyme speedwell, Bog stitchwort, Common mouse-ear, white clover and Marsh willow-herb. Plants restricted to the calcareous flushes on Loyal include Upland scurvy grass, Moss campion, Purple saxifrage, Mossy saxifrage, Alpine mouse-ear, Red fescue, Bluish-mountain meadow grass, Bladder fern, Lesser clubmoss, Yew-leaved fork moss and Ctenidium molluscum. Below these spring communities are bands of grassland containing Bent, Sweet vernal grass and Smooth-meadow grass.

The dwarf birch, Betula nana has a prominent show on Bealach Clais nan 6eap.

CHAPTER FIVE

THE STRUCTURE OF THE COMPLEX AND ITS ENVIRONMENT

The Regional setting

Introduction

Separate structural elements stamp their character on the Northern Highlands of Scotland. From west to east these are the Foreland areas mainly composed of Lewisian rocks, with Torridonian sandstones and Cambrian limestones, separated by the Moine thrust from the Moinian fold belt which in turn is overlain unconformably by Middle Old Red Sandstone in west Caithness.

The Lewisian Gneisses are predominantly orthogneisses lying to the west of the Moine thrust, they occur also as inliers within the fold belt for example the Borgie inlier. The Moine Series consist mostly of siliceous and semipelitic schists and granulites although hornblende-schists and to a lesser extent mica-schists have considerable expression in the Tongue vicinity. Within the Moines a great diversity is exhibited, two of the important ingredients being the injection complexes of Klibreck-Coire and Badenloch to the south and south-east respectively. Foliated granites for example in Strath Naver, Strath Halladale and the immense development straddling the Caithness/Sutherland border are also important rudiments. Unconformable to the Lewisian and Moine Series, Torridonian conglomerates and sandstones are seen to the west of the Moine thrust. In turn the Moine thrust zone centred on Loch Eriboll exhibits most of the Cambrian plus Lower Ordovician sediments, and has a particularly good development of Basal Quartzite and Pipe-rock. The Moine thrust at its closest point lies only 10.5 Kilometres to the north-west of Tongue village.

Intrusive into the Moine metasediments are a series of igneous rocks whose chief components are:-

a) Foliated granites and pegmatites.

b) Syenitic rocks including Ben Loyal, Lock Borralan and Loch Ailsh together with associated Post-Cambrian intrusions of the Assynt district.

c) Scyelites and allied ultrabasic rocks.

d) The Reay diorite.

e) A series of lamprophyric dykes

f) The Rogart, Helmsdale, Migdale and Grudie granites.

Unconformable to the above formations are Middle Old Red Sandstone conglomerates and sandstones which at Strathy Bay incorporate a fish bed within the Caithness Flagstones.

The Moine Series.

The Loyal syenites are emplaced in Moinian sediments which encircle the complex. Siliceous and semi-pelitic schists with granulites are the main constituents of the Moine Series in the north of Scotland. Pelitic schists are best developed in Badenloch Forest, in the Ben Klibreck injection complex and immediately south of Strath Oykell. Trending south-west from the Kyle of Tongue are very prominent belts of hornblendic gneisses which have variously been interpreted as Moinian or thrust masses of Lewisian age. Psammitic types vary from quartzose schists to massive and flaggy grey quartz-feldspar-granulites which carry biotite or muscovite or both. Quartz and feldspar do not segregate into folia as is common in gneisses and less micaceous varieties are therefore often massive. More micaceous members usually exhibit good plane-parallel schistosity owing to the distribution of micas in parallel orientation. Orthoclase is typical although microcline can be important and oligoclase or albite is commonly present and may be as abundant as orthoclase. Granulites have granoblastic texture and the principal minerals are equigranular. Every gradation exists between mica-schists and siliceous granulites. Semipelitic schists generally have a pronounced plane-parallel foliation and are dark or grey according to the proportion of biotite they contain.

Pelitic schists have felts of muscovite and/or biotite forming the major part of the rock, schistosity is pronounced and they frequently contain garnets. These garnet crystals may be idioblastic or xenoblastic and the large crystals form 'eyes', usually with tails of quartz, round which the felts of mica sweep.

Hornblendic gneisses are well shown in the Tongue district, coarse granular gneisses varying from oligoclase - gneiss to hornblende rich gneisses are abundant. Ribigill road quarry exhibits most of the types to be seen including hornblende schists, massive hornblende rock and quartz-epidote-granulite bands within the striped gneiss. The group shows close petrographic similarities with orthogneisses of the Lewisian inliers in Ross-shire and Inverness-shire and have therefore been described as 'rocks of Lewisian type'.

Stratigraphy and structure.

The stratigraphy and structure of the Moinian in Scotland have only be determined for local areas and no general succession has been attempted. In north Sutherland there is an apparent steady upward structural succession eastwards from the Moine thrust, and it has been suggested that the Scaraben quartzite, which outcrops on the Caithness/Sutherland border is the youngest member of a south-easterly dipping series. Isoclinal folding on axial planes dipping east-south-east is however, so prevalent that even a regional succession of dips in this direction has no stratigraphical significance. The occurrence of the Lewisian gneisses in the Borgie inlier appears to offer a key to the solution of the structure in this district, but the asymmetric distribution of pelitic schists and hornblendic gneisses east and west of this inlier presents difficulties. Isoclinal folding is present throughout. The strike of these folds is fairly constant over large areas and axial planes dip as a rule between east and south-east. Superimposed upon the major folds are subsidiary isoclines which are roughly parallel to the main structure, and in consequence the same band of schists may be repeated across the strike while a constant direction of dip is maintained. Pitch of the isoclines is frequent and causes interdigitating and lenticular outcrops. The isoclinal folds may be arranged en echelon with opposing pitch and the outcrops then show sharp bends or 'S' shapes which are liable to sudden change of width.

Regional strike in Sutherland is north-north-east to south-south-west but significant variations are stamped on this.
(a) Adjacent to the Moine thrust plane the strike of the schists is controlled by the strike of the thrust plane and (b) west and south-west of Lairg, an east-south-east strike is universal. This great anomaly is associated with the eastward bulge in the outcrop of the Moine thrust plane in Assynt, with pronounced south easterly deflection of strike in the schists approaching from the north, and with sudden mushrooming along a west-north-west to east-south-east zone on the south of this anomalous area, of a comparatively

narrow pelitic belt which has coursed northwards through Ross-shire.

Other rocks.

Ultrabasic rocks intrusive into normal Moine schists are seen in central Sutherland. Two forms occur, the commonest as small bosses the rest more rarely as sheets, each type is well seen immediately to the south-west of Ben Loyal at Loch an Dherue and on the banks of Loch Fhionnaich. Essentially they are serpentinites or serpentinites with epidiorites.

Basic rocks occurring principally as sills have shared in the folding and have been altered to hornblende-schists, hornblende-biotite schists and chlorite schists. They are common throughout the Moines and are well represented near Kinloch Lodge and at Ben Hope. Metamorphosed minor acid intrusions in the Moine Series are comparatively rare.

Injection complexes.

Injection gneisses or migmatites on the border of Caithness and Sutherland have outcrops exceeding 1800 square kilometres. Similar gneisses have been recognised in central Ross-shire and these may be continuous with the great injection complex which extends through Inverness-shire and north-west Argyllshire to the Sound of Mull. The complex centred on Loch Coire extends north-south for at least 40 km and reaches 30 km in width. It is divisible into three parts:-

(i) An outer "zone of veins", in which acid igneous rocks occur commonly as sills.

(ii) A "zone of injection", in which the schists are intermingled with a comparable volume of granitic material.

(iii) Granite of the complex, occuring in small outcrops widely scattered throughout the zone of injection.

Compared with unaffected Moinian sediments schists in the zone of veins show enlargement of grain, intricate suturing of quartz and feldspar grains, increase in proportion of oligoclase, and reddening of biotite. Within the injection zone gneisses of three kinds are represented

a) injection gneiss, in which igneous and schist components remain discrete though finely interbanded.

b) permeation-gneiss where the discrimination of the igneous and schist members is not possible.

c) augen-injection-gneiss which show augen of feldspar and quartz set along the foliation of normal and permeated schists.

Sillimanite is common in the injection and permeation gneisses formed from pelitic schists. Cheng (1943) has studied the migmatite area around Bettyhill in some detail; here granitic intrusions form sheets more clearly separated from the schists whereas in the Strath Halladale complex, permeation is correspondingly less extensive. These granites are mainly made up of a concordantly intrusive assemblage of foliated and unfoliated sheets in part porphyritic, and with phenocrysts of feldspar in parallel alignment. They contain a variable, often high, proportion of oligoclase, myrmekite is common, and sillimanite widespread. Within the Loch Coire Injection complex bodies of homogeneous igneous rocks are of small size and consist of medium to coarse-grained biotite granite in which oligoclase may be dominant over orthoclase. The Strath Naver granite is the largest mass within the outcrop comprising a streaky biotite-granite which is locally contorted, sheared and encloses masses of sheared hornblendic rock.

This granite cuts the injection-gneisses and therefore cannot be linked with the source of their granitic component. All the injection complexes carry pegmatites. The most noticeable of the structural features in the complexes is the concordance of injected material with the foliation of the schists attesting that the magma was intruded at a time when the schists over large areas were under stress and probably at a high temperature.

Aeolian sandstones, breccias and conglomerates were then laid down sub-aerially to form the Torridonian Sandstone which was later tilted and intensely eroded in post-Torridonian times. In many places the sediments have been removed completely. Cambrian strata were then deposited along a plane of marine denudation, thus basal Cambrian sediments transgress bed after bed of the Torridonian eventually coming to rest directly on the Lewisian gneiss. Cambrian and early Ordovician rocks crop out in normal sequence along a narrow belt southwards from Loch Eriboll, dipping towards the east-south-east at angles between five and twenty degrees. Cambrian strata are intricately involved in the thrusting centred on this belt.

The Post-Cambrian intrusions of Assynt.

The suite of sills.

The Torridonian and Cambrian sediments of Assynt are intruded by an extensive suite of sills of felsite, porphyrite and hornblende-lamprophyre. Very often the intrusions lie within the thrust zone and are often highly sheared. The Canisp porphyry however forms thick sheets in the Torridonian and dykes in the gneiss west of the thrust zone. In total this suite extends approximately 30 k.m. from north to south and 20 km. from east to west. It has been suggested that the original distribution was symmetrical about the Loch Borralan intrusion. Sabine (1953) has made an intensive study of the suite and he recognises six main classes viz:- grorudites, Canisp porphyry, hornblende-porphyrites, nordmarkite-porphyrites, vogesites and ledmorites, these being emplaced in Lewisian gneiss, Torridonian sandstones and Cambrian sediments. Some are found in the Moine Series and these have been affected by thrust movements.

The larger alkalic masses.

Two larger post-Cambrian alkalic masses are found in Assynt. Loch Borralan and Loch Ailsh cover areas of 25 square km and 13 square km respectively. No attempt will be made to describe these at this time as they will be examined in detail later, suffice it to record that quartz-syenite in the case of Borralan and perthosite-nordmarkite-pulaskite at Loch Ailsh are the principal rock types at each locality. Both intrusions contact alter the Cambrian sediments into which they are intruded; dolomitic limestones are converted to diopside-forsterite-tremolite and brucite marbles, but only very limited formation of skarn rocks is seen with development of zoisite, idocrase and grossular garnet.

The zone of thrusts.

Affecting Moinian and especially Cambrian/Ordovician rocks are a series of major thrusts extending from Sleat in Skye to Whitten Head in Sutherland a distance of 195 km. The zone of thrusts varies greatly in width being between 1.5 and 5 km throughout most of Sutherland but expands to 11km in Assynt. In this area, while the base of the zone keeps to its typical north-north-east trend, the outcrop of the highest thrust, the Moine thrust-plane makes a wide semi-circular sweep to the east owing to the denudation of a contemporaneous complex anticlinal fold. The principal fracture is the Moine thrust. Usually well defined, it is occasionally represented by a narrow zone of mylonised schists and Cambrian strata without an obvious plane of fracture. The thrust dips at low angles to the east-south-east and is overlain by Moine Series, whilst beneath it is a zone of intensely disturbed Cambrian, Torridonian and Lewisian rocks divided into massive slices or nappes by a series of thrusts which displace these slices west-north-westwards relative to the underlying rocks.

Within the thrust zone Lewisian gneiss may lie on Torridonian Sandstone or Cambrian strata and Torridonian may rest on Cambrian. Inversions of normal order are usually due to thrusting of older series over the younger, but are occasionally due to isoclinal folds produced by rolling motion along the thrust plane, such folds having considerable variation in magnitude up to great inversions affecting a large portion of a nappe. The major thrust planes are generally inclined at low angles but may be locally steep or folded. Minor thrust planes with steep hade are frequent; closely packed thrusts of this type constitute imbricate structure and result in apparent increase in thickness of the strata.

In the immediate vicinity of the thrusts the metamorphic effects of the displacement are mainly retrograde in character. The displacement westwards relative to formations beneath the thrust is estimated to be in the region of 25 kilometres. Great fractures such as the Moine thrust must have been produced by intense compression in a west-north-west to east-south-east direction. The movements have been shown to be older than certain lamprophyric sheets of the Newer

Granite intrusive suite. Moreover, pebbles of rocks sheared by the movements are found in Middle Old Red Sandstone conglomerates. The thrusts are therefore of Caledonian age.

The 'Newer Igneous Rocks'

Igneous rocks intruded after the regional and injection metamorphism of the Moine Series are collectively known as the Newer Igneous Rocks, broadly they fall into two main divisions, the earlier intrusions of pre-Middle Old Red Sandstone age, and the later comprising minor intrusions of widely differing ages. They may be divided for convenience into:-

(i) The syenites of Ben Loyal, Beinn Stumanadh and Cnoc nan Cùilean.

(ii) Minor intrusions of Ach'uaine Hybrid and Appinite suites.

(iii) Stocks and batholiths of granite, granodiorite and diorite.

(iv) Permo-Carboniferous lamprophyres.

The Loyal syenites.

The principal part of this thesis will examine in detail geological elements of the Loyal intrusions, therefore a brief mention of the salient points only follows. The intrusion is divisible into three separate parts, the largest being Ben Loyal, followed by Beinn Stumanadh and the southern-most and smallest that of Cnoc nan Cùilean. Syenites are emplaced into siliceous and semi-pelitic Moine schists and granulites which they contact alter only to a limited extent. In general a quartzose, leucocratic, hornblende-pyroxene syenite describes the major rock type, alteration is common and much of the rock is peppered with drusy cavities. From its petrographical similarity to the Loch Ailsh intrusion it has been suggested that they may be coeval; such assumptions and equations will be carefully tested later. Basic syenites of a very variable composition occupy the marginal zone of the Cnoc nan Cuilean intrusion and a dyke phase is seen in the encircling granulites.

Ach'uaine hybrid intrusions.

Intrusions of Ach'uaine hybrid type have the form of small bosses, sills and dykes, tending to occur in groups. The best known of the ultrabasic members is scyelite a biotite-hornblende-peridotite. The rocks are unfoliated, the only alteration being the conversion of olivine and pyroxene to serpentine, tremolite, chlorite, magnetite and talc. Basic to acid members often occur together, the same exposure showing syenite or granite, basic and sometimes ultrabasic rock. Alkali feldspar and quartz persist in the basic varieties, and perthitic feldspar and oligoclase occur in all relative proportions. Such intimate relationship of acid and basic magma poses intriguing petrological concepts. The dark minerals are hornblende, biotite and pyroxene, with sphene and apatite often very abundant. Ultrabasic and basic members of the Ach'uaine or Appinite type are commonly enclosed for example in the Ratagain and Lairg granites; these may be regarded as early phases of the intrusive period of the granites.

The granite-granodiorite-diorite suite.

This suite in the Northern Highlands includes the following intrusions.

Locality	Outcrop km^2	Rock types developed
Reay	6.5	Augite-biotite-diorite, augite-granite.
Helmsdale	98	Adamellite
Lairg	70	Granodiorite and biotite-granite.

Locality	Outcrop km^2	Rock Types developed
Grudie	2.6	Quartz-adamellite
Migdale	23	Adamellite
Fearn	31	Adamellite
Ratagain	13	Granite, syenite, diorite, adamellite.
Cluanie	18	Granodiorite, trondhjemite.

Permo-Carboniferous Lamprophyres

Monchiquite dykes are widespread but not numerous in northern Caithness and Sutherland. Trending east to west or north-east to south-west they are exemplified by those outcropping in Achuvoldrach Burn in A'Mhoine on the western side of the Kyle of Tongue.

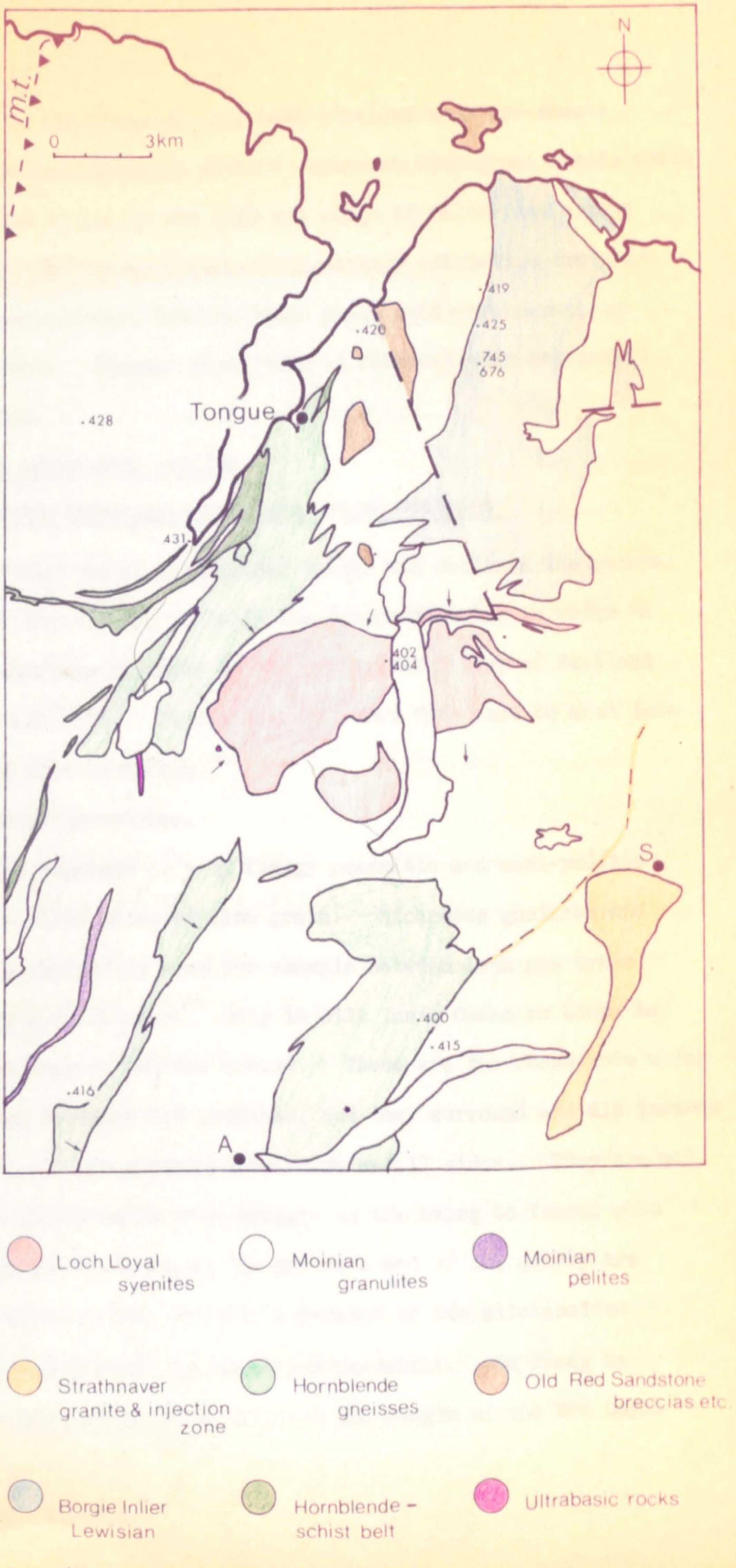
The Old Red Sandstone.

McIntyre et al. (1956) has cast doubt on the age of the Old Red Sandstone outliers of the Tongue district, however the author believes them to be conglomerates of the Barren Red Series and Middle O.R.S. in age. The basal breccia is extremely well displayed on Beinn Bhreac and in total five separate outcrops are encountered topping the hills of Cnoc Craggie, Ben Tongue, Beinn Bhreac, Cnoc an Fhreiceadain and the islands of Eilean nan Ron and Eilean Iosal. The Caithness Flagstones outcrop only to the east of Strathy Point where they include a fossil fish bed with Dipterus macropterus.

Pleistocene and Holocene deposits

Two periods of glacial history can be recognised in the Northern Highlands. In the earlier epoch ice covered all the land and glacier movement was largely independent of topography. The latter stage in which the ice-sheet waned and finally disappeared is divisible into

GEOLOGY OF THE TONGUE DISTRICT



two stages. (i) the stage of confluent glaciers when ice-sheets radiating from many separate centres coalesced into great sheets which swept across lower ground and (ii) the stage of valley and corrie glaciers. In the Tongue district the earlier glaciation traversed south-east to north-west and the later stage south-south-west to north-north-east. Glacial deposition is dominant over erosion in the Tongue area.

The immediate geological setting

An outline of the stratigraphy of the Tongue district

Barber (1960) in an unpublished thesis has outlined the general succession of the Moinian rocks in the Tongue district in which he follows the outcrops surveyed by the Geological Survey of Scotland between 1869 and 1872. He divides the rocks from east to west into the following four divisions

a) Eastern Moine granulites.

These are composed of grey flaggy psammitic and semi-pelitic gneisses or schists often of fine grain. Micaceous gneisses and schists are occasionally seen for example between Loch nam Breac Buidhe and Sgòr Fhionnaich. Only in Allt Innis Ceann an Locha is there a small band of pelitic schist. These are the rocks into which the Loch Loyal syenites are emplaced, and they surround and dip inwards towards the Loyal and Cùilean intrusions on all sides. They are well exposed in a quarry below Cnoc Craggie on the Lairg to Tongue road where pink gneissose bands at the southern end of the quarry are folded into an anticline which is separated by two slickensided planes from an extremely micaceous quartz-schist. On Creag na Speireig the beds strike parallel with the margin of the Ben Loyal syenite, and further folds are generated. Striking west-north-west to east-south-east they are very tightly folded with high dips and development of mullion structures and quartz pencils along subsidiary axes of drag folds. Here the rocks are mainly biotite granulites interbanded with garnet biotite gneisses, biotite schists and quartz granulites, all permeated by dykes and sills of Loyal parentage and 'glazed' by contact alteration. Above Cunside in Allt Chaonasaid the rocks are very quartz rich and close to the contact the feldspar and quartz separate as bands up to 30mm thick. Away from the aforementioned localities the Moine Series dip towards the syenite with little or no disturbance except introduction of pegmatitic or dyke phase material from the intrusion. At Allt Bealach Dubh a minor fault within these granulites is filled with a mixture of blue-green chloritic gouge and a good deal of red feldspar.

b) Hornblendic gneisses

A series of hornblendic gneisses subdivided into an easterly banded hornblende gneiss and a striped belt to the west follow the Eastern Moine granulites. Both are in essence hornblende-biotite gneiss often with a good deal of epidote. Division into the two types rests on the increase in the proportion of hornblende schist bands in the Moine gneisses. The rocks are well seen in the Ribigill road quarry, recently excavated as aggregate for the Tongue barrage, here a grey fine-grained biotitic granulite is overlain by a monomineralic hornblende rock, the whole extensively veined by pink feldspathic material carrying pyrite, beautifully radiating mats of actinolite, specularitic hematite and very prominent epidote crystals some of which have good crystal form and attain a length of ten mm. Much of the feldspathic material has penetrated the main body of the rock and has become intimately mixed with it. Within the striped facies a number of sheared orthopegmatites are found notably between the Loch an Hakel-Bad Salach vicinity and the northern edge of An Garbh-chnoc. Both striped and banded gneisses dip east or south-east at about 30 degrees; they do not occur next to the Loyal syenite although they approach closely in Coille na Cuile and Cnoc Malmsgaig. The series are also well seen to the south of the complex and cover much of the ground between Loch Loyal and Loch Naver, bosses of ultrabasic material are common here.

c) The hornblende schist belt.

The hornblende schist belt is mainly composed of one thick sheet of garnetiferous hornblende-schist of very distinctive character. It extends from the Kyle of Tongue at Coill'Ardachaidh south-westwards through Kinloch Lodge, makes a prominent westerly deflection of strike, and then trends due south along the western face of Ben Hope. A marked foliation is obvious and is due to the alignment of actinolitic needles which sweep around the garnet porphyroblasts forming conspicuous eyes. Typically garnets are up to five mm in diameter although very occasionally they become the chief component of the rock and reach four times this size. At outcrop the rocks are very distinctive with a black aligned matrix and, because of greater resistance to weathering, protruding red garnets.

d) Western Moine granulites.

In the neighbourhood of Kinloch River the most westerly minor hornblende-schist band is underlain by striped hornblende gneisses and then by granulites and a marked pelitic band.

The Lewisian inlier of Borgie

Northwards from the Stumanadh portion of the intrusion the Lewisian inlier of Borgie Forest extends from the headwaters of Allt Ach nan Tot, a distance of twelve km to the coast at Lamigo Bay, it incorporates hornblende and biotitic ortho-gneisses into which north-west, south-east trending dioritic bodies and minor ultrabasic dykes have been intruded. The relationship of this inlier to the Moine sediments is not clearly seen, but the inlier has been involved in the Caledonian folding.

The injection complex

Three km to the east of Beinn Stumanadh the Moine granulites are affected by the northward extension of the Klibreck-Coire injection complex. All divisions of the injection zone are very well displayed over a short distance and five kilometre section east from Loch Bad na Gallaig passes from normal Moine granulites through the outer 'zone of veins' on Long Hill, where granite sills are prominent, through the 'zone of injection' in which igneous and sedimentary portions are approximately equal, and into the Strath Naver granite which stretches north-south over a distance of eight kilometres with narrow width.

Old Red Sandstone outliers.

On all the outliers the predominant rocks are chocolate coloured breccias and conglomerates in which large slabs of Moinian granulites are enclosed. The beds are particularly well shown on Beinn Bhreac and Cnoc Craggie. At Eilean Iosal and Eilean nan Ron at the entrance to the Kyle of Tongue mylonitized rock is found in the conglomerates. McIntyre et al. (op.cit) have thrown doubt on the age of these outcrops, however the author considers them to belong to the Barren

Red Series of Middle Old Red Sandstone age.

Basal breccia and conglomerate from Beinn Bhreac, NC 605565, Middle Old Red Sandstone (hammer 1 foot long)

Permo-Carboniferous Lamprophyres.

Monchiquite dykes outcrop in several widely scattered places within the Tongue district. Four occurrences are known at two localities south, and two north of the Loyal intrusions. The southern occurrences are seen at NC 548421 in a stream draining to Allt Dionach-caraidh and immediately west of Loch Meadie at NC 500420, those in the north are centred on the Achuvoldrach Burn across the Tongue barrage and east of the village at Alltan na Creige. All trend east-west or north-east to south-west, that is parallel to the dykes in Orkney. From stratigraphic evidence elsewhere in Scotland it seems probable that the dykes are of Permian age.

Pleistocene and Holocene deposits.

Glacial deposition is overwhelmingly dominant over erosion. Most of the lowland areas have obvious morainic debris which produces linear smooth ridges circumferential to the Loyal complex. In addition to these, regular and parallel moraines concurrent to and west of the A836 Tongue to Lairg road, have steep gullies cut through them by streams flowing to the Rhian Burn.

These glacial deposits composed of local rocks, having a fairly high content of sand, and with their boulders unsorted give rise to the hummocky ground typically found at low elevation.

Glacial and fluvioglacial morainic debris near Loch Loyal at NC614503

Raised beaches and their associated phenomena are well shown along the eastern side of the Kyle of Tongue. Ard Thunga, the spit projecting into the Kyle delineates a sand/shingle deposit at a height of 13 feet O.D., just above the limit of modern storm waves. This depositional feature is correlated with erosional components such as the 17 foot rock platform cut at Portskerra in the Old Red Sandstone conglomerate, and with wave abraded skerries at Farr Bay and Glaisgeo to the east. At the mouth of the Kyle, Sleiteil demonstrates a rock platform at 25 feet O.D., while at Tongue Lodge a flat-topped bench probably represents a 45 foot O.D. erosional phase. The highest coastal constituents are those related to glacial outwash deposits; ranging in height from 50 foot to 80 foot, these have substantial influence on the topography found at the mouths of the northward flowing streams.

King and Wheeler (1963) have suggested that northward drainage between Tongue and Melvich 'where clearly the route by which the glaciers and their melt-waters carried a very large amount of sand and gravel to the coast, much of this material being deposited in the lower reaches of the valley where flow was restricted by proximity to sea-level. This would cause the glaciers to float and the melt-streams, to deposit their loads in deltaic formations'. Such deltaic deposits are well seen at the mouths of Strath Halladale, Strathnaver and the River Borgie. Sand dunes of recent origin between the Rivers Borgie and Naver have good representation to the west of Bettyhill at Invernaver.

Two periods of glacial history can be recognised in the Northern Highlands. In the earlier period ice covered all the land and ice movement was largely independent of topography. The later stage in which the ice-sheet waned and finally disappeared is divisible into two stages.

(i) The stage of confluent glaciers when ice-sheets radiating from many independent centres coalesced into great sheets which swept across the lower ground and

(ii) The stage of valley and corrie glaciers.

In the Tongue district the earlier glaciation swept south-east to north-west and the later stage south-south-west to north-north-east. Evidence of transport is afforded by glacial striae occurring on outcrops notably east of Beinn Stumanadh such as on Meall a' Bhreac-leathaid and Meall an Spothaidh. In addition to raised beaches and glacial deposits previously mentioned, a shell mound has been described by Tait (1868) and Peach and Horne (1893), from the western shore of the Kyle of Tongue, standing on part of the 25 foot raised beach. Two stone implements have been found there, together with fragments of very coarse pottery. Interestingly the list of shells includes Ostrea edulis (the Oyster) which is no longer found in the Kyle. Anderson, in Tait (op. cit) thought that the deposit was of neolithic age.

The structure of the igneous complex

External relationships and the shape of the intrusions.

Some previous authors have commented upon the external relationships of the Loyal syenites and the form of the intrusions themselves. All agree that they are forceful concordant intrusions and that the country rocks into which they have been emplaced are much disturbed. As to the form of the bodies little agreement is evident. Phemister

(1936) favoured a laccolithic form, whereas King (1942) points out 'the precise form of the intrusion is difficult to ascertain though it is clearly not laccolithic, as Phemister suggests'. Based on contact observations and the universal dip inwards of the surrounding Moine metasediments King concludes that they may be irregular cones with their apices pointing downward together with marginal sheet-like apophyses, thereby resembling the funnel-shaped bodies to which Salomen (1903) has given the name 'ethmolith'. He cites as like examples the Cortlandt complex, Peekskill, N.Y. and others mentioned by Schmitt (1933) from the south-western United States and northern Mexico. Robertson and Parsons (1974) note sharp and vertical or outward dipping contacts on the north, north-west and western sides of Ben Loyal and contrast this with the south and south-west margins where contacts are diffuse and shallow dipping. This shallow dip to the top of the syenite is confirmed by a proton magnetometer traverse which leads these writers to agree with Phemister that Ben Loyal had the form of a sheet or laccolith fed from a flank and that Cnoc nan Cuilean the form of a stock. All observers consider Beinn Stumanadh to be a series of sheet like bodies.

Evidence bearing on the form of the intrusions.

A multiplicity of criteria must be considered in an evaluation of the types of intrusion displayed, but the following observations offer constrictions to the forms contemplated:-

1) With few exceptions, the dip of the granulites is towards the contact, and as the intrusion is approached the dip increases from 20-30 degrees to about 45-60 degrees.
2) At distances of three kilometres from the intrusion the

strike of the Moinian granulites swings from a normal north-east to south-west trend to parallelism with the margin of the syenites.

3) The external shape (i.e. the plan) of the three intrusions differ, those of Loyal and Cùilean are semi-circular, those of Stumanadh linear and sheet like.

4) Along the north, north-west, and west sides of Ben Loyal contacts are seen to be sharp and vertical, predominantly concordant but in detail conspicuously transgressive to the foliation of the Moine granulites. In contrast along the southern margins contacts are diffuse and shallow dipping: geophysical data are consistent with this gentle south-easterly dip. Evidence for outward dip of the syenites is provided in Allt a' Chalbach Coire and in the gorge of Allt Fhionnaich.

5) The Ben Loyal intrusion on the northern and western flanks has outer laminated syenites with structureless homogeneous syenites in the centre and to the east.

6) A dyke phase related to the syenites is apparent; rocks of Loyal parentage being close to the contacts along the northern edge and at greater distances, up to two kilometres, and possibly four kilometres away in Garvalt Hill to the south.

7) Rafts of country rock occur in all three of the intrusions, being especially noticeable in the Loyal mass.

Detail of the discordant contact between the syenite and Moinian metasediments along the northern slope of Sgòr Chaonasaid.

8) Small schist xenoliths, often biotitic and of fine grain are frequently encountered on the northern edge of the Loyal mass. The syenites next to these xenoliths have no obvious compositional difference to uncontaminated rocks, although significantly the yellow miarolytic cavities transgress both syenite and basic xenoliths. Additionally, below the cliff face of Sgòr Chaonasaid, the mafic portion of the syenites are occasionally found in segregated bands up to 45 millimetres thick which cannot be feldspathised xenoliths.

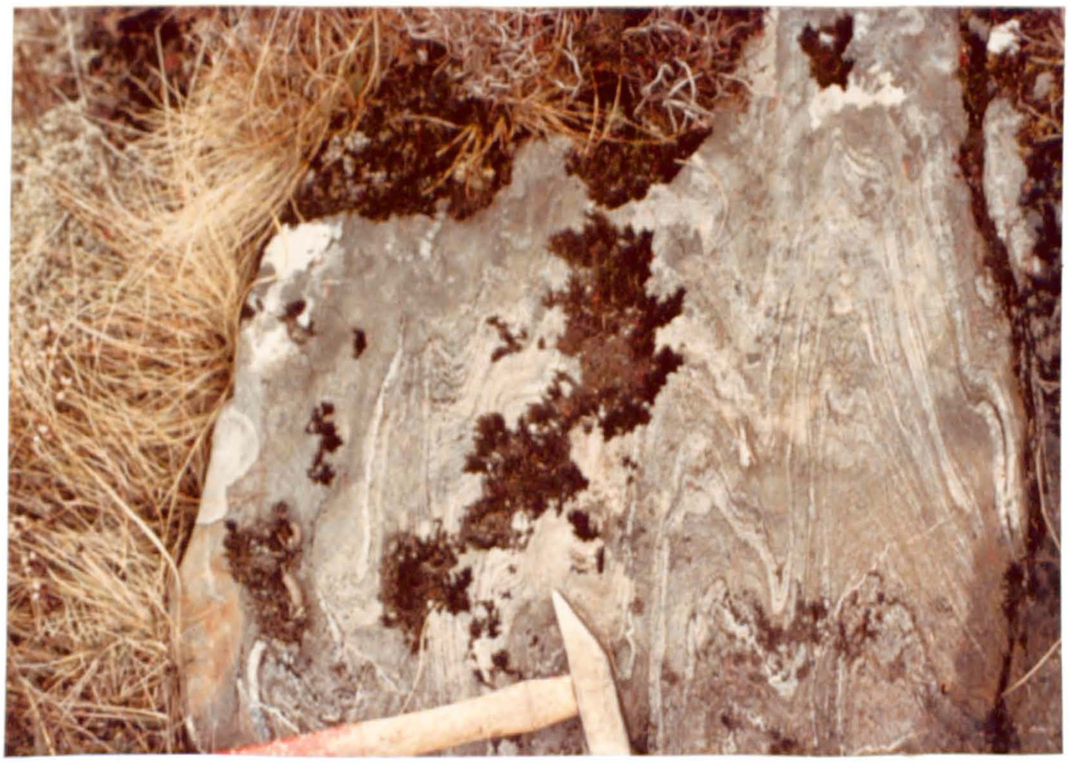
Moinian xenoliths in the Ben Loyal syenite north of Loch na Creige Riabhaich.

9) Thermal effects, principally the production of gneissic appearance in the siliceous schists is manifest notably north of Ben Hiel at Creag na Speireig, within the stream section of Allt Tòrr an Tairbh and in the immediate vicinity of Loch na Béiste. An extensive zone of hybridisation is found where the syenites abut against the feldspathised schists surrounding the Beinn Stumanadh body.

10) Although broadly similar the three intrusions differ chemically from each other in detail.

11) Folding is developed intermittently within adjacent Moine rocks, although undisturbed margins are prevalent.

Folding within the Moine metasediments close to the syenite contact. Immediately east of Creag na Speireig.



Gleitbretter shear-folds within the Moine Series from the Northern margin of Beinn Stumanadh.

12) The rocks of the suite are grouped in the Ab-Or-An-Qtz system in such a way as to imply that magmatic fractionation has been the dominant factor in the generation of the syenites.

13) A basic marginal zone to the Cnoc nan Cùilean intrusion has been postulated.

14) The Cnoc nan Cùilean intrusion is much more radioactive than the other two parts of the complex where high radiometric values obtain predominantly on the north-west flanks of Loyal and the northern edge of Stumanadh.

15) Aeromagnetic contours about the Loch Loyal complex suggest that the Cnoc nan Cùilean mass may have a considerable sub-surface extension to the east of its present outcrop.

16) A series of small radial and concentric faults are developed on the margins of the intrusions and within the surrounding Moine rocks.

17) The whole complex is conspicuously jointed especially on east-west, north-east to south-west, and north-west to south-east directions, the joints dipping towards the south usually at high angles. The western part of Ben Loyal is extensively jointed with cup and ball structure developed.

The deduced form of the intrusions

The author envisages the following sequence of events having taken place during the development of the complex. Over-saturated syenitic magma, generated at depth stoped upwards incorporating at a high structural level 'hornblendic rocks of Lewisian type', this consolidated as the least fractionated portion of the complex to form the stock of Cnoc nan Cùilean. More fractionated and less contaminated magma from this 'magma-chamber' was injected north-west and north-east away from the Cùilean area and encountered resistant Eastern Moine granulites whose dip was steepened at contact and the strike of which bulged before the advancing bubble of magma. The concordancy with the encircling granulites is not seen to hold in detail along the northern edge of the complex and the magma locally transgressed the confines of the Eastern Moine granulites, this could explain the apparent outward dip of the syenite in some of the northern stream sections. The inward dipping foliation of the marginal syenites in Ben Loyal is seen as flattening combined with lateral spread normal to the action of a magma pulse from the south-east, this would also account for finer grain size of the outer laminated syenites and the radial and circumferential faults marginal to the intrusion.

If the large enclosed rafts of Moinian material are roof rocks to the intrusion a picture emerges of Ben Loyal as an irregular flat blister, steep or 'overturned' along its northern edge and dipping gently towards the south-east. In like manner magma found its way along strike to form the partly concordant sheets of Beinn Stumanadh, the uppermost of which reaches a thickness of over 400 m. The three intrusions are therefore pictured as:-

i Ben Loyal ---- A partly concordant diapir at least 640 m thick.
ii Beinn Stumanadh -- Partly concordant sill-like, sheet intrusions.
iii Cnoc nan Cùilean -- A stock at least 300 m in depth.

The outcrop pattern of the complex

The one inch geological survey sheet 108 Altnaharra mapped in 1872-73 shows the Cnoc nan Cùilean mass joined to that of the Loyal mass although the ground between them is obscured by morainic debris. King (1942) maps a strip of Moine schist between the bodies and Phemister in a discussion of this paper agrees that the original continuity of the two intrusions portrayed on the 1" sheet was based on flimsy evidence. Robertson and Parsons in a proton magnetometer traverse between Allt Tòrr an Tairbh and Allt an Lagh-aird provide affirmation that the boundary of the Loyal syenite as contemplated by King lies 600 m too far south; however scrutiny of the relevant stream sections by the author indicates the junction to be sinuous and intermediate between the contacts of these previous writers. The outcrop of Cnoc nan Cùilean departs from that of King in two important respects, a southward bulge to Meall Eudainn was not substantiated and the northern boundary is mapped to the south of Allt Tòrr an Tairbh, Moinian rocks having been found within the stream bed. A much squatter elliptical shape is therefore envisaged in contrast to the circular shape contemplated by King.

By far the greatest modification of outcrop pattern is suggested for the Beinn Stumanadh mass. Broadly three main divisions are represented:-

i the Achnanclach sill, with its extension the Cracknie mass.
ii the Sròn Ruadh - Tarmachan sheet.
iii the main body of Coir'Achaidh nan Sac.

Difficulty in the precise location of contacts is experienced because of rheomorphic effects in the surrounding feldspathic granulites. Outcrops have also been modified by faulting trending north-west to south-east and within Allt Ach nan Clach a broader outcrop of Moinian sediments almost reaches the elbow in the stream at Coire Mor. At the summit of Beinn Stumanadh altered Moinian rocks are intricately invaded by felsitic dykes and the Sron Ruadh - Tarmachan portion of the sheet is separated by an important fault stretching from Coire na Caileig through the upper reaches of Allt Ach'nan Clach in a straight line just south of the triangulation point of Stumanadh to peter out towards Stionach Coire. Evidence from the Allt nan Tarmachan area relating to the Cracknie part of the intrusion shows that the displacement on the Coldbackie fault is less than that indicated on the 1" geological map sheet 114.

Internal relationships of the intrusions.

Structures of the fluid phase.

Three main types of structure are encountered, laminated flow structures, banding due to crystal segregation, and rheomorphic effects caused by transfusion of encircling sediments.

Platy flow structures are seen in both Cnoc nan Cùilean and Ben Loyal but only in the latter is it developed to any marked degree. In the same way as the dip of the foliation of the surrounding Eastern Moine granulites is toward the intrusion so the lamination found along the northern and western margins, is towards the centre of the complex. Substantial variation in the amount of dip exists, although thirty degrees can be taken as representative. Lamination occurs because of an alignment of amphibole and pyroxene crystals, together with feldspar pheno-crysts and is perceptible at some places more evidently than others because of changes in the proportions of the light and mafic minerals within the syenite. Disposition of the amphiboles along the c crystallographic axis in conjunction with feldspar alignment forms a rectilinear structure parallel to the dip directions of these platy flow structures. Origin of this flow alignment is seen as flattening combined with spread normal to the pressure of magma injected from the south-east, squeezing the magma against and into the Eastern Moine granulites.

Along the northern cliffs some of the fallen syenite blocks have mafic rich layers within the normal syenite; the author, because[1] of the continuity, significant textural, and morphological details adjudges these to be connected to internal differentiation processes rather than ingestion of extraneous xenolithic material. Small Moinian xenoliths are found especially marginal to the Loyal mass, lensoid in shape, they roughly parallel the igneous platy foliation although in some cases a disharmony is seen in detail. Junctions between the biotitic xenoliths and the syenite are usually sharp and no evidence of assimilation is available. All data sustain the concept of incorporation of Moinian metasediments rather than the sediments governing the igneous foliation by a process akin to granitization. Yellow drusy cavities also follow the lineation of the feldspars and xenoliths and cut both. Significantly amphibole is much more common in the peripheral parts of the Loyal mass which indicates that different physical conditions prevailed there. At some localities, notably within Allt Tòrr an Tairbh and on Beinn Stumanadh it is arduous, because of the similarity in texture and rock composition, to trace the contact between syenite and Moinian rocks and it seems that locally the sediments became mobile. Feldspathic material is here seen to impregnate and penetrate the more basic granulites and where a grading contact occurs parts of the leucocratic bands of the granulites assume a syenitic aspect.

Detached blocks of basic granulites are seen to be embedded in syenitic material.

Intrusion of feldspathic material of syenitic parentage into hornblendic Moinian country-rock surrounding Cnoc nan Cùilean.

Brecciation and incorporation of Moinian country-rock by syenitic magma, Allt Tòrr an Tairbh, Cnoc nan Cùilean.

Structures of the plastic phase.

As magma nucleates the crystal mesh and residual liquid become capable of sustaining shear, fracture structures are then able to form. Four kinds of structure typify this plastic phase, faulting, jointing, cleavage, and minor igneous phenomena.

Regionally three types of faulting can be distinguished, thrusting connected with the Moine thrust belt, normal faulting, and crush-zones within the Moine Series. The zone of thrusts has been described earlier. Two crush-zones, one cutting the Moine thrust and trending NW-SE through Ben Hutig, and the other, eight km east of Tongue, affecting the Borgie inlier, lying east-west, are at least in part wrench-faults. Normal faulting is seen in the important post-Middle Old Red Sandstone Coldbackie fault which extends 10.5 kilometres from Tongue Bay to Beinn Stumanadh; it downthrows to the north-east to fashion the Old Red Sandstone outlier of Cnoc nan Fhreiceadain and displaces the Cracknie portion of the Stumanadh intrusion relative to the Achnanclach sill.

Auden (1954) has stressed that the north-west to south-east direction of the regional faulting is related to lines of weakness that have existed in the area since Archaean times and he suggests that since many of the fractures cut Caledonian granites they probably originated shortly after the Caledonian orogeny simultaneously with the formation of the Great Glen Fault. Many of the streams and lochs east of Loch Loyal are aligned along this NW-SE direction and probably follow faults within the basement unseen at surface. Excepting the Coldbackie Fault, Loyal syenites are faulted to a limited extent; minor radial and circumferential faults peripheral to the syenites are frequent and larger faults within the igneous bodies are postulated from their morphological details. One of the radial faults in Allt Bealaich Dubh is seen to dip towards the syenite and contains a few centimetres of blue-green chloritic gouge together with a good deal of red feldspar implying that the faults formed during the intrusive period. That many small pieces of syenite have chloritic material along flat faces indicates that radial faulting was widespread but displacement relatively slight. Connected with these radial fractures are circumferential faults coincident with the Moine strike direction along which syenitic sills have been intruded.

Larger faults are stamped on the primitive NW-SE trend of the basement. Within the Loyal mass NNW-SSE faults through Loch Fhionnaich, and a NW-SE fault through Bealach Clais nan Ceap occur, a north-south fault cuts Meall Eudainn in the Cnoc nan Cùilean intrusion and the Stumanadh mass is cut by N.W.-S.E. faults parallel to the Coldbackie fault. These modify the outcrop pattern of the syenite on the Stumanadh summit. According to Gallagher (1971) minor faults at the north-east corner of Loch Loyal, below Sròn Ruadh hold barite and celestite and have high radioactivity.

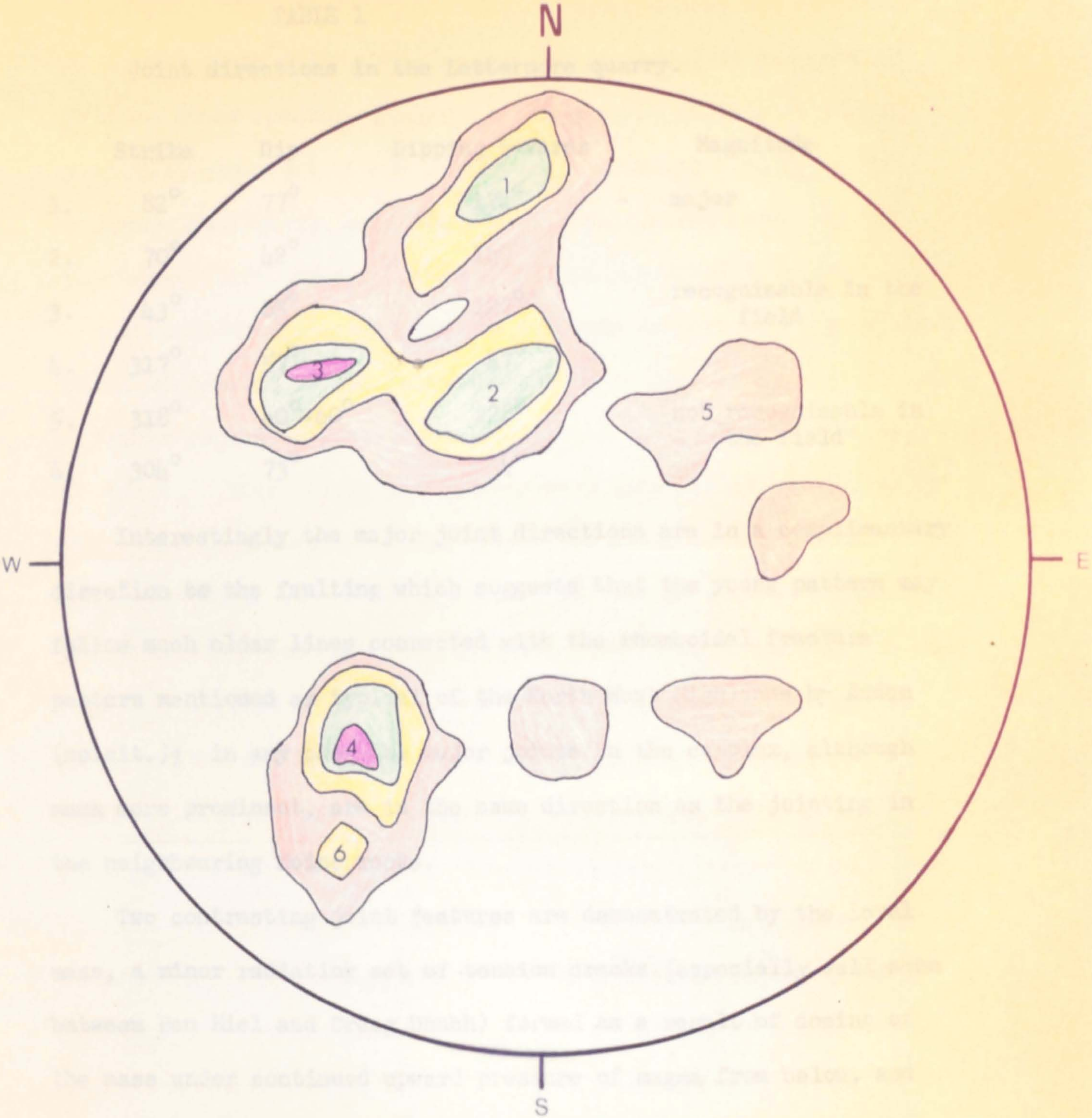
Because of lack of evidence to the contrary (such as slickensides) the obvious cracks in the syenite are referred to as joints. Six joint directions have been recognised of which one master set is extremely strong and persistent, east-west at Lettermore to WSW-ENE at Sgòr Fhionnaich. This principal direction gives rise to the vertical smooth faces so often displayed in the Loyal range. Joints were measured by the author at Lettermore quarry and a plot of poles led to the recognition of six joint directions, four of which are readily identified in the field. Master joints, and the majority of the others, dip steeply towards the south at angles of approximately 77°. Jointing is closely spaced and pervades the whole intrusion, it is usually simple although departures from linearity occur and at Sgòr a' Chléirich curved joints are well developed and alongside the western edge of Loch Fhionnaich cup and ball jointing is seen.

Curved joints in the cliffs of Sgòr a' Chlèirich.

Cup and ball jointing west of Loch Fhionnaich.

Polar projection of joint planes

Lettermore quarry



	STRIKE	DIP	DIP TOWARDS
1	82°	77°	172°
2	70°	42°	160°
3	43°	65°	127°
4	317°	57°	47°
5	318°	40–60°	228°
6	304°	73°	34°

TABLE 1

Joint directions in the Lettermore quarry.

