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THE 'SCOURIE DYKE' SUITE OF THE NORTH-WEST MAINLAND LEWISIAN OF SCOTLAND - with particular reference to the structural geology and geochemistry.

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ABSTRACT

The 'Scourie Dyke' Suite of the North-West mainland Lewisian of Scotland - with particular reference to the structural geology and geochemistry.

The 'Scourie Dykes' were intruded into Scourian gneisses about 1,900 million years ago and were subsequently deformed and metamorphosed about 1,750 million years ago during the Laxfordian orogeny.

The intrusive relationships of the dykes and the deformation styles they show in reworked areas are described for a number of areas between Durness and Loch Torridon. An attempt is made to correlate the deformational and metamorphic episodes that have affected the dykes. The igneous and metamorphic petrology and geochemistry of the different dyke types are described and used to propose a scheme for their evolution.

The density of dyke outcrop in the Lewisian has been measured and the results plotted as contour maps. These maps show that dyke material is concentrated in parallel, NW-SE trending belts perpendicular to the crustal extension. The spacing of the belts is thought to give an indication of the variationin thickness of the crust 1,900 million years ago.

CONTENTS

Chapter I INTRODUCTION

Approximately 1350 square kilometres of Lewisian autochthon crop out on the mainland of Scotland between Cape Wrath and Loch Torridon, a distance of 130 kilometres.

These hard, ice-scoured rocks are very well exposed along the whole extent of their outcrop.

The mainland Lewisian was mapped on a scale of 6 inches to 1 mile by the Geological Survey of Great Britain between 1883 and 1897. In 1907 the memoir by Peach, Horne, Gunn, Clough and Hinxman was published and it describes with great detail and accuracy the basic petrography, structures and deformations of the Lewisian. They constructed the fundamental chronology of events which was based on the differences in gneiss types and their relationships to a series of basic dykes and sills. The authors concluded that, prior to these minor intrusions, metamorphism and deformation on rocks of unknown origin had produced grey pyroxene gneisses. These collectively were called the 'Fundamental Complex'.

After the intrusion of the basic rocks, a reworking affected the rocks producing biotite and biotite-hornblende gneisses and transforming the dykes and sills into hornblende schists.

Using this bipartite chronology the mainland was subdivided into three zones (see Fig. I.1):-

i) The Central Zone - of mainly 'Fundamental Complex' and unaltered intrusives.

ii) The Northern Zone (North of a line from Tarbet to Ben Dreavie)

iii) The Southern Zone (South of Loch Broom), both made up of rocks showing post intrusive alteration.

Sutton and Watson (1951 a,b) continued the Geological Survey's work by a more detailed investigation of the Lewisian around Loch Laxford and Loch Torridon. They named the two metamorphic episodes the Scourian (producing the 'Fundamental Complex') and Laxfordian (post intrusion).

The dykes were used as stratigraphical markers to separate the Laxfordian and Scourian events, all post dyke events being defined as Laxfordian. Sutton and Watson stated that the two metamorphic episodes were separated by a great interval of time, during which a series of uniform dolerite dykes were intruded after uplift and cooling of the Scourian complex. The environment of intrusion was thought to be comparatively near to the surface in a rigid block under tension, and cool enough to chill the dolerite magma.

Their work resolved the Laxfordian metamorphism of the dolerites into stages, and using these stages they sub-divided the Laxfordian fronts of the Loch Laxford and Loch Torridon areas.

The fronts of the Laxfordian reworking were then seen to have a north-west trend and the reworking to have produced amphibolite facies rocks with a general north-west foliation.

Another immediately pre-dyke metamorphism was postulated by Evans (1963,65), Evans and Tarney (1964),&Evans and Lambert (1974). The type area of this metamorphism, of almandine-amphibolite facies producing conditions, is defined by Evans (1965) as the lower three kilometres of the River Inver (Sutherland), the name Inverian being used to describe this metamorphism.

'Absolute' Ages.