	Strike	Dip	Dipping towards	Magnitude
1.	82°	77°	172°	- major
2.	70°	42°	160°	
3.	43°	65°	127°	recognisable in the field
4.	317°	57°	47°	
5.	318°	40°-60°	228°	not recognisable in the field
6.	304°	73°	34°	

Interestingly the major joint directions are in a complimentary direction to the faulting which suggests that the young pattern may follow much older lines connected with the rhomboidal fracture pattern mentioned as typical of the North West Highlands by Auden (op.cit.); in any case the major joints in the complex, although much more prominent, are in the same direction as the jointing in the neighbouring Moine rocks.

Two contrasting joint features are demonstrated by the Loyal mass, a minor radiating set of tension cracks (especially well seen between Ben Hiel and Creag Dhubh) formed as a result of doming of the mass under continued upward pressure of magma from below, and the major cross-joints (Q-joints) normal to the lamination in the outer parts of the Loyal syenite. No obvious S-joints at right angles to this major set are seen, and sheeting is not observed. Closely spaced, less prominent, shallow, southward dipping joints are possibly correlated with Cloos's Lagerklufte (L-joints) although as a rule Loyal joints do not fall into such clear cut categories.

Occasionally the jointing becomes very close-spaced and divides the syenite into thin lenticles and flaggy slabs, it can then be referred to as fracture cleavage. An example of this is visible in a small gorge cut by the stream draining southwards from Loch no Creige Riabhaich; here the cleavage dips north-westwards, at other localities however the dip shows no preferred direction.

Intrusion of the main syenite into the Eastern Moine granulites caused distension of the foliation planes in the schists and formation of radial cracks in addition to distortion of the principal strike direction. These lines of weakness were then filled by a suite of minor igneous phases. Radial cracks fashioned pathways along which dykes were emplaced and distension of the schist foliation planes led to localization of a sill suite. Pegmatitic and aplitic liquids were also able to nose into these susceptible zones. Along the northern edge of the Loyal mass several sills dip concordantly or slightly transgressively, toward the main syenite. Here, as compared with southern areas, these subsidiary igneous phases are not located far from the intrusion. In the south however the dyke phase tends to be located near to the main contact of the syenite whereas sills are encountered up to two kilometres from the margin of the Cùilean and Loyal masses. Pegmatites and aplites in the syenite have a distinct linear element but are apt to be highly irregular when emplaced in the surrounding Moine sediments.

Internal contacts within the intrusions.

In hand specimen rocks from the three intrusions vary in colour. King (1942) has pointed out mafic margins to the normal Cnoc nan Cùilean syenites although the author believes that he has overemphasized their regularity in disposition. Gallagher et al. (op. cit) has tentatively sub-divided the complex into three main lithologies, pink, grey and mafic syenites. He compares the outer laminated Loyal syenites with those of Beinn Stumanadh and plots a grey syenite occupying the central part of the Loyal range. The mafic syenite comprises Cnoc nan Cùilean. Robertson and Parsons (1974) in contrast compare Stumanadh rocks with core rocks from Ben Loyal. They map laminated subsolvus, two feldspar syenites external to core syenites, which are hypersolvus one-feldspar rocks in the Loyal mass.

Highly irregular pegmatite penetrating Moinian metasediments, Sgòr Chaonasaid, Ben Loyal.

The author finds that the three intrusions are best regarded as separate masses. Within the Cnoc nan Cùilean mass variable basic syenites are found throughout most of the complex although leucocratic material is more common towards the centre of the intrusion. Gallaghers' division of Ben Loyal into pink outer and grey inner parts was not substantiated and the pink colour was found to be correlated only with the degree of alteration, and the distribution of the pink and leucocratic types to vary in an unsystematic manner. A finer grain size, together with amphibole instead of pyroxene in the outer parts of the mass is discernible and the author follows Robertson and Parsons in his subdivision of the Loyal mass into outer laminated and inner homogeneous syenites. Beinn Stumanadh is a uniform body dark brown or pink as compared to the Loyal rocks, lamination is absent here and the only variation in the mass is the enrichment of carbonates in the Achnanclach sill. Overall little internal variation is evident within the intrusions.

CHAPTER SIX

THE PETROGRAPHY AND PETROLOGY OF THE COMPLEX

Constituent minerals and modal composition.

Loyal syenites are composed principally of feldspars, both monoclinic and triclinic K-feldspar polymorphs exist together and with albite, bulk 85-90% of the total mineralogical content, the rest is made up of about 10% of amphibole and/or pyroxene along with the accessories sphene, apatite, allanite, iron ores, and quartz in small quantities. Often the mafic minerals cluster together to form loosely held aggregates or clots. Robertson and Parsons (op.cit.) have determined the modal composition of the two varieties of Loyal syenite which are presented below.

The modal analysis of the Ben Loyal syenites (vol %)

	Core	Laminated
Quartz	8.5	10.2
Alkali feldspar (including perthitic) albite	80.8	55.1
Separate plagioclase	4.0	23.8
Pyroxene	4.3	5.6
Amphiboles	0.0	3.7
Accessories	2.4	1.6
	100.0	100.0

These figures are in agreement with the mode quoted for Lettermore quarry by Von Knorring and Dearnley (1960), thus:-

Mode of Lettermore syenite in (wt %) Quartz 12.0, Orthoclase 29.4, Albite 47.4, Hornblende 9.2, Magnetite 1.0, Sphene 1.0, and Apatite a trace. The author has examined eighty thin sections from the complex and finds no significant departure from these figures. The mineralogy of the three parts of the complex will be examined in turn.

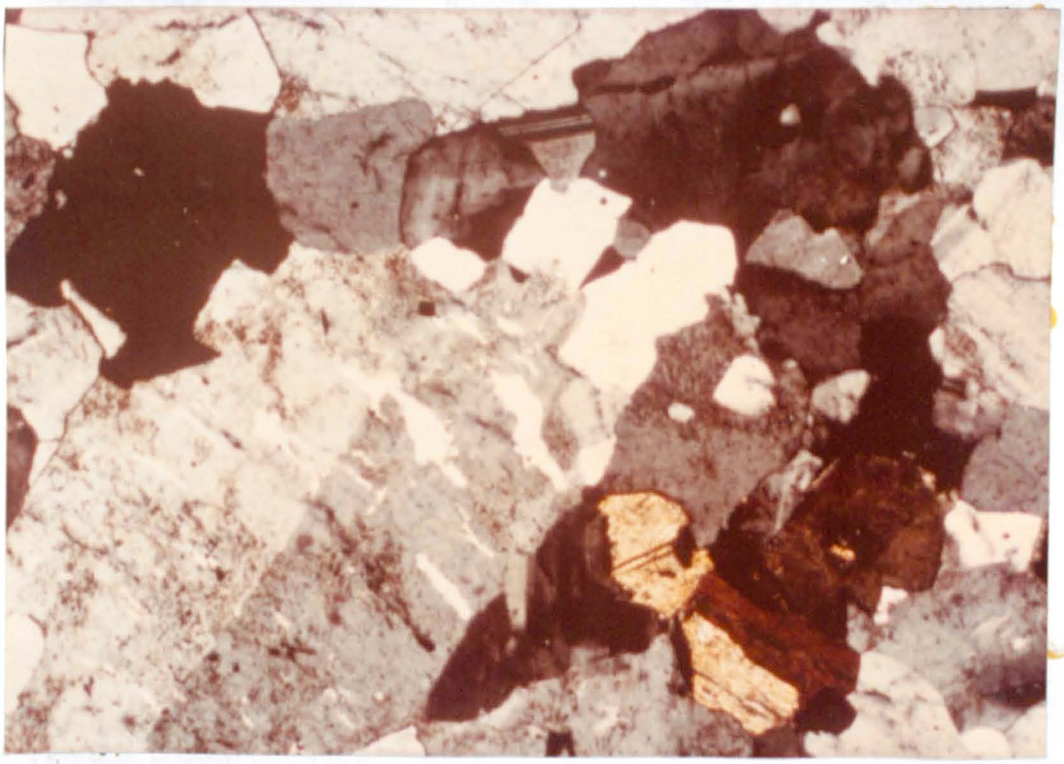
Bulk mineralogy in the syenites

The Ben Loyal syenites.

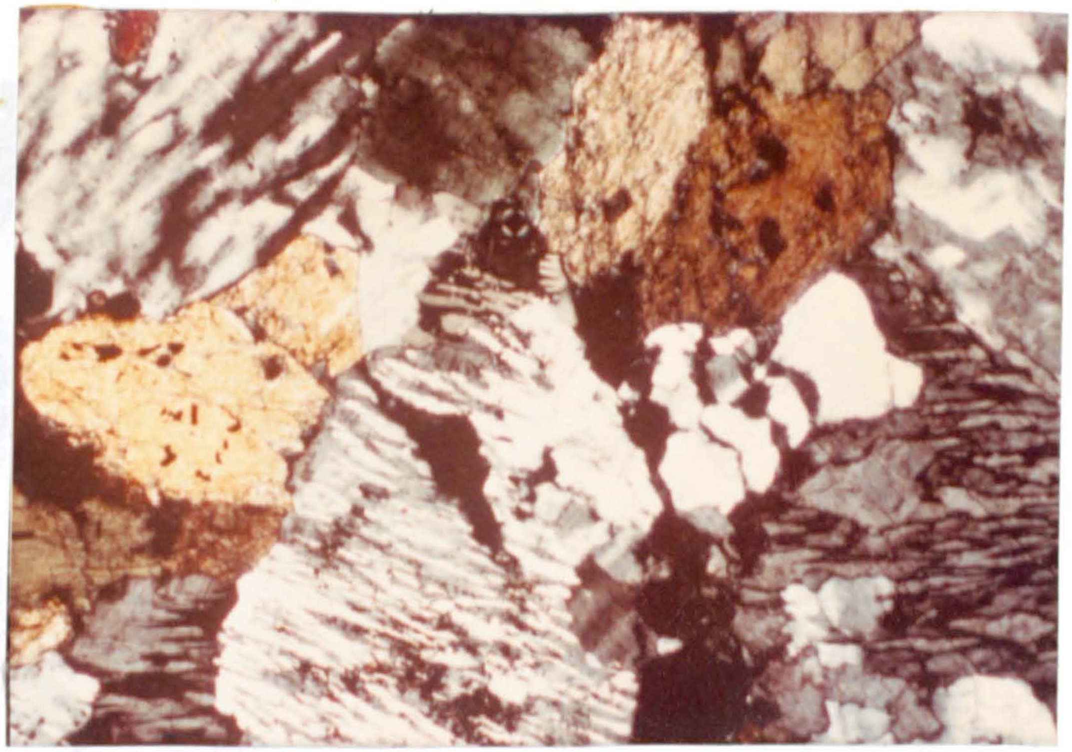
Loyal syenites can be divided petrographically into laminated and core syenites. Laminated rocks contain two distinct types of feldspar, potash feldspar and abundant discrete crystals of plagioclase. Amphibole is common, and quartz with patchy extinction is coarser in these rocks than in the core syenites; bright green pyrexene occurs , and biotite, infrequent and usually close to the Moine contact is pale brown, flattened, and frequently altered to chlorite. Accessory minerals include sphene, apatite, allanite and iron ores principally magnetite.

Potash feldspar occurs as large anhedral crystals with patchy and irregular perthitic albite and as erratically twinned microclines without obvious perthite. Albitic plagioclase is much coarser although variable in grain size, large crystals usually show fine albite twins while smaller grains have broader twin lamellae. Extinction angle measurements have indicated a composition of Ab_{94} for the albite. Small twinned microclines and albite are clear, perthitic alkali feldspars cloudy. Cross-hatched twinning is occasionally obvious. Euhedral zircons are a very minor accessory and have pleochroic haloes when embedded in biotite and hornblende; sphene usually sagenitic or diamond-shaped is sometimes regrown around magnetite, and very thin veins of small rounded quartz crystals occasionally penetrate the syenite. These veins, often only 0.1 mm thick, have very straight margins, only rarely will a feldspar crystal break this linearity indicating a later crystallization sequence for some of the felsic minerals.

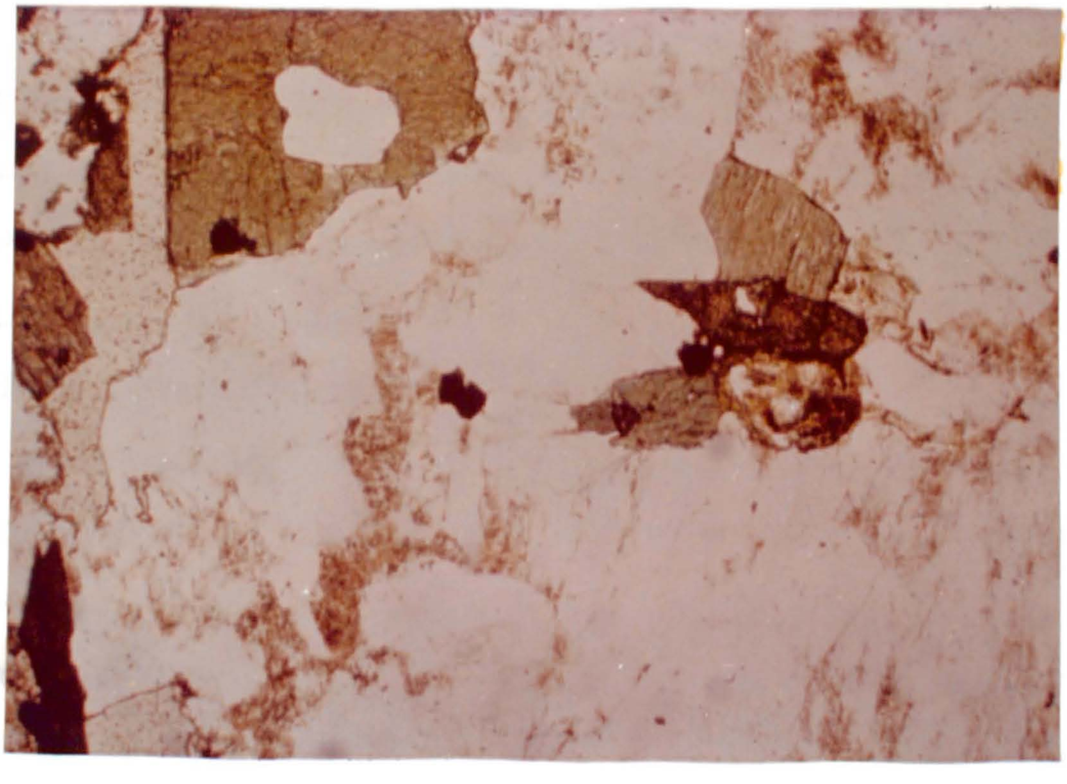
Core syenites of Ben Loyal are one-feldspar rocks essentially composed of a single perthitic feldspar plus a very minor phase of small, interstitial, separate grains of albite.



Laminated two-feldspar nordmarkite, thin-section No. 25596,
Lettermore quarry, Ben Loyal.



One-feldspar core-syenite, thin-section No. 27587 (17804), Northern slope of Creag Riabhaich, Ben Loyal.



Nordmarkite, Lettermore quarry, ordinary light

Nordmarkite, Lettermore quarry, crossed nicols,

thin-section No. 25596

Quartz, in rounded grains is present between the perthitic and alkali feldspars. Generally the perthites have comparatively regular twin lamellae, and zoning is encountered. Interstitial albite and quartz, in narrow zones, separate much coarser subidiomorphic alkali feldspar.

The Beinn Stumanadh syenite.

Beinn Stumanadh hybrid rocks at the contact with the Moine Series are also two-feldspar assemblages with the coarse non-perthitic microcline coexisting with large finely twinned plagioclase; on the other hand in the interior of the mass the rocks resemble in part those of the Loyal core and albite occurs between perthitic alkali feldspars. Of the three intrusions Stumanadh is the richest in microcline. Oscillatory zoning is seen in some of the feldspars, and both pyroxene and amphibole are found together in these syenites. Often carbonate veins extensively replace the mafic minerals in the syenite and late stage deuteric alteration helps hematite pick out the cleavage directions of the feldspars. Cross-hatched feldspar exists and epidote is present in the carbonate veins. In general clouded and clear feldspars are found together.

The Cnoc nan Cùilean mass.

Cnoc nan Cùilean is a one-feldspar type rock which is more basic 4
and potassic than the other parts of the complex. It contains only sodic pyroxene with but slight traces of amphibole. The inner lighter parts (less contaminated?) to the intrusion usually have sutured grain boundaries between the single perthitic feldspars, basic types on the other hand often are of finer grain and possess two feldspars. Parsons and Boyd (1971) have shown that the K-feldspar of Cnoc nan Cùilean is mostly monoclinic. Within the feldspars beautiful perthitic intergrowths are frequent, pyroxene is often idiomorphic, frequently cracked and sometimes zoned, pale-green to bright grass-green from the centre of the crystals outwards. Actinolitic hornblende is a widespead secondary mineral and hastingsite, sphene, apatite and allanite make up the remaining accessory minerals.

Microcline in syenite, slide No. 27609 (19604),

Allt na Leitire Bige, Beinn Stumanadh.

Carbonate within Hematite-stained syenite, Slide

No. 27607 (19404)

Texture of the syenites.

Grain size.

All the rocks from the three intrusions are phanerocrystalline. A measurement of the dimensions of constituent minerals within each of the masses has been undertaken and shows that if one regards 5 mm as the lower limit of coarse-grained rocks the Loyal syenites all fall within the medium grain size range, that is between 1.0 and 5 mm. Alkali feldspars from the laminated Loyal rocks have sizes between 1.0 and 3.0mm with an average of 2.0mm, together with 1.0mm long plagioclases. Crystals from the core syenites, composed essentially of alkali feldspar, have lengths of 2.0 - 8.0mm and are thus coarser than the laminated varieties. The mafic minerals chiefly hornblende and pyroxene increase in size from 1.0 - 2.0mm in the laminated syenites to 2.0 - 5.0mm in core rocks. Sphene at 0.5 - 0.75mm and magnetite at 0.2mm remain approximately constant in the two types. Cnoc nan Cuilean shows the greatest variation in grain size with plates of feldspar up to 5.0mm in length although 0.5 - 2.0 is more usual; large sphenes up to 1.0mm and pyroxene crystals of 1.5mm are typical.

An average two mm grain size for the whole complex is normal which places the rocks firmly in the medium-grain size.

Grain shape.

Hypidiomorphic (i.e. subhedral or hypautomorphic) crystal form is almost universal throughout the Loyal syenites. Columnar or lath-like shapes with modified margins are frequent and are found together with lesser amounts of idiomorphic and allotriomorphic material.

Within the core syenites of Ben Loyal hypidiomorphic perthite feldspars usually have good shape although their margins are irregular and sometimes sutured; laminated rocks have anhedral feldspars with simple unsutured margins. Both hornblende and pyroxene are hypidiomorphic to allotriomorphic and although in many instances their crystals are ragged, an approximate prismatic habit prevails. Crystals displaying idiomorphic outlines include apatite (very occasionally), zircon, allanite and sphene, the latter particularly showing rhombic cross-sections, often twinned, and then displaying arrow-shaped form. Atypically apatite, which is sometimes abundant, forms large allotriomorphic crystals clouded with smudgy inclusions. The feldspar/quartz matrix between the potash feldspars in the one feldspar rocks, and in veinlets cutting others, are composed of equigranular aggregates.

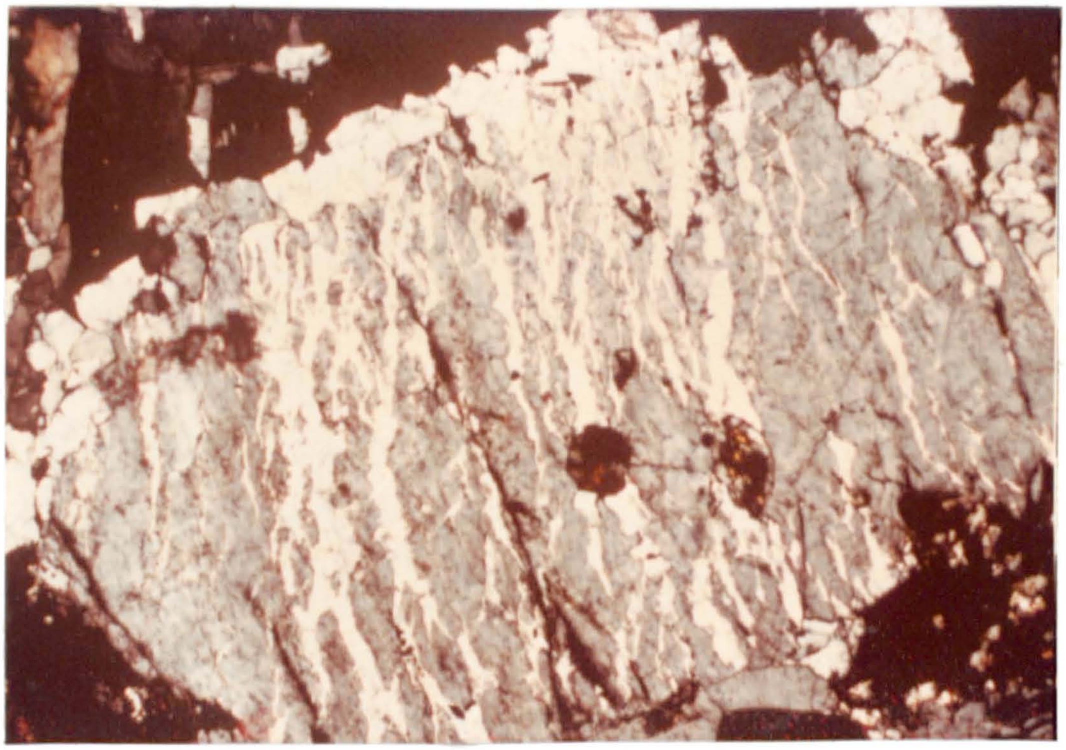
Degree of crystallinity.

The rocks are holocrystalline (eucrystalline).

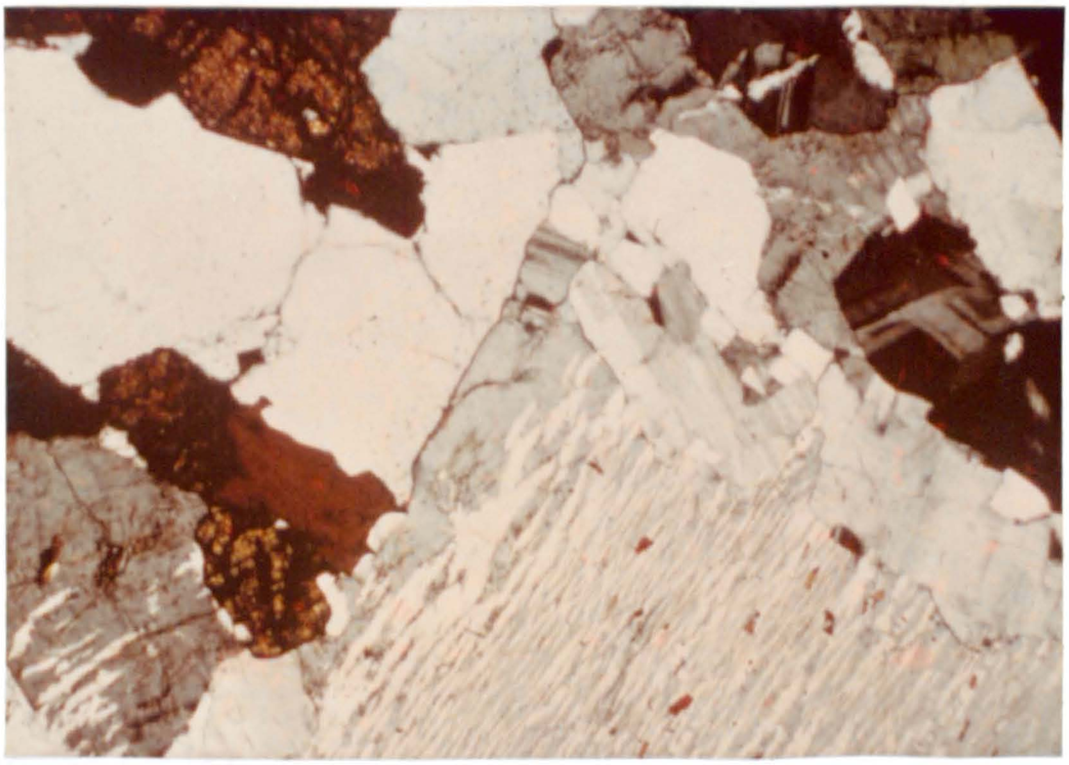
Fabric and contact relationships of the mineral grains.

Variations on a hypidiomorphic-granular texture are uncommon and this feature indicates that crystals have interfered with each others shape during growth. Within the laminated syenites of Loyal a modified equigranular texture of two feldspars with common triple-point junctions and unsutured margins occurs, whereas in the core rocks coarser, cross-hatched and twinned perthites enclose smaller, sutured, albitic, plagioclase. Sutured granular margins are very common within the Cnoc nan Cùilean syenite and also prevail in the Stumanadh body. A saccharoidal mosaic of grains is apparent in some of the aplitic veins.

Porphyritic textures within the rocks of the complex are rarely seen, occasionally however large phenocrysts are scattered sparsely amongst the more normal syenite, but at no time does this approach



26388 Perthitic intergrowth, 'Plumose variety'. Clear strings of albite penetrating orthoclase feldspar, near the summit of Beinn Stumanadh.



27580 (17104). String perthites, Beinn Bheag, the Loyal Range.

a true porphyritic type.

Intergrowth textures, principally perthitic and poikilitic, are important elements within the Loyal rocks, while other symplectic features such as myrmekitic and graphic intergrowths are of but subsidiary importance. Corona structures seen within the Loch Ailsh alkaline suite have not been observed.

Perthitic intergrowths are beautifully displayed in the Loyal complex, all four facies of which exhibit the phenomenon, string perthites especially are developed to perfection within the Cuilean mass. Many different types of intergrowth are shown, in the string perthites, fine tapering strings of clear albite are enclosed in cloudy potash feldspar. With increase in size of the perthite lamellae the sodic portion becomes dominant and can then be referred to as antiperthite. Often the banded intergrowths are approximately at right angles to the c crystallographic axis. The albitic lamellae within the K-feldspar, (which often reach 5 mm in size) tend to occur towards the centre of the crystals and stop before reaching the crystal margins; however varieties in which the stringe do reach the crystal edges are found in association with this more normal condition. A type referred to by King (op. cit.) as a 'plumose' variety is an extension of this and here the margins of the crystal are dominantly albite from which narrowing tongues cut Carlsbad twinning and extend towards the interior. Sometimes albitic strings follow the polysynthetic twinning of microcline crystals. Thickening of the strings leads to rod-microperthite. (strictly all the perthites here described, pegmatitic fractions excluded, should be referred to as micro-perthite as the lamellae are discernible only under the microscope).

A coarse patch perthite, in which twinned albite patches are in optical continuity are enclosed in cloudy K-feldspar, is seen notably in the Cnoc nan Cùilean complex. An opposite to this also occurs in which fuzzy patches of K-feldspar are held in albitic plagioclase forming minor antiperthite.

Oscillatory compositional zoning within the potash feldspars is cut by distinct string perthites accentuated by hematite stains and the perthites transgress further potash feldspar rimming and in optical continuity with, the inner grains. Zone perthite is also developed and cuts Carlsbad twinning and is in turn cut by string perthite at right angles to this direction.

Carlsbad twinning of potash feldspar, the polysynthetic twinning of microcline, and albite twinning are commonly encountered, and where K-feldspar is subordinate discontinuities in the albite twinning produces an effect not dissimiliar to 'chequer-albite'. The cross-hatched twinning of microcline has its most perfect development in the Beinn Stumanadh massif and this is taken to indicate approach to maximum triclinity correlated with the increase in differentiation of this body compared with the other two intrusions.

Interstitial to these perthites, albite, quartz and microcline in discrete rounded grains are found.

All these features exhibited by the perthites are in agreement with the criteria of Alling (1938) for the recognition of exsolution perthites, in that they are coarser towards the centre of the host feldspar grain, approximately uniform throughout the different parts of the grain and concentrated by the structure of the host feldspar. Additionally several of Alling's criteria for replacement are present, especially the tendency for the perthite lamellae to be located at the crystal boundaries and to taper inwards towards the centre of the host. The author prefers that exsolution is the principal factor involved and envisages a magma composed of a homogeneous disordered mixture of soda/potash feldspar which cooled and crystallised as single feldspar rocks and formed hypersolvus core syenites. The plagioclase component of these feldspars is held only in the perthite lamellae. As these crystals continued to cool and on reaching the solvus at approximately 660°C, exsolution began and a separate two feldspar assemblage resulted. As Bowen and Tuttle (1958) have pointed out survival of perthite suggests that either extremely rapid cooling or abscence of volatile fluxes such as water vapour has been the case, since laboratory experiments show that unmixing of sodium feldspars takes place in a few days if water vapour is present to flux the reaction, the latter seems more likely. Additional investigations indicate that most amphiboles may well be unstable in the presence of a moderate or high H_2O vapour pressure. Most perthite-quartz granites carry amphibole as the principal dark mineral, indicating that the lack of extensive unmixing of the alkali feldspars in these rocks may well be a result of the low water content of the magma. In contrast the two feldspar outer laminated syenites, which also hold minor biotite, were potentially richer than core rocks in water, which could explain the preponderance of amphibole over pyroxene in these rocks as well as the expected concentration of pegmatitic veins encountered there. Significantly in these pegmatitic facies hornblende is not found, indicating an excess of water was available during the last parts of the crystallisation process. Intuitively one would expect that the outer laminated two feldspar rocks would be of coarser grain size since they crystallised at a lower temperature in the presence of a higher percentage of water vapour and over a longer period of time than is the case for one-feldspar core rocks. However the contrary case exists and the core rocks are the coarsest of the two variants. This anomaly might be explained by the chilling effect of the surrounding Eastern Moine granulites. The fact that the two-feldspar syenites have no great metasomatic/alteration effect on the surrounding sediments, coupled with a preponderance of amphibole suggests to the author that only a slight concentration of water over that in the core syenites occurred, and he concures with a proposal mooted by Tuttle (1952) that the unmixing of the two feldspars is best regarded as an extension of an ultimate development along the divergent paths of the perthite exsolution. Orville (1963) has shown that alkali redistribution occurs through a vapour phase in response to temperature gradients, these must have been lowest and more volatile-rich at the margins of the Loyal mass. A plot of the Loyal syenites shows that s, the Rittmann Index decreases as the silica content increases, which according to Rittmann (1960) indicates a type of gas transfer operative in the rock magma. Perthites are developed in the pegmatites of Sgor Chaonasaid which suggests that they have sharper tolerance of aqueous conditions than hornblendes; in any case the pegmatites appear therefore to have been unusually 'dry'. Stability field relationships of pargasite determined by Boyd (1956) and on ferropargasites by Gilbert (1966), close to the composition of the Loyal amphibole indicate an upper stability range for this mineral of approximately 820°C at 500 bars vapour pressure, and 925°C at 1000 bars, extrapolation to 250 bars vapour pressure suggests an upper stability range in the order of 660°C, above which break-down to diopsidic pyroxene, olivine, nepheline, anorthite, spinel and water occurs. Plotting this line of stability on the probable minimum percentage water solubility in granitic liquids given by Brown (1970) intimates that the Loyal syenites had in the order of 3.5% H_2O vapour in the magma, which accords well with the data of Ernst (1962) which demonstrate that reibeckitic amphiboles are unstable at temperatures in excess of 610°C and greater than 4% water content, above which they break down to acmite, that is a pyroxene. Loyal rocks then probably lie close to the upper limit of stability of the amphibole and the presence of pyroxene in the core rocks shows that higher temperatures prevailed there. That amphibole/pyroxene and amphilbole along exist elsewhere in the same intrusion shows that the conditions straddled the amphibole stability field indicating a temperature of formation close to 660°C at 250 bars pressure and with about 4% of water vapour in the magma. The core rocks holding pyroxene might therefore be expected to have had an initially higher concentration of water in the magma close to but greater than 4%, but as the temperature fell below the solvus where two feldspar syenites crystallize, and coincidentally amphiboles become stable, water became incorporated in the amphibole structure and thus acted as a kind of buffer to the increased tendency of enrichment in vapour phase as the magma further cooled. Mention has been made above of the intermediate nature of the late stage pegmatitic veins in which perthites are developed but hornblendes suppressed.

The significance therefore of the perthites of the Loyal mass is the limit which they impose on the temperature of formation of the intrusions, and on the depth at which they must have been emplaced, which can only have been shallow. Allowing for the uncertainty in the values of the stability fields mentioned above, and in conjunction with the concept of earth depth zonation proposed by Buddington (1959) in which Loyal could be classified as a lower Epizone or a higher Mesozone pluton, it is apparent that emplacement of the complex was between one kilometre and 6.5 kilometres, with a depth of two kilometres to five kilometres most likely. The theory accords well with Read's (1957) Granite Series, that is a late stage intrusive mechanically emplaced at a comparatively shallow depth.

Myrmekitic intergrowths have only been detected in one of the thin rock sections (26388) from Beinn Stumanadh and is uncommon there.

Poikilitic textures in which the feldspars are totally enclosed within large crystals of the same material occur often, but the texture is never dominated by this particular feature.

The colour and colour index of the syenites.

Assuming those limits proposed by Shand (1947), all except the most mafic portions of the Cnoc nan Cùilean massif can be considered as leucocratic. From point-counting methods on thin sections the colour index of Loyal rocks has been determined as 9, leucocratic 5
to Shand but mesotypic to Johannsen (1931-1938).

Further indices, all calculated from analyses of thirty typical syenites within the complex show that this C.I. is slightly low but of the right magnitude. Thornton and Tuttle (1960) make use of a parameter they call the differentiation index, which is quite analogous to colour index but depends on the sum of normative Or + Ab + Q. The value of the D.I. for Loyal syenites was determined as 87.9. Two other ratios $\frac{FeO}{FeO + MgO}$ and $\frac{K_2O + Na_2O}{K_2O + Na_2O + CaO}$, respectively M, the Mafic Index and F, the Felsic Index were calculated as 85.9 and 87.6. Consideration of all these four parameters indicates a colour index of

12 for Loyal rocks.

Of the three variants in the complex Cnoc nan Cùilean is by far the most mafic and therefore darkest in colour, Loyal rocks are generally white whereas Beinn Stumanadh are dark brown or pinkish.

Varieties within the syenite

Aplitic Veins

Two separate types of aplites are encountered in the area under consideration, regular pink, parallel-sided manifestations in the Cnoc nan Cùilean mass, and those along the northern flank of Sgòr Chaonasaid where they are intimately mixed with pegmatitic material. Both aplites have a marked lack of mafic material and are virtually leucocratic feldspar/quartz/magnetite rocks, the latter mineral on oxidation imparting the pink colour typical of these rocks. The pink colour is uniformly distributed in the Cùilean aplites, but often gives a spotted appearance or follows cracks and bands, between pegmatite in the Loyal types. Often veins range in thickness between 25mm and 75mm, although within the Cùilean mass small dykes from 15mm to 300mm are not uncommon; frequently bifurcating, they are more resistant than the enclosing syenites and thus stand out on weathered surfaces. Contacts with the enclosing syenites are sharp and no chilled margins occur, commonly the aplites are intruded into the syenites but occasionally are, together with pegmatites, found in the Moine country-rocks. Quartz veins at a greater distance away from the igneous contact may represent the last stage in aplitic differentiation. The contrast in the textural relationship between host syenite and aplite is very striking, grain size, 2.0mm in the syenite, averages less than 0.1mm in the aplite, rounded shapes with sutured margins prevail and it is apparent that the grains have interfered with each others growth, an allotriomorphic saccharoidal texture has thus resulted. Mafic minerals in the aplite ceins are minute, and almost always much altered, small ragged remnants of hornblende/pyroxene and very fine sphene and zircon, as well as sparse biotite flakes with chloritic alterations are encountered. Magnetite, the most abundant mafic constituent acts as a nucleus for sphene crystals. Perthites are much less abundant than in the surrounding syenites. Interstitial cross-hatched microcline is present in subsidiary amounts but the chief feldspars are clear albitic plagioclase and cloudy potash feldspar in an approximate ratio of 60:40. Oscillatory zoning is a very marked feature of the albitic plagioclases (it is also present in some perthitic K-feldspars) and suggests that the mineral constituents were in a process of reaction with the liquid fraction of the melt at the time of their consolidation.

Pink aplitic vein cutting the Cnoc nan Cùilean syenite

The aplites are probably related to the primary joint system in the complex although field evidence on this point is not decisive; Cnoc nan Cùilean aplites appear to be related to flat-lying joints while those of Chaonasaid to radial fractures.

Close association of pegmatite and aplite is extremely striking. A series of experiments by Jahns and Burnham (1957,1969) intended to duplicate the natural conditions of pegmatite formation, showed that a fine grained sugary aggregate of quartz and feldspar, i.e. aplite, separates above the "second-boiling point" of the magma. Crystallization causes increasing concentration of water in the remaining liquid and eventually conditions for "second boiling" are reached and a water-rich phase separates. This water rich phase provides space for large crystals to grow but coupled with this the high H_2O content also inhibits nucleation thereby developing only a few crystals, the lowered viscosity provides for more rapid movement of ions and hence for formation of pegmatite. If attainment of the "second boiling point" is pictured as occurring irregularly during cooling for example by slight variations in either temperature or pressure an adequate explanation of the zonation and close association of pegmatite and aplite at Loyal results.

Two aplitic phases were demonstrated by King (op. cit.) in the Cùilean intrusion, the author considers that the first of his types, irregular aplitic veins are in fact only fine grained syenitic material invading xenolithic matter; his second type pink, are numerous and transgress all other structures. A ramifying network of veinlets earlier to this main aplitic phase is intricately enmeshed within the mafic syenites.

Pegmatitic veins.

Both massive boulder and vein-like pegmatitic material are found below the cliffs of Sgòr Chaonasaid on the northern slopes of the Loyal range. One of the veins has been studied in detail and can be taken as typical. The vein is 65mm wide and prominently zoned from margin to centre in the following manner:-

a) A fine-grained quartz/microperthite mixture just 4mm thick.

b) Reaching 20mm from the edge, large toothed perthites up to 25mm in length, but normally approximately 10mm, together with subordinate quartz crystals in rudimentary graphic intergrowths. Both feldspar and especially quartz crystals are aligned at right angles to the vein margins.

c) Very fine white/pink aplitic material to which magnetite is restricted.

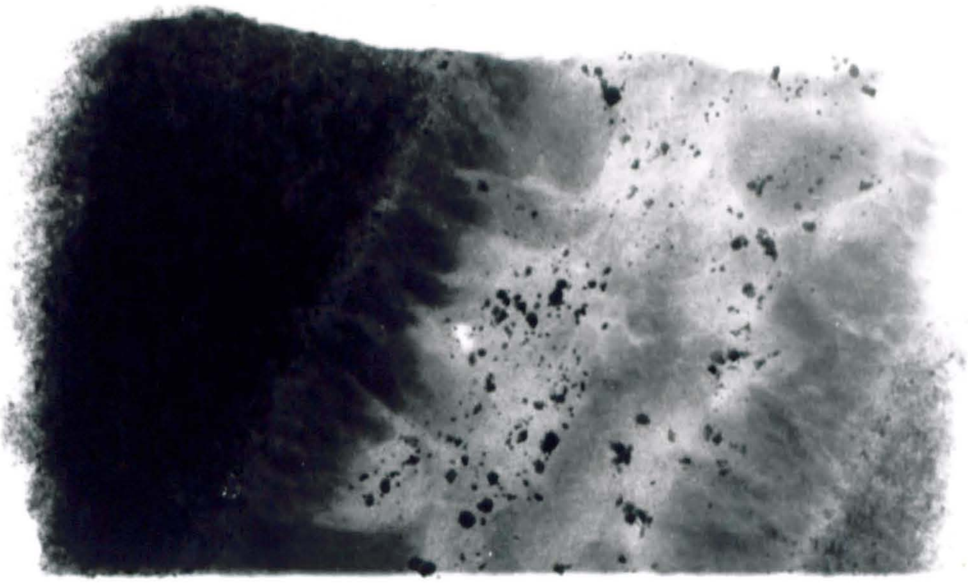
d) The core consisting of coarse perthite/quartz aggregates with large irregular "sub-rounded" quartz crystals.

The junction with the host syenite is very sharp and clear and no contamination between them is seen. Pegmatites are noticeably much more leucocratic, and quartz more obvious, than in the surrounding syenites. In the larger boulder pegmatites perthitic intergrowths have no preferred orientation and the feldspars are sub-rounded and equidimensional at about 25mm; aplitic material here binds together the large feldspars in a manner analogous to the cement in a sandstone.

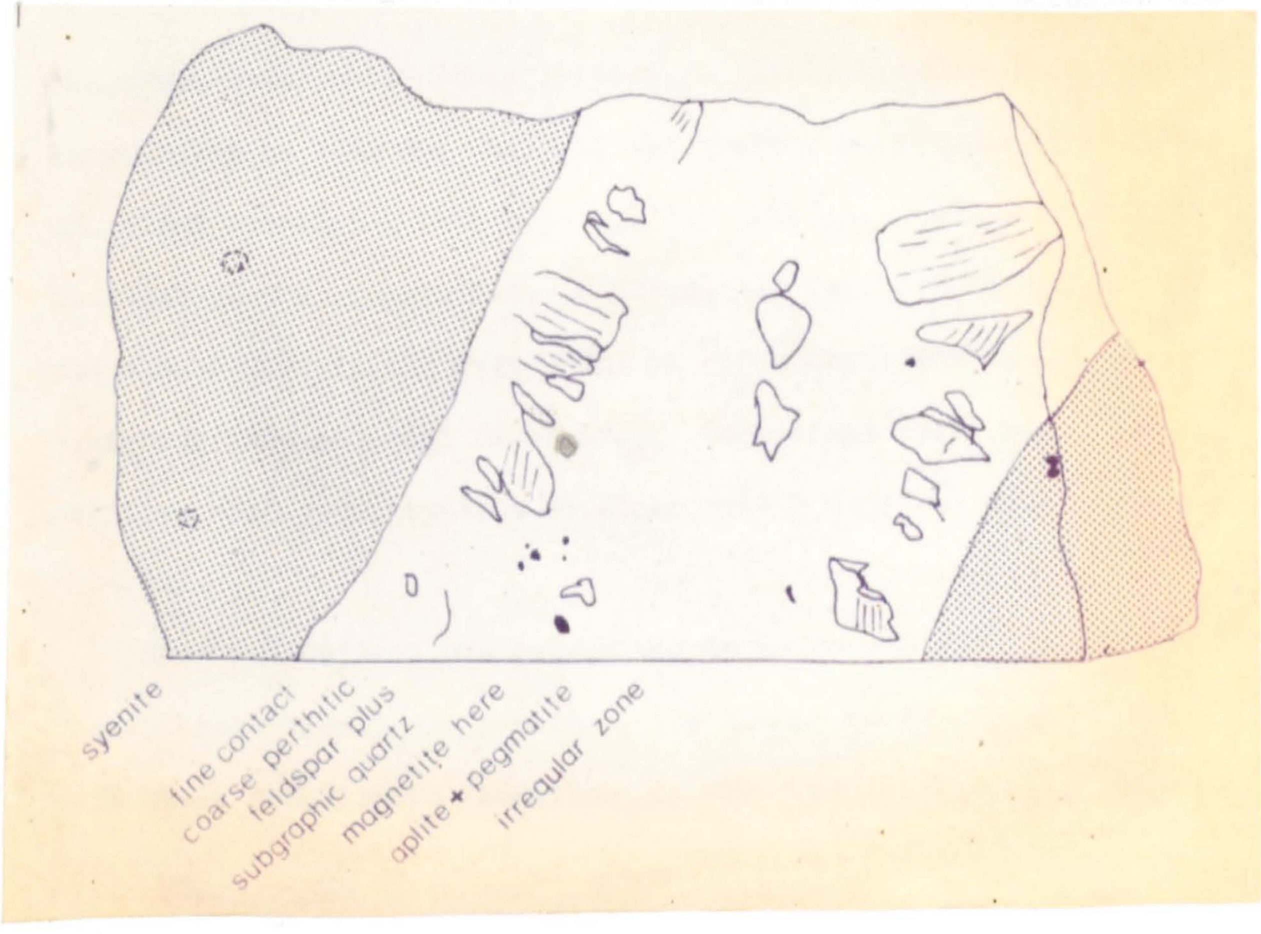
Outside the syenite proper some pegmatites cut Moinian metasediments where they are characteristically very irregular, have a chilled finer grain at their margins, and sometimes incorporate

Pegmatite, Sgòr Chaonasaid, Ben Loyal showing anastomosing cracks centred on Allanite.

Pegmatite, Coille na Cuile, Sgòr Chaonasaid (27575,16704)



X-Ray photograph of a pegmatite vein from Sgòr a Chaonasaid, Ben Loyal, showing the association of coarse perthitic feldspars and fine-grained aplitic material.

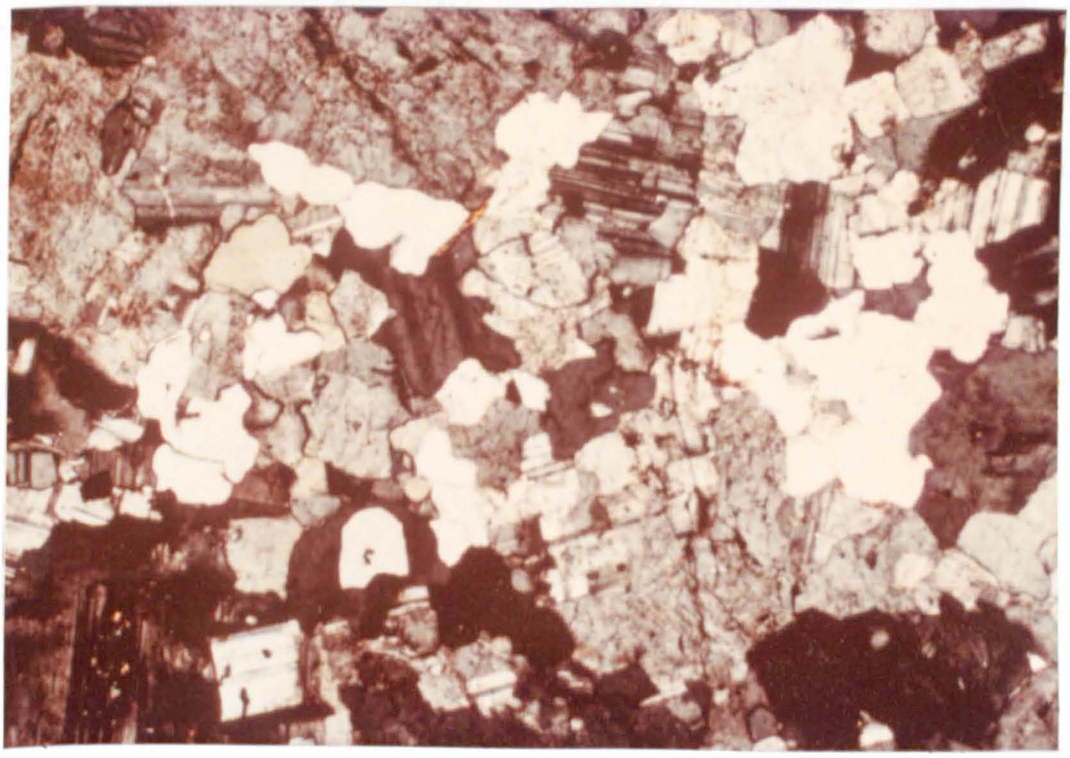


Key to the above X-Ray photograph; showing the restriction of the iron-ores to the central part of the vein.

metamorphic material. In both boulder and vein types fine-grained aplitic matter is intimately associated with pegmatite. Stereoscopic radiography, by a modification of the method suggested by Hamblin & Salotti (1964), has confirmed the persistance of these zones three dimentionally and shows that magnetite is markedly restricted to the aplitic portions of the vein.

Like the aplites, pegmatites are essentially perthite/quartz/ magnetite rocks together with subsidiary quantities of rarer minerals, conspicuous amongst which are allanite and sphene, and equally conspicuous by their absence micas, hornblende and tourmaline. The principal feldspar in the pegmatites is microcline-perthite, (the perthite strings are visible even to the naked eye), the feldspar is patchily green and different parts of a single crystal exhibit both green and white portions; a distinct pale green amazonite does occur. Closely associated with the perthites are "stepped" quartz crystals, (i.e. with horizontally striated prism faces) which on occasion are large and range up to 400mm in size. Poorly terminated quartz crystals up to 70mm are found in the boulder pegmatites where they are often associated with pink aplitic patches. Allanite, the most abundant of the accessories, is frequently idiomorphic, often zoned and almost universally surrounded by brown anastomosing cracks radiating into adjacent feldspars. Occasional small miarolytic cavities hold good crystals of clear quartz together with montmorillonitic material.

Cnoc nan Cùilean has pegmatites in veins and also as irregular segregations within the syenites, the latter being commonly found with basic xenoliths. Additionally the pegmatites contain large crystals of pyroxene and actinolite, which either parallel the margins or are held in a haphazard and irregular fashion within the veins. Cùilean pegmatites are cut by later pink aplitic veins.



Microgranite dyke from Allt Innis Ceann an Locha showing sutured margins of the feldspars and quartz. Slide No. 27590 (18104).

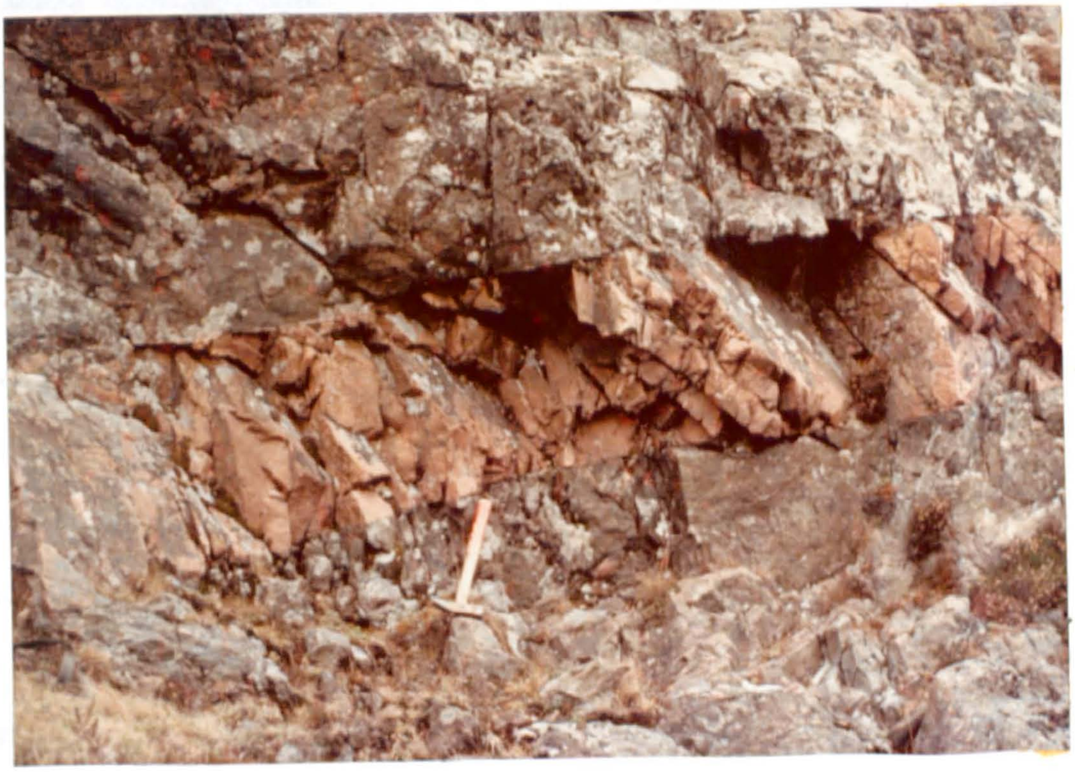
Minor intrusives.

Three types of minor intrusives are found surrounding the igneous complex, dykes, sills and vein-like material. All the rocks are pinkish in colour, of much finer grain size, (the largest grains only reach 1mm in length and the matrix is usually about 0.1mm), and more leucocratic (with a colour index of ± 5) than the normal syenite of the complexes. The rocks are very quartzose, have high combined alkalies, very low lime content and are less sodic than typical Loyal syenites. Essentially they are mixtures of K-feldspar, sodic plagioclase and quartz; sericitization is often prominent and picks out the feldspar cleavages. Small, rounded, sutured grains are the rule although some of the feldspars approach hypidiomorphic shape. Porphyritic textures are not found. Magnetite is the commonest of the mafic minerals and alteration of this has imparted the pink colour typical of these rocks. Biotite and epidote are also present and chloritic gouge is found in fractures cutting the sills and dykes. Three of the dykes have distinctive characteristics, that found in the Tarmachan stream section has micrographic texture and quartz strings cutting the more normal rocks, dykes from the summit of Beinn Stumanadh have large ragged 1mm brown-green biotite flakes which appear to have replaced earlier mafic minerals, and south of Cnoc nan Cùilean in Allt Innis Ceann an Locha the only dyke rock in which perthitic feldspar occurs was located.

Micrograntic vein cutting Moinian metasediments, Allt Ach nan Clach. Specimen No. 27615 (20004, 20104)

Contact between microgranite dyke and Moinian sediments.

Summit of Beinn Stumanadh.



Microgranite sill. Eastern part of Creag Dhubh,

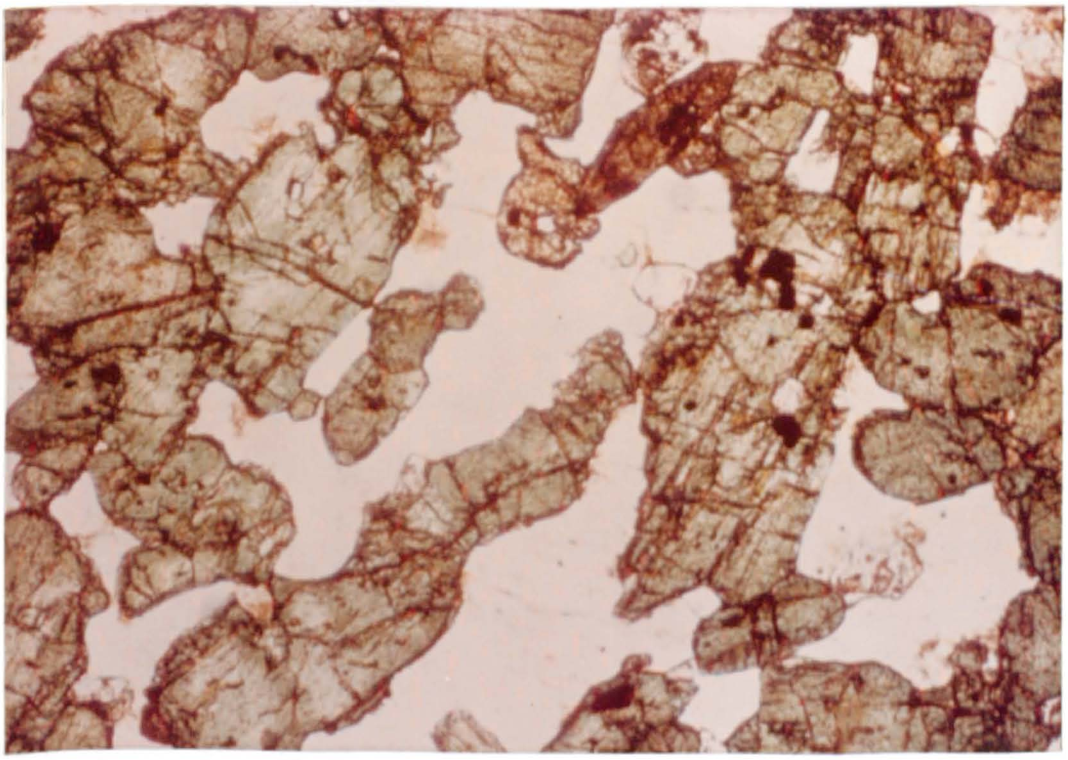
Beinn Stumanadh.

Intrusions dilate the walls of the Moine granulites and are therefore forcefully emplaced, although no obvious mineral orientation is observed in the rocks. Minor igneous intrusives of this type range in size from veins 45-60mm wide to dykes and sills up to 10 metres or more. Contacts with the Moine Series are invariably very sharp but sometimes pink feldspathic material has impregnated, for a short distance only, into the surrounding sediments. In a vein from Allt Ach nan Clach, the igneous fraction was found to be more siliceous ■6 and potassic than the enclosing Moine granulites which are richer in TiO_2, Al_2O_3, iron-oxides, MgO, CaO and Na_2O.

In the classification of igneous rocks proposed by Shand (1947) the minor intrusives fall within the XOpβ (5) division and can thus best be described as leucocratic over-saturated peraluminous sodi-potassic microgranites.

The mafic parts of the Cùilean intrusion.

As in the other parts of the complex the mafic portions of the Cùilean body are composed of two principal felsic minerals, ie. K-feldspar and albitic plagioclase together with sodic pyroxene. As a rule K-feldspar predominates over the other two constituents and crystals of interstitial albite are wedged between the granular mosaic of cloudy microcline crystals. Grain size is extremely variable and inhomogeneous over short distances, feldspars up to 10mm do occur but are usually much finer. Green sodic-pyroxene crystals occasionally reach 4.0 to 6.0mm in length (0.15 - 0.20 mm is more typical) and poikilitically enclose feldspars, iron-ores, sphene and apatite. With increase in the proportion of the pyroxene King (op.cit) has suggested that locally the normal syenite may grade into albiteshonkinites and eventually could be termed pyroxenites. However the increased basicity is correlated with the proximity to incorporated xenoliths and is not continuous over large areas, in fact the most noticeable feature is the heterogeneity of these mafic portions. It seems to the author therefore unjustified that separate names be applied to what are in essence contaminated varieties of the same rock type.



Green pyroxenes in the mafic parts of the Cnoc nan Cùilean syenite.

Miarolytic cavities

Conspicuously within the outer laminated syenites there exist, miarolitic cavities up to 10mm in length filled with a powdery canary-yellow mineral. They are usually irregular in shape and

angular projections into the voids are common; occasionally they are oriented parallel with the amphibole lineation and as pointed out previously, they transgress basic schist xenoliths. Sometimes the druses are sub-circular with diameters of 4mm although more often an elliptical shape is apparent. Hornblende when in contact with the vugs is always altered either to a green actinolite or a dark chocolate soft variety. Few good crystal shapes, usually obvious in such situations are found and only detached apatite crystals within the yellow mineral have angular terminations. In addition to apatite the minerals typical of the syenites are found together with zeolitic and montmorillonitic material. Two zeolites have been found in the cavities, harmotome Ba $(Al_2Si_6O_{16}).\ 6H_2O$ and stilbite (Ca,Na_2K_2) $(Al_2Si_7O_{18}).\ 7H_2O$. A greenish-yellow curdy mineral of the montmorillonite group has been determined as nontronite and this is sometimes admixed with the yellow rare-earth mineral, the presence of which was indicated by Von Knorring and Dearnley (op. cit). Apatite is ubiquitous in its association with this rare-earth mineral and this has led to the physical difficulty in obtaining specimens of sufficient purity for analysis. From laboriously hand picked and magnetic separated material, tested by U.V. spectrographic, XRF, and wet chemical methods it has become clear that ■7
Von Knorring and Dearnley's conclusions are substantially correct and La,Fe,Ce,Ca,Mg hydrated phospho-silicate best describes this mineral. Traces of Ba,Sr,Ti,Pb, Mn,Zr,Be,V,Ga and Na occur and in addition the following elements were found during an XRF scan U,Y,Zn,Sm,Cu,Th,Ni,K,Ag,Nd.

X-ray Diffraction scans of this mineral have shown the following lines.

SIEMENS X-RAY DIFFRACTOMETER SCAN OF THE YELLOW MINERAL FROM LETTERMORE QUARRY, BEN LOYAL.

Radiation Fe Kα, Calibrated against LiF.

d Å
5.22
4.70
4.60
4.53
4.20
3.551
3.510
3.317
3.104
2.875
2.523
2.234
2.220
2.152
1.877
1.742

Order of intensity

1 --- 3.104
2 --- 2.875
3 --- 4.53
4.20
5 --- 3.317
4.70

ASTM Card for Monazite 11-556

d	3.09	2.87	3.30	5.20
I/I_1	100	70	50	13

(Ce,La,Y,Th) PO_4

ASTM Card for Steenstrupine 14-211

d	3.09	2.87	4.20	5.20
I/I_1	100	100	70	30

$(La,Ca,Na)_3(Al,Fe,Mn)_3(Si,P)_3(O,OH,F)_{12}$?

Such an X-ray pattern is not dissimilar to steenstrupine and is substantially the same as monazite (Ce,La,Th) PO_4 and the mineral must therefore be isostructural with the latter, as well as with Huttonite $ThSiO_4$. Pabst and Hutton (1951) have shown that the phosphates of La, Ce, Pr and Nd are isostructural with monazite and huttonite, and in addition Bowie and Horne (1953) have shown that the mineral cheralite together with the synthetic compound $CaTh(PO_4)_2$ also have monazite structure. One significant fact is the absence of thorium in the make-up of the Loyal mineral and in this respect it is worth noting that Gordon (1939) reports a thorium free monazite from Bolivia, and Rose et.al. (1958) found less than 0.1% Th in monazite from Magnet Cove Arkansas. Monazite from other alkaline areas have been shown to have only low thorium contents and this may be a general trend in this type of rock (Jaffe 1955). Both heated and untreated specimens gave the same X-ray pattern. The specific gravity of the mineral at 2.90 is low and this must be correlated with the number of OH ions incorporated in the structure. ■8 The cerium-earths predominate within the mineral, lanthanum and cerium being major components and both samarium and neodymium were evident from XRF analysis. Exceptionally the lanthanum appears to exceed the cerium content. Thorium and uranium although detected were located only in slight traces. In contrast Oftedal and Saebo (1965) have shown that the boundary of the nordmarkite in the Grorud district of Norway has cavities in which rarer minerals, including sphene, zircon, allanite, helvine, milarite, fluorite, hematite, phenacite, bertrandite, ancylite, wulfenite and pyrosmaltite are concentrated, are enriched in yttrium and ytterbium and scandium is present; that is a similar paragenesis is here enriched in the yttrium rare-earths. Interestingly the barium zeolite harmotome is present at both localities, although obvious beryllium mineralisation is conspicuously absent at Loyal.

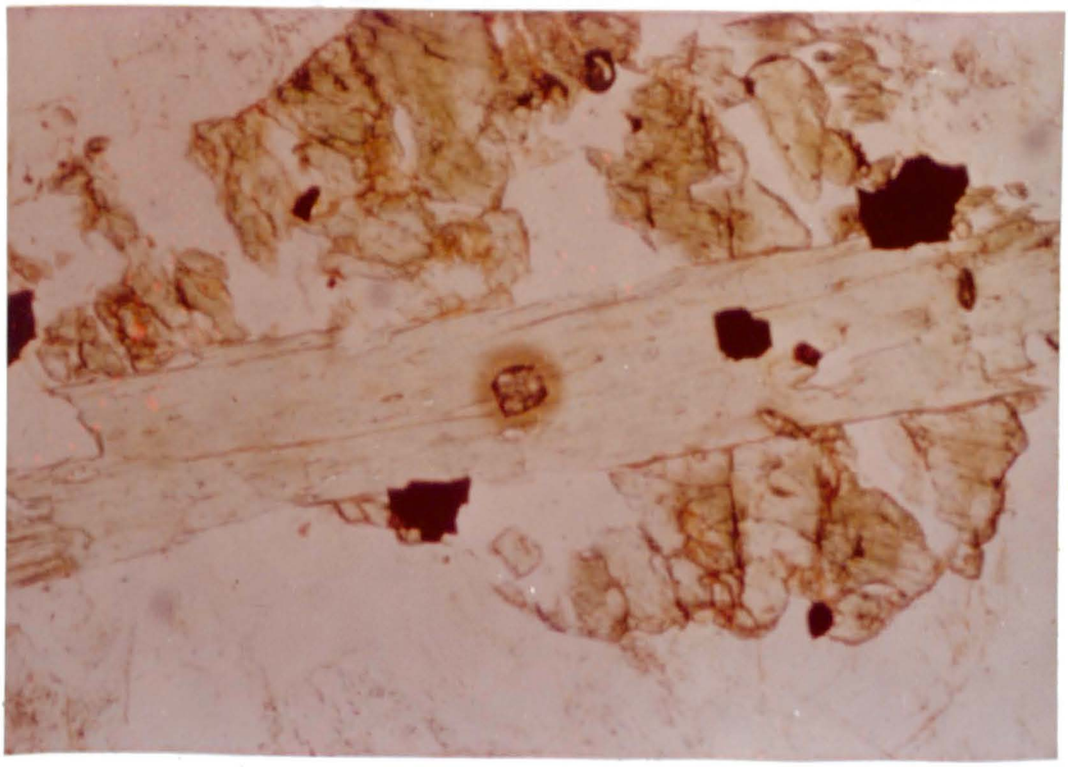
The origin of the miarolytic cavities is probably connected with pegmatite formation and the most likely cause of the phenomenon is the late emission of small quantities of gas pockets towards the close of crystallisation.

Alteration processes within the syenite.

Uralitisation, the pyroxene-amphibole transition.

Contemplation of Bowen's discontinuous reaction series for minerals crystallizing from a magma suggests that there is an inherent tendency for pyroxene to transform to amphibole with increasing differentiation. In the Loyal complex several instances can be cited in which amphibole appears secondary to initial pyroxene, although the overwhelming evidence points to primary crystallization of amphibole. In the Cnoc nan Cùilean body highly pleochroic hastingsitic ■9
amphibole occurs as irregular patches in the pyroxene crystals or independently, and surrounding feldspars are then clouded and sericitised. On occasion ragged outgrowths of pale actinolite ■9
associate with the green pyroxene. Within the Beinn Stumanadh mass however although amphibole and pyroxene coexist they are mostly separate and very rarely show replacive relationships, again at Loyal within the laminated rocks amphibole, near to ferro-edenite, is ■9
the chief component and replacive relationships are not seen. What is observed at Loyal can therefore be expressed as two different phenomena, the first magmatic, and the second probably related to late stage hydrothermal alteration. Eskola (1914) has proposed a mechanism whereby hypersthene and diopside are transformed to a more stable actinolite structure and Boyd (1954,1956) has studied the stability field of tremolites and pargasites which confirm the expected pyroxene-amphibole transition and an extrapolation of his graphs to

Loyal parameters indicates that at 660°C (the perthite solvus) this stability curve is intersected, that is the amphiboles of the laminated syenites are probably primary precipitates. That the secondary amphiboles, uralites, in the Cùilean mass are surrounded by clouded and sericitised feldspars shows that their genesis must be closely tied with this synantectic process. Other deuteric alterations, such as tourmalinisation, kaolinisation and greisening prominent in some granitic provinces are not seen in the Loyal rocks supporting the evidence of a 'dry' melt referred to in a previous section. Pale green biotite cuts both amphibole and pyroxene within the Cnoc nan Cùilean body.



Biotite cutting green pyroxene, Cnoc nan Cùilean. A pleochroic halo surrounds zircon within the biotite. Slide No. 27596 (18704) OL.

Amazonitization.

The occurrence of amazonite is unusual. Excepting the Loyal mineral, the author has been unable to find mention in the literature of other localities from Britain. Its presence at Loyal was first brought to light by Heddle (1879) who showed its occurrence in pegmatitic veins in the cliffs of Sgòr Chaonasaid. The material is scarce and is found only in pegmatitic veins and patches where it is associated with uncoloured microcline microperthites. In comparison with most other amazonites the Loyal mineral is very pale green, the colour is patchily distributed and often colourless microcline grades imperceptibily into the amazonite; not infrequently the green colouration picks its way between the strings of the perthite. Several explanations as to the origin of the green colouration in amazonites have been put forward for example:-

a) the incorporation of chromophore elements including -
   (i) traces of copper (Breithaupt 1847, Des Cloiszeaux, Koksharov)
   (ii) traces of ferrous iron (Eliseev 1949, Bassett 1956)
   (iii) traces of manganese (Przibram)
b) the amount of rubidium in the feldspar (Kapustin 1939 and Zavaritsky 1943)
c) traces of organic matter (Lebedev and Matveyev)
d) incorporation of 'large' rubidium ions, with coincident defects in the structure (Goldschmidt 1933)
e) the thallium content of the feldspars (Goldschmidt 1954)
f) the effect of radioactivity on thallium ions.
g) release of free rubidium ions by irradiation (Ahrens & Machatschki)

h) the substitution of fluorine for oxygen in microcline, (Oftedal 1957)

i) physical differences such as lattice defects or strain (Taylor et al 1960)

j) formation of Z-type colour-centres by a replacement of potassium ions by lead (Zhirov and Shistov 1965)

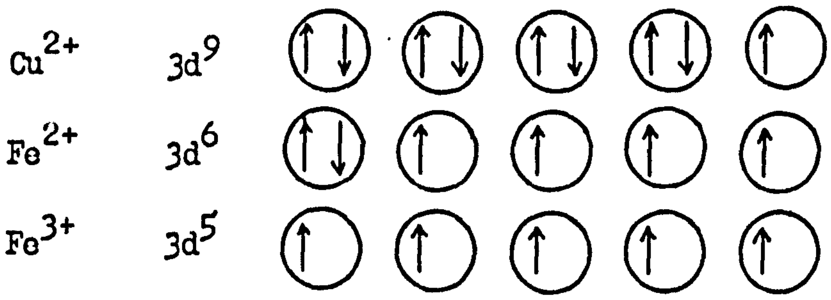
Essential to a correct assessment of the above is the known trace element mineralogy and its association. Often amazonite associates with the minerals of the elements Be,Li,Sn,Nb,Ta and the rare-earths, of these the first three are noticeably absent or present in only ■10 very small traces at Loyal. In other localities throughout the world amazonitic feldspar is characterised by high contents of Rb,Cs,Pb, and Tl. and lithium is sometimes concentrated thus:-

The rarer Group I elements in Amazonites (in p.p.m)

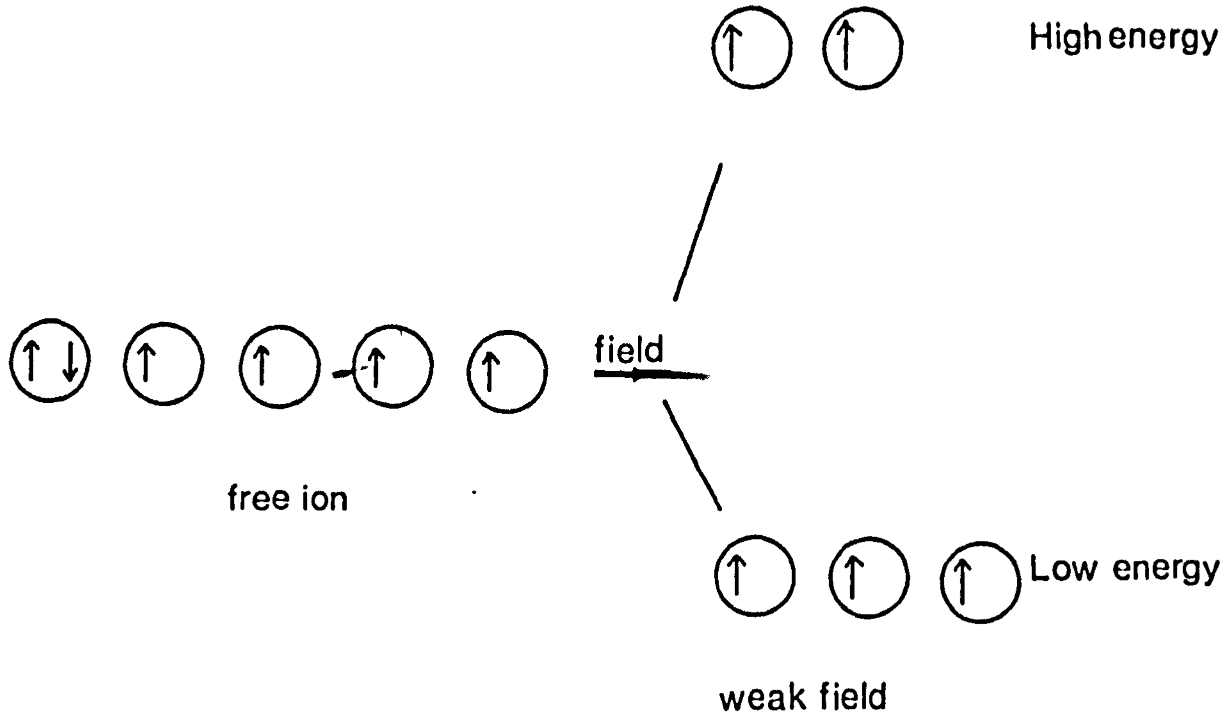
	Li_2O	Rb_2O	CsO
Varuträsk	nd	33,000	6,000
Ilmen Mtns.	nd	31,200	nd
Utö, Sweden	4,700	25,400	2,400
Madagascar	250	10,200	nd
Königshain, Silesia	nd	8,700	nd
Miask, Urals, USSR	5	6, 800	120
Pike's Peak, USA	nd	5,000	30
Zdan Mtn, Czechoslovakia	nd	2,300	50

Work at Pike's Peak USA on co-existing amazonite, reddish feldspar and graphic feldspar indicate a ten times concentration of rubidium in the amazonite, but, as Goldschmidt (1954) pointed out the Zdan amazonite is rubidium poor and some non-amazonitic feldspar for example those at Varuträsk have very high concentrations of rubidium. The high lithium content of the Utö amazonite is due to included blebs of petalite Li $(AlSi_4O_{10})$ and the cesium in like manner is probably related to pollucite. Additionally the Group III elements gallium, at Pike's Peak, and thallium up to 100 ppm in Madagascan amazonite appear to be concentrated in varying amounts. Neves et. al. (1971) have indicated no strontium and in only one case appreciable barium in amazonites from Mozambique, however the author using U.V. spectrographic and XRF techniques for the Chaonasaid amazonite finds K,Na,Al, and Si as majors, Sr,Rb,Pb and Ba as minor constituents and with traces of Fe,Cu,Zn and Ca. Much of the strontium, perhaps 40 - 80%, may be radiogenic derived from the decay of $Rb^{87}_{37} \longrightarrow Sr^{87}_{38} + e^-$. Coexisting white feldspars had only K,Na,Al and Si as major elements and traces only of rubidium and lead. Cesium and lithium are absent in the Loyal amazonite where they have been preferentially incorporated in subsidiary biotite, interestingly this minor biotite contains trace amounts of Be and Sn as well as Rb, just the elements with which amazonite is normally found. Taylor et al (op. cit) likewise report no Li,Sn,Be or F in amazonites from Southern Norway.

From the trace elements contents therefore it is apparent that the majority of amazonites are enriched in rubidium, cesium, thallium, lead and possibly lithium relative to colourless feldspars, but as Goldschmidt has pointed out, rubidium-rich colourless feldspars are found which suggests that Rb cannot be the element responsible for the green colour. An equivalent argument can be presented for both lithium and cesium. Oftedals' (op. cit) observation on fluorine - oxygen replacement is not substantiated by experiment and this then leaves only two mechanisms to account for the green phenomenon. The incorporation of other trace elements within the feldspar structure or crystal defects of various kinds; which ever process is preferred, account must be taken of the patchy nature of the colouration at Loyal. That traces of Fe,Cu and Zn have been found in the Chaonasaid amazonite may be significant since the great majority of coloured inorganic materials contain transition metals. For minerals to appear green (4912-5750 Å) they must absorb radiation in the violet and orange-red region of the visible spectrum, and absorption has a high probability whenever an ion has a partially filled d or f electron shell. Of all the ions possibly present only Cu^{2+} Fe^{2+} and Fe^{3+} ions have unfilled d shells, respectively $3d^9$, $3d^6$ and $3d^5$ all the rest have filled p and d orbitals or unfilled f orbitals. These three ions have the following configurations:-



The interaction of these ions when placed in an electrostatic field on anions within the feldspar structure disturbs the energy of the various d levels and these are then split into two sub-levels, two of the d orbitals in unfavoured positions relative to the other three. Thus for the Fe^{2+} ion:-



the difference in energy of these upper and lower levels is commonly similar to the energy of a photon or radiation in the visible region of the spectrum, and this energy may be absorbed and cause the electron to jump from one level to another, this excitation of the d electrons removes the essential degeneracy of the five d levels and causes the colour of transition - metal complexes. The position of the absorption band(s) shown by these transition metal ions depends on the distance of the negative charges from the central cation and on the electronegativity of the surrounding groups. As the Si - Al - O bonds have considerable covalency (approximately 50% ionic) splitting is increased and more energy is required to excite electrons. Thus the absorption bands move to shorter wavelengths, which could explain the green in the amazonite. The position of the absorption bands depends on the nature of the species producing the negative field in this case oxygens tetrahedrally co-ordinated to metal ions, and therefore the colour is not at all characteristic of a given ion.

Of the three ions, ferric ions show very little interaction with visible light since the 3d electrons are unpaired. Electrons therefore can only occupy the same orbital if the spins are opposed, and excitation can only occur if the spin orientation changes. This transition is said to be spin forbidden, Fe^{3+} does show such spin forbidden transitions but the process is unfavourable as the electrons are reluctant to change spin, and the absorption bands are of feeble intensity. If we are looking to Fe^{3+} for the colour in amazonite we must look to electron delocalization phenomena or simple photochemical reduction processes. A similar argument could be ranged for Mn^{2+} whose electronic configuration is the same as that of Fe^{3+}. Deer, Howie and Zussman (1966) pointing to the replacement of divalent Mg,Sr,Mn and Fe for Ca in the alkali feldspars, are of the opinion that Fe^{2+} is present only as impurities and not incorporated structurally. Divalent copper seems the only possibility remaining if metal d electron transitions are responsible for amazonite colour. Most other amazonites have copper values not normally exceeding 4 ppm so that this seems unlikely.

It has long been known that the green colour of amazonite is destroyed on heating, and experiments by Oftedal (op. cit) confirmed by the author show that the colour is lost between 270°C and 300°C which demonstrates that the green colouration was formed at about 250°C. Conversely if the colourless feldspar is then irradiated under X-rays the colour is restored. Analogous changes can be produced in the laboratory on simple salts such as KCl or CaF_2, where heating again causes bleaching and irradiation revives the blue colour; the changes here are connected with defects in the structure of the ions, either one in which an ion migrates to an interstitial site leaving a vacant hole (a Frenkel defect) or the ion is absent altogether (a Schottky defect) as these are irradiated the free electrons fill the holes in the ionic structure and give rise to F, or colour centres, a similar process could explain the colour of amazonite. However, as the number of Frenkel and Schottky defects increases exponentially with increase in temperature the number never becomes large as this would lead to melting and since the green colour of amazonite forms at temperatures close to 250°C it is to be expected that these defects will be few in number.

The two other common defects in crystals, mosaic and stacking dislocations, are unlikely to cause colour defects. At short wavelengths a further process, charge transfer or photochemical oxidation reduction may take place. For example the intense colours shown by metallic oxides and sulphides are in part due to such changes, thus for ferric oxide:-

$$Fe^{3+} + O^{2-} + \text{photon} \longrightarrow Fe^{2+} + O^{-}$$

All inorganic materials have these spectra but only those with easily reduced cations or oxidised anions will produce this absorption in the visible region. Fe^{3+} substituting for Al^{3+} in the silica tetrahedra of the Loyal amazonite could account for the green colour, the same restrictions as mentioned previously must apply to Fe^{2+}.

Zhirov and Stishov (1965) have outlined an explanation in which Pb leads to a structural distortion of the feldspar lattice where one ion of lead substitutes two of potassium. The author considers this to be the most likely of all explanations, although their concept of active and inactive lead is somewhat vague. These authors envisage active and inactive lead tied in different structural positions thus:-

$$2K^{+} \rightleftharpoons Pb^{2+} \quad \text{active lead}$$

$$K^{+}Si^{4+} \rightleftharpoons Pb^{2+}Al^{3+} \quad \text{inactive lead}$$

this latter coupled substitution having no colour effect.

The process by which this amazonitization takes place is obscure although Zavaritskiy (1943) demonstrated that the depth of colour is related to metasomatism and that amazonitization is a later process than albitization.

The amazonites of Sgõr Chaonasaid are closely associated with allanites rich in thorium, and galena is found within the containing pegmatites, no adjacency between either mineral and amazonite is apparent although their close proximity suggests that both F type colour centres and 'active' lead replacement distortions predominate. Amazonitization is seen principally as a replacement process, related to albitization, later than this and is a type of lead metasomatism thus:-

$$2KAlSi_3O_8 + Pb^{2+} \rightleftharpoons Pb(AlSi_3O_8)_2 + 2K^+$$

The high contents of strontium and barium in the Loyal amazonite indicates less fractionation than is apparent elsewhere and this would accord well with the very pale, patchy green colour of the amazonite and indeed with the marked absence of Be,Li and Sn in the pegmatites.

Epidotization and chloritization

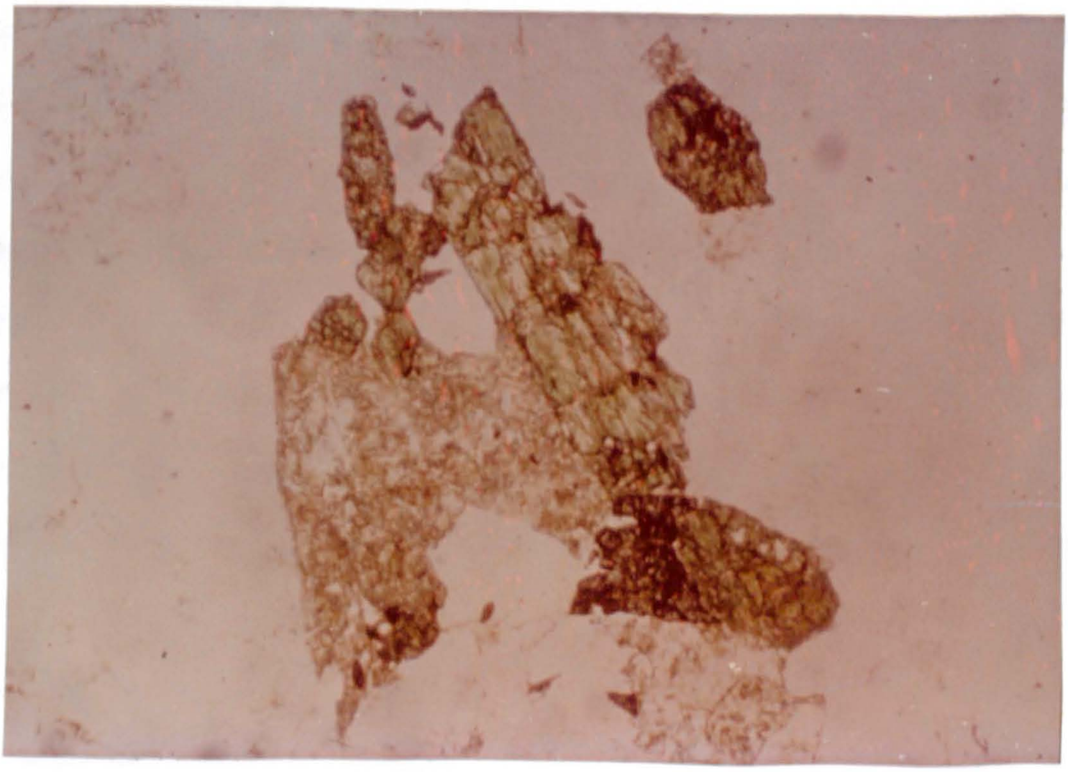
These two minerals are uncommon within the Loyal syenite although green epidote has been separated from the beach concentrate at Loch Fhionnaich.

Thin sections of the syenites show that epidote is concentrated at three sites, along with amphiboles and pyroxenes, where Moinian rocks have been incorporated as xenoliths or in close proximity to the contact, and where alteration of the feldspars is obvious. Chlorite is frequent only in joint planes along the northern edge of the complex. Such a paragenesis, excluding those of obvious Moine parentage, indicates response to a late stage deuteric process in which mafic minerals have been altered to epidote. Evidence for this amphibole - epidote transition is furnished in the almost perfect match in the elements determined for each of the minerals by U.V. spectrographic method. The expected pseudomorphing of the mafic minerals by penninitic chlorite is unseen and corroded hornblende remnants are typical; this could mean that the chlorite has migrated away into joint cracks, an observation confirmed in the joint faces of Sgòr Chaonasaid.

Unrelated to this epidotization is the formation of the cerium-rich epidote, allanite which is common in parts of the intrusion, is several centimetres long in some pegmatites and is a primary crystallate.

Carbonate formation.

The occurrence of strontianite within the Loch Loyal syenites is unusual. As Marmo and Siivola (1966) have shown only exceptionally do barium and strontium form independent minerals in igneous rocks. Gallagher et al (1971) have pointed out the barite and celestite in carbonate rich syenite associated with faulting at the north-east corner of Loch Loyal. Barite occurs also with faulting in the Moine rocks along the northern flanks of the Loyal massif. Late stage carbonate is widespread and occurs within the syenite and in the associated pegmatites, it may be found infilling boundaries between the crystals, occupying oval cavities within the syenite or in distinct bladed forms up to 10mm in length. The oval cavities have very fine acicular white or cream crystals radiating to the void centres. Carbonate replacement is particularly important at Sròn Ruadh within the Beinn Stumanadh mass where strontianite is seen to pseudomorph mafic material. Hematite is an invariable accomplice and frequently, former subhedral hornblendic crystals have their outline margined by this reddish mineral. The whole of the pseudomorph is never fully occupied by a single carbonate grain but is filled with interlocking small anhedral crystals. A full sequence from unaltered mafics to full pseudomorphism is evidence and in longitudinal prismatic sections the carbonate preferentially picks out the cleavage first and is then found, with chloritic material in close attendance, together with ubiquitous iron-ores. Besides these carbonated pseudomorphs a second generation of carbonate is typical in very, very thin veins which transgress perthite lamellae, and pseudomorphs but picks out zone lamellae. So three modes of occurrence, interstitial, pseudomorphic and cross-cutting veinlets are observed broadly related but complex in detail.



Strontianite together with epidote in syenite from Sròn Ruadh, Beinn Stumanadh. Slide No. 27602(19204). Ordinary light.

Heddle (1883) first showed the presence of strontianite in the Chaonasaid cliffs, as well as in the Ben Bhreck boulder which he considered of Loyal parentage, he gave the following analysis for the Bhreck strontianite:-

SrO	58.846
CaO	8.529
CO_2	32.305

Material separated by the author from the Sgor Chaonasaid pegmatites, and examined by U.V. spectrography showed the following elements:-

Major	Sr, Ca, Ba,
Minor	Pb, Fe, Mg
Traces	Mn, Na, Cu, Al, Si, Bi, Cr, Ti, Ag, V, La

The carbonates of Ca, Ba, Sr and Pb are known to form an isostructural group and Foivre (1944) in experimental studies of the $SrCO_3$ - $CaCO_3$ system demonstrated that orthorhombic carbonates of Ca and Sr are isomorphous and form a continuous series of solid solutions. Analogous results were obtained for the $SrCO_3$ - $BaCO_3$ system. Vlasov (1966) indicates that in rare cases strontianite can contain lead. In comparison with other strontianites that at Loyal shows a marked enrichment in both barium and lead, and copper, bismuth and silver are unusual traces. Many strontium minerals carry rare-earth elements mostly of the cerium group in all probability these replace calcium and not strontium, since in these minerals calcium occupies a specific crystallochemical position. That rare earth elements are low in Loyal strontianite suggests that the calcium is replacing part of the strontium and does not occupy a specific crystallochemical site or have a high tenor. What could be concentrated because of its stability in the divalent state compared with other trivalent rare-earths is element 63, europium and its chemical properties are much closer to those of strontium and lead than the other rare earths. The spectrum of Eu is in a portion where it could have been missed due to interference.

Heltz and Holland (1965) found that the solubility of strontianite decreased with increasing temperature and that its precipitation is only likely when the ratio of $^{m}Sr^{2+}/^{m}Ca^{2+}$ reaches a high value. In the paragenèsis under investigation, this seems to produce few problems as the syenite is markedly deficient in calcium.

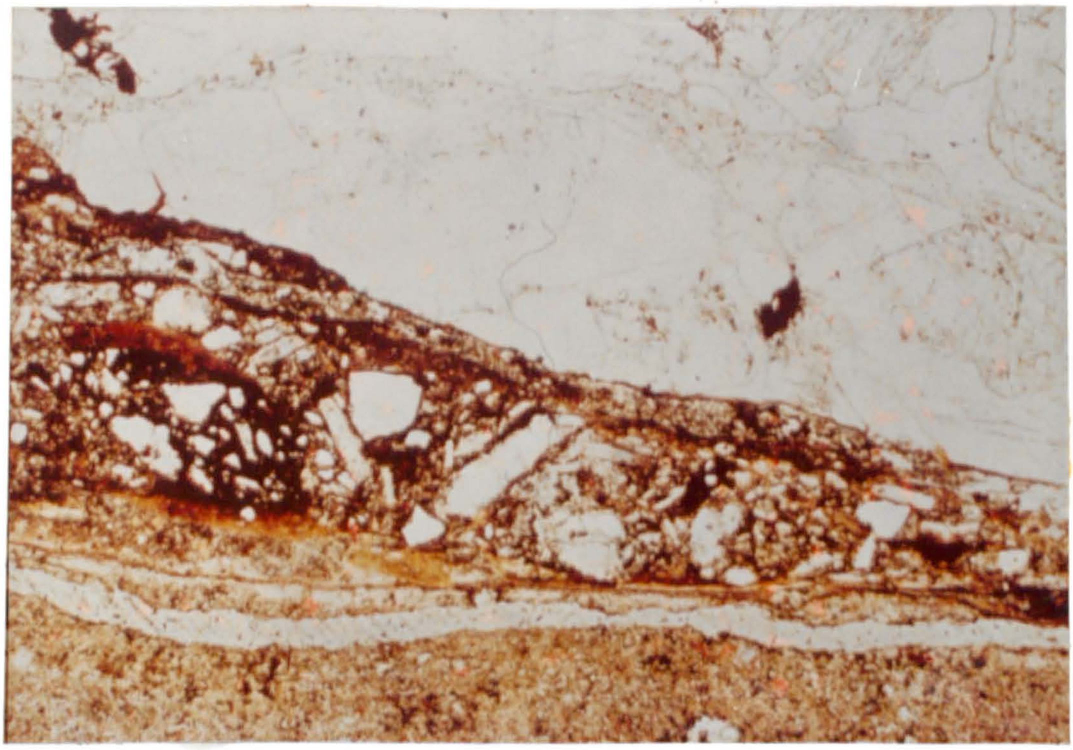
It has long been known that strontium is concentrated in syenites and nepheline syenites and Goldschmidt (1954) considers it a residual derived from fractional crystallization. The increased tenor of Strontium in alkaline rocks can be attributed directly to their more differentiated nature and the none availability of calcium in the magma. That strontianite has not been described more frequently from syenitic rocks is surprising. They have been recorded in association with carbonatites from Malawi and Larsen and Pardee (1929) mention an occurrence in the alkaline rocks of Libby, Montana U.S.A.; the strontianite within the Strontian granite, discovered by Walker in 1764 and described by Hope (1798), occurs together with lead mineralisation. Strontium carbonate in these cases is regarded as a product of late stage hydrothermal mineralisation, however those related to carbonatites and some of those at Loyal must have been primary precipitates at a low temperature; whether they were initially celestite and then reverted to strontianite is not clear.

Where strontianites are found together with lead mineralisation, the usual case, one would expect Pb to be incorporated in the structure, this is not borne out by a search of the literature and its occurrence as a minor constituent at Loyal is therefore unusual. Copper, bismuth and silver as traces might be expected because of their geochemical coherence with lead although Goldschmidt (op. cit) shows the grorudite (a rock closely similar to Loyal syenites) in the Oslo province to be somewhat enriched in silver, a point which will be taken up later when discussing trace elements content of the Chaonasaid galenas.

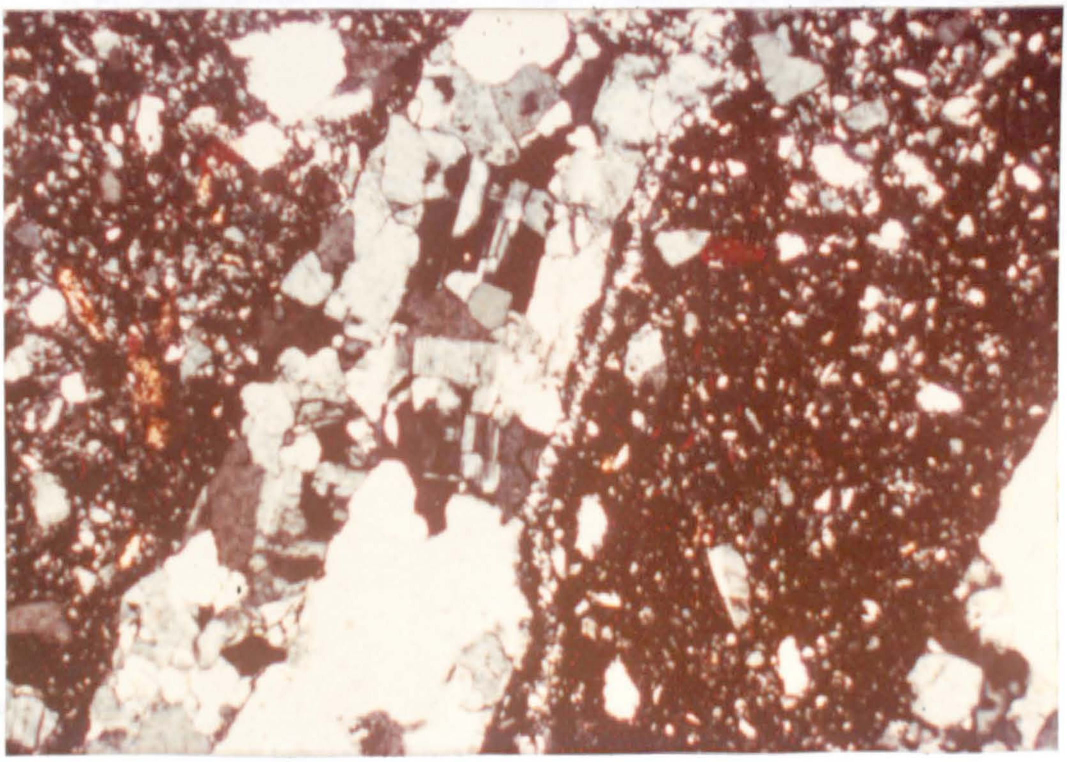
Red-ochre veins

Transgressive to the syenites especially those of Beinn Stumanadh, and usually less than 10mm thick are anastamosing veins of ochreous hematite. These veins punch straight through the syenite matrix totally disregarding grain boudaries and the contact between the two is invariably sharp, although occasionally delimited by very fine strained quartz veinlets. Outer parts to the veins have darker brown compact hematite whilst at the centre of the veins porous light brown material admixed with syenitic fragments is found. Within the compact outer zone aligned 'shards' of quartz and minor feldspar are embedded in rust brown hematite, generally the crystals are below 0.2mm, numerous, and invariably broken. Sub-angular to sub-rounded quartz is found sparsely distributed throughout the porous hematite.

In places, vein material, gives way to a hematitic breccia in which large syenitic pieces are held in a groundmass of hematite; the pieces are again 'shard-like' and reach up to 20mm or more in length. This breccia is seen to perfection in cliffs above Allt nan Tarmachan at the junction between the syenites and Moine sediments. Where the veins impinge on pegmatitic veins they cut them and therefore have a later paragenesis.



Red ochre vein, showing quartz and feldspar 'shards' in the compact outer zone. Slide No. 27605, Sron Ruadh, Beinn Stumanadh.



Hematite-syenite breccia showing feldspar fragments embedded in hematite. Cliffs above Allt nan Tarmachan, Beinn Stumanadh XN. Slide No. 27623.

Hematite is often seen to pick out feldspar cleavages. Magnetite occurs in the syenites close by the veins and the weathering of this mineral has imparted the reddish colour typical of much of the Beinn Stumanadh complex (cf. Sròn Ruadh - red nose). The hematite itself is a red-earthy variety of ochre (reddle) which has titanium and traces of vanadium in its make-up. It is well known that ferric minerals typify late stage magmatic processes and the occurrence of magnetite and hematite in close proximity at Loyal shows the increased differentiation under which the veins were formed. Goldschmidt (1954) has pointed out that hematite dust or crystals within potash feldspar may be due only to its formation from initially 'dissolved' ferric iron within the feldspar lattice. The normal crystallate from acidic rocks is magnetite Fe_3O_4 and the ferric form indicates response to hydrothermal activity.

Zeolite occurrences.

In almost all cases zeolites are located within miarolytic cavities together with a canary yellow rare earth mineral and buff-pink montmorillonite. No extensive zeolitisation occurs at Loyal. Two platy, stilbite and heulandite, and one equant zeolite harmotome, have been found in such circumstances.

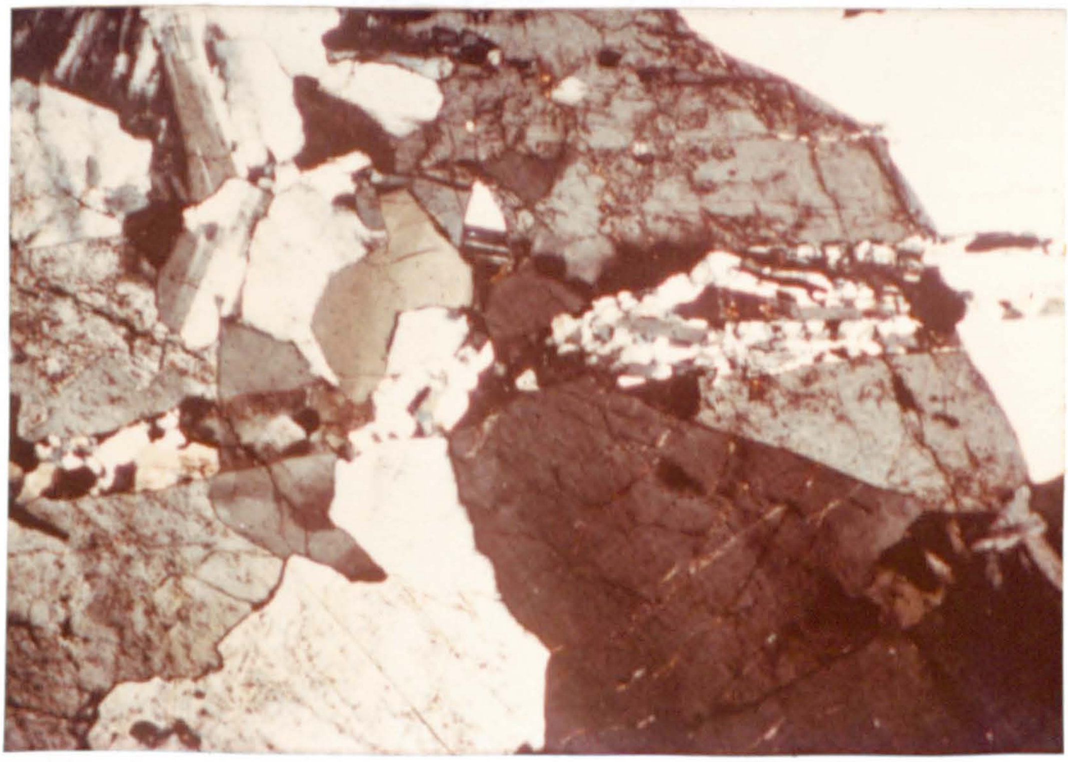
Stilbite	$(Ca, Na_2, K_2)\ (Al_2\ Si_7\ O_{18})\ .\ 7H_2O$
Heulandite	$(Ca, Na_2)\ (Al_2Si_7O_{18})\ .\ 6H_2O$
Harmotome	$Ba\ (Al_2Si_6O_{16})\ .\ 6H_2O$

All three of these are typically late stage low temperature minerals of hydrothermal origin; interestingly natrolite, the harbinger of alkaline conditions, located in borolanite from Cnoc na Sroine, was not seen in Loyal rocks and analcite is conspicuously absent.

Harmotome is also recorded from nordmarkite druses in the Grorud district of Norway (Oftedal and Saebo op. cit).

Quartz veinlets

Cross-cutting the feldspar grains, and closely associated with hematitic alteration are a small number of very thin veinlets filled with a sutured mosaic of minute quartz grains.



Quartz veinlets cutting all other minerals. Allt an Lagh-Aird, Ben Loyal. Slide No. 27595 (18604).

A comparison of Loch Loyal syenites with other localities.

The C.I.P.W. norm

When the syenite from Lettermore quarry is fitted into the system proposed by Cross, Iddings, Pirsson and Washington (1902) the following indices obtain I.5.1.3, that is the Loyal rock is persalane, perfelic, peralkalic and sodi-potassic with nordmarkose and phlegrose affinities. A comparison with 'superior' analysis quoted by Washington (1917) indicates close correspondence with the nordmarkites described by Daly (1903) from Mount Ascutney, Vermont U.S.A. and a syenite porphyry from Huesco Tanks, El Paso Co. Texas examined by Richardson (1909). About a dozen of Washington's analyses of I.5.1.3 type rocks show features closely matching those of Loyal, all except one of which, a granite porphyry, are described as nordmarkites, pulaskites, quartz-syenites and syenites. Two are trachytes showing the volcanic equivalence of these rocks.

Johannsen's classification.

In contrast to the C.I.P.W. system outlined above the method employed by Johannsen (op. cit) is strictly mineralogical, quantitative and modal. The percentage of quarfeloids is 89.1% and therefore Loyal rocks are in Class 2 (although not far removed from Class 1). In the plagioclase fraction the albite content lies between Ab_{90} and Ab_{100} which gives Order 1 and 11.4% Qtz places it within families 5, 6, 7 or 8 (although again not greatly above the 9, 10, 11 or 12 families at 5%). The ratio of the alkali feldspar to plagioclase shows that it occupies Family 6. Summarily then it is designated 216P in the classification of Johannsen which would place it in his sodaclase-granites, however the arbitrary nature of the rock divisions means that parts of the Loyal complex transgress these fixed boundaries and rocks lying in families 116P alaskite, 1110P leuco-sodaclase syenite and 119P nordmarkite are to be expected locally. Significantly a perthosite from Sail an Ruathair, Loch Ailsh described by Phemister (1926) was designated 1110P but the difficulty in assessing the plagioclase content of perthites suggest that this and other perthites ought in fact to belong to the 119P nordmarkite type.