Radiometric studies of the Lewisian by Giletti (1959), Giletti et al (1961), Evans and Tarney (1964), Evans and Park (1964), Evans (1965), Moorbath, Welke and Gale (1969), Moorbath and Park (1972), Lambert and Holland (1972) and Pidgeon and Bowes (1972) have given ages for rocks related to each metamorphism and for cooling of the dykes.

A summary of the radiometric ages is as follows:
the Laxfordian 1.85 to 1.15 x 10^9 years, intrusion of the 'Scourie Dykes' some time between 2.20 and 1.85 x 10^9 years,
the Inverian (Late Scourian) c. 2.25 x 10^9 years,
the Early Scourian c. 2.65 x 10^9 years, and
the 'pre-Scourian' c. 2.9 x 10^9 years.

Most ages for the Lewisian events have been calculated from ^{40}K - ^{40}Ar data. Only a few Rb-Sr isotope concentrations for Lewisian rocks have been measured. Lambert and Holland (1972) gave an age of 1.85 x 10^9 years from an Rb/Sr isochron constructed from twelve specimens of Laxfordian gneiss from north of Loch Laxford and 1.55 x 10^9 years from three similar specimens from Durness.

Two sets of analyses from one rock sample (the whole rock and separated biotites) of dyke by Evans and Tarney (1964) give an age of 2.19 x 10^9 years, assuming an initial $^{86}Sr/^{88}Sr$ ratio of 0.1194.

Pidgeon and Bowes (1972) using ($^{207}Pb/235_U$)-($^{206}Pb/238_U$) data from a total of seven zircon fractions from two samples of Scourian gneiss give an age of 2.70 x 10^9 years for the granulite metamorphism. Moorbath and Park (1972) suggested, from seventeen ($^{207}Pb/204_{Pb}$) - ($^{206}Pb/204_{Pb}$) data points, that the basement gneisses of the southern zone was in existence 2.89 x 10^9 years ago.

The 'Scourie Dykes'

The term 'Scourie Dykes' has been used for all dykes of post-Scourian, pre-Laxfordian age. The name was originally used by Teall (1885) in his description of the petrography of the dyke which crops out on the north side of Scourie Bay.

O'Hara (1961) published four new chemical analyses from members of the 'Scourie Dyke' suite and nine analyses of minerals found in them. From this and observations from dykes scattered between Loch Laxford and south of Lochinver (of which one tenth showed sheared margins with garnets) O'hara suggested that the dykes were intruded into hot (300 to 500°C) and deeply buried gneiss. An interpretation which differed from that of Sutton and Watson (1951a). O'Hara (1962) described four types of basic dykes from a small area near Badcall, Sutherland, (described by Sutton and Watson, 1951a, p 265). He gave their relative ages, outlined their petrography and geochemistry and used these results to reinforce his contention of intrusion of the dykes into a hot but rigid country rock.

Burns (1966) carried out an extensive geochemical and mineralogical investigation of the 'Scourie Dykes' about the northern Laxfordian front in an attempt to quantify the zones with which Sutton and Watson had subdivided the front. Aluminium was found to have been increased at the margins and magnesium decreased across the width of the dykes on metamorphism.

Work on the central zone with its high concentration of dykes resulted in papers by Tarney (1963b) and Evans and Tarney (1964).

Tarney (1963b) established a relative chronology five out of eight distinctive dyke types in the Assynt-Lochinver area. Their varying contact morphology and states of metamorphism were attributed to their intrusion into a hot, but cooling, environment. As the alteration of the picrites did not form serpentine, a temperature of 500°C was invoked for the alteration. The fact that the picrites show coexisting ortho-pyroxene and olivine not reacting was used to fix a pressure of 5 to 6 kilobars. Tarney concludes: "Hence these values serve to confirm the view that the Assynt dykes (except perhaps "the three of uncertain age") were intruded at considerable depth into hot country rock, and that their intrusion does not mark a period of great uplift of the basement rocks."

^{40}K-^{40}Ar radiometric dates for the dykes of Assynt (Evans and Tarney 1964) range from 3.86 to 1.39 x 10^9 years. The very old dates were considered to be spurious by these authors. The fresh picrite dykes have ages which all fall around 2.2 x 10^9 years, fresh dolerites range from 2.05 to 1.85 x 10^9 years and altered dolerites range from 1.80 to 1.40 x 10^9 years.