It is apparent then that the Loyal rocks are intermediate between nordmarkites and sodaclase granites and if 5% quartz is taken as the limit of syenitic rocks, as it is by Johannsen then Loyal rocks are granites. Most other authors have allowed a greater latitude in the free quartz content of syenites and 10% is a figure more often suggested.

Shand's classification

Lettermore rock is best described by the parameters XSpβ(12) in the classification proposed by Shand (op. cit); that is a slightly over-saturated peraluminous soda-potash leuco-syenite.

The fit with Niggli's concept of magma types.

The following Niggli values obtain for the rock from Lettermore Quarry:-

al = 40.60   mg = 0.63
fm = 12.95   qz = +12.58
c = 5.56   si' = 262.70
alk = 40.89   ti = 2.57
si = 275.20   p = 0.26
k = 0.39   h = 7.34

Since the Quartz Number, qz, is an expression of saturation with respect to SiO_2 a positive value in this parameter indicates that free quartz is to be expected. Similarly the degree of silication, as conceived by Rittmann (1933) Si^o equal to $\frac{si}{si - qz}$ is greater than one and therefore Loyal is oversaturated with respect to silica. The quantity of alkali feldspars present, 2alk, is equal to 81.78, which is divided between sodium feldspar Ab, (1 - k) 2alk, equal to 49.89 and potassium feldspar Kf, k2alk equal to 31.89. A measure of the alumina over the alkalies is a determination of the anorthite content in the case of Lettermore T = (al-alk) = -0.29 showing that anorthite is absent. At Loyal c > (al - alk) which shows that after the formation of alkali feldspars, some calcium will remain which cannot be combined with alumina and must therefore be incorporated in the dark constituents. This part of the calcium is known as c' which totals +5.85 in Lettermore. Subtraction of (alk - al) shows +0.29, viz. the alkali is in very slight excess which suggests that alkali hornblendes can be expected to occur. Alkali feldspar ratios indicate 61% sodium feldspar and 39% potassium feldspar. Burri (1959) has shown that very calcium poor or calcium free alkaline rocks can be adequately representated on an alk, al, fm triangle within an al - fm - c - alk tetrahedron and when Loyal rock is fitted into such a triangle it plots very close to leucocratic alkali syenites described by Lacroix (1916) from Alter Pedroso in Portugal. Niggli (1936) used the values si, al, fm, c, alk, k and mg in the formation of 'magma types' in order to characterize the rock chemistry, he stressed however that these types refer exclusively to the chemical relations and therefore do not represent any form rock classification. In the sense intended 'magma type' is merely an abbreviated designation for rock chemistry and actual mineral composition is not taken into account. Three principal divisions are used based on the ratio of al:fm, al:alk and the c value, as compared to the average composition of the upper lithosphere thus:-

	si	al	fm	c	alk	k	mg
Average igneous rock	200	30	32	18	20	0.35	0.50
Loyal	275	41	13	5.5	41	0.39	0.63
correlation	+	+	-	-	+	=	=

Magma types, such as Loyal, for which al is positive and fm negative are termed salic magmas; also al alk and it is therefore relatively alkali-rich and with values of 5.5 Loyal is a c-poor magma.

In a comparison with tabulated magma types of the sodic series, a very close approach to the nordmarkitic type of alkali-granitic magma was evinced thus:-

	si	al	fm	c	alk	k	mg
Loyal	275	41	13	5.5	41	0.4	0.6
a4 Nordmarkitic	280	41	15	5	39	0.3	0.15
e1 Bostonitic	230	46	12.5	2	39.5	0.3	0.3
e2 Pulaskitic	210	40	18	10	32	0.3	0.3
g1 si-Sodic syenitic	300	35	28	5	32	0.25	0.2

Type a = alkali-granitic magma type

Type e = subplagiofoyaitic " "

Type g = sodic-syenite " "

From these calculated Niggli Numbers the following information has been gained.

a) Free quartz is present.

b) The ratio of sodium feldspar to potassium feldspar is approximately 3:2.

c) Alkalis are in very slight excess (or approximately equal to al) and therefore alkali pyroxenes and /or amphiboles can be expected.

d) It is of a salic (sub-femic) magma type.

e) It is a type relatively rich in alkali components.

f) It is a c-poor magma type.

With the reservations noted previously on the use of ratios, and "magma types" not being strictly of a classificatory nature it seems that the Lettermore rock is best described as a quartz-nordmarkite.

A chemical comparison of Loyal rocks against the average compositions of igneous rocks.

A table is presented overleaf in which Lettermore rock is compared with the average chemical composition of igneous rocks as reported by Nockolds (1954). It is apparent that the average alkali-syenite and especially the average alkali-trachyte approximates very closely to the Lettermore rock. In regard to the oxides, quartz-diorites, granodiorites and alkali granites are more siliceous, the latter especially so. Alumina is much more abundant in the average nepheline syenites and only in alkali-trachyte and nepheline syenite do similar CaO percentages obtain. Only the trachyte and alkali-syenite approximate to Lettermore in Na_2O content, the nepheline syenite had significantly higher and the rest significantly lower percentages. All the alkali-rich rocks have similar potash contents. From this superficial comparison it then seems that Loyal rocks are close to both the average alkali syenite and the average alkali-trachyte, especially the latter.

A world-wide comparison

A comparison with rocks of similar chemical composition worldwide, in Table again shows the close affinities with quartz-syenites, nordmarkites and trachytes; pulsaskitic types are silica deficient in comparison. Many of the rocks within the table show very close similarities with the Lettermore rock and analyses VIII and XV are almost identical.

A Scottish-North American Petrographic Province?

Within the Northern Highlands of Scotland besides the Loch Loyal syenites four other alkaline complexes are known namely Loch Ailsh, Loch Borralan the Glemelg-Ratagain complex and the metamorphosed syenite of Glen Dessarry together with the minor intrusions described by Sabine (op. cit.). Additionally in recent years their have come to light areas in which soda-metasomatism has played an important role. These include Cluanie (Leedal 1952), Ve Skerries (Walker 1932), Derry Lodge and Glen Lui (McLachlan 1951), the Inverness-Foyers area (Deans, Garson & Coats 1971), and Loch Hourn and Glen Cannich (Tanner & Tobisch 1972).

Dewey (1969) in his appraisal of the Appalachian/Caledonian orogen shows a close alignment of the Moine thrust with the Luke Arm fault and the Logans thrust in North America and it may be significant that in a similar tectonic setting alkaline magmatism is widespread. Varying degrees of alkalinity in rocks from Newfoundland down as far as New York State (the Novanglian petrographic province of Pirsson and Washington) is evidenced, and the Monteregian province of Canada (chemically very close to Loyal syenites) is tied intimately to the St. Lawrence Rift system. In support of the tectonic setting influencing the alkaline magmatism it might be noted that all the plutonics of the North West Highlands lie close to the Moine thrust, and as Hall (1969) has demonstrated, a marked parallelism with the Caledonian structures exists in the variations in normative albite and orthoclase, quartz and Na_2O/K_2O.

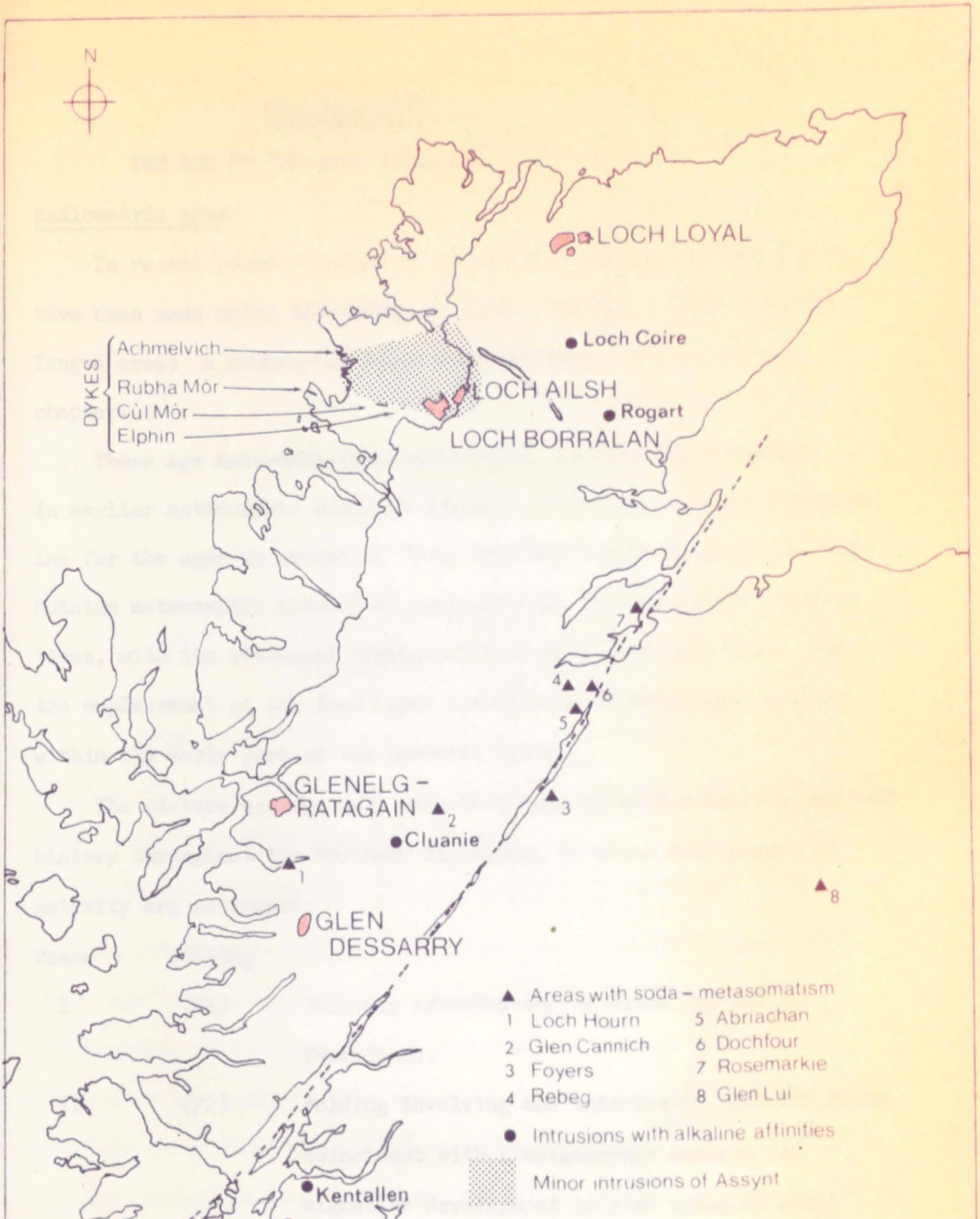
A comparison with Caledonian Newer Igneous Rocks.

A cursory glance at the following table reveals obvious differences between Loyal rocks and more "normal" Newer Igneous Rocks. In particular Newer Igneous Rocks are relatively enriched in SiO_2, FeO, and CaO and correspondingly poorer in Al_2O_3, Na_2O and K_2O. The aegirine granite of Rockall (Sabine 1960) is of Tertiary age and is added to the table only for comparative purposes. Although the syenitic plutons differ chemically from the North West Highlands Newer Igneous Rocks, these latter are more sodic when compared with the Grampian Granites. It appears that an alkaline petrographic province existed over the north-west portion of Scotland during Caledonian times.

Whether one regards the reconstruction of Scotland in O.R.S. times, as similar to that envisaged by Garson and Plant (1972) or by the simple displacement along the Great Glen Fault by Kennedy (1948) it becomes clear that if the ratio of the alkalies $Na_2O:K_2O$ are plotted on the outline of Scotland, ratios greater than unity are found only along and north west of the Great Glen Fault. Third order trend surfaces determined by Hall (op. cit.) show high normative albite trending through Jura, Kintyre, the Ross of Mull, Strontian and on through northern Scotland. Low normative Or follows the same path. These observations are indicative of higher temperatures prevailing in the central portion of the orogen and broadly mirror the Barrovian metamorphic zones (Barrow 1893) and the central geochronological zone of Watson (1964). Manifestations of alkaline type magmatism, following this alignment, occur from Kentallen northwards to the Shetland islands, although only north of Glen Dessarry are alkaline igneous rocks common. Nicholls (1950) considers the Glenelg-Ratagain complex to be a hybridization between petrographic provinces, the North-West Highlands Alkaline Province and a South West Highlands calc-alkaline type. The southern extension of the alkaline portion of this mixed assemblage is seen in the local development of alkali syenites in the appinite - lamprophyre suites in Moidart and further south in the kentallenite-aplite suite, which is also distinctly alkaline.

A summary of all available evidence.

Lettermore rock closely approximates to trachytes, quartz-syenites and nordmarkites and is best described as a leucocratic, soda-potash quartz-nordmarkite.



Alkaline magmatism in the North-West Highlands

CHAPTER SEVEN

THE AGE OF THE LOCH LOYAL SYENITES

Radiometric ages

In recent years a number of potassium-argon age determinations have been made using the isotope dilution method on rocks from the Tongue area; a summary of these is presented at the end of the chapter.

These age determinations bear witness to three main events. An earlier metamorphic event in Lewisian (Pre-Cambrian) times accounting for the ages in excess of 700my from the Borgie Inlier; the main Moinian metamorphic episode at about 422 my, that is within Silurian times, with its attendant overprinting of ages on Borgie rocks, and the emplacement of the Loch Loyal syenites about 400my ago, that is within the early part of the Devonian System.

The picture accords well with that determined for Moinian tectonic history throughout the Northern Highlands, in which four phases of activity are envisaged.

Phase	Folding	
I	(F1)	Tectonic interleaving of Moine and Lewisian formations.
II	(F2)	Folding involving the interleaved Lewisian rocks, coincident with a metamorphic maximum and migmatite development in some areas at about 500my.
III	(F3)	F3 deformation in the Moines. The accompanying metamorphism, weak on the western margin of the Moine Nappe, increasing eastwards with the development of migmatites. The closing of the Moine mineral systems w.r.t. Ar at about 422my.

Phase	Folding	
		Earliest granitic magmatism (eg Rogart 415my).
IV	(F4)	Conjugate folding, thrusting and local retrogressive metamorphism associated with the movement of the Moine Thrust. The main Caledonian magmatism with the emplacement of post orogenic granites into and through migmatites at about 402 ± 11my, in some cases at least, synchronous with thrust movements. (Bailey & McCallien 1934) Middle Old Red Sandstone sedimentation.
		Later minor intrusives of porphyrite, basic andesite and lamprophyres.

In summary the Loch Loyal syenites were emplaced about 400my ago, the earliest part of the Devonian system, into Moinian rocks which had become closed systems some 20my earlier.

Stratigraphic evidence concerning the age of the Loyal syenites.

Stratigraphic criteria offer little evidence in the assignment of an age to the Loyal rocks. Geikie (1888) in his examination of the breccias on Cnoc Craggie reveals that "upwards of 40% of the pebbles in the conglomerates are composed of the syenite of Ben Loyal". McIntyre et al (op. cit.) however failed to confirm such a finding and the author has searched blocks of the O.R.S. breccia at Craggie quarry and Beinn Bhreac and finds no rocks of Loyal parentage there.

The syenites are clearly intrusive into the Moine metasediments and therefore later, but the age relative to the Loch Ailsh and Loch Borralan intrusions further west is at present guesswork, although radiometrically they are contemporaneous within the limits of experimental error. If they are of the same age, as has been suggested by Read (1931) then the Loyal nordmarkite must be older than the thrust movements, or very close to it in age since unsheared alkali-syenite is seen to cut sheared borolanite in the Loch Borralan mass. The few stratigraphical constraints placed on the age of the Loyal syenites therefore support the radiometric ages, ie as late Silurian or early Lower Devonian.

A Summary of the potassium/argon ages of rocks from the Tongue district.

Locality	Grid Ref.	Rock type	Mineral	Method	Ref. No.	Age + Error in my.
Allt an Leacach	521374	semipelitic schist	biotite	1D	(3)	416
An Dubh Loch	522597	semipelitic schist	biotite	1D	(3)	428
Kyle of Tongue	553531	pelitic schist	biotite	1D	(3)	431
Tongue	605595	pelitic schist	biotite	1D	(2)	420 ±19
Craggie quarry	610527	muscovite schist	muscovite	1D	(2)	396 ±18
		"	"	TV	(2)	415 ±19
		semipelitic migmatite		1D	(3)	398
Round Hill, Loch Naver	622394	"	biotite	1D	(3)	400
		"		1D	(3)	401
Grumbeg, Loch Naver	627386	"	biotite	1D	(3)	415
4 mls. N.E. of Tongue	641608	semipelitic schist	muscovite + biotite	1D	(2)	419 ± 19
Bettyhill	709605	semipelitic schist	biotite	1D	(3)	410
Bettyhill	711621	biotite-muscovite schist	biotite	1D	(1)	390
Ben Loyal		Loyal nordmarkite	hornblende	1D	(2)	378 ± 17
Lettermore quarry	612498	"	pyrox	1D	(4)	404 ± 10
		"	"	1D	(4)	402 ± 9
		biotite-hornblende schist	hb + little biotite	1D	(2)	437 ± 23
Borgie Inlier		biotite-schist		1D	(2)	407 ± 18
Crocach quarry	640596	"	biotite	TV	(2)	422 ± 19
		"		TV	(2)	423 ± 19
		basic sill	hb	1D	(2)	370 ± 17
Borgie Inlier	640585	large ultrabasic body containing hb	hb	1D	(2)	745 ± 62
				1D	(2)	676 ± 57

KEY

I.D. = Isotope dilution

T.V. = Total volume

(1) = Giletti et al 1961

(2) = Miller & Brown 1965

(3) = Brown et al 1965

(4) = Brown, Miller & Grasty 1968

CHAPTER EIGHT

RADIOACTIVITY ASSOCIATED WITH THE LOYAL SYENITES.

Radiometric traverses in the Loch Loyal massif.

Radiometric traverses covering the Loch Loyal complex were undertaken by the author using a scintillation ratemoter, type NE 148A, manufactured by Elliott Process Instruments Ltd. The ratemeter is sensitive only to gamma radiation between 0 and 3000 micro-rôntgens per hour (ur/hr). Unlike a geiger counter, wherein the counts due to cosmic rays give an irreducible minimum reading equivalent to about 6ur/hr, there is no significant background with this instrument. Full scale deflection on the most sensitive range (x1) is due to about 130 counts per second, of which approximately only one count per second would be due to the affects of cosmic radiation; it is therefore possible to detect very low values of radioactivity.

Values prevailing in the Moine sediments away and close to the intrusion were measured in order to determine a regional background for the Tongue district. In few cases did this background exceed 12ur/hr and in many instances was between 5 and 10ur/hr; in particular extremely low values obtained over areas underlain by thick glacial drift. Unfortunately because of the great topographical variation within the Loyal range, it proved impossible to work to a grid system, even so several areas of anomalous radioactivity were delimited. 11

In general Moinian country rocks had <10ur/hr and Loyal syenites >20ur/hr. Measurements approximating to 30ur/hr are not uncommon in granitic terraines but readings in excess of this point to abnormal radioactivity. Four main radioactive anomalies were located:-

i. The west and north-west flank of Ben Loyal including the Loch Fhionnaich area.

ii. In the vicinity of Lettermore quarry.

iii. Along the eastern half of the Cnoc nan Cùilean intrusion.

iv. The northern edge of the Stumanadh mass from Sròn Ruadh as far as Cracknie.

A broadly similar condition was found by Ball & Plant in Gallagher (op. cit.). The Cnoc nan Cùilean mass was by far the most radioactive of the three bodies. High counts were obtained in the Allt Liath stream section within the basic syenites of Cùilean where values of 60ur/hr obtained. Below the cliffs of Sròn Ruadh, together with carbonate mineralisation, readings in excess of 120ur/hr were located in altered pink syenite. This rock was subsequently crushed, ground to a fine powder in an agate mortar and leached with concentrated hydrochloric acid and hydrogen peroxide, filtered and evaporated to dryness. Both treated and untreated material were then tested by XRF analysis. A concentration of Th, Zn, Pb, and U was obtained in the leached material, and the amount of thorium very greatly exceeded the other elements. In the untreated specimen thorium was again seen to have the highest tenor.

A consideration of trace element chemistry in the Loyal rocks suggests that the following natural radioactive isotopes possibly occur there - K^{40}, Rb^{87}, La^{138}, Ce^{142}, Nd^{144}, Sm^{147}, Nd^{150}, Ta^{180}, Bi^{209}, Th^{232}, U^{234}, U^{235}, and U^{238}. However since many of these have low crustal abundance and occur only in minute quantities in the Loyal syenite it is evident that Th^{232} is the chief radioactive element involved. U^{238} must be of secondary importance and the rare-earths do contribute to the picture. Potassium because of its voluminous occurrence in potash feldspars must contribute some considerable part to the overall radioactivity and Rb^{87} because of its concentration in amazonite should impart an increase to pegmatite radioactivity. Since radium is one of the chief gamma emitters in natural radioactivity it is clear that the thorium (4n) series is the chief decay pattern; the uranium (4n + 2) series is of lesser importance.

The principal decay series producing anomalous radioactivity within the Loyal mass are therefore:-

a) $${}_{90}Th^{232} \xrightarrow[13{,}900my]{h.l.} {}_{82}Pb^{208} + 6\,{}_{2}He^{4} + \text{energy (4n series)}$$

b) $${}_{92}U^{238} \xrightarrow[4{,}498my]{h.l.} {}_{82}Pb^{206} + 8\,{}_{2}He^{4} + \text{energy (4n + 2 series)}$$

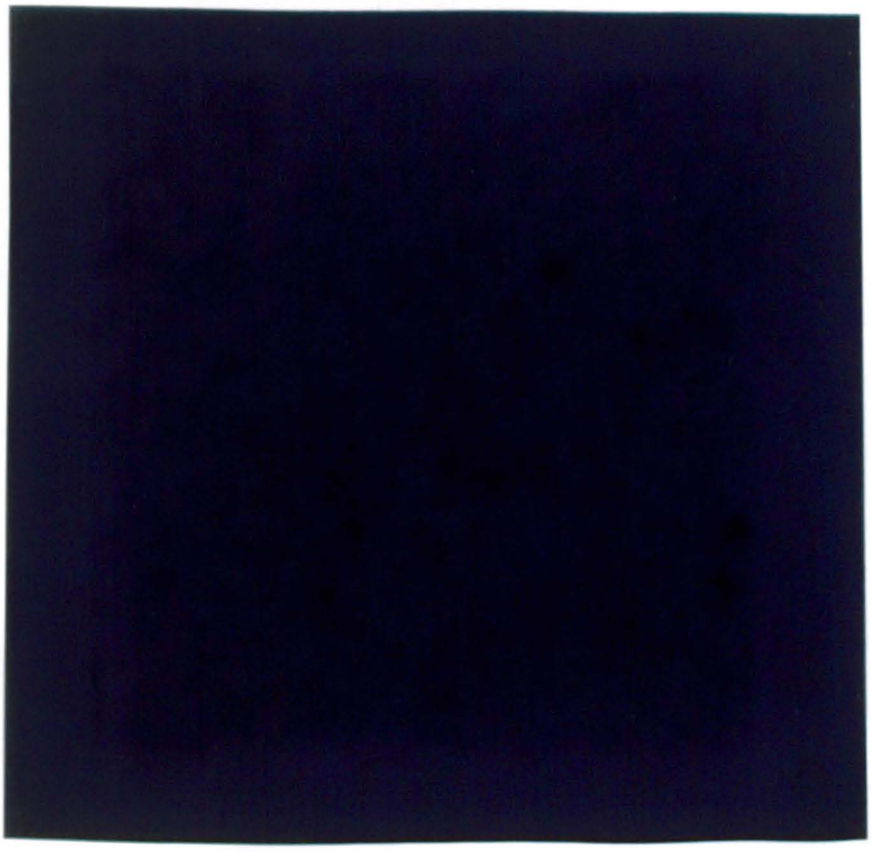
c) $$\begin{tikzcd} & \beta\text{ particle} \arrow[r, "h.l.", "11{,}850my"'] & {}_{18}Ar^{40} \\ {}_{19}K^{40} \arrow[ur, dash] \arrow[dr, dash] & & \\ & \epsilon\text{ capture} \arrow[r, "h.l.", "1{,}470my"'] & {}_{20}Ca^{40} \end{tikzcd}$$

d) $${}_{37}Rb^{87} \xrightarrow[50{,}000my]{h.l.} {}_{38}Sr^{87} + e^{-}$$

K^{40} and Rb^{87} are confined to the feldspars, whilst the bulk of the thorium resides in allanite (orthite) with smaller amounts located in thorite and thorianite. Uranium is found in the yellow monazite type mineral of Von Knorring and Dearnley, in the niobotantalate mineral polycrase and with montmorillonite. Rare-earth elements occur in the yellow mineral of Lettermore, in allanite, apatite and sphene.

Autoradiography of the Lettermore nordmarkite.

A cut block of drusy nordmarkite from Lettermore quarry was placed on a non-screen medical X-ray film (Kodak Kodirex) sensitive to α β and γ radiations (Bowie 1951) for a period of six weeks and showed a faint but distinct outline of the syenite block together with local "hot-spots" unrelated to the drusy cavities. The author is familiar with like conditions where sub-commercial grade uraninite was tested in which excellent detail takes just three hours to develop and such a long exposure for so faint an outline indicates the rather low tenor of radioactivity within the main syenite.



Autoradiograph of nordmarkite from Lettermore quarry (exposure time 45 days).

CHAPTER NINE

A CHEMICAL AND TRACE ELEMENT COMPARISON OF THE LOYAL ROCKS

Tables of major element chemistry, normative mineralogy, trace element content and various ratios applicable to the Loyal rocks are presented at the end of this chapter. A detailed comparative study has been undertaken of the following relationships:- 12

a) Moinian metasediments have been compared with the syenites.

b) Differences between the three syenites in the complex have been examined.

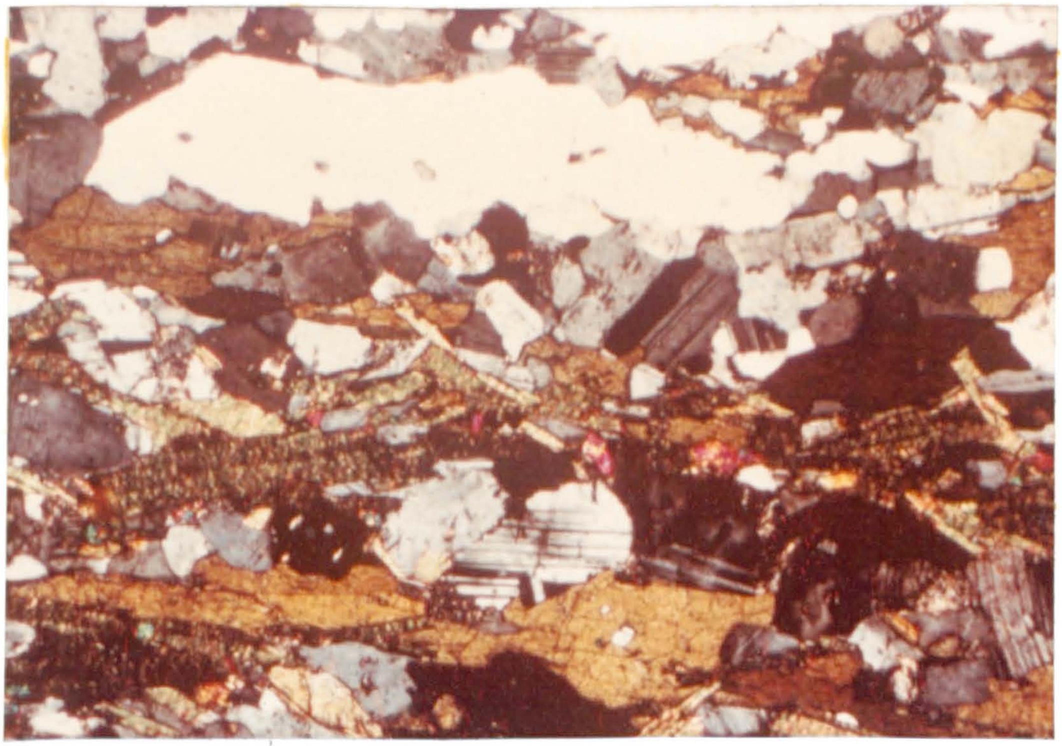
c) Pegmatitic veins and basic segregations have been compared with the typical Loyal nordmarkite.

d) A comparison has been made with the other alkaline intrusions in northern Scotland.

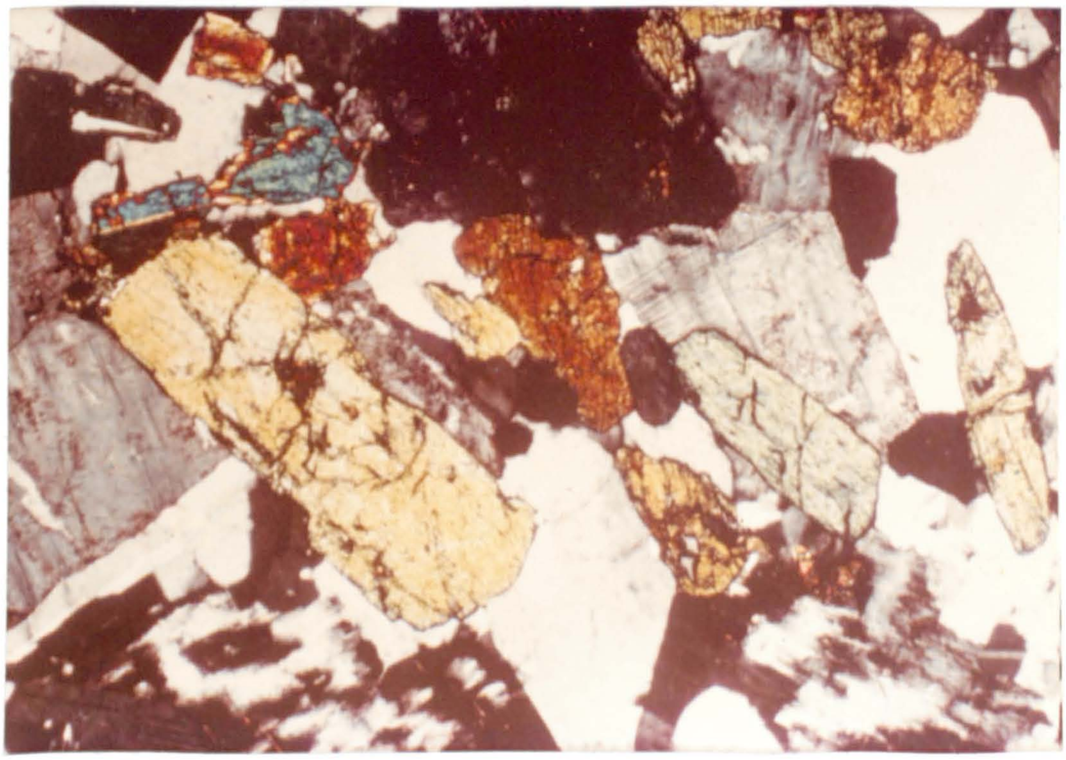
Differences between the Moinian metasediments and the Loyal syenites.

Each of the three intrusions in turn were compared with the surrounding Moinian country rocks and the following relationships demonstrated. Moinian sediments are always enriched, relative to the syenites in SiO_2, FeO, MgO, CaO (except Cùilean), trace amounts of Cr, Co, Ni, Sc and possibly Zn and, reflecting the concentration of Sr, Pb, K, and La in the syenites, the ratios Rb:Sr, Rb:Pb, Rb:K and Ce:La are again higher for the Moine Series. Conversely syenites have obvious enrichment in Na_2O, K_2O, Al_2O_3, Sr, Nb, Zr, Ba, La, Ce, Rb, Y, Pb, P, F, and the rare-earth elements. The ratios Ba:Pb and Ba:Ca, higher in the syenites, show the concentrqtion of barium in these rocks, similarly high Zr:Y ratios are indicative of magmatic processes prevailing there.

Such concentrations conform well to known geochemical patterns and the ferromagnesian rich Moine metasediments might be expected to have



Quartz-feldspar-epidote-mica schist. Moinian metasediment, Chalbhach-coire, Ben Loyal (27567)



Coarse syenite with bright green amphiboles, Càrn an Tionail, Ben Loyal (27582, 17304 XN).

complementary high Cr, Co, Ni, and Sc. Likewise several of the elements concentrated within the syenites are known to associate with leucocratic feldspar rich assemblages.

Differences between the three syenites of the complex.

The following factors emerged in a comparison between all three components of the complex.

1. The Cnoc nan Cùilean intrusion compared with the other two bodies is:-

   a) richer in TiO_2
   b) " " Al_2O_3
   c) " " K_2O
   d) " " MgO
   e) " " CaO
   f) " " FeO
   g) " " Sr
   h) most melanocratic
   i) has the highest specific gravity.
   j) " " " Ba:Pb ratio
   k) " " " Rb:Pb ratio
   l) K_2O exceeds Na_2O
   m) has high normative Or

   a) deficient in silica
   b) " " Na_2O
   c) " " Ni
   d) " " Pb
   e) " " La & total RE's
   f) has a low Rb:K ratio.

2. The Ben Loyal intrusion compared with the other two bodies is:-

   a) richer in Na_2O
   b) " " Fe_2O_3
   c) " " Cr
   d) " " Ni

   a) deficient in CaO
   b) " " K_2O
   c) " " Ba
   d) " " Sr

e) richer in Co   e) deficient in Rb

f) probably richer in Y

g) " " " Ce

h) Na_2O exceeds K_2O

i) Is often ac normative

3. The Beinn Stumanadh intrusion compared with the other two bodies is:-

a) richer in CO_2 a) probably deficient in MgO

b) " " Rb

c) " " MnO

d) " " total rare-earth elements

e) probably richer in Zr

f) " " " Nb

g) most leucocratic

h) has the highest Ba:Ca ratio

i) " " " Ba:Sr ratio

j) " " " K:Ca ratio

k) " " " Rb:Sr ratio

l) Is usually c normative

In summary, Cnoc nan Cùilean is most potassic, calcic, aluminous and richer in ferromagnesian minerals than the other two intrusions. It is more heterogeneous and melanocratic and this is the cause of the higher specific gravity found there. It is rich in strontium but deficient in silica, soda, nickel, lead and rare-earth elements. Potash exceeds soda in the body. As mentioned previously it is radiometrically the most active and from limitations imposed by its mineralogy, the least fractionated of the three intrusions.

Ben Loyal is the richest of the three in soda and this is reflected in the occurrence of acmite in the norm. Increased Fe_2O_3 together with Cr, Ni, and Co, reflect the concentration of these elements in the amphibole typical of this intrusion. Yttrium and cerium are also concentrated here. Loyal is the least calcic and potassic of the intrusions; barium and strontium are also lowest, and low rubidium mirrors the low potassium content of these rocks.

The most leucocratic of the intrusions, Beinn Stumanadh is enriched in barium, rubidium, carbonates and total rare-earth element content as well as the ratios reflecting this concentration viz. Ba:Sr, Ba:Ca, Rb:Sr. High potash content is revealed by the greatest K:Ca ratios, and only Stumanadh is conspicuously c normative.

Chemical differences therefore support the hypothesis mooted earlier that Ben Loyal, Beinn Stumanadh and Cnoc nan Cùilean are separate, distinct intrusions.

Minor igneous phenomena compared with the Loyal nordmarkite.

Pegmatites and other vein material are much richer in silica than the Loyal syenites and complementary to this are poorer in alumina (i.e. they have less feldspar in their make-up). The pegmatites are deficient in the other principal oxides viz, TiO_2, Fe_2O_3, FeO, MnO, Na_2O and possibly K_2O in comparison with the Loyal syenite. Only Pb, Rb and possibly Cr and Co are concentrated in the pegmatites and these others Ni, Zn, Sr, Nb, Y, Zr, Ba, La, and Ce are enriched in the normal syenite (from electron-probe data the pegmatites are also richer in Cu, Ag, Th and S). The veins and pegmatites are extremely leucocratic, lower in total alkalis and much lower in total rare-earth elements than the parent rock. In contrast basic segregations present the mirror image to pegmatite and vein chemistry and are enriched in TiO_2, Fe_2O_3, FeO, MnO, CaO, P_2O_5, and F all of which can be traced to the known mineralogy. A very marked concentration of the following trace elements was found in the mafic portions - Zn, Nb, Y, Zr, Ba, Sc, La, Ce, and Sn again only Pb and Rb (and possibly Sr) were concentrated in the main syenite. In an earlier section it was noted that the mafic constituents in the rock form clots, and the trace-element chemistry is consistent with amphibole/sphene aggregates. Barium concentration is less easy to account for. Increase in the mafic components in these basic segregations is attended by increase in melanocratic character and higher specific gravity. Total alkalis in these segregations are much lower than in the Loyal parent rock and the ratios Na:Ca and K:Ca very much higher in Loyal reflect this, together with the large calcium content of the basic segregations. This CaO content is contained exclusively in the sphene ■13 and amphibole and does not reside in the feldspars.

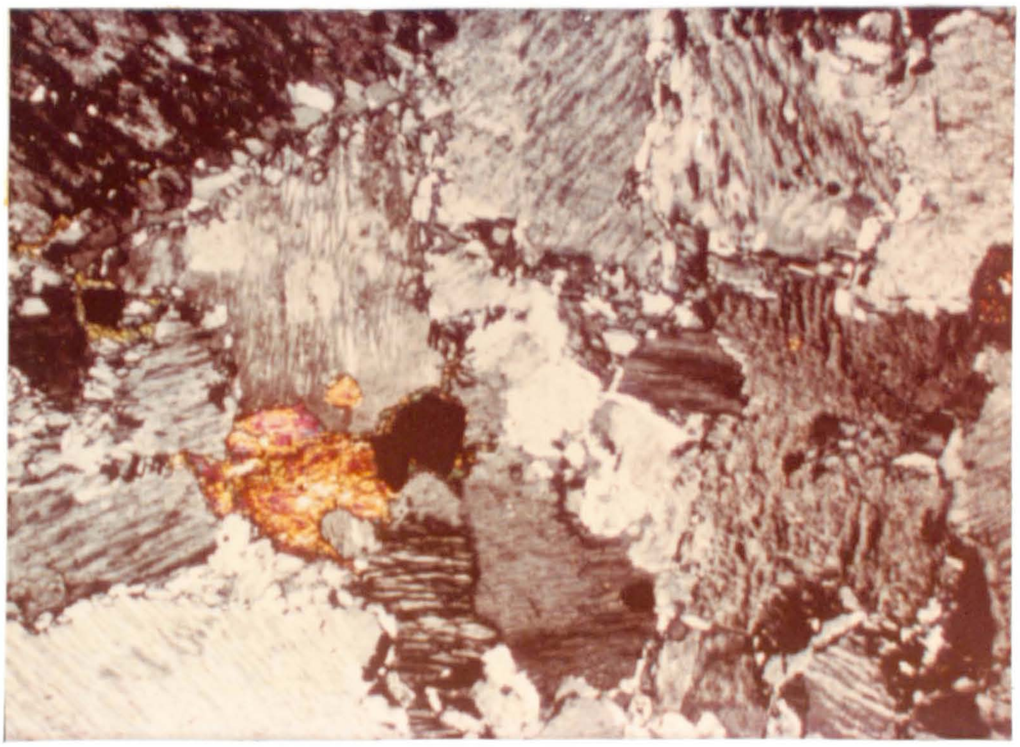
Reflecting the very leucocratic and quartz-rich nature of the minor igneous suite of Loch Loyal, sills and dykes show a deficiency in TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO and CaO. Total alkalis are again lower than the parent rock whereas silica and possibly MgO are enriched in the dyke and sill phases. With the exception of Pb which was approximately equal, all other trace-elements were enriched in the Loyal syenite (Cr, Co and Sn were indeterminate). The very high ratio of Na:Ca in these sills and dykes shows their extreme calcium impoverishment.

A comparison of the two extremes, basic segregations and pegmatites and veins shows a very strong concentration of Ni, Zn, Sr, Nb, Y, Zr, Ba, Sc, La, Ce, and Sn in the mafic portions, rubidium and lead in the pegmatites, and more unusually, although not strongly, a definite concentration of chromium and cobalt in the latter.

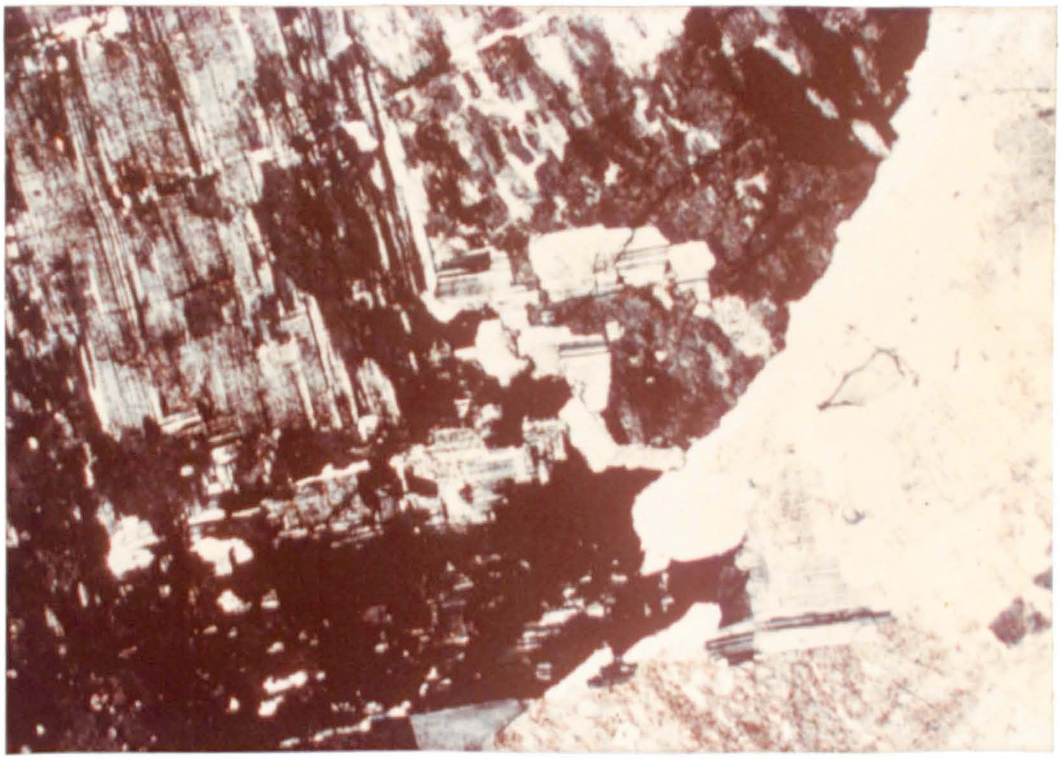
A comparison with other alkaline rocks in Scotland.

Rocks collected by the author from two other alkaline intrusions in Assynt, Loch Borralan and Loch Ailsh were analysed and compared with the Loch Loyal body. The silica contents in each case were found to be approximately the same, Loyal was poorest of the three in Al_2O_3 and Na_2O and richest of all in MnO, MgO, CaO, Ni, Rb, Sc, Ce, La, and probably Pb. The Cnoc na Sroine syenite from Loch Borralan is the most potassic and also the richest in barium, although less than Beinn Stumanadh and Cnoc nan Cùilean because Loyal is the poorer of the three parts in this element. It is obvious therefore that Loyal is less alkaline than the two other intrusions, but is richer in rare-earth elements, Pb and Rb, the latter is of especial interest since Borralan is richest of the three in potassium, two elements of close geochemical coherence. Trace element parameters support the theory put forward by Parsons (1972) that the three alkaline intrusions are separate in time and cannot have been derived from a single magma.

Two other rock types from the Borralan intrusion, borolanite and ledmorite, together with a syenitic rock from Allt Cnoc Fhionn in the Glenelg-Ratagain complex and another of the "Nower Granite" suite, the Cluanie granite were analysed. In each case the Borralan rocks showed the same geochemical pattern and were enriched in Cr, Co, Zn, Sr, Rb, Y, and Sc and Loyal was richer in Ba, Pb, Ni, and the rare-earths La and Ce. Rb here is then in its reversed role to that in the syenites where Loyal has the greater Rb content, this may be explained by the very high (8%) content of potash in these two rocks. The rest of the trace elements are consistent with the mafic sub-silicic nature of these rocks.



Loch Ailsh syenite (27632,21604)



Loch Borralan syenite, Cnoc na Sroine (27640,22404)

The Glenelg-Ratagain syenite was found to be lower in silica, potash and BaO than the Loyal body and higher in those oxides associated with the ferromagnesian minerals. The rare-earth elements, Ba, Pb, Nb, and Y were again found to be concentrated in the Loyal nordmarkite. Cluanie granite had the lowest content of trace elements of all the rocks tested. This granite is soda-rich with the development of trondhjemites, and is potash poor (2.5%) and Leedal (op.cit.) has shown that metasomatic activity has played an important role in its generation. It was found to be fundamentally different to the other alkaline intrusions examined above.

A sub-silicic, potash rich syenite from Madagascar was analysed and when compared with the trace-element pattern at Loyal, a considerable enrichment in Rb, Zn, Y, Nb, Cr, and Ni was found in the former, Loyal however was much the richer in strontium and lead.

A comparison with other Caledonian Newer Igneous Rocks.

Loyal rocks are much more sodic and very greatly deficient in calcium compared with other Caledonian granites. Additionally they are far removed from the Caledonian parent magma envisaged by Nockolds and Allen (1953). However several of the trace elements are markedly enriched when contrasted with the values given by Nockolds & Mitchell (1948). Pb, Ba, La, Ce, Y, Zr and Nb are higher at Loyal whereas Cr, Ni, and Rb are lower; Co, Sr, and Sc have approximately the same amounts. Interestingly when the rubidium content of Loyal rocks is plotted on a log graph against % potassium it falls within the zone of rubidium depletion as contemplated by Taylor (1965).

A summary of the chemical features of the Loch Loyal alkaline complex.

Compared with other Scottish alkaline rocks, those of Loch Loyal are:-

i. Relatively poor in Na_2O.
ii. Relatively enriched in CaO.
iii. Rich in Pb.
iv. Rich in Rb.
v. Rich in Ba.
vi. Rich in Sr (although only where mineralised).
vii. Rich in Nb.
viii. Rich in rare-earth elements.

In the Loch Loyal complex:-

ix. Ben Loyal is the most sodic.
x. Lanthanum is concentrated relative to cerium in the Loyal body.
xi. Cnoc nan Cùilean is the most potassic.
xii. Cnoc nan Cùilean is the most calcic.
xiii. Cnoc nan Cùilean is richest in ferromagnesian minerals.
xiv. Beinn Stumanadh is richest in total rare-earth elements.
xv. Beinn Stumanadh is richest incarbonates.
xvi. Beinn Stumanadh is richest in Rb.

Trace element enrichment in the Loyal nordmarkites.

Lead

In the study by Nockolds and Mitchell (op. cit.) the trace element content of lead in most of the Caledonian Igneous suite remained below the level of analytical sensitivity. Within the Loch Loyal rocks both 14 Ben Loyal and Beinn Stumanadh rocks carry greater than 60ppm Pb; Cnoc nan Cùilean has lower amounts with 35ppm. Lead, having an ionic radius of 1.20Å, occurs in silicate structures mainly as the Pb^{2+} ion displaying diadochic substitution with K^+ (1.33A). According to the rules proposed by Goldschmidt (1937) divalent lead, because of its high charge should be relatively concentrated during magmatic crystallisation in the early formed potash minerals. But entry of lead into orthoclase (i.e. into amazonite in the Chaonasaid cliffs) causes an increase in covalency of the metal-oxygen bonds and this has the effect of weakening them considerably. Such replacement is finite and therefore most of the lead remains in the magmatic fluid and is concentrated in the late stage pegmatitic liquors where it is precipitated as the sulphide galena; a situation found in the pegmatites along the northern slopes of Ben Loyal.

Barium and strontium.

Usually Ba^{2+} (1.34A) is captured by K^+ (1.33Å) in igneous processes. At Loyal, although this must have been important, such very high concentrations as occur ($>$4000ppm) indicate additional low-temperature hydrothermal activity to have taken place. Much the same explanation can account for the occurrence of strontianite although only during the very late stages of magmatic activity does the amount exceed that found in other Caledonian igneous rocks.

Tin

Tin is concentrated only in the basic segregations of the Loyal nordmarkite, and only then by about 5ppm, where it is held exclusively in the mineral sphene. Here Sn^{2+} (0.93A) is camouflaged by Ca^{2+} (0.99A). Tin remains below the detection limit in the more "normal" syenites.

Rare-earth elements.

Throughout the Caledonian plutonic suite Nockolds and Mitchell (op. cit.) noted a deficiency in yttrium and lanthanum. At Loyal however these elements together with other rare-earth elements are markedly concentrated.

The following rare-earths indicated by asterisk have been found in the Loyal rocks:-

	Element	Atomic No.	Symbol	Ionic radius	Valency	at Loyal
Yttrium Earths	Scandium	21	Sc	0.81	Sc^{3+}	*
	Yttrium	39	Y	0.92	Y^{3+}	*
Cerium earths	Lanthanum	57	La	1.14	La^{3+}	*
	Cerium	58	Ce	1.07	Ce^{3+}	*
				0.94	Ce^{4+}	
	Praseodymium	59	Pr	1.81	Pr^{3+}	*
				1.06	Pr^{4+}	
	Neodymium	60	Nd	1.04	Nd^{3+}	*
	Promethium	61	Pm	not known in nature		
	Samarium	62	Sm	1.00	Sm^{3+}	*
					Sm^{2+}	
	Europium	63	Eu	0.98	Eu^{3+}	
					Eu^{2+}	?
Yttrium earths	Gadolinium	64	Gd	0.97	Gd^{3+}	*
	Terbium	65	Tb	0.93	Tb^{3+}	
				0.81	Tb^{4+}	
	Dysprosium	66	Dy	0.92	Dy^{3+}	?
	Holmium	67	Ho	0.91	Ho^{3+}	
	Erbium	68	Er	0.89	Er^{3+}	
	Thulium	69	Tm	0.87	Tm^{3+}	
	Ytterbium	70	Yb	0.86	Yb^{3+}	
					Yb^{2+}	*
	Lutetium	71	Lu	0.85	Lu^{3+}	

From this list it is apparent that lanthanum and all the cerium earths have been found in the Loyal rocks, the Yttrium earths Gd, Yb, possibly Dy, Y and Sc have been located but with the exception of yttrium only in very small amounts.

Relative abundances follow the Oddo-Harkins rule quite well, that is even atomic number elements are far more abundant than those elements on either side of it in the periodic table. However the La:Ce ratio as mentioned previously, shows lanthanum concentrated relative to cerium.

The rare-earth elements are distributed both in early crystallised minerals and more especially in the late-stage yellow phosphosilicate found in the drusy cavities at Lettermore quarry. Sphene, allanite and polycrase are the other chief containers of the rare-earths.

Ionic radii of the trivalent rare-earth ions vary between 1.14Å for La^{3+} and 0.85Å for Lu^{3+} and consequently it can be expected that a diadochy exists with Ca^{2+} (0.99Å), and that they can be concentrated in earlier calcium minerals such as sphene. However they are also concentrated in residual fractions of a crystallising magma and the diadochy with divalent calcium must therefore be tempered by the greater electronegativities of the rare-earths. Because of their resemblance to the alkaline-earth metals, Eu^{2+}, Sm^{2+} and Yb^{2+} may be expected to substitute for calcium in sphene leaving the other rare earths to concentrate in late stage liquors. Why lanthanum is concentrated relative to cerium is difficult to uhderstand but Ce^{4+} is known to be stable compared with the trivalent rare-earth elements. These may then migrate to be redeposited as the lanthanum enriched yellow mineral in the drusy cavities from the outer parts of the Loyal mass. In support of this contention some highly oxidised pegmatites related to alkaline rocks are known which have cerium in the quadrivalent state and the orange colour in the thorite group of minerals (known from the Loyal syenites) may be due to the presence of the ceric ion.

Niobium and the role of complex formation in its concentration.

In the Loyal nordmarkites niobium is found chiefly in sphene and is therefore enriched in the basic segregations. One important exception to this is seen in a brown resinuous metamict mineral separated from the pegmatites, after heating, showed the d spacings characteristic of polycrase, a niobotantalate. Powder diffraction showed 2.948, 1.809 & 1.544 as the strongest lines, very close to the 2.95, 1.81 & 1.54 for polycrase quoted by Faria (1964). He is of the opinion that polycrase is a titanium-rich variety of euxenite, itself a member of the euxenite-aeschynite series with end-members euxenite $YNbTiO_6$ and aéschynite $CeNbTiO_6$. Usually polycrase is enriched in the yttrium earths which would explain the occurrence of gadolinium, dysprosium and ytterbium (all even no. elements) in some of the XRF scans. Polycrase normally has greater than 10% Nb_2O_5, TiO_2, (UO_3), and yttrium-earths and less than 5% Ta_2O_5, ThO_2 cerium-earths, (Fe_2O_3), (MnO), CaO, ZrO_2 and PbO. (brackets indicating that the oxidation state is unknown). Interestingly the other Group V elements antimony (Sb) and bismuth (Bi) found with galena in the Chaonasaid pegmatites are close to Nb^{5+} and Ta^{5+} geochemically and radius ratios for the quinquivalent ions are all similar. Bismuth however is normally trivalent under natural conditions. Niobium and tantalum (0.69A & 0.68A) in the sphene substitute for Ti^{4+} (0.64A) and sphenes with 1-2% Nb_2O_5 are known where the niobium occurs as either $NaSiNbO_5$ or $CaAlNbO_5$. The fact that Nb_2O_5 is enriched in titanium minerals of pegmatites, the reversal of normal ionic trend, supports the contention that Ti^{3+}, Nb^{5+} and Ta^{5+} are not present as free ions in late stage processes but act as complex ions such as $(TiO_6)^{8-}$ and $(NbO_6)^{7-}$ by polymerisation through oxygen bridges. In such cases the complex titanium anions would have a lower (negative) charge than the anions containing Nb and Ta and the apparent reversal of the crystallisation sequences could be explained.

Within a magma ions occupy two fundamentally different structural positions. On the one hand are ions possessing high ionic potentials of which Si^{4+} is typical, these form the centres of oxygen tetrahedra and are the so called "network formers". The other type includes ions of low ionic potential such as Na^{+}, which do not enter the network but exist in the holes between the tetrahedra - these are the "network modifiers".

Network formers include nearly all cations with charges greater than three and also some of the smaller trivalent ions. At Loyal these include Si^{4+}, Al^{3+}, Ti^{4+}, P^{5+}, Nb^{5+}, and C^{4+}. Network modifiers are composed of univalent, divalent and some of the larger trivalent ions, all are characterised by low ionic potentials and at Loyal comprise Na^{+}, K^{+}, Rb^{+}, Ca^{2+}, Sr^{2+}, Ba^{2+}, Pb^{2+} and the trivalent rare-earth elements. Intermediate between these formers and modifiers are Co^{2+}, Ni^{2+}, Zn^{2+}, Mg^{2+}, Cu^{2+}, Fe^{3+}, V^{3+}, Cr^{3+} and Sc^{3+}. In most magmas these elements are forced to occur as network modifiers but in pegmatitic and alkaline rock types, some occur as network formers. The structure of most minerals crystallising from a magma is based on and SiO_4^{4-} tetrahedron linked in various ways and this imposes only two possible roles for a trace-element complex, it may either replace SiO_4 tetrahedra in silicate minerals or be precipitated as separate phases. From geometrical restrictions it is clear that for a complex to substitute for SiO_4, it must be tetrahedrally coordinated and of the MO_4 type of structure - no other structures would be accepted. Thus in the case of Loyal rocks CO_3^{2-} would be expected to concentrate and later to crystallise as primary carbonate, a feature known to occur in the Beinn Stumanadh body.

The larger the charge on the central cation, the smaller will be the tendency for MO_4 complexes to replace SiO_4 tetrahedra in silicates. Increasing the charge on M involves a reduction in the net charge on the complex which reduces its ionic bonding energy with respect to SiO_4^{4-} and makes it less likely to replace SiO_4^{4-}. Consequently PO_4^{3-}, NbO_4^{3-}, TaO_4^{3-}, and SO_4^{2-} are expected to be concentrated relative to SiO_4^{4-} at Loyal. From geometrical considerations the larger the size of the central cation the less likelyhood is there that MO_4 groups will replace SiO_4, accordingly TiO_4^{4-} and ZrO_4^{4-} are concentrated.

If the rules proposed by Rosenbusch (1882) are applied to a cooling granitic magma the accessory minerals must be amongst the first to crystallise out. It is well known however that the common accessories mica, apatite, sphene, monazite etc. carry the bulk of the rarer trace-elements, and for the elements to be precipitated in pegmatites it is essential that they are not precipitated early during the crystallisation sequence. Most nepheline-syenites crystallise contrary to the Rosenbusch rule, a sequence termed agpaitic by Fersman (1929). This author considered this exception due to complex formation. Fersman thinks it is a prerequisite that an excess of total alkalis over alumina be present for complex formation and consequent agpaitic crystallisation to occur. However work at Loyal is in agreement with the ideas of Ringwood (1955) that the ratio of (Na + K) to Al is not the critical factor involved, and complex formation does take place when (Na + K) $\leqslant$ Al.

Thorium.

Although Th^{4+} (1.02Å) is found in sphene it does not replace Ca^{2+} (0.99Å) readily in silicate minerals because of the difficulties in altering electrostatic neutrality and the relatively large size of its ion (Wickmann 1943). It tends then to accumulate in residuals and at Loyal is concentrated in pegmatitic allanites where it replaces cerium.

The anomalous behaviour of chromium and nickel.

Cr^{3+} and Ni^{3+} are concentrated in the Ben Loyal mass when they might have been expected in the more mafic Cnoc nan Cùilean intrusion and normally the geochemical tendency of chromium and nickel is to enter early ferromagnesian minerals. Occasionally these elements have been concentrated in late stage residual phases, for example in the granophyre of the Skaergaard intrusion, Greenland described by Wager & Deer (1939) and this concentration in the more leucocratic intrusion of Loyal shows that Cr & Ni probably behaved as network formers, entering MO_4 complexes, rather than the usual network modifying role replacing Fe^{2+} and Fe^{3+}. This suggests that some volatiles were available during the late stage evolution of the Loyal melt.

Soil and Peat samples.

Twenty eight azonal soil and peat samples from each of the three intrusions, Ben Loyal, Cnoc nan Cùilean and Beinn Stumanadh were collected, dried, crushed and ignited. The ash was then analysed for the following trace-elements Nb, Sr, Y, Rb, Zr, Co, Cu, Cr, Ni, Zn and Pb, by X-ray fluorescence spectrography to determine if the humic part of the soils had concentrated any of the elements. Most soils were mixtures of syenitic debris and rudimentary peat soil; four of them were almost pure Sphagnum and Hypnum peats. No suggestion is implied in the study that the soils are residual and in any case peats have only been developed from 7000 BC, and more rapidly from the close of the Atlantic Period at about 4000 BC to the present day.

Sample 904, the richest of all in peat, shows a marked concentration of cobalt, copper, nickel, zinc, probably lead and possibly chromium and a depletion in Nb, Sr, and Rb relative to those samples which have syenitic fragments in their make-up. Soil samples reflect the high strontium content of the Cùilean intrusion; and Beinn Stumanadh soils are probably richest in cobalt.

When compared with trace-element contents of the underlying syenites the soils are:-

a. strongly enriched in Y, Cr, Ni, and Zn.
b. enriched in Cu, Pb, and Co.
c. equal in Zr content.
d. slightly depleted in Sr, and Rb.
e. strongly depleted in Nb.

Two factors, the geochemical coherence of the enriched elements with iron and their take-up in peat litter account for the observed concentration. All the enriched elements have been noted by several authors previously as having increased tenor in forest litter, humus and coal ashes, especially is this true of nickel.

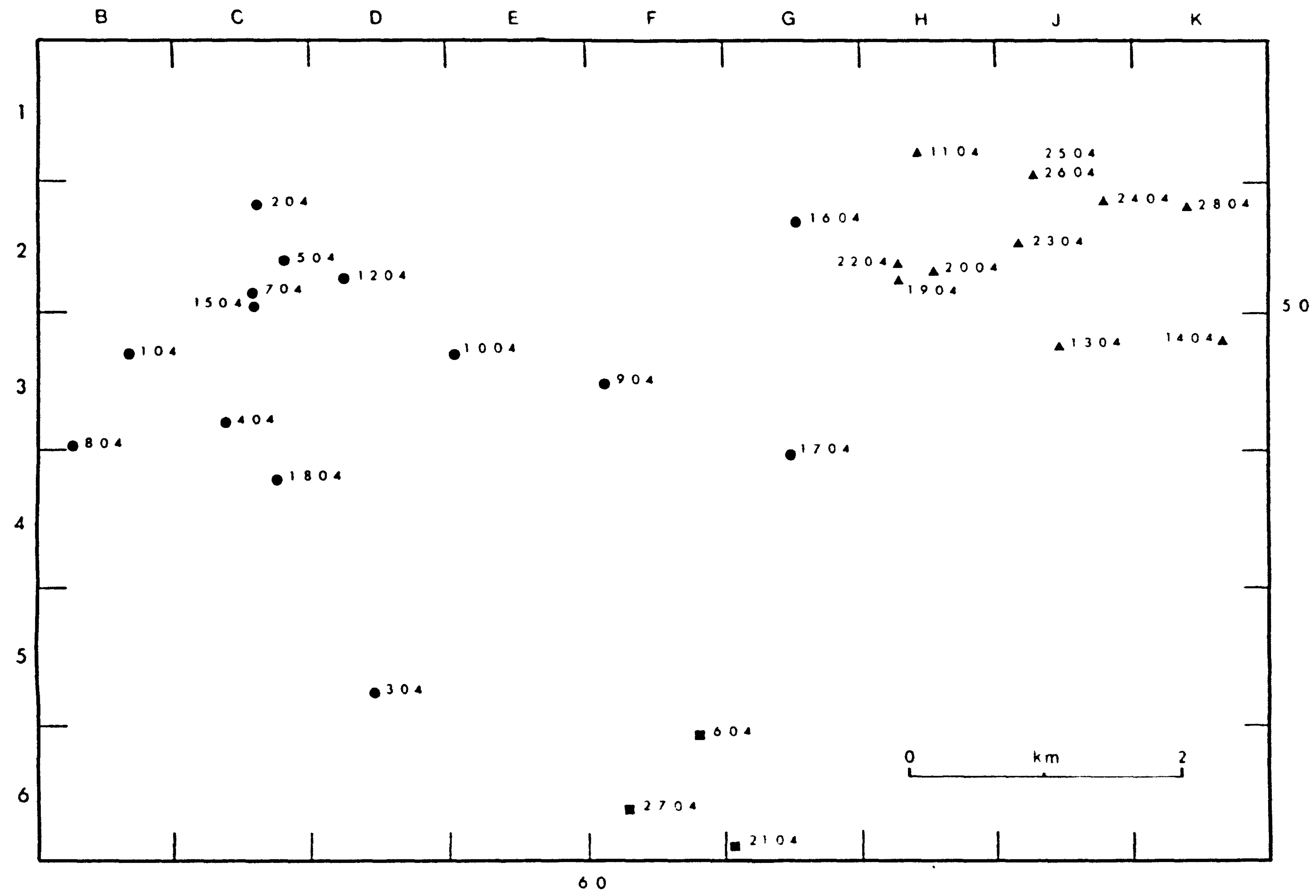
Zinc concentration is related to amphibole and pyroxene crystals remaining after solution of feldspars. (in this connection humic acids are known to be strong solvents). Another indication in the Loyal area that zinc is enriched in the vegetable matter concerns the preponderance of arboriferous fungi in Coille na Cùile. The metabolism of many fungi is dependent on the availability of zinc and the almost universal occurrence of these fungi on the trunks of downy birch suggests that this tree may selectively concentrate the element. Lead is known to be fixed in the rhizoids of mosses.

SOIL SAMPLES TRACE ELEMENT CONTENTS IN PPM. 15

Sample No.	Nb	Sr	Y	Rb	Zr	Co	Cu	Cr	Ni	Zn	Pb
Loyal											
104	13	1418	-	127	328	17	(102)	52	26	43	18
204	7	933	-	72	251	18	(137)	64	37	45	69
304	18	1490	-	98	453	13	(97)	42	27	45	13
404	22	1439	-	126	499	15	(98)	38	26	55	-
504	12	1644	-	77	434	15	(109)	92	53	51	-
704	24	1415	-	127	453	14	(103)	39	27	63	76
804	4	3640	-	84	217	17	(10)	101	39	37	0?
904	0	591	-	23	65	256	(661)	83.	75	574	399
1004	9	950	-	43	304	58	(110)	78	27	33?	-
1204	15	1490	-	120	365	44	(134)	45	29	73	-
1504	22	1586	54	127	458	14	(101)	39	25	64	-
1604	12	1465	37	94	272	22	(98)	55	25	40	-
1704	11	1576	47	79	374	25	(99)	64	41	55	-
1804	5	1530	36	150	567	12	(105)	47	21	25	-
Cnoc nan Cùilean											
604	18	1741	-	134	422	12	(98)	47	25	45	-
2104	13	3541	45	96	193	17	-	45	32	51	50
2704	17	2868	44	93	342	31	-	-	36	51	48

Sample No.	Nb	Sr	Y	Rb	Zr	Co	Cu	Cr	Ni	Zn	Pb
Beinn Stumanadh											
1104	11	892	-	81	400	30	(137)	100	36	27	-
1304	17	788	50	176	425	22	(102)	63	30	23	-
1404	6	669	69	0	198	69	(129)	88	33	39	-
1904	20	1375	58	138	452	19	-	54	28	33	94
2004	3	886	67	28	243	44	-	75	64	169	61
2204	11	2327	50	123	401	34	-	55	21	29	59
2304	7	695	30	65	407	28	-	107	49	32	49
2404	19	1595	68	107	464	25	-	43	32	75	136
2504	4	450	37	78	292	28	-	-	78	43	35
2604	9	663	29	71	288	25	-	-	56	35	50
2804	15	954	45	74	526	32	-	-	53	117	-
Peat samples											
904	0	591	-	23	65	256	(661)	83	75	574	399
1004	9	950	-	43	304	58	(110)	78	27	33?	-
1204	15	1490	-	120	365	44	(134)	45	29	73	-
1404	6	669	69	0	198	69	(129)	88	33	39	-

Copper values are bracketed since 100 ppm represented a background count for this element.



SOIL SAMPLE GRID

LETTERMORE NORDMARKITE COMPARED WITH AVERAGE IGNEOUS ROCKS AS DETERMINED BY NOCKOLDS

	Lettermore Normarkite	Alkali Granite	Grano-Diorite	Quartz-Diorite	Alkali-Trachyte	Alkali Syenite	Nepheline Syenite	Andesite	Basalt (Tholeite)	Lettermore Nordmarkite
SiO_2	64.94	73.86	66.88	66.15	61.95	61.86	55.38	54.20	50.83	64.94
TiO_2	0.81	0.20	0.57	0.62	0.73	0.58	0.66	1.31	2.03	0.81
Al_2O_3	16.25	13.75	15.66	15.56	18.03	16.91	21.30	17.17	14.07	16.25
Fe_2O_3	1.68	0.78	1.33	1.36	2.33	2.32	2.42	3.48	2.88	1.68
FeO	1.00	1.13	2.59	3.42	1.51	2.63	2.00	5.49	9.06	1.00
MnO	0.06	0.05	0.07	0.08	0.13	0.11	0.19	0.15	0.18	0.06
MgO	1.03	0.26	1.57	1.94	0.63	0.96	0.57	4.36	6.34	1.03
CaO	1.56	0.72	3.56	4.65	1.89	2.54	1.98	7.92	10.42	1.56
Na_2O	6.08	3.51	3.84	3.90	6.55	5.46	8.84	3.67	2.23	6.08
K_2O	5.88	5.13	3.07	1.42	5.53	5.91	5.34	1.11	0.82	5.88
H_2O	0.52	0.47	0.65	0.69	0.54	0.53	0.96	0.86	0.91	0.52
P_2O_5	0.26	0.14.	0.21	0.21	0.18	0.19	0.19	0.28	0.23	0.26

LETTERMORE NORDMARKITE COMPARED WITH SIMILAR ROCKS WORLDWIDE.

	Nordmarkites								Syenites							Pulaskites		Trachytes		
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	Lettermore
SiO_2	64.88	64.04	65.43	58.17	58.46	69.43	67.30	64.51	66.22	64.56	63.28	60.02	60.24	61.03	65.12	60.03	62.08	63.37	64.58	64.94
TiO_2	0.69	0.62	0.16	2.09	-	0.18	0.17	0.75	0.22	0.90	0.95	0.45	0.94	0.67	0.48	0.14	0.79	-	0.13	0.81
Al_2O_3	16.24	17.92	16.96	16.07	16.56	15.87	17.44	16.75	16.22	16.22	17.48	18.06	18.54	15.52	16.43	20.76	17.76	16.47	17.52	16.25
Fe_2O_3	1.37	0.96	1.55	1.30	5.69	0.36	1.56	2.05	1.98	2.87	2.89	3.57	0.54	5.08	0.96	4.01	0.77	4.45	2.56	1.68
FeO	2.70	2.08	1.53	5.04	2.59	2.50	1.76	1.00	0.16	1.73	1.41	3.57	2.36	2.98	1.92	0.75	2.27	1.21	0.96	1.00
MnO	0.14	0.23	0.40	0.07	tr	0.06	0.16	0.21	tr	0.12	-	0.14	0.00	0.07	0.28	tr	0.14	-	0.08	0.06
MgO	0.89	0.59	0.22	1.20	0.62	0.12	0.14	0.60	0.77	0.63	0.66	0.69	0.76	0.47	0.36	0.80	0.88	0.51	0.22	1.03
CaO	1.92	1.00	1.36	3.42	2.61	1.13	1.00	1.38	1.32	1.21	0.52	0.25	2.29	1.87	0.94	2.62	3.35	1.27	0.39	1.56
Na_2O	5.00	6.67	5.95	7.41	6.23	5.11	7.08	6.08	6.49	5.61	5.86	6.26	6.59	6.19	6.43	5.96	6.94	5.88	6.41	6.08
K_2O	5.61	6.08	5.36	4.65	5.44	4.97	4.87	5.74	5.76	5.77	6.18	6.24	5.44	5.15	5.46	5.48	4.50	5.57	6.23	5.88
H_2O	0.65	1.18	0.82	0.60	1.21	0.43	0.10	0.77	0.32	0.18	0.65	0.75	1.22	1.24	0.42	0.59	0.60	0.76	0.41	0.32
P_2O_5	0.13	-	0.02	0.42	-	0.06	0.04	0.14	0.10	0.16	0.25	0.23	0.27	0.13	0.14	0.07	0.20	-	tr	0.26

Index

I	Mt. Ascutney Vermont,USA. nordmarkite (Daly 1903)
II	Tonsenas, Christiana, Norway, classic nordmarkite (Brogger 1933)
III	Shefford Mtn., Quebec, Canada. nordmarkite (Frisch 1970)
IV	Kakarsuak, Narsak, S. Greenland. nordmarkite (Ussing 1912)
V	Cabo Frio, Rio de Janeiro, nordmarkite (Wright 1901)
VI	Mt. Monadnock, Vermont. quartz-nordmarkite (Wolff 1929)
VII	Cuttingsville, USA. nordmarkite (Wolff 1929)
VIII	Huesco Tanks, El Paso Co. Texas, syenite-porphyry (Richardson 1909)
IX	Gray Butte, Bear Paw Mts., Montana. quartz-syenite porphyry (Weed & Pirsson 1896)
X	Parvavara, Gellivare, Sweden. syenite (Hogbom 1910)
XI	Mont Antsutrotro, Madagascar. aegirine-syenite (Lacroix 1913)
XII	Darkainle, Borama district, Armo hill, Somali Republic, amphibole -syenite (Gellatly 1963)
XIII	Leeuwfontein, Pretoria. red syenite (Shand 1921)
XIV	Morotu district, Sakhalin USSR. syenite (Yagi 1953)
XV	Pine Hill, Brome, Canada. porphyritic microsyenite (Valiquette & Archambault 1970)
XVI	Fourche Mtn, Little Rock, Arkansas. classic pulaskite (Washington 1901)
XVII	Brome, Canada. pulaskite (Valiquette & Archambault 1970)
XVIII	Carapook, Victoria, Australia. trachyte (Dennant 1901)
XIX	Mt. Beerwah, Glass House Mtns., Queensland. trachyte (Jensen 1906)

LETTERMORE NORMARKITE COMPARED WITH OTHER SCOTTISH ALKALINE ROCKS.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Loyal
SiO_2	69.92	67.19	61.79	64.85	68.71	66.56	61.30	69.94	61.96	65.41	64.28	64.81	64.94
TiO_2	0.15	0.07	0.90	0.42	0.36	0.16	0.71	0.03	0.92	0.17	0.39	0.30	0.81
Al_2O_3	16.63	17.72	16.90	17.72	16.77	19.41	17.68	19.02	16.61	18.94	17.23	14.97	16.25
Fe_2O_3	0.74	0.87	3.10	1.76	0.66	1.53	1.97	0.62	1.25	0.97	1.84	5.28	1.68
FeO	0.46	0.26	1.07	0.68	1.20	0.22	2.21	0.32	5.13	0.39	0.66	0.71	1.00
MnO	0.04	0.03	0.19	0.02	0.08	tr	0.08	0.12	0.10	0.03	0.23	0.27	0.06
MgO	0.03	0.01	0.90	0.47	0.75	0.32	1.51	0.01	2.17	0.24	0.59	0.38	1.03
CaO	0.90	0.28	2.44	1.21	2.54	0.68	2.11	0.46	2.64	0.77	2.09	1.00	1.56
Na_2O	6.82	6.28	5.26	5.81	5.71	10.64	5.70	8.99	4.10	7.45	7.50	7.27	6.08
K_2O	3.42	7.14	6.96	6.17	2.71	0.34	6.13	0.52	3.98	5.21	4.02	4.70	5.88
H_2O	0.38	0.08	0.43	0.58	0.23	0.34	0.67	0.36	1.13	0.27	0.37	0.32	0.52
P_2O_5	0.02	0.01	0.34	0.13	0.07	0.16	0.34	-	-	0.08	0.14	0.10	0.26

Key.

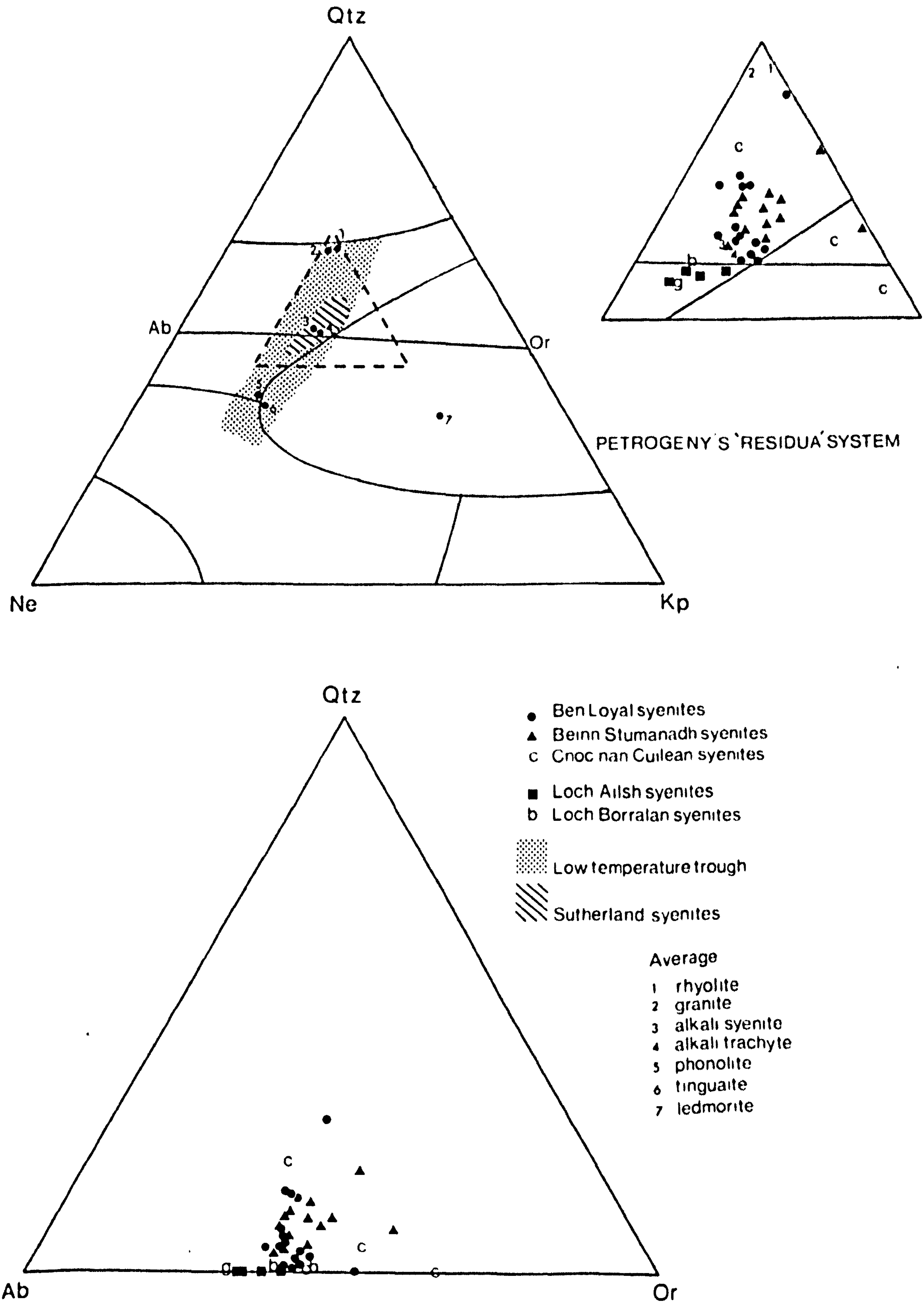
I	Cnoc na Sroine, Loch Borralan, quartz-syenite (Tilley 1958).
II	Cnoc na Sroine, Loch Borralan, aegirine-aplite (Tilley 1958).
III	Derry Lodge, Aberdeen-shire, aegirine-granulites (McLachlan 1951)
IV	Glenelg-Ratagain complex, nordmarkite (Nicholls 1950).
V	Cluanie, granodiorite (Leedal 1952).
VI	Ve Skerries, Shetland, albitite (Walker 1932).
VII	Glen Dessarry, Inverness-shire, leucocratic-syenite, (Richardson 1968).
VIII	Glen Lui, Braemar, soda-pegmatite, (McLachlan 1951).
IX	Loch Hourn, biotite-psammite, (Tanner & Tobisch 1972).
X	Sail an Ruathair, Loch Ailsh, perthosite, (Phemister 1926).
XI	River Oykell, Loch Ailsh, pubaskite, (Phemister 1926).
XII	Sail an Ruathair, Loch Ailsh, aegirine-melanite-syenite, (Phemister 1926).

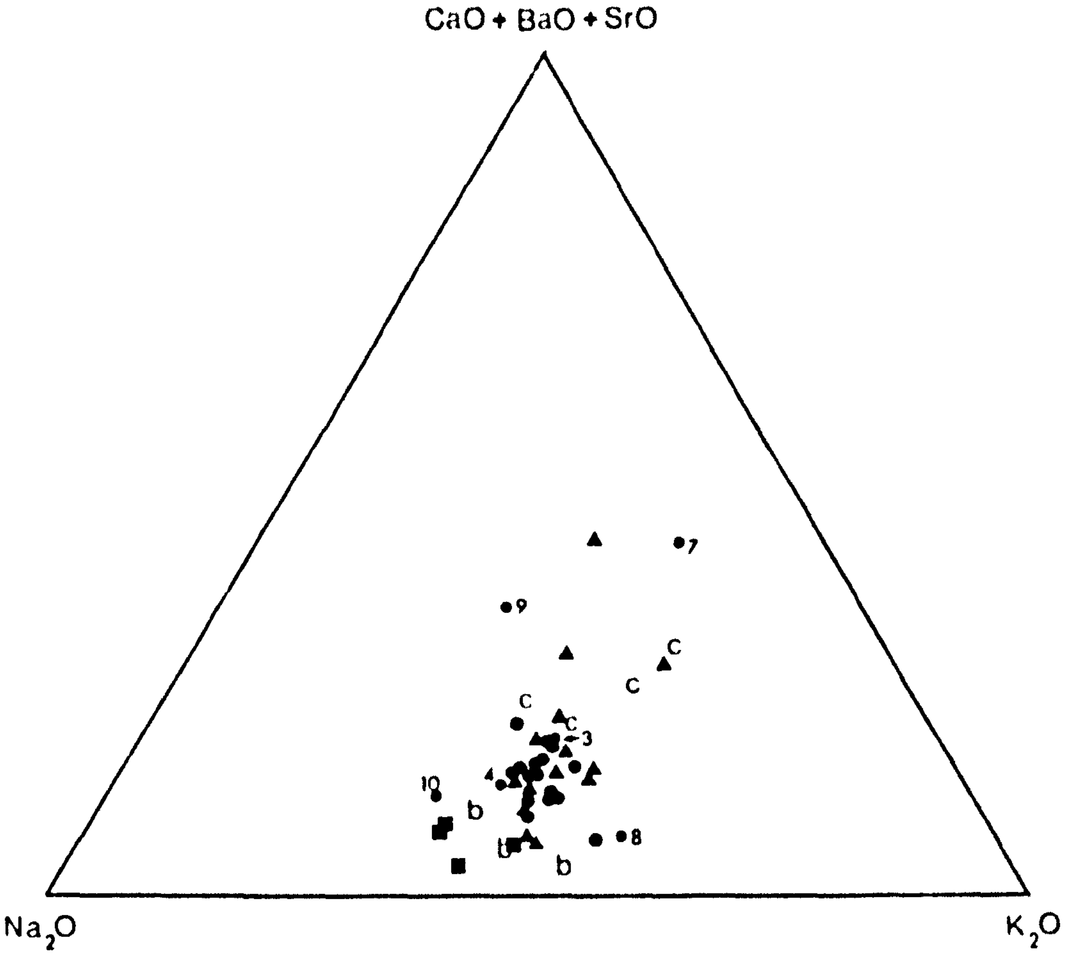
LETTERMORE NORDMARKITE COMPARED WITH OTHER "NEWER IGNEOUS" ROCKS.

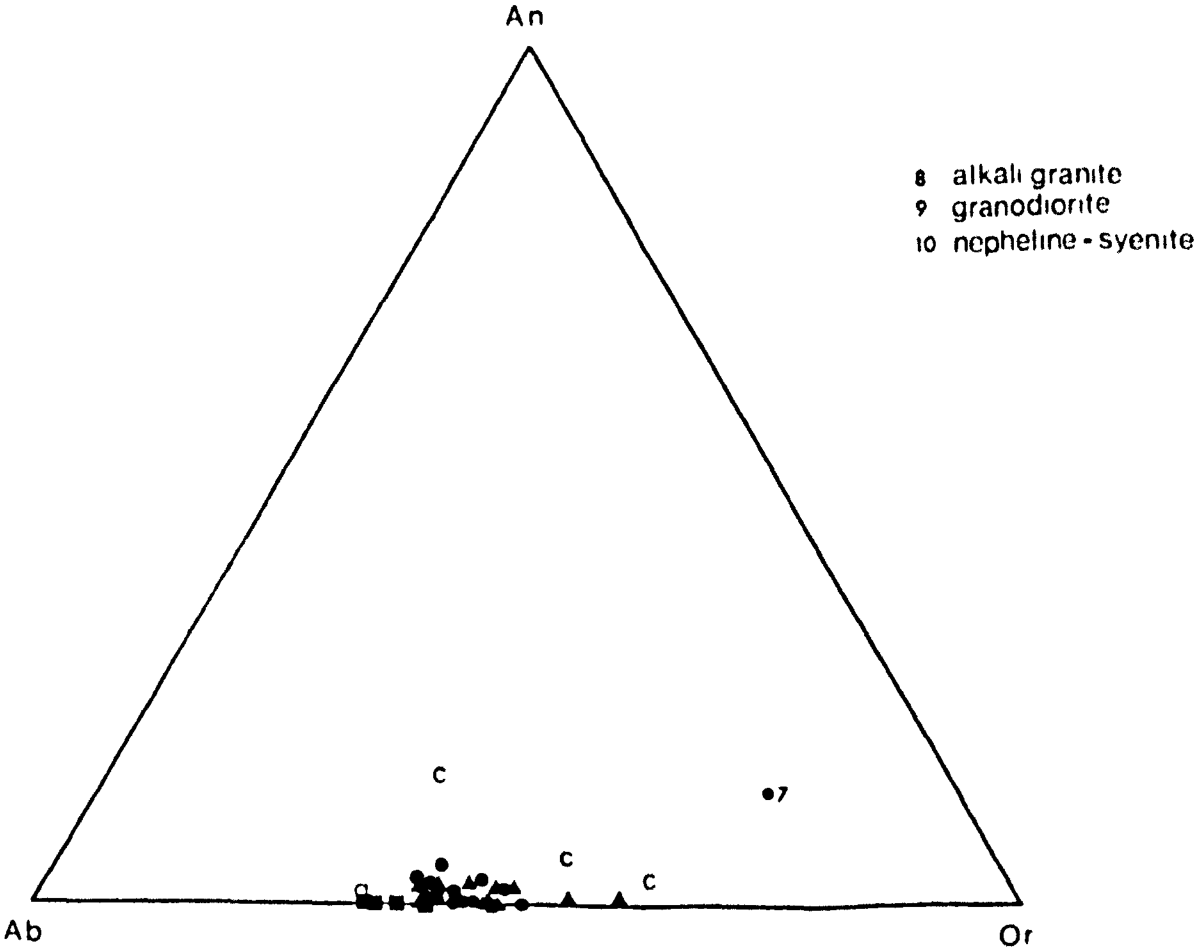
	I	II	III	IV	V	VI	VII	VIII	IX	Lettermore
SiO_2	74.92	74.32	65.0	61.44	71.18	71.25	66.91	69.01	70.31	64.94
TiO_2	0.16	0.26	0.80	0.64	0.47	-	0.67	-	0.26	0.81
Al_2O_3	13.41	13.76	15.2	16.03	14.78	18.03	15.09	17.74	7.53	16.25
Fe_2O_3	0.86	1.14	0.95	1.17	1.20	1.29	1.70	0.97	8.32	1.68
FeO	0.29	0.45	2.6	3.92	1.35	0.34	2.13	2.05	2.44	1.00
MnO	0.05	0.03	0.06	tr	0.06	-	-	-	0.15	0.06
MgO	0.28	0.47	2.4	4.25	0.82	0.38	2.02	0.48	0.02	1.03
CaO	0.32	0.90	3.8	6.02	1.58	2.61	3.32	1.95	0.35	1.56
Na_2O	4.18	3.65	4.8	3.69	3.10	2.25	4.16	2.73	5.26	6.08
K_2O	4.69	4.82	2.3	1.88	4.82	3.09	3.16	3.94	4.19	5.88
H_2O	0.56	0.35	1.4	1.02	0.26	0.82	0.70	1.18	0.43	0.52
P_2O_5	0.04	0.04	0.22	0.14	0.38	0.13	0.17	-	0.33	0.26

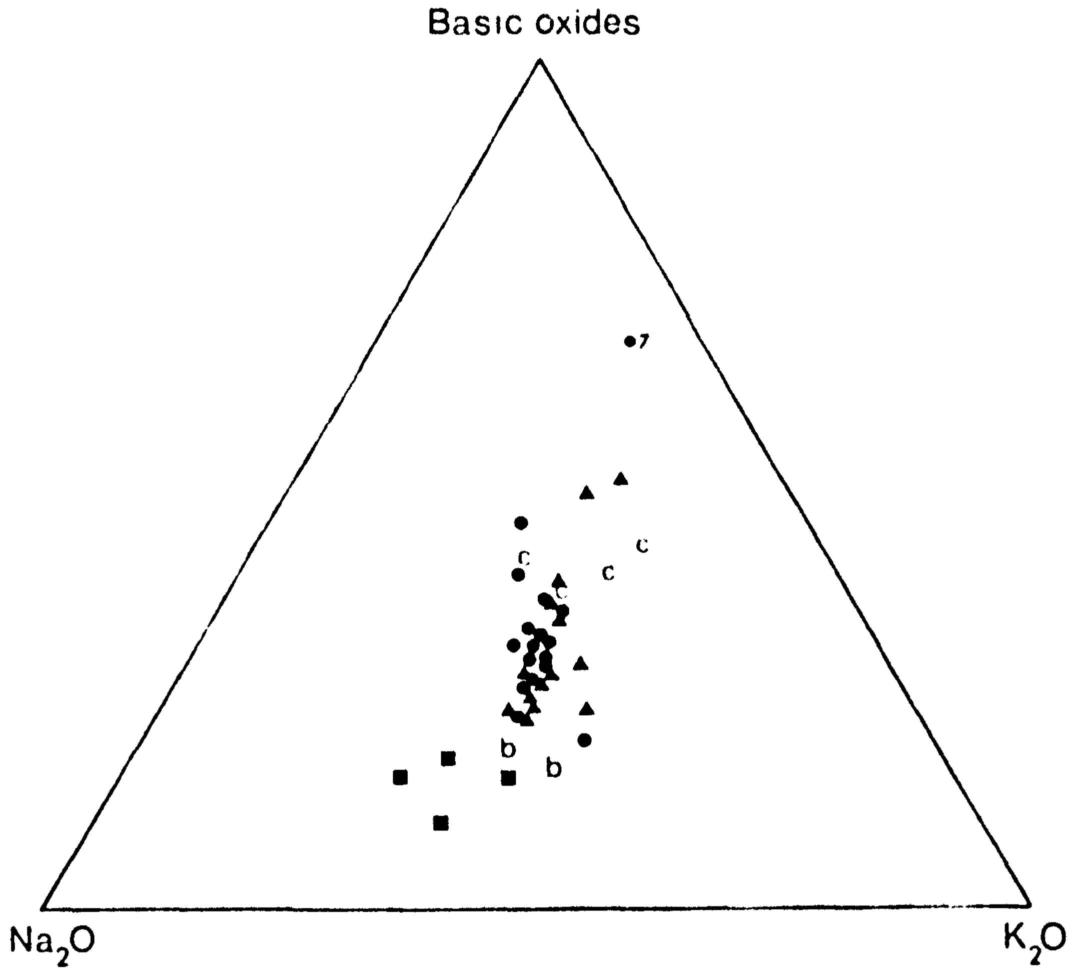
Key

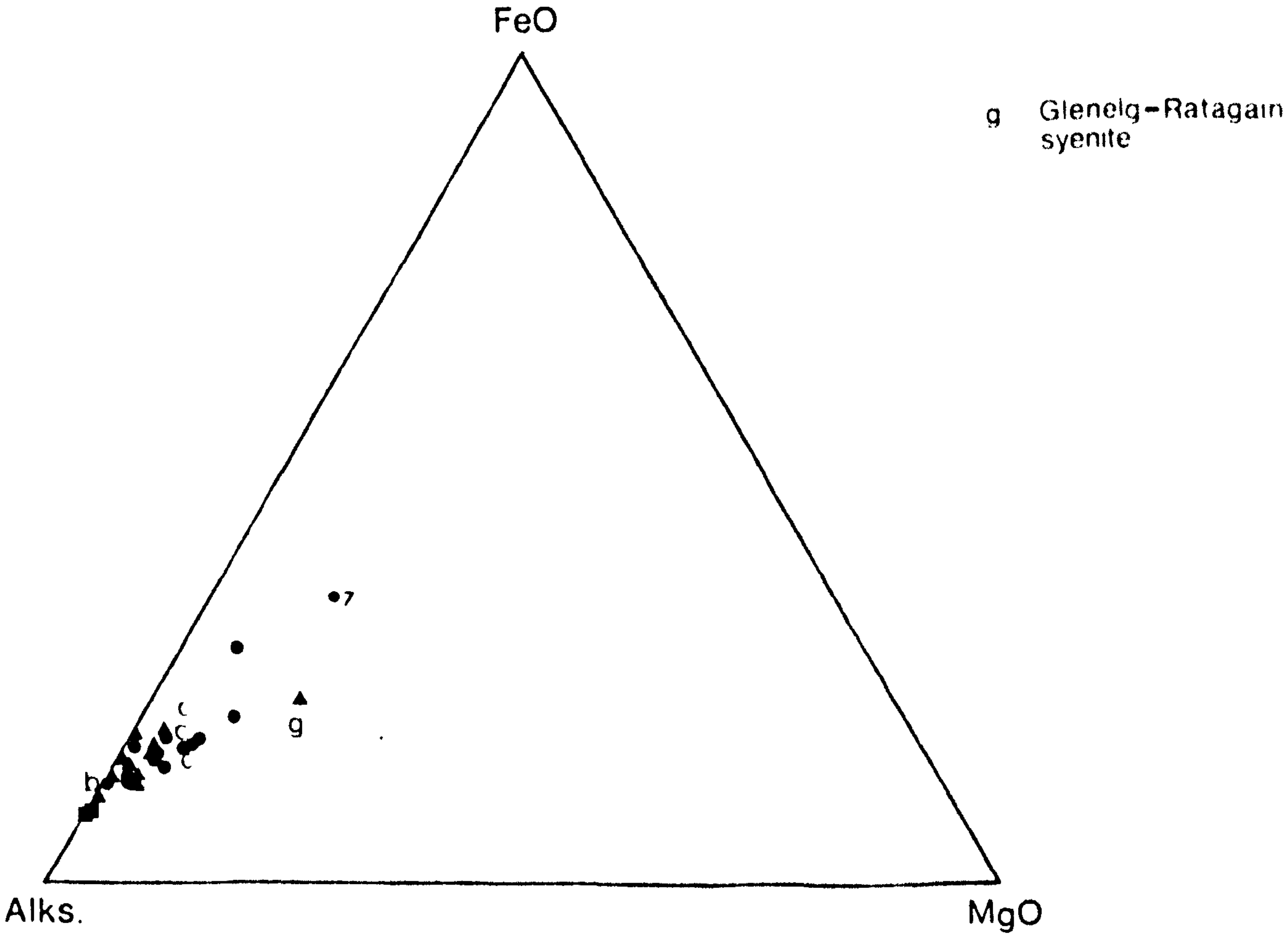
I	Ballater, granite (Hall 1969).
II	Ross of Mull, granite, (Hall 1969).
III	Strontian, tonalite, (Mercy 1963).
IV	Glen Banvie, Perthshire, tonalite, (Holgate 1950).
V	Cairnsmore of Fleet, biotite granite (Gardiner & Reynolds 1937).
VI	Abriachan, adamellite, (Hatch, Wells & Wells 1961).
VII	Moor of Rannoch, granodiorite, (H, W & W 1961).
VIII	Rubislaw, adamellite, (H, W & W 1961).
IX	Rockall, aegirine-granite (Sabine 1960).


Qtz
Ab
Or
Ne
Kp
PETROGENY'S 'RESIDUA' SYSTEM
Qtz
Ab
Or
● Ben Loyal syenites
▲ Beinn Stumanadh syenites
c Cnoc nan Cuilean syenites
■ Loch Ailsh syenites
b Loch Borralan syenites
Low temperature trough
Sutherland syenites
Average
1 rhyolite
2 granite
3 alkali syenite
4 alkali trachyte
5 phonolite
6 tinguaite
7 ledmorite


CaO + BaO + SrO
7
9
c
c
c
c
3
4
10
b
b
b
8
Na₂O
K₂O


An
8 alkali granite
9 granodiorite
10 nepheline - syenite
c
7
c
c
a
Ab
Or


Basic oxides
7
c
c
c
c
b
b
Na$_2$O
K$_2$O


FeO
g Glenelg–Ratagain syenite
7
c
c
c
g
b
Alks.
MgO

MAJOR CHEMISTRY, CIPW NORMS, TRACE ELEMENT CONTENT AND ELEMENT RATIOS FOR THE LOCH LOYAL ROCKS AND THEIR ALLIES.