Park (1964), Bowes and Ghaly (1964), Bowes and Khoury (1965), Khoury (1968) and Bowes (1968) have all described dykes which they consider not to be part of the "Scourie Dyke" suite, i.e. not post-Scourian, pre-Laxfordian. Park (1970a) subsequently argued that all the dykes should be included within the 'Scourie Dykes' suite.

The deformation and intrusion patterns of the dykes of the Tollie antiform was discussed by Park (1970b) who suggested that the intrusion path of the dykes was greatly controlled by a strong Inverian foliation. The presence of this Inverian foliation resulted in the change of trend of intrusions, and the change from dykes to sills upon entering a strong sub-horizontal Inverian foliation.

Park and Cresswell (1972, 1973) discussed the control of intrusion as shown in areas near the main Laxfordian fronts and pointed out the similarity of structures shown by certain of the 'Scourie Dykes' to the syn-kinematic dykes found in Greenland by Allaart (1967) and Watterson (1968), and suggested that some of the 'Scourie Dykes' were syn-kinematic with the Inverian deformation.

Aims of Present Study

The aim of this study was to survey the dykes throughout the mainland outcrop in order to establish:

(a) the possible conditions of the country rock on intrusion of the dykes and any variations in these during time and space,

(b) the relative ages of the different dyke sets to each other and to deformational and metamorphic events,

(c) the variations in the manner of deformation of the dykes in response to the Laxfordian metamorphic events.

(d) the possible origin and path of evolution of the magma that was intruded to form the 'Scourie Dykes'.

Methods of Research

Field mapping was carried out on Ordnance Survey 1:10560 maps and enlargements.

Standard techniques of structural, petrographic and petrofabric analysis were used. A five-axis universal stage was used for the determination of optic orientation and extinction angles of minerals.

X-ray diffraction photography was used for accurate mineral identification when optical methods were unsatisfactory.

Chemical analyses were carried out on solutions of rock powders and on powders by emission spectrograph and X-ray fluoresence methods.

A census of dykes shown on the Geological Survey 1:10560 maps was carried out to produce dyke density and trend maps.

Other techniques used and greater details of those mentioned will be found in the relevant chapters.

Chapter II FIELD RELATIONSHIPS

The field geology of the 'Scourie dykes' is described for seven areas from within the area under study. They are:

a) Cape Wrath to Loch Laxford

b) Loch Laxford to Scourie

c) Scourie to Loch Poll

d) Loch Poll to Strathan

e) Gruinard Bay

f) Loch Maree to Gairloch

g) Loch Torridon

Within each area the pre-dyke history, the dyke types present and the deformation of the dykes are described, although for any one topic, or topics, they may be subdivided so that intra-area variations can be described.

For each area the intrusion of the dykes is considered to represent the deformation phase Dd, the pre-dyke deformations are coded Dc, Db and Da, and the post-dyke deformations are coded De, Df, etc. The coding of events only describes the relative age of the events for the area under discussion.

For each area particular facets of geology may be discussed and conclusions drawn. Conclusions for the whole of the region are made at the end of the thesis.

Cape Wrath to Loch Laxford

Durness

On the east side of the Kyle of Durness there are scattered, poorly exposed outcrops of Lewisian. One such outcrop on Beinn an Amair reveals a number of dykes. These were considered by Peach et al (1908) to be a part of the 'Scourie Dyke' suite. Three epidiorite (meta-gabbro) dykes and one hornblendeite dyke have been found.

Two episodes of pre-dyke deformation are recognized. These have produced:

(a) isoclinical and intrafolial folds (F_b) of a previously banded system (S_a), which form a sharp continuous banding (S_b) that often includes ultra-basic boudins, and

(b) the folding of S_b into small to large scale folds, (F_c).

Epidiorite dyke emplacement was discordant to all pre-dyke structures although the extreme weathering out of the hornblendite dyke has obscured its intrusive contacts.