KEY:-

1 MAJOR OXIDE CONSTITUENTS IN PERCENTAGES

SI = SIO2
TI = TIO2
AL = AL2O3
FE2 = FE2O3
NA = NA2O
H+ = H2O+
H- = H2O-
P2 = P2O5
RE = TOTAL RARE-EARTHS
TOT = TOTAL

2 CIPW NORMS

CONVENTIONAL

3 TRACE ELEMENT CONTENTS IN PARTS PER MILLION PPM

? = NOT DETERMINED

4 ELEMENT RATIOS

SG = DENSITY
MI = MAFIC INDEX
FI = FELSIC INDEX
RIT = RITTMANN INDEX

16104 - 27567	MICA SCHIST CHALBHACH COIRE	575500
16204 - 27568	SYENITIC VEIN CHALBACH COIRE	575500
16304 - 27571	SYENITE W. FACE OF SGOR A CHLEIRICH	566485
16404 - 27572	SYENITE W. EDGE OF SGOR FHIONNAICH	562483
16504 - 27573	SYENITE HEAD OF BEALACH DUBH	564486
16604 - 27574	SYENITE, IRON STAINED, SGOR CHAONASAID	577502
16704 - 27575	PEGMATITIC VEIN COILLE NA CUILE	580503

C.I.P.W. NORMS

	16104	16204	16304	16404	16504	16604	16704
Qtz	16.75	43.12	5.70	4.09	12.14	25.68	25.76
C	0.00	0.41	0.00	0.00	0.00	0.73	0.00
Zr	0.01	0.06	0.06	0.06	0.03	0.03	0.01
Or	5.83	15.60	34.58	35.23	33.51	32.98	29.79
Ab	33.84	32.91	50.43	51.61	45.80	36.55	41.33
An	25.09	6.22	0.19	1.21	0.00	1.18	0.00
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ac	0.00	0.00	0.00	0.00	2.81	0.00	1.24
Ns	0.00	0.00	0.00.	0.00	0.59	0.00	0.86
Di	4.16	0.00	5.35	2.89	2.90	0.00	0.91
Wo	0.00	0.00	0.00	1.01	0.00	0.00	0.00
Hy	6.80	0.66	0.89	0.00	0.43	0.00	0.14
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	4.52	0.42	2.09	1.66	0.00	0.00	0.00
Cm	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Hm	0.00	0.00	0.00	0.57	0.00	1.33	0.00
Il	1.01	0.23	0.78	0.66	0.47	0.44	0.04
Ru	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Ap	0.17	0.02	0.71	0.55	0.57	0.44	0.03
Hap	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fl	0.07	0.02	0.20	0.12	0.12	0.02	0.03
H_2O+	0.87	0.23	0.30	0.17	0.33	0.39	0.03
H_2O-	0.10	0.05	0.07	0.08	0.11	0.12	0.01
others	0.04	0.03	0.03	0.08	0.03	0.03	0.04
Silica undersat	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	16104	16204	16304	16404	16504	16604	16704
SI	60.66	78.32	66.11	64.90	68.72	72.63	74.99
TI	0.53	0.12	0.41	0.35	0.25	0.24	0.02
AL	16.83	11.91	16.20	16.91	15.04	14.26	13.49
FE2	3.12	0.29	1.40	1.72	0.97	1.33	0.43
FEO	3.10	0.58	1.40	0.78	0.74	0.18	0.31
MNO	0.12	0.02	0.06	0.05	0.04	0.03	0.01
MGO	2.54	0.00	1.01	0.51	0.31	0.00	0.00
CAO	6.19	1.18	1.56	1.49	0.83	0.24	0.10
NA	4.00	3.89	5.96	6.10	6.09	4.32	5.49
K2O	0.99	2.64	5.85	5.96	5.67	5.58	5.04
H+	0.87	0.23	0.30	0.17	0.33	0.39	0.03
H-	0.10	0.05	0.07	0.08	0.11	0.12	0.01
P2	0.07	0.01	0.27	0.21	0.21	0.14	0.01
CO2	0.00	0.00	0.00	ND	ND	ND	ND
OTH	0.03	0.02	0.03	0.03	0.03	0.03	0.04
ZR	0.01	0.02	0.04	0.04	0.02	0.02	0.01
BAO	0.04	0.10	0.48	0.46	0.32	0.31	0.18
SRO	0.05	0.08	0.12	0.15	0.12	0.10	0.07
F	0.04	0.01	0.11	0.07	0.07	0.02	0.01
BE	0.01	0.01	0.05	0.05	0.03	0.03	0.01
TOT	99.30	99.98	101.47	100.03	99.90	99.97	100.25

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	16104	16204	16304	16404	16504	16604	16704
CR	103	19	1	4	10	12	16
CO	36	22	17	21	21	29	98
NI	51	1	14	5	5	12	0
ZN	43	6	45	41	27	9	1
SR	512	765	1218	1534	1185	1004	658
RB	29	45	97	92	100	98	82
NB	3	2	21	19	17	14	81
Y	11	3	20	21	13	6	5
ZR	112	198	377	393	193	238	116
BA	369	1021	4813	4626	3205	3117	1763
PB	20	99	74	62	67	62	108
SC	26	6	6	6	2	6	3
LA	21	11	98	107	55	44	5
CE	99	76	412	322	256	265	53
SN	2	4	5	3	2	2	1

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + REE., & ELEMENT RATIOS

	16104	16204	16304	16404	16504	16604	16704
SG		2.603	2.596		2.588		
MI	72.1	100.0	75.1	83.8	85.5	100.0	100.0
FI	43.5	84.7	88.3	89.0	93.4	97.6	99.1
RIT	1.28	1.20	6.20	6.87	5.72	3.40	3.66
NA+K	4.99	6.53	11.81	12.06	11.76	9.00	10.53
NA:K	4.04	1.47	1.02	1.02	1.07	0.77	1.09
K:NA	0.248	0.679	0.982	0.977	0.931	1.297	0.913
NA:CA	0.646	3.297	3.821	4.094	7.337	17.009	54.990
K:CA	0.160	2.237	3.750	4.000	6.831	23.250	50.400
RB:SR	0.057	0.059	0.080	0.060	0.084	0.098	0.125
RB:PB	1.450	0.455	1.311	1.484	1.493	1.581	0.759
RB:K	0.003	0.002	0.002	0.002	0.002	0.002	0.002
RE	131	90	530	450	324	315	63
CE:LA	4.714	6.909	4.204	3.009	4.655	6.023	10.60
ZR:Y	10.182	66.00	18.85	18.71	14.85	30.67	23.20
PB:ZN	0.465	16.50	1.644	1.518	2.481	6.333	108.00
BA:SR	0.721	1.335	3.956	3.016	2.705	3.195	2.679
BA:PB	18.45	10.31	65.04	74.61	47.34	50.27	16.32
BA:CA	0.006	0.087	0.309	0.310	0.346	1.299	1.763

16804 - 27576 BASIC SEGREGATION IN SYENITE, CHAUNASAID, 579503

16904 - 27577 SYENITE, COILLE NA CUILE, CHAONASAID, 578502

17004 - 27579 SYENITE," 2130' PLATEAU " 571485

17104 - 27580 SYENITE, BEINN BHEAG, 578483

17204 - 27581 SYENITE, AN CAISTEAL, 578488

17304 - 27582 SYENITE, CARN AN TIONAIL, BEN LOYAL, 575477

17404 - 27583 MOINIAN METASEDIMENT, ALLT CHAUNASAID, 587506

16804 - 27576 BASIC SEGREGATION IN SYENITE, CHAONASAID, 579593

16904 - 27577 SYENITE, COILLE NA CUILE, CHAONASAID, 579502

17004 - 27579 SYENITE," 2130' PLATEAU " 571485

17104 - 27580 SYENITE, BEINN BHEAG, 578483

17204 - 27581 SYENITE, AN CAISTEAL, 578488

17304 - 27582 SYENITE, CARN AN TIONAIL, BEN LOYAL, 575477

17404 - 27583 MOINIAN METASEDIMENT, ALLT CHAONASAID, 587596

	16804	16904	17004	17104	17204	17304	17404
SI	58.82	65.72	63.72	63.42	64.76	64.41	87.20
TI	1.21	0.35	0.46	0.43	0.35	0.40	0.23
AL	11.26	15.78	15.39	16.67	16.23	16.34	7.78
FE2	7.31	2.42	2.68	3.00	2.25	0.95	1.15
FEO	0.86	0.10	1.03	0.04	0.18	1.32	0.38
MNO	0.22	0.05	0.10	0.06	0.05	0.05	0.01
MGO	3.84	0.57	1.63	0.60	0.56	0.33	0.20
CAO	5.33	1.60	2.22	1.51	1.65	1.26	0.04
NA	4.63	6.65	6.54	6.00	6.06	6.20	0.26
K2O	4.28	5.80	5.94	6.40	6.34	6.42	1.22
H+	0.45	0.01	0.17	0.54	0.35	0.15	1.09
H-	0.17	0.06	0.07	0.12	0.12	0.09	0.23
P2	0.27	0.20	0.13	0.27	0.19	0.23	0.00
CO2	ND	ND	ND	ND	ND	ND	ND
OTH	0.03	0.03	0.02	0.03	0.03	0.03	0.03
ZR	0.10	0.04	0.04	0.04	0.03	0.03	0.01
BAO	0.37	0.47	?	?	?	0.39	0.05
SRO	0.08	0.14	0.08	0.13	0.10	0.11	0.01
F	0.25	0.24	0.15	0.08	0.06	0.06	0.01
BE	0.16	0.04	0.08	0.08	0.06	0.07	0.00
TOT	99.64	100.27	100.45	99.42	99.42	100.04	99.90

C.I.P.W. NORMS

	16804	16904	17004	17104	17204	17304	17404
Qtz	5.73	4.32	0.14	2.03	3.61	1.14	80.61
C	0.00	0.00	0.00	0.00	0.00	0.00	5.94
Zr	0.15	0.06	0.06	0.06	0.04	0.04	0.01
Or	25.30	34.28	35.11	37.83	37.47	37.95	7.21
Ab	34.09	48.88	46.09	50.12	48.19	48.31	2.20
An	0.00	0.00	0.00	0.00	0.00	0.00	0.27
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ac	4.48	6.51	7.75	0.57	2.72	2.75	0.00
Ns	0.00	0.00	0.10	0.00	0.00	0.24	0.00
Di	18.84	3.22	7.53	3.25	3.03	7.26	0.00
Wo	0.00	0.76	0.00	0.18	1.15	0.00	0.00
Hy	0.94	0.00	1.79	0.00	0.00	0.46	0.50
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	0.00	0.00	0.00	0.00	0.00	0.00	0.59
Hm	5.76	0.17	0.00	2.80	1.31	0.00	0.74
Il	2.28	0.32	0.87	0.21	0.49	0.76	0.44
Sph	0.01	0.47	0.00	0.79	0.23	0.00	0.00
Ru	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ap	0.66	0.53	0.31	0.65	0.46	0.76	0.00
Hap	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fl	0.48	0.52	0.29	0.12	0.09	0.08	0.03
H_2O+	0.45	0.01	0.17	0.54	0.35	0.15	1.09
H_2O-	0.17	0.06	0.07	0.12	0.12	0.09	0.23
others	0.19	0.07	0.02	0.00	0.03	0.03	0.04
Silica undersat	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	16804	16904	17004	17104	17204	17304	17404
CR	18	12	22	0	3	1	27
CO	25	7	26	14	15	10	54
NI	44	8	17	13	9	16	11
ZN	137	34	?	?	?	35	21
SR	804	1411	767	1312	974	1056	66
RB	74	108	88	102	101	102	144
NB	57	20	22	21	2	21	1
Y	65	20	24	23	20	27	3
ZR	1015	395	381	394	335	333	133
BA	3666	4674	?	?	?	3926	528
PB	78	80	51	66	66	68	11
SC	20	5	9	8	7	9	6
LA	434	92	208	200	150	213	5
CE	1147	337	637	580	443	510	59
SN	6	5	?	?	?	4	2

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	16804	16904	17004	17104	17204	17304	17404
SG				2.566		2.603	2.603
MI	68.3	81.7	70.7	83.5	81.6	74.8	89.2
FI	62.6	95.9	84.9	89.1	88.3	86.5	97.1
RIT	5.23	7.50	8.63	7.44	7.03	7.62	-
NA+K	8.19	12.45	12.48	12.40	12.40	12.62	1.48
NA:K	1.08	1.15	1.10	0.94	0.96	0.96	0.21
K:NA	0.924	0.872	0.908	1.067	1.046	1.035	4.692
NA:CA	0.869	4.156	2.946	3.974	3.672	3.163	5.500
K:CA	0.803	3.625	2.676	4.238	3.842	3.276	30.500
RB:SR	0.092	0.077	0.115	0.078	0.104	0.097	2.182
RB:PB	0.949	1.350	1.725	1.545	1.530	1.500	13.091
RB:K	0.002	0.002	0.001	0.002	0.002	0.002	0.012
RE	1646	449	869	803	613	750	66
CE:LA	2.643	3.663	3.063	2.900	2.262	2.395	11.800
ZR:Y	15.62	19.75	15.88	17.13	16.75	12.33	61.00
PB:ZN	0.569	2.353	?	?	?	1.943	0.524
BA:SR	4.560	3.313	?	?	?	3.718	3.000
BA:PB	47.00	58.43	?	?	?	57.74	48.00
BA:CA	0.069	0.292	?	?	?	0.200	1.320

17504 - 27584 MOINIAN METASEDIMENT 587506

17604 - 27585 SYENITE, ALLT CHAONASAIDE 587506

17704 - 27586 SYENITE, LOCH NA CREIGE RIABHAICH 582491

17804 - 27587 SYENITE, N. SLOPE CREAG RIABHAICH 585494

17904 - 27588 SYENITE, GLAS-CHOIRE BEAG 585471

18004 - 27589 SYENITE, CREIG NA SPEIREIG 586467

18104 - 27590 MICROGRANITE DYKE, ALLT INNIS 582451

	17504	17604	17704	17804	17904	18004	18104
SI	83.44	67.36	61.47	61.55	63.06	68.51	71.17
TI	0.02	0.35	0.49	0.89	0.43	0.27	0.25
AL	9.57	16.71	16.33	16.10	17.08	15.40	15.25
FE2	0.16	1.05	1.96	4.09	2.37	1.19	1.48
FEO	0.14	1.18	0.99	1.06	0.39	0.79	0.00
MNO	0.00	0.05	0.07	0.07	0.06	0.05	0.01
MGO	0.00	0.11	1.02	0.90	0.56	0.44	0.00
CAO	0.55	0.72	2.34	2.26	1.49	1.42	0.34
NA	3.47	5.47	6.47	5.84	5.61	5.54	4.76
K2O	2.37	5.46	6.93	5.19	6.60	5.31	5.64
H+	?	0.37	0.42	0.78	0.47	0.35	0.26
H-	0.09	0.15	0.15	0.39	0.20	0.11	0.10
P2	0.00	0.18	0.33	0.39	0.26	0.14	0.09
CO2	ND	ND	ND	ND	ND	ND	ND
OTH	0.02	0.03	0.02	0.02	0.02	0.02	0.02
ZR	0.00	0.04	0.04	0.45	0.03	0.03	0.03
BAO	0.12	0.51	0.49	0.40	0.68	0.33	0.37
SRO	0.02	0.17	0.14	0.13	0.13	0.08	0.14
F	0.02	0.06	0.10	0.05	0.04	0.01	0.00
RE	0.00	0.06	0.05	0.06	0.10	0.05	0.06
TOT	99.99	100.03	99.81	100.62	99.58	100.04	99.97

C.I.P.W. NORMS

	17504	17604	17704	17804	17904	18004	18104
Qtz	52.91	12.60	0.00	3.56	2.35	13.42	20.95
C	0.25	0.54	0.00	0.00	0.00	0.00	0.53
Zr	0.00	0.06	0.06	0.67	0.04	0.04	0.04
Or	14.01	32.27	40.96	30.68	39.01	31.38	33.34
Ab	29.36	46.28	37.08	49.41	47.47	46.87	40.27
An	2.93	3.74	0.00	2.45	2.04	1.52	2.38
Ne	0.00	0.00	4.52	0.00	0.00	0.00	0.00
Ac	0.00	0.00	5.67	0.00	0.00	0.00	0.00
Ns	0.00	0.00	0.67	0.00	0.00	0.00	0.00
Di	0.00	0.00	7.90	4.99	3.22	2.68	0.00
Wo	0.00	0.00	0.34	0.45	0.64	0.98	0.00
Hy	0.09	1.09	0.00	0.00	0.00	0.00	0.00
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	0.23	1.52	0.00	1.07	0.21	1.72	0.00
Hm	0.00	0.00	0.00	3.36	2.23	0.00	1.48
Il	0.04	0.66	0.93	1.69	0.82	0.51	0.02
Ru	0.00	0.00	0.00	0.00	0.00	0.00	0.24
Ap	0.00	0.52	0.84	0.99	0.71	0.29	0.00
Hap	0.00	0.00	0.00	0.00	0.00	0.07	0.28
Fl	0.05	0.12	0.16	0.03	0.04	0.00	0.00
H_2O+	0.30	0.37	0.42	0.78	0.47	0.35	0.26
H_2O-	0.09	0.15	0.15	0.39	0.20	0.11	0.10
others	0.02	0.09	0.07	0.07	0.06	0.03	0.02
Silica undersat	0.00	0.00	3.82	0.00	0.00	0.00	0.00

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	17504	17604	17704	17804	17904	18004	18104
CR	17	8	9	25	0	7	9
CO	77	42	28	31	19	34	21
NI	1	7	16	12	9	7	8
ZN	0	39	47	43	32	28	16
SR	180	1698	1436	1310	1346	820	1429
RB	55	99	87	65	102	89	72
NB	0	21	20	35	15	16	13
Y	1	15	29	59	26	19	21
ZR	18	354	447	4502	337	337	327
BA	1170	5072	4938	3994	6812	3271	3745
PB	18	99	56	89	52	50	71
SC	3	6	8	13	7	5	5
LA	0	79	114	116	260	84	146
CE	41	460	388	449	665	364	395
SN	1	2	0	5	2	1	2

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + REE., & ELEMENT RATIOS

	17504	17604	17704	17804	17904	18004	18104
SG		2.554			2.513	2.524	2.579
MI	100.0	95.5	75.9	85.4	83.4	82.6	99.9
FI	91.4	93.9	99.4	83.0	89.1	73.4	96.8
RIT	0.84	4.98	12.37	6.67	7.55	4.69	4.03
NA+K	5.84	10.93	13.40	11.03	12.21	10.85	10.40
NA:K	1.46	1.00	0.93	1.13	0.85	1.04	0.84
K:NA	0.683	0.998	1.071	0.889	1.176	0.958	1.185
NA:CA	6.309	7.597	2.765	2.584	3.765	3.901	14.00
K:CA	4.309	7.583	2.961	2.296	4.430	3.740	16.588
RB:SR	0.306	0.058	0.061	0.050	0.076	0.109	0.050
RB:PB	3.056	1.00	1.554	0.739	1.962	1.730	1.014
PB:K	0.002	0.002	0.001	0.001	0.002	0.002	0.001
RE	42	554	531	624	951	467	552
CE:LA	41*	5.823	3.404	3.371	2.552	4.333	2.705
ZR:Y	18.0	23.6	15.41	76.31	12.16	17.74	15.57
PB:ZN	18*	2.538	1.191	3.070	1.635	1.756	4.438
BA:SR	6.500	2.987	3.439	3.049	5.061	3.989	2.621
BA:PB	65.00	51.23	88.13	44.88	131.0	65.42	52.75
BA:CA	0.213	0.704	0.211	0.177	0.457	0.230	1.101

18204 - 27591	SYENITE,	BEALACH CLAIS NAN CEAP	594496
18304 - 27592	SYENITE,	SUMMIT CNOC NAN CUILEAN	597462
18404 - 27593	SYENITE,	S. END OF CNOC NAN CUILEAN	596458
18504 - 27594	SYENITE,	W. END OF CREAG DHUBH	605498
18604 - 27595	SYENITE,	ALLT AN LAGH-AIRD	607485
18704 - 27596	SYENITE,	ALLT NAN CUILEAN	603464
18804 - 27597	DYKE,	ALLT TURR AN TAIRBH	609471

	18204	18304	18404	18504	18604	18704	18804
SI	63.33	63.14	62.28	62.55	65.69	66.16	73.42
TI	0.43	0.46	0.32	0.39	0.35	0.40	0.05
AL	16.78	16.66	16.51	16.55	16.28	17.81	14.48
FE2	1.13	1.07	1.31	1.08	1.42	0.27	0.63
FEO	1.66	1.62	1.39	1.57	0.45	2.12	0.08
MNO	0.05	0.07	0.08	0.06	0.06	0.04	0.00
MGO	1.04	0.82	0.94	0.88	0.33	0.48	0.00
CAO	2.04	3.01	2.56	2.32	0.68	2.01	0.33
NA	5.92	4.38	5.56	6.32	6.02	4.63	6.13
K2O	6.18	7.33	6.48	6.66	5.77	4.36	4.31
H+	0.25	0.08	0.51	0.41	1.09	0.41	0.23
H-	0.11	0.07	0.13	0.12	0.57	0.13	0.07
P2	0.23	0.31	0.22	0.26	0.25	0.16	0.00
CO2	ND	ND	ND	ND	ND	ND	ND
OTH	0.02	0.02	0.02	0.02	0.02	0.02	0.02
ZR	0.04	0.05	0.01	0.04	0.01	0.04	0.01
BAO	0.56	0.71	0.43	0.50	0.67	0.52	0.10
SRO	0.15	0.20	0.13	0.14	0.16	0.22	0.01
F	0.07	0.02	0.01	0.04	0.02	0.01	0.01
RE	0.04	0.06	0.06	0.07	0.07	0.03	0.00
TOT	100.03	100.08	98.95	99.98	99.91	99.82	99.88

C.I.P.W. NORMS

	18204	18304	18404	18504	18604	18704	18804
Qtz	0.69	3.61	0.35	0.00	7.28	15.86	21.34
C	0.00	0.00	0.00	0.00	0.00	1.64	0.00
Zr	0.06	0.07	0.01	0.06	0.01	0.06	0.01
Or	36.53	43.32	38.30	39.36	34.10	25.77	25.47
Ab	50.09	37.06	47.04	42.42	50.93	39.17	50.18
An	1.00	4.29	0.98	0.00	0.40	10.88	0.00
Ne	0.00	0.00	0.00	3.05	0.00	0.00	0.00
Ac	0.00	0.00	0.00	3.12	0.00	0.00	1.48
Ns	0.00	0.00	0.00	0.44	0.00	0.00	0.00
Di	7.40	7.44	7.31	9.43	2.00	0.00	0.00
Wo	0.00	0.83	1.17	0.00	0.38	0.00	0.81
Hy	0.64	0.00	0.00	0.00	0.00	4.28	0.00
Ol	0.00	0.00	0.00	0.02	0.00	0.00	0.00
Mt	1.64	1.55	1.90	0.00	0.63	0.39	0.11
Hm	0.00	0.00	0.00	0.00	0.98	0.00	0.04
Il	0.82	0.87	0.61	0.74	0.66	0.76	0.09
Sph	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ru	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ap	0.60	0.58	0.28	0.67	0.68	0.29	0.00
Hap	0.00	0.22	0.27	0.00	0.08	0.12	0.00
Fl	0.11	0.00	0.00	0.04	0.00	0.00	0.02
H_2O+	0.25	0.08	0.51	0.41	1.09	0.41	0.23
H_2O-	0.11	0.07	0.13	0.12	0.57	0.13	0.07
others	0.09	0.04	0.03	0.02	0.09	0.05	0.02
Silica undersat	0.00	0.00	0.00	2.59	0.00	0.00	0.00

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	18204	18304	18404	18504	18604	18704	18804
CR	13	3	0	0	0	4	19
CO	30	20	15	19	12	16	31
NI	13	9	8	12	12	5	0
ZN	36	33	40	34	46	20	12
SR	1506	1984	1259	1354	1633	2233	645
RB	92	96	81	82	72	100	82
NB	15	24	17	14	17	10	0
Y	10	20	21	28	24	18	0.5
ZR	365	549	65	372	78	397	67
BA	5610	7064	4332	4976	6657	5320	952
PB	55	36	38	61	80	33	52
SC	7	7	6	8	8	7	4
LA	88	125	123	158	160	37	3
CE	302	456	414	525	485	271	51
SN	3	4	2	0	4	1	3

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	18204	18304	18404	18504	18604	18704	18804
SG		2.657		2.582			2.574
MI	74.2	78.0	80.5	76.7	85.3	85.3	100.00
FI	85.6	79.0	82.5	84.8	94.6	81.7	97.0
RIT	7.41	7.06	7.25	9.25	6.41	3.75	3.73
NA+K	12.10	11.71	12.04	12.98	11.79	9.49	10.44
NA:K	0.958	0.598	0.858	0.949	1.043	0.953	1.422
K:NA	1.044	1.674	1.165	1.054	0.958	1.050	0.703
NA:CA	2.902	1.455	2.172	2.724	8.853	2.303	18.576
K:CA	3.029	2.435	2.531	2.871	8.485	2.418	0.417
RB:SR	0.061	0.048	0.064	0.061	0.044	0.045	0.127
RB:PB	1.673	2.666	2.132	1.344	0.900	3.030	1.577
RB:K	0.001	0.001	0.001	0.001	0.001	0.002	0.002
RE	400	601	558	711	669	326	54.5
CE:LA	3.432	3.648	3.366	3.323	3.031	7.324	17.00
ZR:Y	36.5	27.45	3.095	13.285	3.250	22.055	134.0
PB:ZN	1.528	1.091	0.950	1.794	1.739	1.650	4.333
BA:SR	3.725	3.560	3.441	3.675	4.077	2.382	1.476
BA:PB	102.0	196.22	114.00	81.57	83.21	161.21	18.31
BA:CA	0.275	0.235	0.169	0.214	0.979	0.265	0.289

18904 - 27598 SYENITE, ALLT TORR AN TAIRBH 605466

19004 - 27599 SYENITE, PEGMATITIC, INCLUSION RICH 605466

19104 - 27600 SYENITE, BASIC MARGINAL, ALLT LIATH 615461

19204 - 27602 SYENITE, DYKE, N.E. CORNER LOCH LOYAL 623508

19304 - 27603 SYENITE, SRON RUADH 624509

19404 - 27607 SYENITE, COILLE NA LEITIRE BIGE 625503

19504 - 27608 SYENITE, SRON RUADH 626508

	18904	19004	19104	19204	19304	19404	19504
SI	60.66	57.50	58.35	63.27	66.17	62.50	63.19
TI	0.54	0.61	0.54	0.16	0.25	0.30	0.29
AL	16.49	14.30	13.26	12.40	16.41	14.97	16.98
FE2	0.722	3.02	1.95	0.79	1.46	2.14	1.50
FEO	1.84	2.25	2.79	0.77	0.02	0.10	0.41
MNO	0.07	0.13	0.19	0.10	0.06	0.08	0.06
MGO	1.14	2.37	2.33	0.30	0.00	0.00	0.00
CAO	3.81	6.85	6.48	4.56	1.41	3.90	1.54
NA	3.85	2.67	3.77	4.06	5.17	5.03	5.96
K2O	8.71	7.19	6.82	6.01	6.91	5.88	6.05
H+	0.14	0.32	1.07	0.85	0.35	0.95	0.39
H-	0.08	0.09	0.16	0.19	0.03	0.09	0.06
P2	0.47	0.75	0.74	0.11	0.13	0.19	0.11
CO2	0.00	ND	0.49	3.00	0.90	3.23	1.13
OTH	0.02	0.01	0.02	0.01	0.03	0.02	0.02
ZR	0.03	0.04	0.07	0.03	0.04	0.04	0.03
BA	1.14	1.93	0.68	0.79	0.60	0.42	0.61
SRO	0.32	0.40	0.19	1.92	0.15	0.15	0.62
F	0.03	0.04	0.05	0.10	0.01	0.10	1.03
RE	0.08	0.04	0.05	0.10	0.08	0.06	0.06
TOT	100.14	100.51	100.00	99.52	100.18	100.15	100.04

C.I.P.W. NORMS

	18904	19004	19104	19204	19304	19404	19504
Qtz	0.00	1.98	0.04	15.08	8.96	10.73	5.35
C	0.00	0.00	0.00	0.00	0.00	0.33	0.63
Zr	0.04	0.06	0.10	0.04	0.06	0.06	0.04
Or	51.48	42.50	40.31	35.52	40.84	34.75	35.76
Ab	27.79	22.59	30.24	30.32	43.74	42.56	50.43
An	2.07	6.01	0.00	0.00	1.23	0.00	0.00
Ne	2.59	0.00	0.00	0.00	0.00	0.00	0.00
Ac	0.00	0.00	1.46	2.29	0.00	0.00	0.00
Ns	0.00	0.00	0.00	0.33	0.00	0.00	0.00
Di	10.41	15.03	19.28	4.35	0.00	0.00	0.00
Wo	2.12	4.39	1.14	1.85	0.11	0.00	0.00
Hy	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	1.04	4.38	2.09	0.00	0.00	0.00	0.00
Hm	0.00	0.00	0.00	0.00	1.46	0.00	1.50
Il	1.03	1.16	1.03	0.30	0.17	2.14	0.00
Sph	0.00	0.00	0.00	0.00	0.42	0.00	0.00
Ru	0.00	0.00	0.00	0.00	0.00	0.30	0.29
Ap	0.88	1.17	1.38	0.29	0.30	0.47	0.31
Hap	0.35	0.78	0.44	0.00	0.05	0.00	0.00
Fl	0.00	0.00	0.00	0.22	0.00	0.18	2.58
Cc	0.00	0.00	1.19	7.72	2.35	7.02	0.94
Chaly	0.00	0.00	0.00	0.00	0.00	0.29	0.76
H_2O+	0.13	0.31	1.06	0.85	0.35	0.95	0.39
H_2O-	0.08	0.09	0.16	0.19	0.03	0.09	0.06
others	0.05	0.05	0.07	0.11	0.11	0.25	0.57
Silica undersat	2.19	0.00	0.00	0.00	0.00	0.00	0.00

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	18904	19004	19104	19204	19304	19404	19504
CR	0	0	0	0	0	0	0
CO	13	13	18	11	21	13	4
NI	12	16	27	4	8	7	5
ZN	30	56	92	42	29	17	16
SR	3149	3996	1852	19220	1459	1504	6193
RB	115	85	84	79	122	128	98
NB	29	38	35	5	23	23	15
Y	43	64	51	63	24	26	18
ZR	261	393	713	304	350	347	305
BA	11416	19293	6766	7866	5918	4161	6062
PB	31	1	25	16	53	32	80
SC	10	17	16	12	6	10	5
LA	138	304	262	143	168	143	140
CE	626	1094	937	562	569	477	401
SN	6	7	8	3	5	6	0

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	18904	19004	19104	19204	19304	19404	19504
SG	2.791		2.759		2.544	2.587	2.645
MI	71.3	70.1	69.0	85.1	100.00	100.0	100.0
FI	76.7	59.0	62.0	68.8	89.5	73.7	88.6
RIT	9.50	6.94	8.01	5.50	6.33	6.15	6.67
NA+K	12.56	9.86	10.59	10.07	12.08	10.91	12.01
NA:K	0.442	0.371	0.553	0.676	0.748	0.855	0.985
K:NA	2.262	2.693	1.809	1.499	1.337	1.169	1.015
NA:CA	2.902	0.390	0.582	0.890	3.666	1.290	3.870
K:CA	2.286	1.050	1.052	1.32	4.901	1.508	3.929
RB:SR	0.037	0.021	0.045	0.009	0.088	0.065	0.016
RB:PB	3.710	85.0	3.360	4.938	2.415	3.063	1.225
RB:K	0.001	0.001	0.001	0.002	0.002	0.002	0.002
RE	807	1462	1250	768	761	646	559
CE:LA	4.536	3.599	3.576	3.930	3.387	3.336	2.864
ZR:Y	6.070	6.141	13.98	4.825	14.583	13.346	16.944
PB:ZN	1.033	0.017	0.272	0.382	1.828	1.882	5.00
BA:SR	3.625	4.828	3.653	0.409	4.056	2.767	0.979
BA:PB	368.26	192.93	270.64	491.63	111.66	130.03	75.715
BA:CA	0.300	0.282	0.104	0.173	0.419	0.107	0.394

19604 - 27609 SYENITE, ALLT NA LEITIRE BIGE 627491

19704 - 27610 SYENITE, S. END LEITIRE BIGE 627497

19804 - 27611 SYENITE, EASTERN SHORE, LOCH LOYAL 628482

19904 - 27614 SYENITE, ALLT ACH NAN CLACH 632505

20004 - 27615 VEIN, ALLT ACH NAN CLACH 632505

20104 - 27615 VEIN, ALLT ACH NAN CLACH 632505

20204 - 27616 SYENITE, S.W. OF COIRE NA CAILEIG 631501

	19604	19704	19804	19904	20004	20104	20204
SI	64·36	64·38	67·61	67·17	75·97	?	67·01
TI	0·33	0·28	0·29	0·29	0·55	0·09	0·33
AL	16·23	16·41	15·63	16·49	12·24	10·88	16·83
FE2	0·64	0·65	0·95	2·00	1·49	?	1·68
FEO	1·53	1·03	1·37	0·60	1·28	?	0·54
MNO	0·06	0·05	0·05	0·03	0·07	0·01	0·07
MGO	0·54	0·49	0·47	0·00	0·55	0·00	0·04
CAO	1·34	1·14	0·92	0·31	1·29	?	0·29
NA	6·40	6·13	6·02	5·89	3·12	3·26	6·19
K2O	5·71	6·00	5·62	5·85	4·16	5·20	5·87
H+	0·10	0·00	0·16	0·52	0·16	0·00	0·18
H-	0·07	0·07	0·09	0·13	0·03	0·05	0·07
P2	0·22	0·17	0·18	0·13	0·06	0·01	0·19
CO2	ND	ND	ND	ND	ND	ND	ND
OTH	0·03	0·03	0·03	0·03	0·03	0·02	0·04
ZR	0·04	0·02	0·03	0·03	0·03	0·01	0·04
BAO	0·48	0·49	0·32	0·32	0·13	0·16	0·53
SRO	0·15	0·13	0·06	0·12	0·04	0·08	0·11
F	0·09	0·07	0·08	0·01	0·03	0·01	0·02
RE	0·06	0·06	0·05	0·04	0·02	0·00	0·10
TOT	98·38	97·60	99·93	99·96	101·25	19·78	100·13

C.I.P.W. NORMS

	19604	19704	19804	19904	20004	20104	20204
Qtz	2.76	3.51	9.17	9.88	38.24	nd	7.97
C	0.00	0.00	0.00	0.00	0.34		0.00
Zr	0.06	0.03	0.04	0.04	0.04		0.06
Or	33.75	35.46	33.22	34.58	24.59		34.69
Ab	51.70	51.01	49.11	49.83	26.40		52.37
An	0.00	0.00	0.00	1.42	6.26		0.92
Ac	1.85	0.76	1.61	0.00	0.00		0.00
Ns	0.08	0.00	0.00	0.00	0.00		0.00
Di	5.32	4.74	3.23	0.00	0.00		0.25
Wo	0.00	0.00	0.00	0.16	0.00		0.20
Hy	1.18	0.22	1.43	0.00	1.71		0.00
Mt	0.00	0.56	0.57	1.19	2.16		1.01
Hm	0.00	0.00	0.00	1.18	0.00		0.98
Il	0.63	0.53	0.55	0.55	1.04		0.63
Ru	0.00	0.00	0.00	0.00	0.00		0.00
Ap	0.59	0.46	0.48	0.34	0.15		0.63
Hap	0.00	0.00	0.00	0.05	0.00		0.00
Fl	0.17	0.13	0.15	0.00	0.05		0.01
H_2O+	0.10	0.00	0.16	0.52	0.16		0.18
H_2O-	0.07	0.07	0.09	0.13	0.03		0.07
others	0.09	0.09	0.08	0.07	0.05		0.14
Silica undersat	0.00	0.00	0.00	0.00	0.00		0.00

TRACE ELEMENT CONTENTS OF LOYAL ROCKS

	19604	19704	19804	19904	20004	20104	20204
CR	4	4	7	9	43	22	0
CO	35	9	22	48	22	15	17
NI	11	9	8	8	9	1	11
ZN	41	29	45	12	23	6	38
SR	1511	1320	582	1199	378	844	1122
RB	96	105	122	104	104	115	115
NB	15	15	27	16	10	0	20
Y	20	14	12	11	19	3	32
ZR	396	172	348	341	338	91	425
BA	4831	4893	3175	3179	1333	1649	5296
PB	76	81	63	85	35	49	144
SC	6	8	5	3	11	3	4
LA	161	130	121	80	22	3	257
CE	402	478	388	314	185	59	674
SN	4	4	2	2	3	0	0

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	19604	19704	19804	19904	20004	20104	20204
SG	2.566	2.530		2.517			2.552
MI	81.5	78.9	84.4	100.00	85.0	100.00	98.2
FI	90.0	91.4	92.7	97.5	84.9	?	97.7
RIT	6.50	6.67	5.70	5.78	1.74	?	6.20
NA+K	12.11	12.13	11.64	11.74	7.28	8.46	12.06
NA:K	1.121	1.022	1.071	1.007	0.750	0.627	1.055
K:NA	0.892	0.979	0.934	0.993	1.333	1.595	0.948
NA:CA	4.776	5.377	6.543	19.00	2.419	?	21.345
K:CA	4.261	5.263	6.109	18.870	3.225	?	20.241
RB:SR	0.064	0.078	0.210	0.087	0.275	0.136	0.102
RB:PB	1.263	1.296	1.937	1.224	2.971	2.347	0.799
RB:K	0.002	0.002	0.002	0.002	0.003	0.002	0.002
RE	583	622	521	405	226	65	963
CE:LA	2.497	3.677	3.207	3.925	8.409	19.667	2.623
ZR:Y	19.800	12.29	29.00	31.00	17.79	30.33	13.28
PB:ZN	1.854	2.793	1.400	7.083	1.522	8.166	3.789
BA:SR	3.197	3.707	5.455	2.651	3.526	1.954	4.720
BA:PB	63.566	60.407	50.396	37.400	38.086	33.653	36.78
BA:CA	0.361	0.429	0.345	1.025	0.103	?	1.826

20304 - 27617 SYENITE, HILL IN COILLE A' PHUILL 639509

20404 - 27618 SYENITE, N.E. OF BEINN STUMANADH 645501

20504 - 27619 DYKE, SYENITIC ALLT NAN TARMACHAN 644506

20604 - 27620 DYKE, SYENITIC, S.E. OF STUMANADH 641498

20704 - 27621 PEGMATITIC FACIES IN MOINES 641498

20804 - 27622 ALTERED MICACEOUS ROCK, STUMANADH 641497

20904 - 27624 SYENITE, CLIFFS ABOVE TARMACHAN 646498

	20304	20404	20504	20604	20704	20804	20904
SI	62.13	?	76.84	67.89	72.57	60.91	64.44
TI	0.35	0.35	0.08	0.39	0.03	0.68	0.31
AL	15.95	?	11.52	16.38	14.34	17.72	16.04
FE2	2.43	2.43	1.21	2.35	0.27	3.43	1.97
FEO	0.25	0.43	0.07	0.00	0.00	2.56	0.28
MNO	0.07	?	0.01	0.02	0.01	0.08	0.05
MGO	0.46	?	0.00	0.34	0.00	1.53	0.17
CAO	2.74	?	?	0.47	0.59	0.08	1.49
NA	5.74	4.69	3.94	4.90	1.83	4.45	6.09
K2O	6.41	7.09	5.82	5.78	10.07	5.86	6.61
H+	0.31	0.00	0.07	0.37	0.00	1.48	0.37
H-	0.11	0.08	0.11	0.18	0.03	0.18	0.12
P2	0.23	0.32	0.00	0.11	0.01	0.18	0.13
CO2	2.00	ND	ND	ND	ND	ND	1.03
OTH	0.03	0.02	0.02	0.03	0.05	0.05	0.03
ZR	0.04	0.06	0.02	0.04	0.00	0.06	0.05
BAO	0.47	0.53	0.12	0.50	0.17	0.53	0.55
SRO	0.12	0.13	0.06	0.22	0.05	0.18	0.14
F	0.06	0.06	0.02	0.03	0.00	0.06	0.03
RE	0.07	0.10	0.01	0.05	0.01	0.05	0.07
TOT	100.67	16.46	99.92	100.05	100.03	100.07	99.97

TRACE ELEMENT CONTENTS

	20304	20404	20504	20604	20704	20804	20904
CR	0	0	19	8	19	45	1
CO	15	12	20	21	27	17	18
NI	11	3	2	8	0	30	12
ZN	41	39	4	23	0	120	26
SR	1246	1344	588	2154	475	1783	1393
RB	112	130	11	129	248	122	106
NB	24	26	6	25	0	13	16
Y	24	31	6	33	1	28	18
ZR	445	618	171	382	12	644	479
BA	4707	5308	1197	5025	1701	5267	5512
PB	80	46	58	73	102	119	94
SC	10	7	0	4	4	13	4
LA	170	264	11	88	8	102	172
CE	491	706	90	340	60	324	478
SN	4	1	4	2	3	4	4

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	20304	20404	20504	20604	20704	20804	20904
SG	2.591						
MI	85.5	?	100.0	87.3	100.0	80.6	93.1
FI	81.6	?	?	95.8	99.3	94.5	89.5
RIT	8.25	?	3.34	4.59	4.83	6.16	8.11
NA+K	12.15	11.78	9.76	10.68	11.90	10.31	12.70
NA:K	0.895	0.661	0.677	0.848	0.182	0.759	0.921
K:NA	1.117	1.512	1.477	1.180	5.503	1.317	1.085
NA:CA	2.095	?	?	10.426	3.102	55.625	4.087
K:CA	?	?	?	12.300	17.068	73.25	4.437
RB:SR	0.016	0.097	0.189	0.060	0.522	0.0684	0.0761
RB:PB	1.400	2.826	1.914	1.767	2.431	1.025	1.128
RB:K	0.002	0.002	0.002	0.002	0.002	0.002	0.002
RE	685	1001	107	461	69	454	668
CE:LA	2.888	2.674	8.182	3.864	7.500	3.176	2.779
ZR:Y	18.54	19.94	28.50	11.58	12.00	23.00	26.61
PB:ZN	1.951	1.179	14.50	3.174	102*	0.992	3.615
BA:SR	3.778	3.949	2.036	2.333	3.581	2.954	3.957
BA:PB	58.838	115.39	20.638	68.836	16.676	44.26	212.0
BA:CA	0.172	?	?	1.069	0.288	6.583	0.3699

21004 - 27625 SYENITE, CLIFFS AT TARMACHAN 646499

21104 - 27626 SYENITE, CLIFFS AT TARMACHAN 646499

21204 - 27627 SILL / MOINE CONTACT, LOCH NAM BREAC 657496

21304 - 27628 SILL, MICROGRANITE, FACING LOCH NAM BREAC 657496

21404 - 27629 SYENITE, WATERSHED W. OF CREAG DHUBH 652496

21504 - 27613 PEGMATITIC INTRUSIVE, CREAG BHREAC 655499

21604 - 27632 SYENITE, CONTACT, LOCH AILSH, ASSYNT 324120

	21004	21104	21204	21304	21404	21504	21604
SI	64.40	62.54	60.90	76.56	64.63	72.25	65.51
TI	0.30	0.61	1.11	0.05	0.41	0.69	0.22
AL	16.23	13.96	17.55	13.33	16.66	13.15	18.12
FE2	2.54	2.07	2.71	0.52	1.74	1.02	1.12
FEO	0.33	1.93	3.83	0.00	1.01	3.30	0.37
MNO	0.08	0.08	0.07	0.01	0.07	0.08	0.02
MGO	0.49	2.77	1.93	0.00	0.00	1.20	0.00
CAO	1.87	3.51	1.80	0.22	1.29	1.86	0.57
NA	5.32	3.56	5.44	4.62	5.29	2.79	7.20
K2O	6.16	7.41	2.94	4.39	6.75	2.70	6.47
H+	0.22	??	1.00	0.05	0.32	0.55	0.00
H-	0.12	0.10	0.14	0.11	0.10	0.04	0.03
P2	0.26	0.66	0.19	0.00	0.28	0.13	0.03
CO2	1.10	ND	ND	ND	0.72	ND	ND
OTH	0.03	0.05	0.05	0.03	0.03	0.03	0.01
ZR	0.05	0.05	0.04	0.01	0.04	0.03	0.02
BAO	0.39	0.51	0.14	0.08	0.47	0.07	0.20
SRO	0.11	0.13	0.06	0.02	0.11	0.02	0.09
F	0.05	0.20	0.12	0.00	0.03	0.05	0.00
RE	0.07	0.06	0.04	0.01	0.08	0.02	0.1
TOT	100.12	100.20	100.06	100.01	100.03	99.98	99.99

C.I.P.W. NORMS

	21004	21104	21204	21304	21404	21504	21604
Qtz	8.50	5.94	10.53	32.32	7.52	38.38	0.00
C	0.29	0.00	2.73	0.51	0.24	2.61	0.00
Zr	0.07	0.07	0.06	0.01	0.06	0.04	0.03
Or	36.41	43.80	17.38	25.95	39.90	15.96	38.24
Ab	45.01	30.12	46.03	39.09	44.76	23.61	54.12
An	1.47	0.23	7.44	1.35	1.18	8.33	0.00
Ne	0.00	0.00	0.00	0.00	0.00	0.00	1.34
Ac	0.00	0.00	0.00	0.00	0.0	0.00	3.24
Ns	0.00	0.00	0.00	0.00	0.0	0.0	0.01
Di	0.00	10.62	0.00	0.00	0.0	0.0	0.70
Wo	0.00	0.00	0.00	0.00	0.0	0.0	1.16
Hy	1.22	3.00	7.90	0.00	0.0	7.21	0.00
Mt	0.45	3.00	3.93	0.00	2.29	1.48	0.00
Hm	2.23	0.00	0.00	0.52	0.16	0.0	0.00
Il	0.57	1.16	2.11	0.02	0.78	1.31	0.42
Ru	0.00	0.00	0.00	0.04	0.00	0.0	0.00
Ap	0.67	1.65	0.47	0.00	0.75	0.31	0.00
Hap	0.00	0.00	0.00	0.00	0.00	0.0	0.08
Fl	0.06	0.31	0.22	0.00	0.01	0.08	0.00
Cc	2.70	0.00	0.00	0.00	1.85	0.00	0.00
H_2O+	0.22	0.30	1.00	0.05	0.32	0.55	0.00
H_2O-	0.12	0.10	0.14	0.11	0.10	0.04	0.03
others	0.10	0.11	0.09	0.04	0.11	0.05	0.11
Silica undersat	0.00	0.00	0.00	0.00	0.00	0.00	1.13

TRACE ELEMENT CONTENTS

	21004	21104	21204	21304	21404	21504	21604
CR	1	70	97	19	6	65	21
CO	18	16	22	25	24	36	13
NI	10	83	28	0	12	23	1
ZN	41	71	87	6	25	50	5
SR	1102	1293	635	235	1083	261	859
RB	116	185	162	115	117	132	46
NB	19	31	15	1	23	12	17
Y	23	20	39	3	21	34	7
ZR	468	541	422	84	429	280	196
BA	3873	5114	1391	811	4678	731	1984
PB	76	58	75	62	54	26	39
SC	4	11	23	0	6	15	1
LA	171	69	71	0	150	30	15
CE	509	478	260	48	593	149	99
SN	2	6	7	2	3	?	2

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	21004	21104	21204	21304	21404	21504	21604
SG	2.591	2.677					2.617
MI	85.5	60.4	78.5	100.0	100.0	80.2	100.0
FI	86.0	75.8	82.3	97.6	98.0	74.8	96.0
RIT	6.20	6.22	4.01	2.42	1.04	1.04	8.34
NA+K	11.48	10.97	8.38	9.01	12.04	5.49	13.67
NA:K	0.864	0.480	1.850	1.052	0.784	1.033	1.113
K:NA	1.158	2.081	0.547	0.950	1.276	0.968	0.899
NA:CA	2.845	1.014	3.022	21.00	4.101	1.500	12.63
K:NA	3.294	2.111	1.633	19.95	523.3	1.452	11.35
RB:SR	0.1053	0.1431	0.2551	0.4894	0.1080	0.5057	0.0536
RB:PB	1.526	3.190	2.240	1.855	2.167	5.077	1.179
RB:K	0.002	0.003	0.006	0.003	0.002	0.005	0.00007
RE	703	567	370	51	764	213	121
CE:LA	2.977	6.928	3.662	48*	3.953	4.967	6.60
ZR:Y	20.35	27.05	10.82	28.00	20.43	8.235	28.00
PB:ZN	1.854	0.817	0.862	10.333	2.160	0.520	7.800
BA:SR	3.515	3.955	2.191	3.451	4.319	2.801	2.310
BA:PB	50.960	88.172	18.547	13.081	86.629	28.115	50.871
BA:CA	0.207	0.146	0.0772	0.369	0.363	0.039	0.348

21704 - 27633 SYENITE, LARGE E.-W. DYKE LOCH AILSH 328136

21804 - 27634 SYENITE SOUTHERN PART, LOCH AILSH, 325125

21904 - 27635 BOULDER OYKELL RIVER, LOCH AILSH, 327135

22004 - 27636 SYENITE, WITH MELANITE, SAIL AN RUATHAIR 334140

22104 - 27637 MAFIC MICACEOUS BOULDER, LOCH AILSH, 334140

22204 - 27638 SYENITE, FOOTBRIDGE, RIVER OYKELL, AILSH 328139

22304 - 27639 QUARTZ-SYENITE, CNOC NA SROINE, BORRALAN 260120

	21704	21804	21904	22004	22104	22204	22304
SI	75.34	64.79	76.15	64.08	34.99	65.48	70.21
TI	0.10	0.23	0.08	0.14	0.25	0.22	0.13
AL	12.77	17.41	12.92	18.01	13.70	18.29	16.42
FE2	1.53	1.39	1.45	3.14	2.46	2.28	0.82
FEO	0.00	0.24	0.00	0.00	1.41	0.00	0.35
MNO	0.02	0.02	0.01	0.06	0.14	0.05	0.02
MGO	0.00	0.01	0.00	0.00	35.57	0.00	0.00
CAO	0.02	0.73	0.01	0.69	0.13	0.12	0.64
NA	5.69	8.77	5.17	8.03	0.10	7.87	7.23
K2O	4.45	5.65	3.97	5.18	3.35	5.51	3.71
H+	0.00	0.02	0.00	0.00	7.18	0.00	0.15
H-	0.06	0.10	0.11	0.08	0.11	0.08	0.15
P2	0.00	0.03	0.00	0.01	0.00	0.00	0.00
CO2	ND	ND	ND	ND	ND	ND	ND
OTH	0.05	0.01	0.02	0.03	0.03	0.08	0.01
ZR	0.03	0.01	0.04	0.05	0.02	0.02	0.01
BAO	0.01	0.26	0.05	0.31	0.43	0.31	0.17
SRO	0.00	0.18	0.01	0.17	0.04	0.06	0.11
F	0.01	0.00	0.00	0.01	0.16	0.01	0.01
RE	0.01	0.01	0.01	0.07	0.00	0.04	0.01
TOT	100.09	99.86	100.00	100.06	100.17	100.42	100.15

C.I.P.W. NORMS

	21704	21804	21904	22004	22104	22204	22304
Qtz	27.60	0.00	30.79	0.00	0.00	0.00	12.85
C	0.00	0.00	0.06	0.00	9.91	0.00	0.00
Zr	0.04	0.01	0.06	0.07	0.03	0.03	0.01
Or	26.30	33.39	23.46	30.62	0.00	32.57	21.93
Ab	40.91	55.48	43.74	58.55	0.00	61.74	61.17
An	0.00	0.00	0.20	0.00	0.00	0.00	1.46
Lc	0.00	0.00	0.00	0.00	14.31	6.00	0.00
Ne	0.00	1.42	0.00	2.84	0.46	0.91	0.00
Kp	0.00	0.00	0.00	0.00	0.88	0.00	0.00
Ac	4.43	4.02	0.00	3.64	0.00	2.80	0.00
Ns	0.51	2.68	0.00	0.00	0.00	0.00	0.00
Di	0.00	0.25	0.00	0.00	0.00	0.00	0.00
Wo	0.00	1.94	0.00	1.95	0.00	0.27	1.06
Hy	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol	0.00	0.00	0.00	0.00	62.32	0.00	0.00
Mt	0.00	0.00	0.00	0.00	3.57	0.00	0.82
Hm	0.00	0.00	1.45	1.88	0.00	1.31	0.26
Il	0.04	0.44	0.02	0.13	0.47	0.11	0.25
Sph	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Pf	0.00	0.00	0.00	0.14	0.00	0.38	0.00
Ru	0.06	0.00	0.07	0.00	0.00	0.00	0.00
Ap	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Hap	0.00	0.08	0.00	0.00	0.00	0.00	0.00
Fl	0.02	0.00	0.00	0.02	0.55	0.13	0.02
Cc	0.00	0.00	0.00	0.00	0.20	0.00	0.00
Magn	0.00	0.00	0.00	0.00	0.08	0.00	0.00
H_2O+	0.00	0.02	0.00	0.00	7.18	0.00	0.15
H_2O-	0.06	0.10	0.11	0.08	0.11	0.08	0.15
others	0.06	0.02	0.03	0.10	0.03	0.12	0.02
Silica undersat	0.00	1.20	0.00	2.46	31.57	0.89	0.00

TRACE ELEMENT CONTENTS OF LOCH AILSH AND BORRALAN ROCKS

	21704	21804	21904	22004	22104	22204	22304
CR	20	23	19	10	22	13	16
CO	29	16	21	12	15	1	25
NI	0	2	0	0	8	0	1
ZN	20	17	8	36	103	59	18
SR	45	1756	65	1730	442	630	1092
RB	138	39	62	57	67	48	7
NB	22	8	26	41	2	22	4
Y	5	7	15	20	0	18	18
ZR	336	103	391	512	152	194	136
BA	127	2577	462	3102	4264	3106	1720
PB	148	30	41	131	12	527	25
SC	0	2	0	0	4	0	2
LA	9	15	18	201	0	94	8
CE	87	104	111	508	43	243	71
SN	0	3	4	4	3	4	2

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	21704	21804	21904	22004	22104	22204	22304
SG	2.614	2.613		2.575	3.105	2.573	
MI	100.0	99.3	100.0	100.0	10.2	100.0	100.0
FI	99.8	95.2	99.9	95.1	96&.4	99.1	94.4
RIT	3.31	12.0	2.52	9.08	-1.13	8.36	4.42
NA+K	10.14	14.42	9.14	13.21	3.45	13.38	10.94
NA:K	1.279	1.552	1.302	1.550	0.0296	1.428	1.949
K:NA	0.782	0.644	0.768	0.645	33.50	0.700	0.513
NA:CA	284.5	12.01	517.0	11.64	0.769	65.58	11.297
K:CA	222.5	773.97	397.0	7.507	25.77	45.917	5.797
RB:SR	3.0667	0.0222	0.9538	0.0329	0.152	0.076	0.006
RB:PB	0.932	1.300	1.512	0.435	5.583	0.091	0.280
RB:K	0.0031	0.0006	0.002	0.02	0.001	0.002	0.002
RE	101	126	144	729	43	355	97
CE:LA	9.666	6.93	6.167	2.527	43*	2.585	8.875
ZR:Y	67.20	14.71	26.07	25.60	152*	10.78	7.555
PB:ZN	7.400	1.765	5.125	3.639	0.1165	8.932	1.389
BA:SR	2.822	1.468	7.108	1.793	9.647	4.930	1.575
BA:PB	0.858	85.90	11.268	23.679	355.3	5.894	68.80
BA:CA	0.064	0.353	4.62	0.450	3.28	2.588	0.269

22404 - 27640 SYENITE, MID-HEIGHT, CNOC NA SROINE 255123

22504 - 27641 SYENITE, BASE OF CNOC NA SROINE, 250123

22604 - 27642 SYENITE BOULDER, SROINE, LOCH BORRALAN 250123

22704 - 27643 LEDMORITE, LEDMORE RIVER, ASSYNT, 248120

22804 - 27644 SYENITIC ROCK, GLENELG-RATAGAIN COMPLEX.

22904 - 27645 RED GRANITIC ROCK, ROAD WORKS DORNIE.

23004 - 27651 MAFIC SILL, INTRUSIVE INTO CLUANIE GRANITE.