Although they are a great distance within the northern Laxfordian zone, very little Laxfordian deformation has affected the dykes. This is typically inhomogeneous, the deformation being more widespread towards the Kyle. The regional effect has been to rotate the dykes and the pre-dyke structures into parallelism about a plane of ESE strike with a steep dip to the SSW. (See Fig. II.1). Deformation of the dykes also varies greatly over this small area.

As elsewhere the strain within the dykes has been concentrated at the margins to produce a parallel foliation in the dyke and the contact gneiss. From the translation of the gneiss foliations the movement of the Laxfordian shearing is seen to have been downwards to the south with a slight dextral component. Within the areas of low Laxfordian deformations a faint foliation may be found in the dykes. This is approximately parallel to the shear zones.

Only the strongest foliations in the dykes tend to remain unobscured by a post - shearing granulitic mineral growth. The resulting coarse grained texture in hornblende, oligoclase-andesine, sphene and apatite (± quartz, biotite) pervades both gneisses and dykes and is not associated with deformation. Minor retrogression of this assemblage is linked with the small scale plication of foliations, F_f.

Richonich to Loch Laxford

Few intrusive sheets of post-Scourian age have been recognized north of Loch Laxford. This is considered to be due to their absence rather than to their misidentification as basic bodies of Scourian age. The country rocks of this area are banded hornblende, biotite and biotite-hornblende granoblastic gneisses which often contain ultra mafic boudins.

A small number of thin amphibolites have been described by Dash (1969) from Creag Gharbh Mhor. Such bodies are generally concordant but sometimes are discordant(dykes)and have experienced a similar history to those found between the Rhiconich River and the Laxford River. Both areas have suffered the Laxfordian metamorphism, the members of the Scourie Dyke Suite are now granoblastic hornblende-oligoclase-epidote-sphene (± biotite) rocks. Within the Rhiconich River-Laxford River area they have been folded and cut by many granite and pegmatite sheets. Because of this, their outcrop is patchy with a NW-SE (Laxfordian) trend in the south which swings to a NE-SW trend further North (see Fig. II.2).

The intrusions show a variety of styles of intrusion and deformation with the well banded amphibolite facies gneisses. Three bodies of 'Scourie Dyke' suite origin are exposed at Creag a Bhaid Choill (0.7 km

North East of the Quarry on the River Laxford). Two of these bodies must be considered as sills. They are concordant to the banding of the gneiss over nearly all of the outcrop, and follow the banding faithfully.

Exceptions to this are uncommon but their appearance reinforces the contention of originally concordant intrusion. The most relevant exposures occur at the end of the intrusions. In one such exposure (NC 2310-4812) a sill ends suddenly with an almost vertical and highly discordant contact, the upper contact being transgressive so that the sheet reaches its maximum thickness here. (See Fig. II 3a). To the east (NC 2365-4820) a sheet thins out by division into short lived tongues, which here have a concordant base and a stepped upper contact (Fig. II.3c). In addition to the widespread banding of the gneisses a more fissile foliation is locally present. This foliation (see Fig. II.3b), a transposed early banding, is clearly seen to be pre-sill. The sill follows both foliations but does not show deformation associated with the shearing of transposition. This, a late-Scourian deformation, is equated with the Gualin phase of Chowdhary and Bowes (1972), and with the Inverian which is considered by Holland and Lambert (1972) and Park and Cresswell (1972) to have been operative in this area. To the south at NC 2336-4785 a sheet has a vertical contact (trend 150°N) with horizontally banded gneisses. This undoubtedly indicates an intrusive dyke contact. However, this contact is deformed by a steep Laxfordian deformation (F_e) on its south contact towards concordancy and a Laxfordian trend (here c. 110°N).

Three elongate outcrops of 'dykes' to the south and west of Cnoc a Garbh-bhaid Mhoir (NC 26-48) (see Fig II.2) also show many examples showing the control of banding on intrusion (see Fig. II.3f). Observed discordant contacts are confined to the middle of these three outcrops in an area where a pre-dyke deformation has rotated the generally sub-horizontal gneisses to a steep NNW-SSE attitude. Thicker bodies (>2m) are generally discordant but adjacent thin bodies (c. 30 cm) are concordant.