	22402	22504	22604	22704	22804	22904	23004
SI	65.64	63.36	65.65	47.23	60.44	61.29	61.56
TI	0.30	0.56	0.32	1.06	0.72	0.46	0.61
AL	17.53	17.76	17.88	16.88	15.81	15.30	15.68
FE2	1.77	2.76	0.83	8.08	1.44	2.20	3.73
FEO	0.43	0.91	0.82	0.14	2.29	0.67	2.75
MNO	0.03	0.06	0.02	0.15	0.08	0.06	0.06
MGO	0.00	0.18	0.00	2.47	2.67	0.85	1.91
CAO	0.35	0.86	0.21	7.82	3.62	2.49	3.53
NA	7.15	7.04	6.42	2.86	6.43	6.07	5.69
K2O	6.28	5.33	7.26	8.29	4.45	4.88	2.01
H+	0.14	0.25	0.09	2.92	0.52	0.68	0.92
H-	0.09	0.23	0.10	0.20	0.12	0.16	0.85
P2	0.00	0.03	0.00	0.47	0.46	0.22	0.17
CO2	ND	ND	ND	0.94	ND	3.17	1.03
OTH	0.02	0.02	0.02	0.02	0.02	0.02	?
ZR	0.01	0.02	0.01	0.03	0.03	0.03	0.02
BAO	0.22	0.28	0.16	0.14	0.23	0.44	0.07
SRO	0.16	0.21	0.13	0.18	0.23	0.26	0.08
F	0.00	0.06	0.07	0.06	0.11	0.10	0.04
RE	0.01	0.03	0.01	0.03	0.04	0.04	0.01
TOT	100.13	99.95	100.00	99.97	99.71	99.39	100.72

C.I.P.W. NORMS

	22404	22504	22604	22704	22804	22904	23004
Qtz	0.57	0.47	0.45	0.00	0.00	7.29	13.04
C	0.00	0.00	0.00	0.00	0.00	0.03	0.45
Zr	0.01	0.03	0.01	0.04	0.04	0.04	0.03
Or	37.12	31.50	42.91	41.39	26.30	28.84	11.88
Ab	55.21	59.56	51.55	0.00	50.94	51.36	48.23
An	0.00	1.18	0.00	8.78	1.16	0.00	10.10
Lc	0.00	0.00	0.00	5.97	0.00	0.00	0.00
Ne	0.00	0.00	0.00	13.11	1.88	0.00	0.00
Ac	4.66	0.00	2.40	0.00	0.00	0.00	0.00
Ns	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Di	0.45	1.03	1.15	13.34	11.66	0.00	0.00
Wo	1.05	1.10	0.00	0.86	0.00	0.00	0.00
Hy	0.00	0.00	0.46	0.00	0.00	0.00	5.80
Ol	0.00	0.00	0.00	0.00	2.26	0.00	0.00
Mt	0.23	1.51	0.00	0.00	2.09	0.00	5.41
Hm	0.00	1.72	0.00	8.08	0.00	2.20	0.00
Il	0.57	1.06	0.61	0.61	1.37	0.26	1.16
Pf	0.00	0.00	0.00	1.26	0.00	0.00	0.00
Ru	0.00	0.00	0.00	0.00	0.00	0.32	0.00
Ap	0.00	0.08	0.00	1.13	1.13	0.56	0.41
Hap	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fl	0.00	0.14	0.19	0.04	0.15	0.18	0.05
Cc	0.00	0.00	0.00	2.16	0.00	4.59	2.37
Magn	0.00	0.00	0.00	0.00	0.00	1.78	0.00
Chaly	0.00	0.00	0.00	0.00	0.00	0.98	0.00
H_2O+	0.14	0.25	0.09	2.92	0.52	0.68	0.92
H_2O-	0.09	0.23	0.10	0.20	0.12	0.16	0.85
others	0.03	0.05	0.03	0.05	0.02	0.08	0.06
Silica undersat	0.00	0.00	0.00	13.29	2.48	0.00	0.00

TRACE ELEMENT CONTENTS OF BORRALAN ROCKS + OTHERS

	22402	22504	22604	22704	22804	22904	23004
CR	16	14	17	27	88	21	?
CO	24	14	24	23	24	16	?
NI	0	0	0	6	68	13	?
ZN	20	45	19	54	49	30	49
SR	1594	2076	1284	1788	2340	2600	861
RB	87	71	92	169	51	74	48
NB	4	12	5	0	13	8	4
Y	2	28	8	74	10	8	13
ZR	113	168	101	296	315	258	232
BA	2182	2800	1624	1379	2303	4364	767
PB	42	34	39	7	23	19	?
SC	1	3	1	18	12	7	14
LA	11	43	22	48	83	85	18
CE	100	198	110	215	320	260	111
SN	2	4	0	4	2	2	0

SPECIFIC GRAVITY, INDICES, TOTAL ALKS + RES., & ELEMENT RATIOS

	22404	22504	22604	22704	22804	22904	23004
SG			2.535	2.700			
MI	100.0	95.5	100.0	76.9	61.3	78.0	66.5
FI	97.5	93.5	98.5	58.8	75.0	81.5	68.6
RIT	8.75	8.01	9.17	38.6	8.28	8.15	3.35
NA+K	13.43	12.37	13.68	11.15	10.88	10.95	7.70
NA:K	1.121	1.321	0.884	0.345	1.445	1.244	2.831
K:NA	0.892	0.757	1.131	2.899	0.692	0.804	0.353
NA:CA	20.429	8.186	30.571	0.366	1.776	2.438	1.612
K:CA	17.94	6.197	34.57	1.060	1.229	1.950	0.569
RB:SR	0.055	0.034	0.072	0.095	0.022	0.028	0.060
RB:PB	2.071	2.088	2.359	24.14	2.217	3.895	?
RB:K	0.001	0.001	0.001	0.002	0.001	0.002	0.002
RE	113	269	140	337	413	353	142
CE:LA	9.091	4.605	5.000	4.479	3.855	3.059	6.167
ZR:Y	56.50	6.00	12.625	4.000	31.50	32.25	17.85
PB:ZN	2.10	0.7556	2.053	0.129	0.469	0.633	?
BA:SR	1.404	1.349	1.265	0.7712	0.984	1.678	0.891
BA:PB	51.95	82.35	41.64	197.0	100.13	229.68	?
BA:CA	0.623	0.326	0.7733	0.018	0.064	0.175	0.022

CHAPTER TEN.

MINERALOGY.

Separatibn of the minerals.

Material for examination was separated by a variety of techniques including hand-crushing in a steel percussion mortar, panning of beach sand from the northern shore of Loch Fhionnaich at NC 567485 and hand- ■16 picking from the rock. Minerals were washed, polished, dried and then further purified using a Frantz isodynamic magnetic separator, finally all material was hand-picked under a binocular microscope when only uncontaminated fragments were retained for analysis.

The mineralogy and geochemistry of strontianite, zeolites, polycrase, amazonite and the yellow rare-earth mineral have been detailed elsewhere in this thesis. This chapter will examine amphibole and sphene from the Ben Loyal syenite and describe an electron-microprobe study of lead mineralisation from the pegmatites of Sgor Chaonasaid.

Major chemistry of the Loch Fhionnaich amphibole.

In the appended table the Loyal amphibole is compared with analyses presented in the literature; an examination of these shows that the Loyal amphibole is:-

i Closely comparable with the average hornblende from granites as determined by Tschirwinsky (1913) although richer in Na_2O and Fe_2O_3, and similar to green hornblendes from the Scottish Newer Igneous suite analysed by Nockolds and Mitchell (1948) and Deer (1937).

ii Low in alumina compared with all the other amphiboles in the table.

iii Highly silicic (parameters ii & iii are necessarily complementary) iv Much less sodic than arfvedsonites and magnesiokatophorite.

v Significantly different from mboziite, hastingsite, basaltic hornblende and the alkali-amphiboles.

These relationships are demonstrated clearly when the analyses are plotted within an FeO, Al_2O_3, MgO triangular diagram.

The trace element content in ppm of the amphibole was found to be:-

Loyal amphibole		Loyal syenite
* Sc	34	8±
* Co	45	<30
* Ni	133	<15
* Zn	395	40±
Rb	3	100±
Sr	148	>1200
Y	11	>20
Zr	164	>350
Nb	8	>20
* Sn	7	3±
Ba	28	>4000
La	15	>100
Ce	131	>400

* = elements concentrated in the amphibole.

Scandium, cobalt, nickel, zinc and tin were found concentrated in the amphibole relative to the parent rock; Zn, Ni, and Sc especially are markedly enriched. Qualitative U.V. spectrography showed the following trace elements to be present Pb, Cr, V, Be, Cu, Ga and Mo, this trace element pattern when compared with those determined for hornblendes by Nockolds and Mitchell (op. cit.) and Heitainen (1971) shows lower values of Y, Sc, and Ba for the Fhionnaich specimen, (the latter surprisingly so because of the relative enrichment of the Loyal complex in barium) and higher amounts of Zr, Sr, and probably Ni.

Physical properties of the amphibole.

Amphibole comprises roughly 10% of the Loch Loyal syenites. In hand specimen the mineral is black or very dark green in colour and is usually found as poorly terminated lath-like prisms, normally about 2mm in length. The density was determined by carefully diluting Clerici solution with water until the amphibole grains sank and then allowing evaporation until the mineral fragments just floated, the specific gravity of the liquid was then found on the Westphal balance, this was 3.2280 ± 0.001.

A summary of the optical characteristics of the amphibole.

a. Biaxial negative.

b. Two cleavage directions parallel to (110) at angles of 56° and 124° (not always well seen).

c. Pleochroic, pale yellowish green/pale green/dark grass green, absorption formula $X < Y < Z$

d. Elongation-positive, i.e. length slow.

e. Birefringence. Polarisation colours are obscured by the strong colour of the mineral.

f. Axial angle $2V \simeq 50^\circ$, i.e. low, (as estimated from Wrights curved isogyre method). 17

g. Indices of refraction $n\alpha = 1.651$

$n\beta = 1.653$

$n\gamma = 1.668$

as measured by liquid immersion method.

h, Twinning is rather common with twin plane as (100)

Infra-red spectrum of the amphibole.

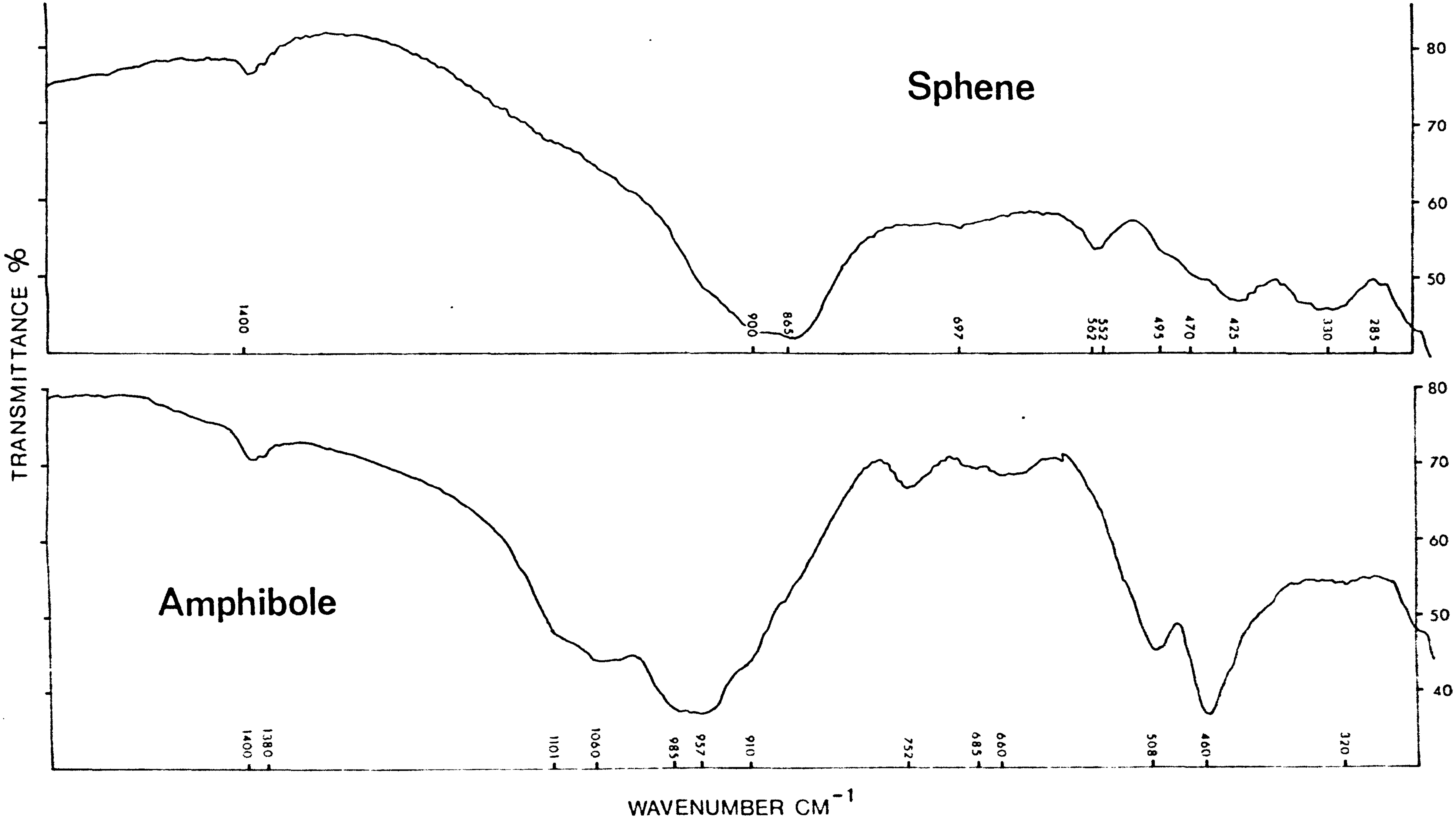
The infra-red absorption spectrum showed the following absorption peaks.

Wavenumber (cm^{-1})

320
* 460
* 508 ------ Si - O bending peaks
660
685 ------ Si - Si stretching peaks
* 752
910
* 957
985 ------ Si stretching peaks, connected with Al-Si substitution.
1060 ------ M - O bands connected with Fe/Mg substitution
*1101
1380
*1400
2920
3120
3660 ------ connected with the hydroxyl group.

* = main peaks.

This spectrum is determined by the vibrational modes of the atomic or molecular structure within the amphibole and is uniquely characteristic being a complex function of inter-atomic distances, bond angles, forces, and the relative masses of the constituent atoms. The assignment of absorption peaks to specific bond types is difficult although most



INFRA-RED ABSORPTION SPECTRA

metal-oxygen bonds have vibrations between 2000 & 850 cm^{-1}, and silicates show marked absorption peaks near to 1000 cm^{-1} caused by the Si-O stretching vibration, with Si-O bending vibrations at longer wavelengths between 665 - 400 cm^{-1}.

Faye and Nickel (1970) using polarised optical spectra of a number of amphiboles have shown that the green hues of calcic amphiboles are a direct consequence of the absorption of violet-blue light, connected with $O^{2-} \rightarrow Fe^{3+}$ charge transfer, and red-orange light connected with $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer processes.

The X-ray diffraction pattern of the Fhionnaich amphibole.

A table of d spacings is appended below. The pattern is similar to that of tremolite and synthetic ferropargasite although the third strongest reflection, 2.71 is not well marked in the Loyal example. Unlike hornblende, the strongest reflection for the Loyal mineral is at 8.37.

X-RAY DIFFRACTOMETER SCAN OF AMPHIBOLE FROM LOCH FHIONNAICH, BEN LOYAL.

d spacings
9.04
8.37
4.50
4.23
3.85
3.38
3.26
3.122
2.944
2.799
2.734
2.703
2.591
2.531
2.382
2.340
2.327
2.163
2.016
2.001
1.895
1.818
1.558
1.441

Relative Intensities

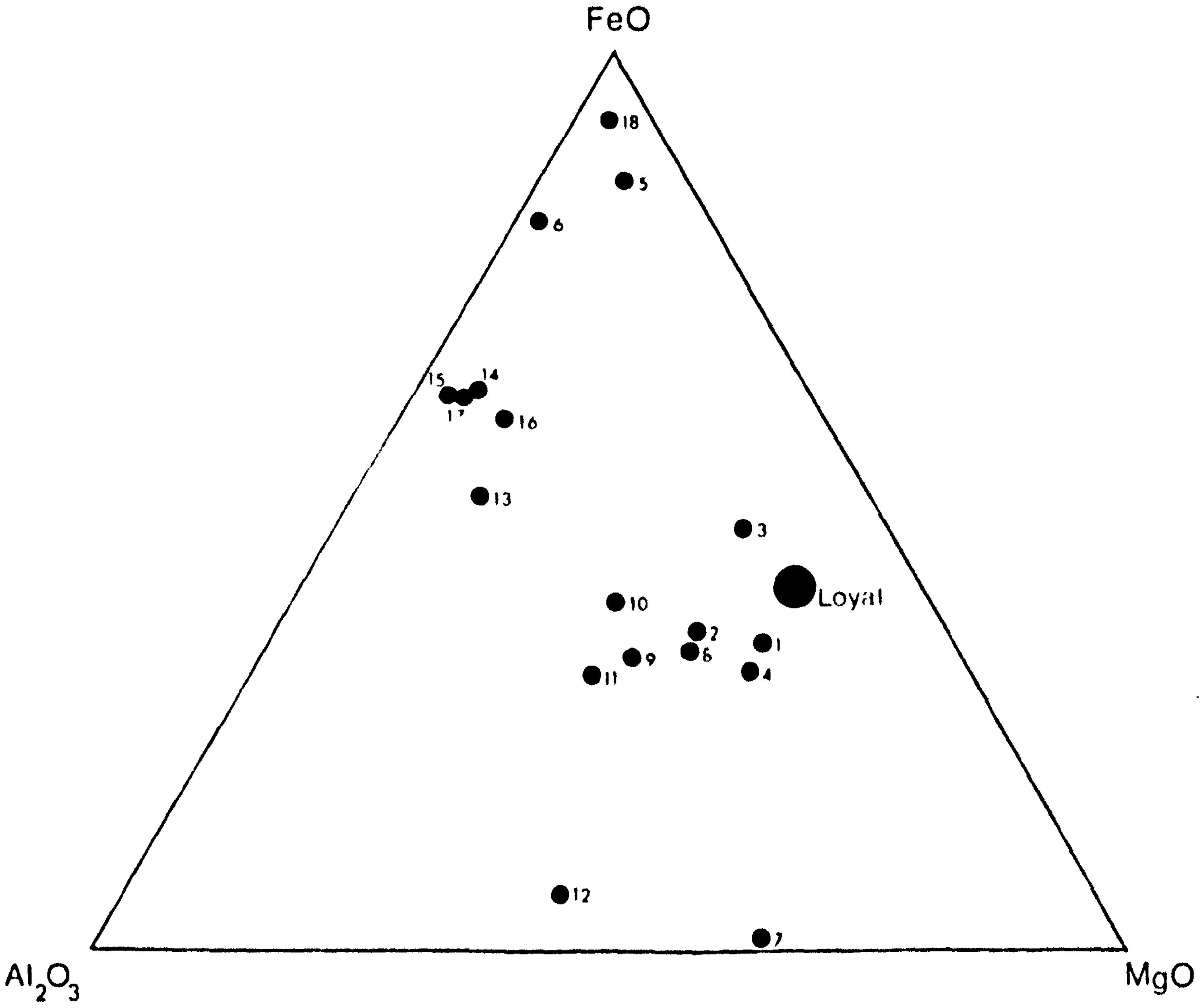
	d spacings	I
1.	8.37	100
2.	3.122	62
3.	1.441	16
4.	1.895	15
5.	9.04	13
6.	2.799 4.502	12

AMPHIBOLE ANALYSES

	Loyal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Loyal
SiO_2	49.40	48.55	45.84	50.18	45.51	48.51	45.99	45.79	43.76	43.08	41.99	39.48	39.95	36.95	36.86	37.13	37.08	38.56	48.41	49.40
TiO_2	0.57	0.27	1.73	1.58	1.32	1.10	1.00	1.20	0.78	0.90	1.46	0.30	1.68	6.25	1.04	0.30	0.89	0.96	1.32	0.57
Al_2O_3	3.40	5.71	7.75	4.27	6.60	1.08	5.57	11.37	8.33	11.41	11.62	12.99	17.58	15.02	12,10	12.50	11.77	10.31	1.81	3.40
Fe_2O_3	6.17	2.41	4.22	2.78	4.09	17.53	9.19	0.42	6.90	4.74	2.67	7.25	7.25	3.62	7.41	11.15	5.82	13.12	11.25	6.17
FeO	10.76	10.56	11.19	14.18	9.48	14.31	26.00	0.42	10.47	11.42	14.32	10.73	2.18	19.40	23.35	21.55	22.02	18.72	23.81	10.76
MnO	0.62	0.15	0.31	0.30	0.19	0.66	1.08	0.39	0.50	-	0.25	1.00	tr	-	0.77	0.60	1.33	1.91	0.75	0.62
MgO	12.54	14.76	12.86	11.75	14.74	1.31	0.49	21.11	12.63	12.41	11.17	11.47	14.15	4.34	1.90	0.83	3.46	1.24	0.06	12.54
CaO	10.08	13.73	11.62	11.84	5.60	5.43	4.93	12.71	9.84	11.61	11.52	12.91	11.96	10.25	10.59	7.54	10.94	5.78	1.18	10.08
Na_2O	2.95	1.88	2.04	0.95	6.01	7.87	3.26	2.51	3.43	1.98	2.49	1.70	3.16	1.34	1.20	3.84	2.54	4.71	7.37	2.95
K_2O	0.83	0.81	0.93	0.51.	2.20	1.48	1.10	1.69	1.28	1.23	0.98	2.39	1.98	1.33	3.20	2.81	2.07	2.73	1.52	0.83
H_2O	1.12	0.91	1.40	2.13	1.47	1.65	1.35	0.67	0.65	1.64	0.61	0.76	0.41	2.59	1.30	1.95	0.92	1.66	1.07	1.12
P_2O_5	0.03	0.06	nd	nil	nd	nd	0.02	nd	nd	-	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.03
F	1.36	nd	-	nd	-	nd	0.20	2.76	1.82	nd	0.80	0.05	0.03	nd	0.27	nil	1.94	0.30	2.95	1.36
Li_2O	0.03	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.03
Cl	-	nd	-	nd	nd	nd	0.02	nd	nd	nd	nd	nd	nd	nd	nd	-	0.14	0.15	nd	

Key to Amphibole Analyses

1. Average of a number of hornblendes from granites (Tschirwinsky 1913).
2. Green hornblende from tonalite, Morvern-Strontian complex, (Nockolds & Mitchell 1948).
3. Green hornblende from pegmatite in the Carsphairn complex, (Deer 1937).
4. Magnesiokatophorite from theralite, Montana, (Wolff 1939).
5. Arfvedsonite from alkali-rich monzonites, Morotu district of Sakhalin, (Yagi 1953).
6. Amphibole from alkali-granite, Otanmaki, Finland, (Hytonen & Heikkinen 1966).
7. Hornblende from Grenville Township, Quebec, (Clarke 1911).
8. Hornblende from Renfrew, Ontario, (Clarke 1911).
9. Green hornblende from syenite, Plauen, (Kunitz 1930).
10. Hornblende from Edenville, New York, (Clarke 1911).
11. Hornblende from Monte Somma, Italy, (Clarke 1911).
12. Basaltic hornblende, Bilin, Bohemia, (Clarke 1911).
13. Titaniferous amphibole from calc-alkali-syenite, Koraput, Orissa, (Bose 1963/64).
14. Hornblende, Cornwall, New York, (Clarke 1911).
15. Alkali-amphibole from nepheline syenite, Darkainle, Somali Republic, (Gellatly 1963).
16. Hastingsite from outer quartz-syenites, Marangudzi ring complex, Rhodesia, (Borley & Frost 1963).
17. Mboziite, S. W. Tanzania, (Brock et al 1964).
18. Arfvedsonite, from syenite, East Greenland, (Deer, Howie & Zussman 1963).



COMPOSITION OF THE LOYAL AMPHIBOLE

Analysis of the amphibole enabled the chemical formula to be calculated as:- ■18

$$\overset{A}{(Na_{0.47}\ K_{0.16})_{0.63}}\quad \overset{X}{(Ca_{1.61}\ Na_{0.39})_2}\quad \overset{Y}{(Mg_{2.82}\ Fe^{2+}_{0.71}\ Ti_{0.08}\ Mn_{0.02}\ Zn_{0.01})_{5.00}}$$

$$\overset{Z}{(Si_{7.39}\ Al_{0.61})_8}\quad O_{22}(OH_{1.27}\ F_{0.73})_{2.00}$$

or more approximately as

$$(Na_{0.5}\ K_{0.2})_{0.7}(Ca_{1.6}\ Na_{0.4})_2\ (Mg_{2.8}\ Fe^{2+}_{1.4}\ Fe^{3+}_{0.8})_5\ (Si_{7.4}\ Al_{0.6})_8$$

$$O_{22}(OH_{1.3}\ F_{0.7})_2$$

Since calcium is the major tenant of the X site it follows that the Fhionnaich mineral is a calciferous amphibole as defined by Phillips (1966) and when a summation of Na atoms in the formula is plotted against the number of Al atoms lies in the Ed s.e. (sensu extensus) field of Phillips and Layton (1964). Potassium is placed in the A site since it probably cannot replace calcium in X positions as sodium does.

When all the properties are considered the amphibole at Loyal is found to be a relatively soda-rich, alumina-poor calciferous amphibole intermediate between ferroactinolite and ferroedenite but closer to the latter for which the term magfedenite could be a convenient contraction.

The location of the trace elements within the amphibole structure.

Elements of the first transition series.

Ti, Mn, Fe and to a lesser extent Zn are major elements within the amphibole structure, the other transition metal ions Sc, V, Cr, Co, Ni and Cu are all found as traces. Scandium substitutes isomorphously for magnesium or ferrous iron, trivalent vanadium follows ferric iron closely, cobalt and nickel are known to have a close geochemical coherency with Fe, and chromium to both Fe and Mg. Trivalent ions similar to Fe^{3+} are concentrated within the M_2 position of the amphibole structure, whilst elements close to Fe^{2+} are enriched in M_1 and M_3 sites.

Lithium

The lithium content of the amphibole was determined with a grating flame photometer at 6707Å. A value of 330 ppm Li was obtained, this lithium replaces Mg^{2+} in the Y positions in the amphibole structure.

Gallium.

As usual this Group IIIB element is camouflaged in the Al position within the Z site.

Beryllium.

The increased concentration of this element in the Loyal amphibole supports Goldschmidt's observation of preferential concentration in pyroxenes and amphiboles from nepheline syenites, again the element probably replaces Al although it is possible that some replacement of divalent zinc occurs.

The major chemistry of the Loch Fhionnaich sphene.

The major chemistry of the sphene is compared in the appended table with analyses from the literature. From this it is seen that the Loyal sphene is closely comparable to most others although having a lower niobium content.

Trace element content of the Fhionnaich sphene.

Compared with the trace element content of the Loyal syenite sphene is enriched in Zr, Nb, Y, Sc, La, Ce, Sn and Ni and depleted in Sr, Rb, Ba, Zn, and Co and with the exception of Zn, Co and Ni is markedly enriched in all other traces when contrasted with the coexisting amphibole. ■19

TRACE ELEMENT CONTENT OF THE LOYAL SPHENE IN PPM

Li	0
Sc	28
Co	0
Ni	29
Zn	10
Rb	0
Sr	229
Y	911
Zr	496
Nb	1013
Sn	82
La	1711
Ce	6188

In a qualitative examination by U.V. spectrography these additional elements were also found as traces:-

Pb, V, Cr, Cu, Yb, Mo, and Ga

Physical and optical features of the sphene.

Euhedral "diamond-shaped" crystals which are moderately pleochroic from pale-yellow to brown are typical. A prominent parting is always present and the mineral has a very high relief. A density of 3.603 was determined by pyknometer. Zabavnikova (1957) contends that the physical properties especially specific gravity and refractive indices are closely related to the composition of sphenes, and that the elements which cause an increase in density are mainly rare-earths and niobium. This author also suggests a connection between composition of the sphene and its origin and he notes that the accessory sphenes of acid igneous rocks and pegmatites are characterised by the presence of rare-earths. With such a high density as the Loyal sphene possesses one would expect the summation of rare-earths and niobium to be high with 3% or more placing it in the keilhauites, it has however only about 1% total rare-earths plus niobium and does not therefore fit into the scheme proposed by Zabavnikova. Because of its high content of Fe + Al, together with low rare-earth content the Fhionnaich sphene may best be described as a grothite. Two other sphenes a dark red-brown variety from Khan mine S.W.A. and a green specimen from Madagascar had densities of 3.607 and 3.514 respectively, these figures support Zabavnikova's observation that pale-coloured sphenes have lower densities and hence lower rare-earths. This latter observation was confirmed by U.V. spectrography.

Infra-red spectrum of the sphene.

The infra-red spectrum showed the following peaks:-

Wavenumber cm^{-1}

285
* 330
* 425
470
495 Si-O bending peaks
552
* 562
697 Si-Si stretching peak?
* 865
* 900 Si-O stretching peaks
*1400 M-O bands
2920
3100

* = main absorption peaks.

SPHENE ANALYSES

	Loyal	1	2	3	4	5	6	7	8	Loyal
SiO_2	30.21	30.44	29.32	30.35	30.66	30.59	30.46	30.22	30.32	30.21
TiO_2	35.38	39.66	35.26	35.44	33.87	33.51	38.06	34.33	33.70	35.38
Al_2O_3	1.39	0.00	1.02	2.15	3.21	2.86	nil	0.28	4.44	1.39
Fe_2O_3	2.52	0.00	1.34	2.50	1.80	1.41	0.40	2.24	nil	2.52
FeO	0.50	0.14	1.05	-		0.69		0.62	0.20	0.50
MnO	0.12	0.05	0.03	0.25	0.07	0.05	-	0.18	0.01	0.12
MgO	0.08	0.00	0.36	0.10	0.04	nil	0.12	0.60	0.16	0.08
CaO	26.98	27.20	25.72	26.46	26.24	26.26	23.97	26.75	28.40	26.98
Na_2O	0.04	0.37	0.14	-	0.86	0.52	1.75	nil	0.16	0.04
K_2O	0.03	0.00	0.07	0.02	0.11	nil	nil	0.41	nil	0.03
H_2O	0.47	0.64	0.82	1.10	0.60	0.58	0.78	0.65	0.72	0.47
F	0.56	0.61	-	0.67	0.11	0.20	0.33	0.60	1.40	0.56
R.E.	0.88	0.37	4.51	1.06	1.56	1.89	0.74	2.12	0.30	0.88
Nb_2O_5	0.10.	0.34	-	-	0.89	0.93	2.27	1.38	0.69	0.10
Ta_2O_5	nd	0.01	-	nd	nil	nil	0.23	nil	0.03	nd
SrO	0.02	0.32	-	nil	nil	0.43	1.04	tr	0.01	0.02
PbO	tr	nd	-	nd	-	0.01	-	-	-	tr
ZrO_2	0. 05	0.11	tr	-	nil	0.19	0.20	0.02	0.06	0.05
Others	0.25	0.10	0.10	0.28	-	-	-	-	0.11	0.25

Key to Sphene Analyses

1. Light reddish-brown sphene from nepheline syenite, Kola Peninsula, USSR (Sahama 1946).

2. Black sphene from pegmatite, Ethiopia (Morgante 1943).

3. Sphene from Wainui Inlet beach sand, N.W. Nelson, New Zealand, (Hutton 1950).

4. Brown sphene from an acid pegmatite, Slyudyanka USSR, (Zabavnikova 1957).

5. Reddish-brown sphene from granite, Borshchevochnyi Range, USSR, (Zabavnikova 1957).

6. White sphene, from an alkalic pegmatite, Lovozero, Kola, USSR, (Zabavnikova 1957).

7. Reddish-brown sphene from granite, Kuraminskii Range USSR, (Zabavnikova 1957).

8. Grothite, Parainen, Finland, (Sahama 1946).

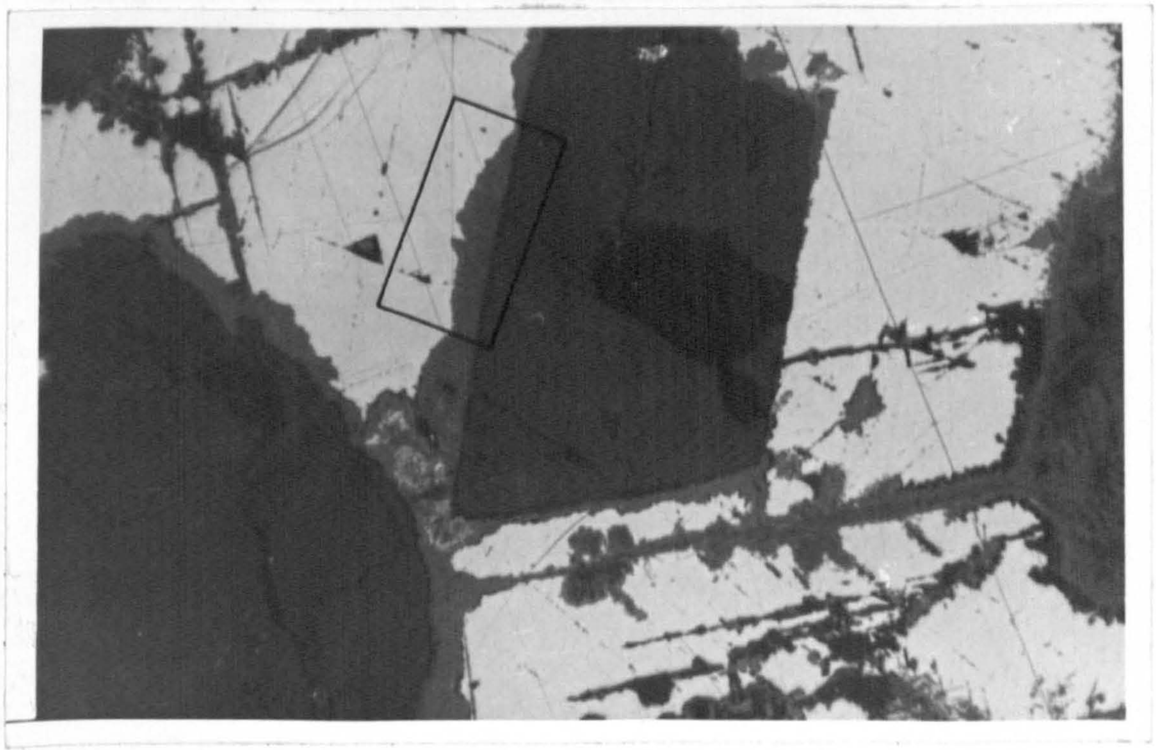
The location of trace elements within the sphene structure.

Yttrium, cerium and lanthanum in the Fhionnaich sphene replace calcium in the general formula $CaTi(SiO_4)$ (O,OH,F) and although not of such tenor as to warrant the name keilhauite, 0.9% of rare-earth oxides is considerably greater than the rare-earth content of sphenes from Caledonian granites of Western Scotland quoted by Lyakhovich (1962) as 0.06%. Loyal sphene is not radioactive and all the thorium in the complex seems to have been concentrated in the allanite. Strontium is concentrated with the calcium as are the minute traces of Ba and Pb.

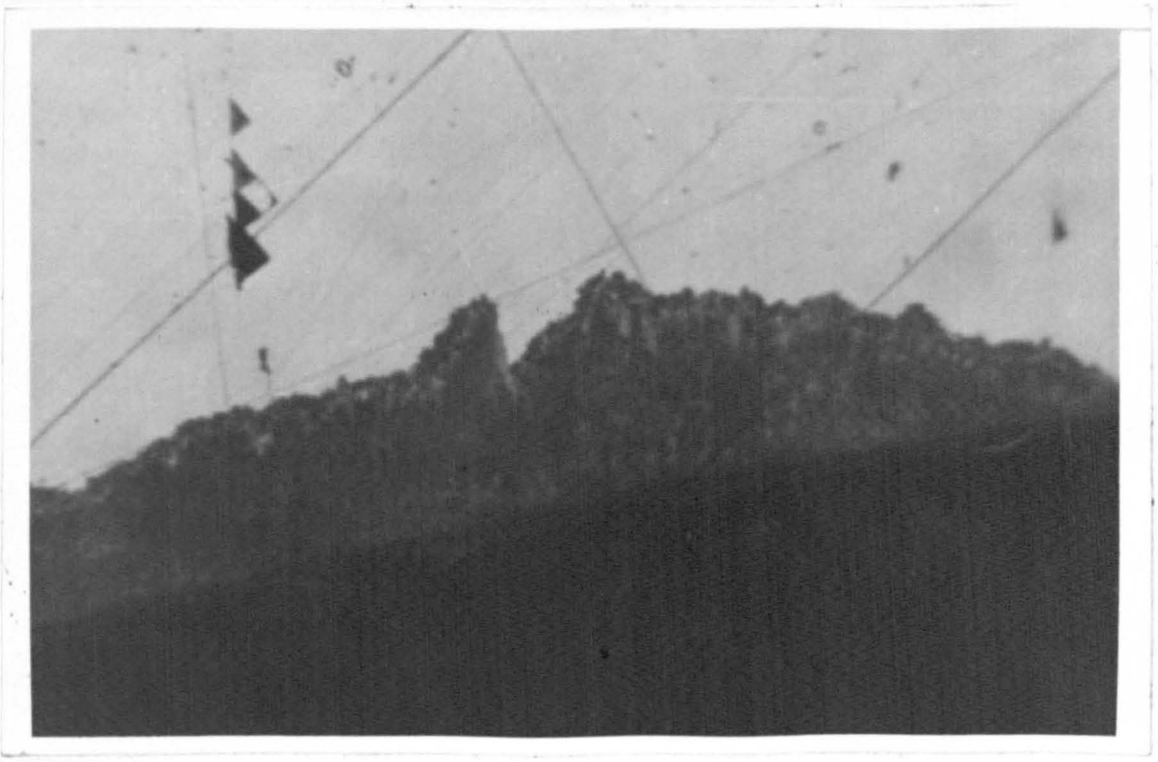
Substitutions for titanium in the structure include first transition series elements, aluminium and the important substitutions of Nb and Sn. Niobium may substitute for Ti^{4+} but it is more likely that sphene is an isomorphous mixture of compounds or minerals of which the bulk is $CaTiSiO_5$, together with subsidiary compounds such as $NaNbSiO_5$ and $CaAlSi_4OH$. Stanniferous sphenes are known and Lyakhovich & Balanova (1969) have suggested 280 ppm as typical of sphenes from alkali syenites. Loyal sphene with 82ppm although lower than this value represents a very marked concentration of this element over that within the parent rock or its other minerals; here the amount is less than 5ppm or below the level of instrument sensitivity. In contrast the Nb content of the sphene at Fhionnaich with 1000ppm is almost twice that taken as typical of alkali syenites by Lyakhovich and Balanova; a situation not unexpected in view of the presence of polycrase in the pegmatites of Sgòr Chaonasaid. Zirconium is found with tantalum substituting for titanium.

The association at Loyal of sphene, allanite, the yellow rare-earth phospho-silicate and polycrase is unusual. Tauson (1965)

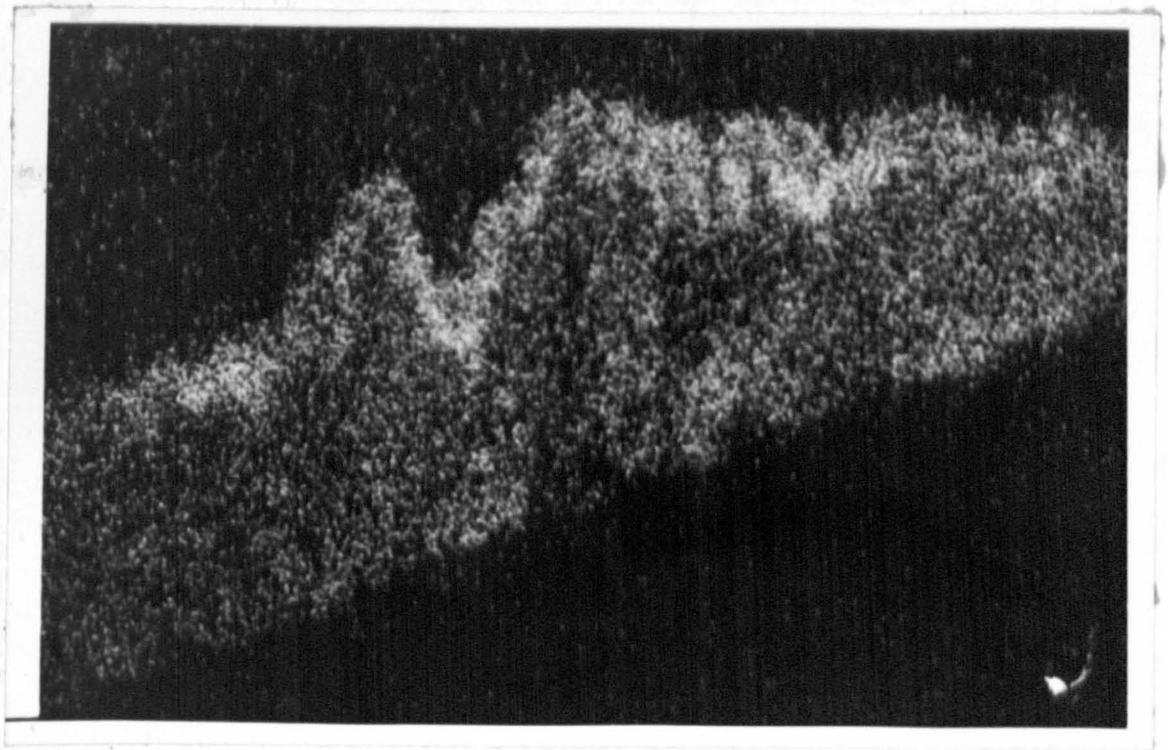
Electron-microprobe study of galena from the Sgòr Chaonasaid pegmatites. Polished specimen No. 2147



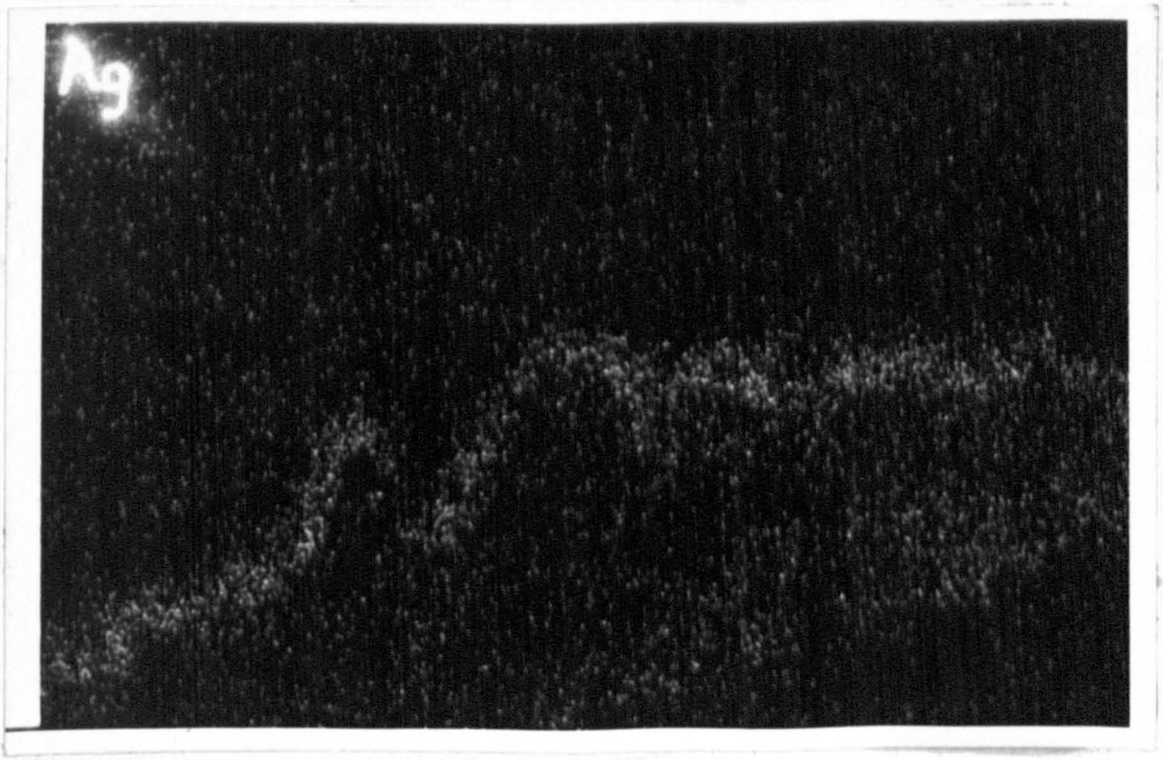
Reflection photomicrograph of the galena/quartz contact from Sgòr Chaonasaid pegmatite, Ben Loyal (X5,OL).



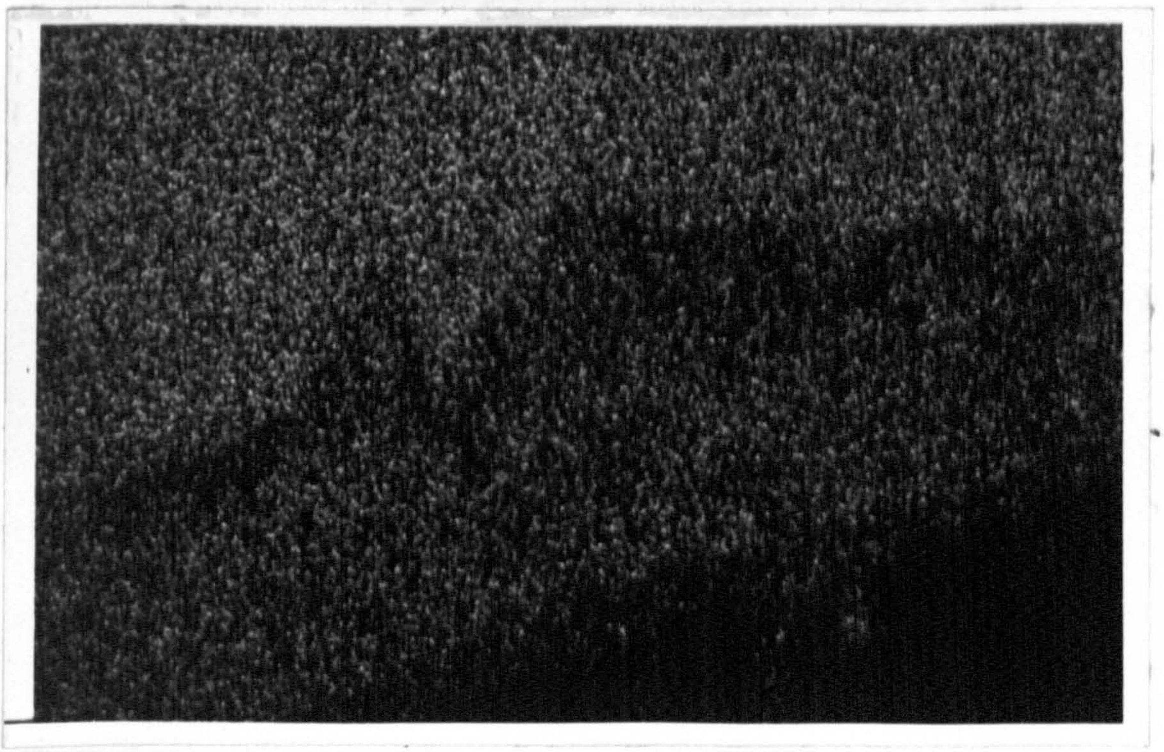
Reflection photomicrograph. Detail of mineral zonation showing the irregular junction between galena and stromeyerite (X28,OL).



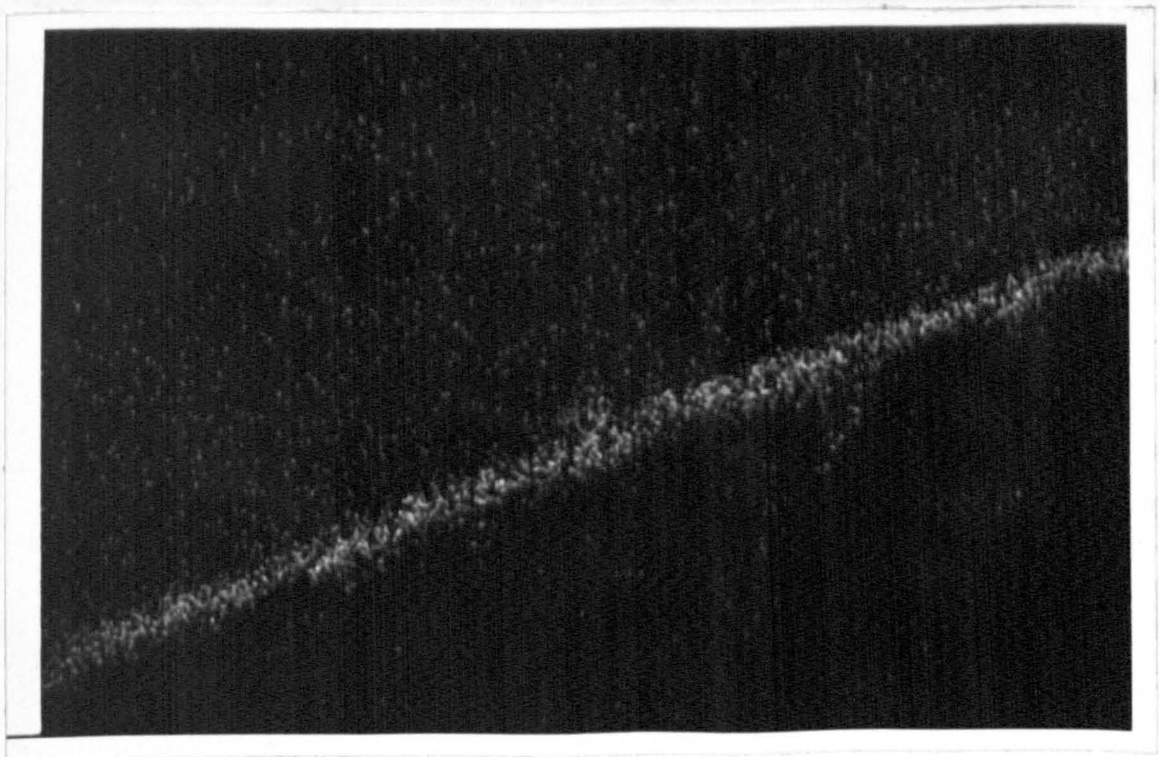
Electron-microprobe photograph showing the distribution of copper at the galena/quartz junction.



Electron-microprobe photograph showing the concentration of silver at the galena boundary. The concentration marks the position of bismuthian stromeyerite.



Electron microprobe photograph showing the deficiency of lead in the quartz and stromeyerite.



Electron-microprobe photograph showing the restriction of barite to a narrow band abutting the quartz.

divides granitoids into orthite-bearing and monazite-bearing types, each with the following mineralogy:-

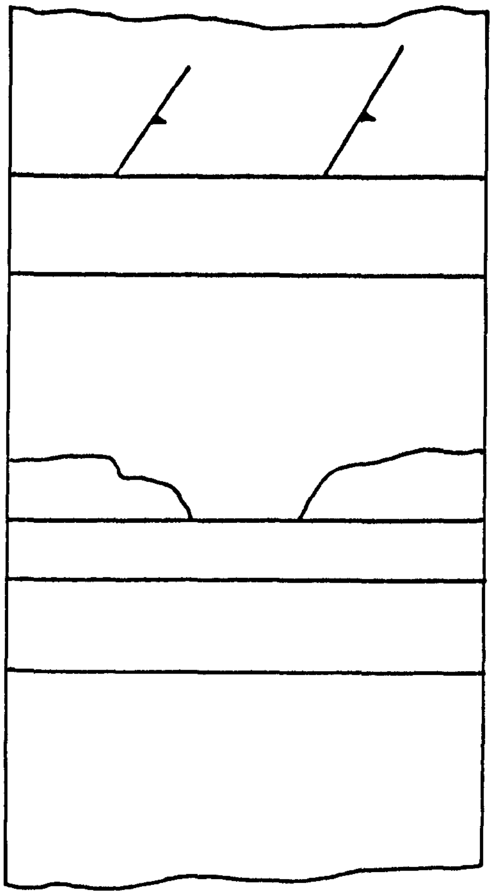
Orthite-bearing granitoids	Monazite-bearing granitoids
Orthite (Allanite)	Monazite
sphene	ilmenite
magnetite	

and Pavlenko et. al. (1960) are of the opinion that "In normal granites of the sphene-orthite type accessory tantaloniobates are absent." Again Loyal is intermediate between two types.

Electron microprobe investigation of the galena from the Chaonasaid pegmatites

Galena is uncommon in the Sgòr Chaonasaid pegmatites. Specimens occurring together with amazonitic feldspar and large allanite crystals were examined by electron-microprobe and XRF methods. A qualitative XRF scan showed the presence of Pb, Cu, Bi, Fe, Sr, Ba, Ag, Sb, Ca, Mn, Cr, and Zn, these elements were confirmed by microprobe analysis. A photographic study of element distribution at the junction of the galena and enclosing perthitic feldspar was undertaken which demonstrated a mineral zonation between the two phases.

A schematic representation of the mineral zonation between the galena and feldspar at Sgòr Chaonasaid:-



Zone	Formula or elements	Mineral
A	PbS	Galena
B	Cu,Ag,Bi,S	bismuth-rich stromeyerite
C	Cu,Pb,(Fe,Zn)S	complex coppe lead sulphid
D	a)$PbCO_3$b)$PbSO_4$	cerussite & anglesite
E	$BaSO_4$	barite
F	SiO_2	quartz
G	$KAlSi_3O_8$	feldspar

All the very prominent cleavages of the galena are outlined by the minerals of zones B & C. The galena was both cupriferous and argentiferous and as is usual contained both zinc and iron. Immediately adjacent to the galena, in the zone B, is a metallic sulphide in which copper, silver and bismuth are the sole constituents; no structural information is available for this mineral but its composition is suggestive of a bismuth-rich stromeyerite. It appears that Cu, Bi and Ag have migrated away from the main part of the galena to be redeposited at the crystal margins and in cleavage planes. Antimony has not been similarly concentrated indicating a different ionic mobility under these prevailing conditions compared with copper, bismuth and silver. Zone C comprises a complex copper-lead sulphide along the outer edge of which irregular patches of greenish and white non-metallic crystals are found. These were determined as anglesite $PbSO_4$ and cerussite $PbCO_3$. Succeeding these irregular patches is a very prominent extremely regular band of barite $BaSO_4$. An iron-deficient band coincides with quartz which is followed by perthitic feldspar.

The mineralogy of strontianite, zeolites, polycrase, amazonite and the yellow rare-earth mineral have all been detailed in previous sections of this thesis and will not be examined here.

Four other minerals from the Loyal complex where tested for trace-elements using either qualitative XRF or U.V. spectrographic analysis. Thus:-

Allanite	Apatite	Epidote	Biotite
Fe	Sr	Ti	Majors K,Mg,Fe,Al,Si
Ce	Fe	Cr	Minors Ca, Na
Th	Ba	V	Traces
Mn	La	Ga	Ba
La	Pb	Pb	Rb
Nd	Y	Ni	Cs
Sr	Ce	Yb	Mn
Pb	Zr	Cu	Cr
Zn	Mn		Ti
Gd	Ti		Li
Cu	Zn		V
Ti			
U			

Allanite in the Loyal complex is metamict and only displays a characteristic powder photograph when heated above 500°C. The wide density range of allanites, between 3.4 and 4.2, is correlated with the degree of metamictization and alteration, low density minerals having high water contents. Density of the Loyal mineral was determined as 3.74. As mentioned previously most of the thorium resides within this mineral and is therefore responsible for the anomalous radio-activity associated with the Loyal syenites.

Biotite occurs occasionally in the laminated syenites and concentrates Group I elements especially Li, Rb and Cs. Lithium substitutes for Al, Rb and Cs for K, and Mn of Fe^{2+}. It was the only mineral in the complex to show traces of cesium.

The Beinn Bhreac boulder.

An erratic boulder weighing approximately 100 tons and cut by a 2' vein of pegmatite was found by Heddle on the western slopes of Beinn Bhreac. Heddle (1883) considered the boulder "..... as mineralogically the most wonderful and interesting stone in Scotland"; he dynamited the block and removed all the pegmatite for examination. A three day search of the slopes of Beinn Bhreac by the author and others failed to reveal similar material.

Heddle describes the pegmatite as, embedded in Loyal syenite, conspicuously zoned, and having very large feldspars up to 15½" in length. The following minerals were identified in the boulder:-

cleavelandite
microcline
amazonite
oligoclase
thorite = orangite
strontianite
smoky quartz
rock crystal
lepidomelane
sphene

flourite
telluric iron
magnetite
specularite
ilmenite
bruiachite
zircon
allanite
tourmaline
vreckite (bhreckite)
yttrotantalate

The vein was zoned from outside towards the centre thus:-
babingtonite - fluorite - sphene - allanite - thorite - magnetite - lepidomelane - cleavelandite - ilmenite - amazonite - oligoclase - quartz - specularite - bhreckite.

The minerals are of much greater size than those found in the Sgor Chaonasaid pegmatites of Ben Loyal and some of the feldspars of Bhreac exceed 1' in length, babingtonite was 1" - 2" and thorite occurred as "bean-size" crystals. Mineralogically the Beinn Bhreac boulder is very similar to the Chaonasaid pegmatites and must be a coarse representative of these. Development of lepidomelane and tourmaline suggests further concentration of volatiles relative to that typical of the Loyal syenites. No pegmatites resembling this remarkable stone are now seen within the Loyal range and this boulder appears to be unique.

CHAPTER ELEVEN

PETROGENESIS AND HISTORICAL REVIEW.

The Ben Loyal syenite was emplaced after the folding of the Moine sediments and later than most other Newer Igneous plutonic rocks, it is either very late syn-orogenic (i.e. simultaneous with the Moine thrust movements) or post-orogenic in age. Any theory of origin must ultimately be found in the partial fusion of sediments at depth within the Caledonian orogenic belt. However anatexis of sedimentary rocks produces melts approximating to granites and not oversaturated syenites, and as Morse (1969) points out syenites and their extrusive equivalents trachytes occupy a paradoxical position among igneous rocks. Within petrogeny's residua system (Schairer 1950) Loch Loyal rocks in common with other syenites and trachytes lie in projection on a critical undersaturation line, the alkali feldspar join. From all evidence, syenitic liquids lie on a thermal maximum relative to their neighbours granite (rhyolite) and nepheline syenite (phonolite). A mechanism is therefore required which can cause a magma to remain critically saturated throughout its fractionation history and terminate on a thermal maximum instead of fractionating off towards either oversaturated or undersaturated compositions.
The majority of syenites are hypersolvus one-feldspar rocks and the attainment of the two feldspar boundary does not appear to be critical to syenitic fractionation. Loyal rocks are relatively quartz-rich for syenites (on the boundary of the sodaclase granites of Johannsen) and Morse points out that most hydrous syenites (those containing amphibole or biotite) have silica-oversaturated trends. When the normative salic components of igneous rocks are plotted in petrogeny's

residua system they are seen to fall within a trough in close correspondence with experimentally determined melting minima for granites and nepheline syenites. However Hamilton & MacKenzie (1965) have shown that this relationship does not hold with syenites. Most syenites show a strong maximum on the feldspar join at Or_{40} with subsidiary trends towards granites and nepheline syenites; in particular Loyal syenites trend towards granites, and Loch Ailsh and Loch Borralan are undersaturated. This persistant syenitic maximum near Or_{40} suggests a crystal $\rightleftharpoons$ liquid control as being the dominant magmatic process involved.

Many authors, following Harker (1916), have stressed the tectonic conditions under which alkaline magmatism is supposed to develop. Stable cratonic areas or regions of crustal foundering are considered favoured areas for alkaline rocks and according to the above author are relatively inconspicuous among rocks developing in igneous activity of orogenic belts. The three large alkaline masses of Sutherland are closely associated with the waning of the Caledonian orogeny. More likely for these is the association of alkaline magmatism with faulting in the manner envisaged by Evans (1925) in which a residua rich in alkalis was pressed out and concentrated from the zone of anatexis. Daly and Shand have stressed the close affiliation of the Loch Borralan and Loch Ailsh syenites with the Durness Limestone but Sabine (op. cit.) has demonstrated the widespread occurrence of several alkaline dykes at a considerable distance away from the limestone outcrop within the Lewisian foreland.

If the origin of the Loyal syenites is sought in the anatexis of Caledonian sediments a method has to be found in which granitic melts are changed to syenitic types. As Wyllie & Tuttle (1961) have shown shales begin to melt at temperatures not greatly in excess of the melting temperature of granite and experiments by Winkler (1957, 1958) indicate that the first liquid produced would resemble the 'ichor' or granite pore-magma of the 'transformists'. Water-saturated granite liquids fabricated in this way can exist only for a few degrees above the solidus and the normal product of anatexis would be a mush composed of crystals and water-under-saturated granite liquid. Because of its lower density the magma would then rise and differentiation of the liquid phase occur in response to the changing conditions.

Loyal syenites are of a later age than the surrounding migmatitic granites and granodiorites which suggests to the author that the alkaline magmatism in northern Scotland could be the final differentiates of these earlier plutonic phases. Concentration of soda utilising weaknesses created by thrusting resulted in emplacement of the three alkaline masses in Sutherland. Other alkaline occurrences such as Glenelg-Ratagain, Glen Dessarry and Loch Hourn not far removed from the Moine thrust may be closely connected with this alkaline petrographic province although the ages are known to be different. The Assynt suite is more alkaline than the Loyal rocks which could be the result of longer differentiation due to greater distance of magma transport from its source. Certainly all the three igneous phases in Sutherland have freed themselves from the deep zones of anatexis to invade lightly metamorphosed rocks at higher structural levels, namely the epizone of Buddington (op. cit.). Granites with syenites as local variants are a well known association for example within the White Mountain petrographic province of New Hampshire and Vermont (Chapman & Williams 1935), and in the Oslo province of Norway

(Barth 1945).

Increased sodic content of the magma resulted in a 'reworking' of the granite, which several Russian authors have considered a type of metasomatism in which Na, U, Th, Nb, rare-earths and Sr are augmented over that typical of rocks generated by anatexis. According to Ginzburg (1970) increase of these elements in sub-alkaline granitic magma, to which Loyal is related, results in rare-earth polymetallic formation and either low/medium temperature hydrothermal mineralisation or various types of metasomatism of which only amazonitisation is important at Loyal. The trace element mineralogy is intermediate between the granites and aplogranites of Sitnin (1970).

The history of the Loyal syenites can be summarised thus:- A granitic crystal mush dislocated from the zone of anatexis was subjected to special conditions under which the magma changed its composition and alkalinity increased. Critical assessment of the geological environment under which sodic rocks in the northern Highlands developed shows that most are connected with faulting. Other criteria often used as an explanation of alkaline rock genesis such as limestone assimilation, salt incorporation or environmental stability are considered unimportant. However the author has shown that the three intrusions of Sutherland ought to be regarded as separate intrusions because of chemical parameters. No precise coeval relationships are suggested only that similar processes can occur at different times in equivalent structural situations. The magma being less dense than the rocks in which it occurs rose and with increasing differentiation the soda content built up. In conjunction with this U, Th, Nb, RE's and Sr were selectively leached out either from the sedimentary pile or more likely from granitic material in a manner analogous to soda metasomatism. This critically saturated magma was then emplaced, usually concordantly but in detail conspicuously transgressively to the Moine metasediments. Of the three intrusions at Loch Loyal, Cnoc nan Cùilean represents the earliest and least differentiated of the intrusions and here magma stoping upwards incorporated hornblendic xenoliths of 'Lewisian type' imparting to it an increased basicity. More fractionated and less contaminated magma was injected away from the Cuilean area and in the case of the Loyal intrusion the advancing bubble of magma deformed the surrounding granulites and led to the formation of a feldspar flow lamination within the marginal syenites. Core rocks consolidated as one-feldspar rocks, marginal syenites as two-feldspar rocks. The syenites therefore cannot have been far removed from the feldspar solvus and at pressures prevailing under geological conditions this is indicative of a temperature of about 660°C. Encircling granulites are often feldspathic and where they abut the syenites a rheomorphic effect is evidenced and the junction is frequently transitional. Large rafts of Moinian metasediments within the Loyal mass are probably roof remnants. The rocks of the intrusions then consolidated as medium grained over-saturated syenites and various faults and joint systems were initiated, as the temperature began to fall aplitic, pegmatitic and dyke phases were formed. The Na:K ratio ensured that crystallisation did not proceed according to the Rosenbusch rules but followed a path akin to Fersman's agpaitic crystallisation; accessory minerals then became enriched in the rarer trace elements. Low temperature hydrothermal mineralisation with the deposition of strontium and barium carbonates together with red-ochre veining followed and was in turn displaced by a phase in which gas pockets set free from the late magmatic liquors led to rare-earth concentration in drusy cavities. Finally at a temperature close to 250°C a type of lead metasomatism analogous to that envisaged by Zhirov and Shishov (op.cit.) gave rise to amazonitic feldspars within the pegmatites of Sgòr Chaonasaid.

Mackie (1928) in his examination of heavy accessory minerals from the Newer granites of Scotland concluded that the occurrence of sphene and hornblende contraindicate the presence of monazite, and allanite and monazite appear to contraindicate one another. The yellow phospo-silicate of Lettermore quarry has the structure of monazite and closely resemble it chemically. Again Bugaets & Sadovskii (1970) have shown that high soda granitoids are favourable to Nb/Ta mineralisation and high potash contents unfavourable; both soda and potash are about 6% at Loyal. Each of these observations again confirm the intermediate character of the Loch Loyal syenites which has recurred throughout this thesis.

CHAPTER TWELVE

CONCLUSIONS

The Loch Loyal syenites were intruded to a high structural level into grey flaggy psammitic or semi-pelitic Moine granulites at the very end of the Caledonian orogeny about 400m.y. ago. All three intrusions of the complex are roughly concordant to the regional structural trend although in detail each is transgressive to the strike of the Moinian country rocks. Eastern Moine granulites encircle the Loyal syenites and in almost all cases the dip of the metasediments is towards the intrusions. Contacts are not much altered although locally folding is evident.

A feldspar lamination exists in the outer parts of the Loyal mass which is correlated with the flow movements of a partially crystallised magma. Amphibole is the prevalent mafic mineral in these outer one-feldspar rocks and this is accompanied by pyroxene in the coarser two-feldspar core rocks.

Jointing is a very noticeable feature throughout the complex, the master joints trending E-W or ENE-WSW.

The syenites, medium grained quartz-nordmarkites, are composed principally of feldspars which bulk 85-90% of the rock; the rest is made up of about 10% of amphibole and/or pyroxene with other accessories in smaller quantities. Most of the feldspars display perthitic intergrowths in agreement with Alling's criteria for exsolution.

Limits imposed by feldspar mineralogy and amphibole stability suggest that the Loyal rocks crystallised close to the feldspar solvus at 660°C and with 4% or less of H_2O vapour in the magma.

In comparison with other members of the Caledonian Newer Igneous suite Loyal rocks are much more sodic, very greatly deficient in calcium and strongly enriched in barium. However Loyal syenites are much less sodic than Loch Ailsh and Loch Borralan the two other alkaline masses in Sutherland. Compared with these Loch Loyal is enriched in MnO, MgO, CaO, Ni, Rb, Sc, Co, La, & Pb; the rare-earth elements and lead especially being concentrated within the Loyal mass.

Aplites and pegmatites are intimately associated and both are feldspar/quartz/magnetite rocks. A zonation is apparent in the veins, aplitic material and iron ores being restricted to the centre and coarse feldspar perthites radiate from the margins. Green amazonite is restricted to these pegmatites; the colouration is envisaged as a structural distortion of the feldspar lattice produced by a type of lead metasomatism (amazonitization) where one lead ion substitutes for two of potassium.

Subsidiary sill and dyke phases surrounds the Loyal syenites. Both are more acidic than the parent rock and may best be described as sodi-potassic microgranites.

Late stage deuteric and low temperature hydrothermal mineralisation are important elements in the history of the Loyal rocks and a gas phase connected with these synantectic processes brought about a redistribution of rare-earth elements which were selectively concentrated and deposited in miarolytic cavities as a yellow rare-earth phosposilicate. Strontianite, barite and hematitic veining were also associated with this mineralisation.

Anomalous radioactivity centred on the Loch Loyal intrusions is due to the thorium content of allanites. Of the three intrusions Cnoc nań Cùilean is by far the most radioactive, also the most melanocratic and richest in TiO_2, Al_2O_3, K_2O, MgO, CaO, FeO and Sr. Within the Ben Loyal syenite Na_2O exceeds K_2O in amount and this is reflected in the occurrence of acmite in the norm. Beinn Stumanadh is the most leucocratic and analyses are frequently c normative.

The tantalo-niobate mineral polycrase occurs within the pegmatites of Sgor Chaonasaid together with allanite, strontianite and galena. The latter mineral shows a zonation, silver, copper, bismuth and barium being deposited as complex sulphides between the silicate and sulphide phases. Silver and copper have been fixed as bismuthian stromeyerite both edging the galena and picking its way between the prominent cleavages.

The Loyal amphibole is closely comparable with, although richer in Na_2O and Fe_2O_3 than, the average hornblende from granites as determined by Tscherwinsky. Lithium, at 330 ppm, is concentrated in the amphibole replacing Mg^{2+} in the Y positions of the structure. A convenient contraction, magfedenite, is suggested to cover the chemical parameters of the Loyal amphibole.

The Loyal sphene has a high density which is usually correlated with a high rare-earth plus niobium content, but it contains only 0.9% of RE + Nb and does not fit into the scheme proposed by Zabavnikova. When compared with sphenes from other Caledonian Igneous rocks of Scotland it is much enriched in rare-earths and niobium; it may best be described as a grothite.

The intermediate character of the Loyal syenites has recurred throughout this thesis, for example it lies between the nordmarkites and the sodaclase-granites of Johannsen, it is closely related to the sphene-orthite granitoids of Tauson but holds a mineral of monazite structure, and again contrary to the conclusions of Pavlenko Loyal syenites do contain tantalo-niobates.

Evidence from trace element chemistry shows that the three alkaline intrusions of Sutherland, should be regarded as separate bodies, although broadly related to a postulated N.W. Highlands alkaline petrographic province which may have been initiated much earlier in the Caledonian orogeny and have included areas of soda-metasomatism, the Glen Dessarry metamorphosed syenite and the Glenelg-Ratagain igneous complex. Similar intrusions in the New England States of North America, communally the Monteregian magmatic province, could be distantly related to this Scottish province.

The origin of the Loyal syenites is not thought to be connected with the limestone hypothesis advocated for alkaline rock genesis by Daly and Shand or to the special tectonic conditions envisaged by Harker. Anatexis of sediments and/or the reworking of granitic rocks at depth together with extreme differentiation connected with faulting is seen as the most likely source of the Loyal syenites.

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(Sheet 2)


Achnanclach sill
Cracknie
BEINN STUMANADH
LOCH LOYAL
LOCH SYRE
Loch Beag
Eilean Mòr
Eilean nan Craobh
Loch na Faoileig
Loch a' Phrìosain
Loch na Garbh-shròin
Garvalt Hill
Zone of Injection
Strathnaver granite
Gull Loch
Corre Buidhe
Langdale Burn
Bailloire
Loch nan Coinean
Loch Meleag
Druim Meleag
Loch nan Con-donna
LOCH NAN EALACHAN
Cnoc Airigh M
Allt Creag an Fhithich
Creag Creagan an Fhithich
Creag Bhreac
Coire nam Breac
Loch nam Breac
Coire Beag
Meall an Spothaidh
Cnoc nan Damh
Meall Meadhonach
Allt Òba Mheadhonaich
Allt Meall a' Bhràghad-leathaid
Sìonach Coire
Allt Sìonach Coire
Beinn Stumanadh
Achadh nan Sac
Sròn Ruadh
Coire na Cuile
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Core
Laminated
Ben Loyal syenite
Cnoc nan Cuilean syenite
Beinn Stumanadh syenite
Undiffentiated Moine metasediments
Strathnaver granite
Syenite dyke
Microgranite dyke
Coldbackie fault
Lineations compiled from aerial photographs
35
Dip in degrees
Dip of feldspar lamination
16104
Analysed rock sample
27658
Other rock sample
Soil sample
Ratemeter values ur/hr
Areas of highest radioactivity
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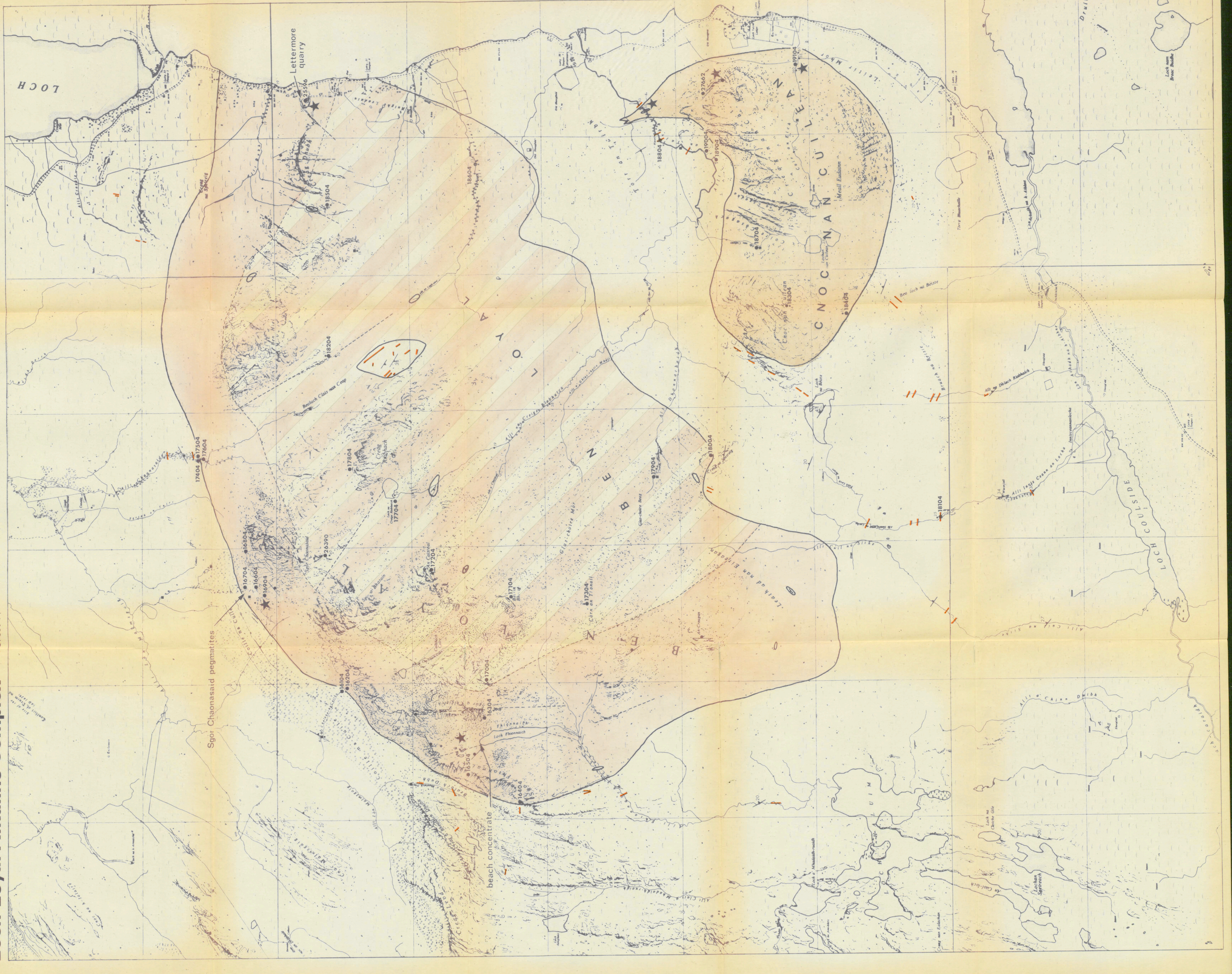
2
MAP SHEETS

Loch Loyal Alkaline Complex

(Sheet 1)



Appendix

APPENDIX

Notes on Text

Note 1 (Page 53 line 6) Mafic rich layers

Mafic rich layers are encountered within the outer laminated syenites at the base of the Sgor Chaonasaid cliffs. A typical example from this locality, No. 16804 (27576), has been examined petrographically and chemically and analyses pertaining to this are presented between pages 168 and 172 of this thesis.

In hand specimen this band has a thickness of 40 mm and is markedly melanocratic with a colour index of 35, compared with the surrounding syenites whose C.I. approximates to 10. Within the mafic layers feldspars are of the same size as in the surrounding syenites but the mafic components show an increase in size from 1.0 - 2.0 mm usual for laminated rock, to 2.0 - 3.0 mm within the segregation. A prominent lineation in these mafic rich layers follows that in the laminated syenites and each hornblende crystal is aligned parallel to the margin of the band. The mafic rich layers contrast strongly with Moinian xenoliths also found enclosed within the outer parts of the Ben Loyal syenite. Xenoliths are irregular, always have a definite boundary, are sometimes rimmed with brown iron oxides, and contain biotite; mafic rich layers have no distinct interface but a boundary at which feldspar is accompanied by amphibole the latter increasing both in amount and size. Mafic rich parts carry no biotite, have constant linearity which extends over several metres, and their constituent minerals are concordant with the feldspar lineation (whereas Moinian xenoliths are often conspicuously transgressive in detail).

Mineralogically the mafic rich layers are the same as the contiguous syenites with a slight increase in magnetite content and an increase in the number of sphene and zircon crystals, only the mineral proportions are changed. This is reflected in the increased tenor of TiO_2, Fe_2O_3, FeO, MnO, MgO, CaO, H_2O, ZrO_2, F and rare-earth elements and a decrease in SiO_2, Al_2O_3, Na_2O, K_2O, BaO and SrO when the layers are compared with the 'typical' syenite (see page 169 for a major element comparison between the mafic rich layer and a 'typical' syenite, 16904, from the same area).

These differences are readily explained by the complementary decrease in feldspar and increase of hornblende, sphene and magnetite described above. Trace element data, detailed on page 171, supports the major chemistry data showing increased values of Cr, Co, Ni, Zn, Nb, Y, Zr, Sc, La and Ce and a decrease in Sr and Rb.

Differing mineralogy and structural detail relating to xenolithic and layered material as outlined above suggest to the author that crystal differentiation has been an operative factor in the generation of the mafic bands.

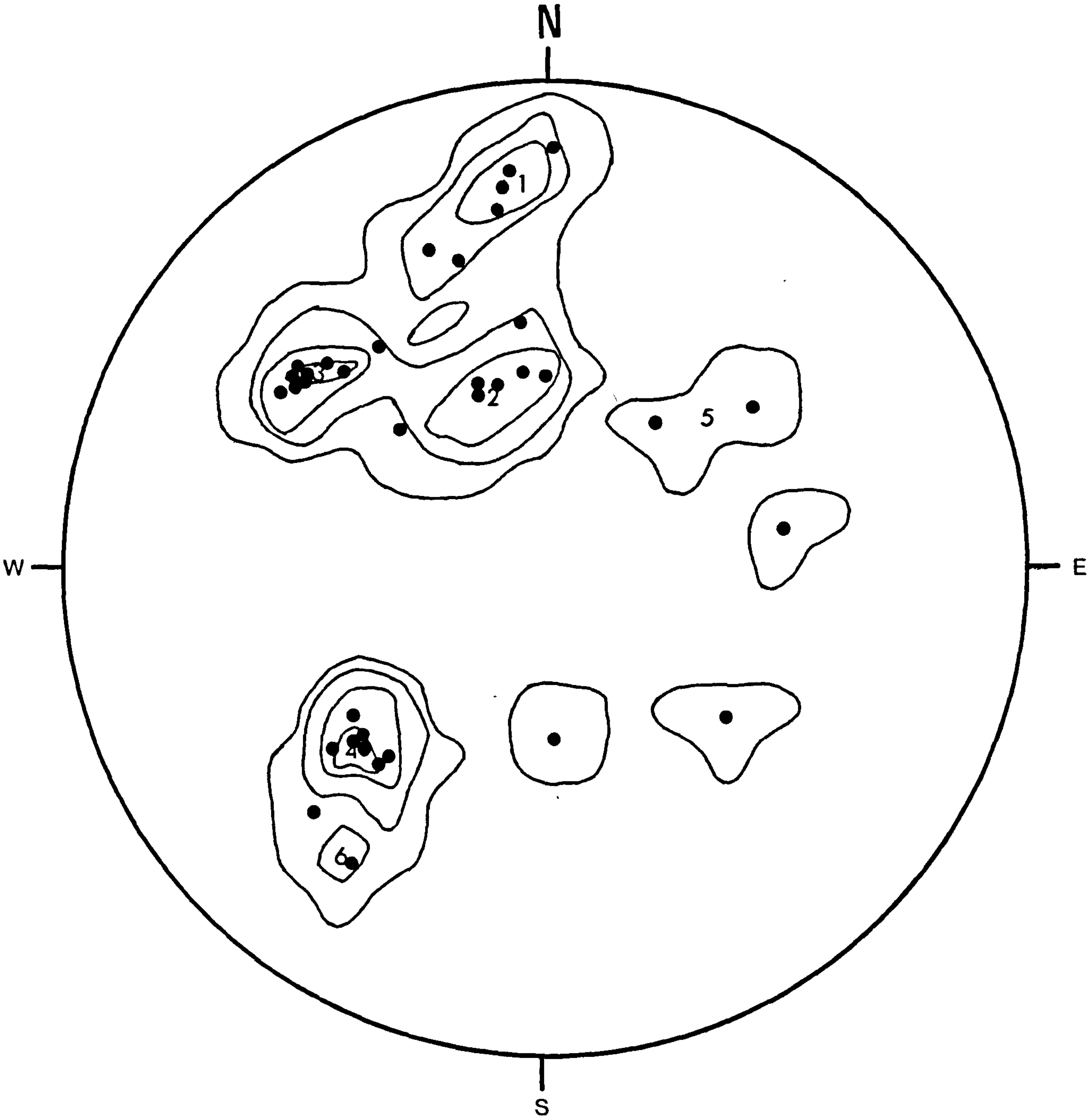
Note 2 (Page 59 & 60) Joints in the Lettermore Quarry

Thirty-six joint directions were measured using a Brunton compass/clinometer in the middle and lower sections of the Lettermore quarry the poles of which are plotted on the stereogram which accompanies this note. Emphasis was placed on the determination of subsidiary joint directions since the master joints (No. 1) were well defined and of uniform direction.

The diagram was contoured by the method suggested by Phillips

Polar projection of joint planes

Lettermore quarry



	STRIKE	DIP	DIP TOWARDS
1	82°	77°	172°
2	70°	42°	160°
3	43°	65°	133°
4	317°	57°	47°
5	318°	40-60°	228°
6	304°	73°	34°

in "The Use of Stereographic Projection in Structural Geology". A circle of 1 cm radius cut in cardboard was centred successively on the intersections of a squared grid placed beneath a tracing plot of the poles and the number of values falling within the circle was plotted at the intersections. Red areas encompass all intersections, yellow those areas where two poles occur, green three and purple greater than four.

Analysis of the regional joint system by measurement was undertaken by a study of aerial photographs.

Note 3 (Page 64 last line) Thin section work.

Eighty thin sections representing most of the analysed specimens were examined under the petrological microscope. Results for each examination were tabulated on separate sheets on which a general rock description, mineralogy, grain size, colour index, a sketch of the thin section and any unusual features displayed were tabulated. Chemistry was also detailed on the same sheet. The sheets assembled for each of the three intrusions were then examined and compared those of Ben Loyal being divided into core and laminated rocks. With the Ben Loyal and Beinn Stumanadh rocks quartz-nordmarkite was the dominant rock especially so towards the contact of the intrusions. Within the outer parts of the Ben Loyal syenite laminated rocks had two feldspars, potash feldspar and abundant discrete crystals of plagioclase. Rocks from the centre of the intrusion were composed of a single perthitic feldspar. With increased quartz in the outer part of the complex some rocks transgressed Johannsens syenite/granite boundary and would best be regarded as sodaclase granites.

By far the greatest variation in rock type was found in the Cnoc nan Cuilean intrusion. These rocks are extremely variable; all are composed of feldspar and pyroxene whose proportions change markedly. The principal rock type is still described as syenite since basic patches are disseminated within the rock and are not segregated into distinct bodies separate from the main intrusion.

Within the outer parts of the Cuilean mass the 'host' syenite, a pink leucocratic relatively coarse grained rock is transitional into a compact fine grained basic syenite, banded types and basic patches where pyroxene predominates. Pegmatitic patches are frequent and occasionally have pyroxene crystals 1 cm in length. The author prefers not to give these contaminated syenites another name since they do not form separate bodies. If they were contiguous the more mafic rich segregations could be described as pyroxenites. The range for each constituent is quartz 0 - 15% with a mean of 10%, alkali feldspar 55-80%, pyroxene in the Cuilean mass 5-90% (in the clots), amphibole 0-17% with a mean of 10% (principally in the laminated rocks of Loyal) and accessories 2-5% with sphene about 1%, magnetite 1%, and zircon and apatite each less then 1%.

Note 4 (Page 69 line 10) The basicity of the Cnoc nan Cuilean intrusion.

Analyses 18304 and 18904 are presented in support of the contention that the Cuilean boxy is more basic and potassic than the Ben Loyal and Beinn Stumanadh masses (see pages 179 & 184).

The potash content in the Cuilean samples exceeded that of all 16 analyses of typical Loyal rocks 16304, 16404, 16504, 16604, 16904, 17004, 17104, 17204, 17304, 17604, 17704, 17804, 17904, 18004, 18204, and 18604. Loyal values having a mean value of 6.07 K_2O and therefore being at least 1% deficient in potash. Higher potash contents prevail in the Beinn Stumanadh rocks but of 15 analyses (19204, 19304, 19404, 19504, 19604, 19704, 19804, 19904, 20204, 20304, 20404, 20904, 21004, 21104 and 21404) only one exceeds that found in the Cuilean rocks. These 15 analyses had a mean potash figure of 6.29 again lower by a margin of 1%.

Using the same samples as above only two from each of Loyal and Stumanadh exceeds the values for the total basic oxides for that attaining in the Cuilean syenites - in each case, 19204 & 21104 at Stumanadh, the rock is darker than is typical for the intrusion, this is also true of sample 17004 from Ben Loyal and sample 17804 was collected close to syenite containing Moinian xenoliths. Basic oxides for the Cuilean mass therefore exceed those prevailing in the other two intrusions by approximately 2%. This increased basicity associated with the Cuilean intrusion is expected from the darker aspect of the rocks both in hand specimen and in the field.

Note 5 (Page 79 line 17) Colour Index

Thirty-four thin sections were examined some from each of the three intrusions the mean C.I. of which clustered around 9. The Ben Loyal body was the least variable of the three intrusions with extreme colour indices of 4 and 17 with the vast majority, 14 of 16 samples having a C.I. between 5 and 12. Beinn Stumanadh had the most leusocratic samples extremes ranging between 5 and 12 with most colour indices clustering about 10. All Cnoc nan Cuilean samples had colour indices between 14 and 19. The value for the colour index of 9 referred to on page 79 is the mean of these 34 figures.

Since the Loyal rocks are principally feldspars and quartz with hornblende + magnetite and sphene the author considered it worthwhile to determine three other indices from his chemical analyses to verify the above conclusions, these were the differentiation index, the mafic index and the felsic index. In the event the differentiation index proved most useful and the D.I. of 87.9 quoted on page 79, the mean of 34 syenites indicates a mafic content of 12, both other indices support this figure. However it must be appreciated that these calculated figures are in weight % and the colour index in volume %. On page 64 the mode of Loyal syenites are given both in volume % and weight % and the average figure of 12 approximates closely with the sum of the mafic components in Von Knorring & Dearnleys' mode for laminated syenites from Lettermore Quarry.

Note 6 (Page 90 line 8) Moinian metasediments and Dyke rocks

A total of six Moinian granulites surrounding the igneous complex have been analysed:- *16104 - page 164, 17404 - page 169, 17504 - page 174, 20004 - page 189, * 20804 - page 194, and *21204 - page 199. Six dyke rocks were also examined petrologically and chemically these are:- 18104 - page 174, 18804 - page 179, 19204 - page 184, 20504 - page 194, 20604 - page 194 and 21304 - page 199.

Two distinct types of Moines are encountered quartz-rich metasediments and more basic mica/hornblende schists; the type referred to on page 90 are those in which the microgranite veins and dykes are emplaced, such as that in the photograph on page 88.

The chemistry of the two contrasting Moine sediments may be summarised thus:-

	Quartz-rich Moines	Mica/Hb schists
SiO_2	75%	60%
Al_2O_3	10%	17%
Fe Oxides	4%	6%
MgO	1%	2%
CaO	2%	2-6%
Na_2O	3%	4-5%
K_2O	3%	3%

Micaceous schists are referred to by an asterisk the rest are siliceous Moines.

Notes 7 & 8 (Pages 92 & 94) The yellow rare-earth mineral.

Tests on the yellow rare-earth mineral were both quantitative and qualitative but serious difficulties arise in the purification of sufficient material for analysis. The mineral is frequently admixed with very fine crystalline apatite and can only be collected during dry weather when a distinction can be made between this mineral and a similar greenish-yellow montmorillonite also occasionally present in the syenite druses. Four people each spent three days within the Lettermore Quarry extracting material from the druses.

Material intergrown with syenite was discarded and the rest then separated using a binocular microscope and hand-picking only those mineral fragments which were uncontaminated, this process took several weeks of continuous picking when a total of 3 grams of purified material remained. However this still held minute crystals of apatite. Separation of this apatite from the yellow mineral was achieved in two ways. Firstly the mixture was passed through a magnetic separator three times and a separation of yellow powder and apatite made. Examination under binocular microscope then revealed no apatite crystals; to make sure no apatite remained this material was pressed through a nylon seive the mesh size of which was less than the minimum diameter of the apatite crystals. The purified mineral which then totalled approximately 0.8g, (because of losses in the separation technique) was divided into two parts, one for classical determination, the remainder for U.V. Spectrographic and XRF analysis.

Because of the small quantity of material available a full analysis was not possible but a comparison with Von Knorring and Dearnleys' 1960 determination was possible for some of the major oxides. Two analyses were undertaken the first on the above separated material and a check analysis on further material separated in the laboratory, thus:-

Von Knorring & Dearnleys' analysis	
SiO_2	18.84
TiO_2 Al_2O_3	1.90
$(La,Nd)_2O_3$ CeO_2	32.00
Fe_2O_3	10.61 *
FeO	nd
MnO	0.04
MgO	1.90
CaO	6.61
Na_2O	-
K_2O	-
H_2O +	6.51
H_2O -	6.06
P_2O_5	15.87
ZrO_2	-
	100.34

	1st analysis	2nd analysis
SiO_2	25.02	23.02
R_2O_3	13.42	25.86
R.E.	24.59	18.47
CaO	2.72	3.70
H_2O+	8.52	4.61'
H_2O-	5.91	6.93
P_2O_5	nd	13.40

* = total iron as Fe_2O_3

' = heating discontinued at 800°C.

Considerable variation between the analyses is evident but rare-earth elements, water and phosphorus were again found to have high tenor. In two cases the H_2O+ had values greater than 6%, the exception being analysis 2. This resulted because heating was discontinued at 800°C since at temperatures in excess of this reaction with the platinum crucible occurred. The specific gravity of 2.90 is quoted from Von Knorring & Dearnleys' paper (p 390) and is compared with monazite SG 5.0 - 5.3 and steenstrupine SG 3.4. Increase of SiO_2 at the expense of P_2O_5 will reduce the specific gravity slightly, as will substitution of other major oxides for the rare-earth oxides but as the mineral contains between 12 and 15% of water it is likely that OH ions within the structure cause the specific gravity to be low.

A portion of the yellow powder was tested qualitatively by U.V. spectrography using copper rods which confirmed La, Fe, Ce, & P as majors together with the traces listed at the foot of page 92. The rest of the mineral was scanned by XRF analysis and further traces determined.

Note 9 (Page 95 lines 12, 15, 19) Subsidiary amphiboles.

Hastingsitic amphibole and pale actinolitic amphibole were determined optically. They differ in both form and optical properties from the ferro-edenite typical of the Loyal intrusion. Thus hastingsite occurs as small flakes within pyroxene crystals and displays different pleochroism from X brown-yellow, Y dark green, to z very dark blue-green compared with the usual amphibole colours of pale yellowish green/ pale green/dark grass green. The refractive indices of these hastingsitic flakes, between 1.686 and 1.700 was higher than those obtaining in the ferro-edenite. Actinolitic amphibole formed ragged outgrowths associated with green pyroxenes, pleochroic colours were less intense than those of ferro-edenite. Refractive indices ranged from 1.635 to 1.658. However the reliability of these names does not carry the same weight as that for the amphibole ferro-edenite where optical data is supported by chemical analyses.

Note 10 (Page 98 line 10) The trace-element content of Amazonite.

Trace element contents on the Loyal amazonite (S3434) were undertaken with a U.V. spectrograph at three ranges 2200Å, 2750Å and 4450Å using graphite cups and carbon rods. Uncoloured feldspar (S3433) was determined on the same plate so that the two could be compared directly. Qualitative XRF scans were also done in conjunction with the above and the absence of lithium confirmed using an A 1740 grating flame-photometer set on the lithium peak at 6707Å. All determinations and interpretation of U.V. plates and XRF scans were performed by the author.

Note 11 (Page 127 line five from bottom) Ratemeter readings.

During the initial reconnaissance of the area each of the intrusions was traversed to determine the radiometric background prevailing over the complex - this was determined as 20µr/hr. Areas covered by drift had lower backgrounds and those over Moine rocks away from the intrusions had < 10µr/hr. The author was familiar with the background reading over the Aberdeen granite which is 30µr/hr. Each stream section was then traversed and readings in excess of 30µr/hr were noted and plotted on the maps in the back folder as $\cdot_{35}$. Some values less than 20µr/hr are presented on the map close to the syenite contact within the Moine metasediments.

Note 12 (Page 131 line3) The chemical and trace element comparison.

The detailed comparative study of the relationships referred to on page 131 was possible from an appraisal of data listed between pages 162 & 212 of this thesis. The major chemistry of these rocks was determined by the author using XRF analyses of fused samples and running them against a known standard rock of a similar type, from which values of SiO_2, TiO_2, Al_2O_3, total Fe, MnO, MgO, CaO, K_2O and P_2O_5 were obtained. The alkali metals Na_2O and K_2O were then determined using an EEl flame-photometer. Water at 110°C was determined by weighing a powdered rock sample before and after heating in an oven and allowing time for stabilization. Water above 110°C was analysed by the Penfield tube method. Carbon dioxide was first tested for by addition of dilute hydrochloric acid to powdered rock samples and observing under the microscope if effervescence occurred; those samples showing a positive acid reaction were then analysed in standard CO_2 apparatus in which carbon dioxide liberated by concentrated phosphoric acid attack was absorbed in two 'U' tubes by ascarite (sodium hydroxide-asbestos), CO_2 content then being calculated by weight differences before and after the experiment. Eight samples representing the three intrusions were then tested by grating flame-photometer for lithium, all determinations proved negative.

Ferrous iron content for all samples was then undertaken using the vanadate method suggested by Wilson (1955). A fluorine spθt test showed which specimens were expected to have high values of this element. The test was highly sensitive and because a large proportion of the rocks showed some reaction, fluorine was determined colorimetrically using a Hilger Uvispek spectrophotometer. Finally thirty-three specific gravities on rocks weighing between 1Kg and 2Kg were undertaken.

Quantitative trace element contents of the rocks were then determined by XRF methods. Fourteen elements were determined using several different programmes. All experimental work was solely the authors. Elemental ratios were calculated and normative values worked out by the departmental computer programme.

For comparative purposes three sheets were constructed for each of the following rock types:- Moine rocks, sills and dykes, Ben Loyal syenites, Beinn Stumanadh syenites, Cnoc nan Cuilean syenites, basic segregations, pegmatites and veins, Loch Borralan syenite and Loch Ailsh syenites. These detailed major chemistry, trace element chemistry and element ratios thus making a total of twenty-seven comparison sheets. Each were then able to be checked against one another both visually and numerically. In this way it was possible to elucidate the differences between the Moinian metasediments and the syenites, to compare the chemical relationships between the three parts of the intrusions themselves, and also to determine their similarities and dissimilarities with the other alkaline intrusions in Scotland.

Note 13 (Page 136 line 13) The calcium content of the Feldspars.

U.V. spectrographic analysis indicated only trace amounts of calcium in the feldspars. Additionally the most leucocratic of the syenites (principally feldspar + quartz rocks) when plotted on a triangular diagram Na_2O - K_2O - CaO, lie adjacent to the Na_2O - K_2O side of the triangle, CaO increasing only in the rocks having a relatively high mafic mineral content. The Loyal amphibole contains 10% CaO and sphene 27% CaO. Thus apart from trace element quantities the feldspars then have no calcium in their makeup which resides chiefly in the amphibole and sphene. CaO is also found in strontianite where it forms approximately 8% of the mineral.

Note 14 (Page 140 line three from bottom) The analytical sensitivity of lead.

The minimum amount of lead detectable in Nockolds and Mitchells' study was 10 ppm.

Note 15 (Page 149 table) Soil sample location.

The soil sample numbers on page 149 are located both by a soil sample map tied to the National grid on page 151 and by small square symbols on the large maps in the back folder.

Note 16 (Page 213) Amphibole from the Fhionnaich beach sand.

The use of beach sand from Loch Fhionnaich was justified after confirming that amphiboles extracted from the rock did not differ from these by analysis. Rock from Lettermore quarry was first broken into chips approximately 2" square using a rock splitter and then carefully hand crushed in a steel percussion mortar until the material passed through a 30 mesh sieve. This was decanted and washed with distilled water, dried in an oven and then combed with a hand magnet to remove magnetite. Initial separation of the mafic minerals from the feldspar was undertaken on a Frantz magnetic separtor at 0.5 amps and a tilt of 25/15°. At the same angle but with 0.375 amps a good separation of sphene from amphibole was obtained. This amphibole fraction was then polished using a magnetic stirrer and finally hand-picked when only pure grains were retained for analysis. Two analyses by XRF were done thus:-

Lettermore Amphibole

	Analysis 1	Analysis 2
SiO_2	50.08	49.13
TiO_2	0.55	0.56
Al_2O_3	3.30	3.28
Total Fe	17.57	17.52
MnO	0.61	0.60
CaO	9.83	9.70
K_2O	0.83	0.79
Na_2O	2.63	3.09
P_2O_5	0.04	0.02

Both analyses compare favourably with that determined on the Fhionnaich amphibole quoted on page 220.

Silica and alumina were checked by wet chemical methods and alkalis, determined by flame photometry, gave a good check of the potash content.

Note 17 (Page 215) Agreement of calculated 2V with estimated 2V.

Since the mineral is optically negative the following relationship should be true

$$(\gamma - \beta) < (\beta - \alpha)$$

The refractive indices determined by liquid immersion method for the Loyal amphibole ($\alpha = 1.651$, $\beta = 1.653$ and $\gamma = 1.668$) indicate an error in the value of the intermediate index β which ought to be closer to γ .

Refractive indices were determined by examination of a large number of grains showing the highest polarisation colours and taking α and γ as the lowest and highest indices found. was found from grains showing uniform illumination between crossed nicols when the stage was rotated. Since this value of β is erroneous the formula for the calculation of 2V could not be applied.

The substitution of Mg by Fe^{2+} and Si by Al in tetrahedral coordination exercises a major control on the refractive indices of hornblendic minerals; substitution being accompanied by higher indices. From the composition of the Loyal amphibole together with the density and $n\gamma$ values a $2V_\alpha$ between 70° and 80° is obtained from Tröger's diagram in Deer, Howie and Zussman.

Note 18 (Page 223) The atomic Formula of the amphibole.

The formula for the Fhionnaich amphibole on page 223 is in error due to an omission during transcription and should read as $(Mg_{2.82}\ Fe^{2+}_{1.36}\ Fe^{3+}_{0.71}\ Ti_{0.08}\ Mn_{0.02}\ Zn_{0.01})_{5.00}$ in the Y site. A recalculation is presented on the appended table. From this it is apparent that the number of ions in the formula for 23 and

Note 18.

	Wt.% of oxides	Molecular Wt.	Molecular prop. of oxides	Atom. props of oxygen from each mol.	Nos. of anions on basis of		No. of ions in formula	
					23 oxgn.	24 oxgn.	23 oxgn.	24 oxgn.
SiO_2	49.40	60	0.8233	1.6466	14.6551	14.7336	7.33	7.37
Al_2O_3	3.40	102	0.0333	0.0999	0.8891	0.8939	0.59	0.59
Ti_2O_3	0.57	80	0.0071	0.0142	0.1264	0.1270	0.06	0.06
Fe_2O_3	6.17	160	0.0386	0.1158	1.0306	1.0362	0.68	0.68
FeO	10.76	72	0.1494	0.1494	1.3297	1.3368	1.33	1.34
MnO	0.62	71	0.0087	0.0087	0.0774	0.0778	0.08	0.08
MgO	12.54	40.3	0.3112	0.3112	2.7697	2.7846	2.77	2.78
CaO	10.08	56	0.1800	0.1800	1.6020	1.6106	1.60	1.61
Na_2O	2.95	62	0.0476	0.0476	0.4236	0.4259	0.85	0.85
K_2O	0.83	94	0.0088	0.0088	0.0783	0.0787	0.16	0.16
H_2O	1.12	18	0.0622	0.0622	0.5536	0.5566	1.11	1.11
F	1.36	19	0.0716	0.0716	0.6373	0.6407	0.64	0.64
P_2O_5	0.03	142	0.0002	0.0010	0.0089	0.0089	0.00	0.00
Li_2O	0.03	30	0.0010	0.0010	0.0089	0.0089	0.02	0.02
Total	99.86			2.7180				
				- 0.0358				
				2.6822				

Factors $\frac{23}{2.5842} = 8.9002$

$\frac{24}{2.6822} = 8.9479$

24 oxygens agree well and the water value is therefore good. From which the following atomic formula ensues:-

Site

A $(Na_{0.46}\ K_{0.16}\ \square_{0.38})\ 1.00$

X $(Ca_{1.61}\ Na_{0.39})\ 2.00$

Y $(Mg,\ Li_{2.80}\ Fe^{2+},\ Mn_{1.42}\ Fe^{3+}_{0.69}\ Ti_{0.06}\ \square_{0.06})_{5.03}$

Z $(Si_{7.37}\ Al_{0.60})\ 7.97\ O_{22}(OH_{1.11}\ F_{0.64}\ O_{0.25})\ 2$

This may be represented by the basic formula :-

$(Si_{7.37}\ Al_{0.63})\ 8.00$

$(Mg_{2.92}\ Fe_{1.67}\ Al_{0.41})\ 5.00$

$(Ca_{1.61}\ Na_{0.39})\ 2.00 \quad (Na_{0.62})$

i.e. X = 0.39, Y = 0.41, Z = 0.63 on calculation this has indicated that the basic formula approximates to:-

$Ed_{62}\ Tr_{19}\ G_{19}$

Note 19 (Page 225 line 2) Enrichment of traces in sphene.

For this "and with the exception .... amphibole."
Read this "and with the exception of Li, Be, Zn, Co and Ni is markedly enriched in all other traces, excepting Sc, Rb, and Ba which were of the same order, when contrasted with the coexisting amphibole".