Discordant contacts are invariably E-W and near vertical. These are considered to be joints that have been filled by the dyke magma.

These sheets, now amphibolites, show igneous banding and xenoliths and are weakly foliated. This foliation is formed by the oblate nature of feldspars and is found at and parallel to the contacts. More commonly a subtle mineral lineation is found and is related to the Laxfordian folding.

A strong foliation (S_e) is found at the dyke contacts at Creag a Bhaid Choill. This foliation is asymptotic to the margin and suggests a dextral sense of movement along the dyke contact.

This first deformation of the dykes is due to a strong belt of shearing that trends NW-SE and has its full effect from south of Badcall Quay (NC 227 478) to Badnabay (NC 220 467) (the Badnaby Zone of Sutton and Watson 1951a and 1962).

It is this deformation that has deformed the discordant sheets towards concordance and folded the dykes, sills and gneisses into asymmetrical and symmetrical open folds, F_e, on the northern flank of the shearing zone.

The schistose fabric at the margins, mentioned above, is associated with rotation of consistent sense, of igneous bands and pegmatite veins. The movement has a dextral sense looking eastwards, about a S.W.-dipping plane. The same movement is given by the folding of the sills. All the information gathered from this area indicates a simple shear strain on a south-west dipping plane with top moving down and to the west.

It may be that the initial stages of this movement caused the marginal schistosity by flexural slip and was followed by folding.

A mineral lineation is found in amphibolites and gneisses which is parallel to the hinge of the folds. This lineation plunges at a low angle to the south east and is at right angles to the direction of movement on the shear plane.

Here, as at Durness, metamorphism continued after these first and main deformations and gave all the rocks a granoblastic texture which obscures most of the previous textures in the amphibolites.

After this metamorphism a later quartz foliation, S_f, was produced. This is seen especially well in the amphibolites and post dates the granoblastic mineral growth. Folds whose axial planes are marked by the foliation fold dyke contacts and vary from close to tight. This foliation is steep (generally vertical) and strikes from SE-NW (to E-W). Evidence of this deformation has not been seen at Craig a Bhaid Choill. It is often found around Cnoc a Garbh Bhaid Mhoir where the folding and/or the quartz foliation of this deformation occur along most exposed stretches of the amphibolite contacts.

Between Craig a Bhaid Choill and Druim na h'-Aimhue, areas of similar position to the Laxfordian Shear zone, the dyke outcrops trend in different directions due to the change in the attitude of the gneissosity. Not only does gneissosity change from sub-horizontal to dip to the south-east going from west to east but the lineation steepens from horizontal to c 45^{o} to the south-east. S_f foliation swings through c 30^{o} and the deformation producing this foliation is found more often.

Fig. II.2 shows that the discordance of dyke intrusion coincides with an area of gneisses which are not sub-horizontal. The gneisses are steep and have a general NNW-SSE trend and are of pre-dyke origin. This orientation is due to tight folding which has not been recognised elsewhere in this area and cannot be linked with either of the two pre dyke fold phases found. This deformation is considered to be post horizontal folding and to have an immediately pre-dyke age of origin.

This belt of tight folds has had little controlling effect on the intrusion of magma. Thus in this area the presence of a sub-horizontal and pre-dyke attitude of the gneisses and vertical joints in vertical gneisses are the only factors which have controlled the intrusion of the magma.

Loch Laxford to Scourie

Watson (in Sutton and Watson 1951a) divides the gneisses of the Scourie district into charnockitic and and non-charnockitic types, the non-charnockitic (hornblende-biotite-sphene) suite being produced after the charnockitic suite. Lambert and Holland (1972) indicate that between Rubha Ruadh (NC 163 513) and Geodh nan Caluman (NC 157 477) there exists an area of 'Inver Assemblage' "amphibolized pyroxene-granulites" which they believe to be an assemblage resulting from two successive metamorphisms (Inverian and Laxfordian).

The age of formation of structures within the gneisses is not readily apparent in the field, as both the Inver and Laxford assemblages are in amphibolite facies and the tectonic trends are of similar strike, see Beach et al (1973). By definition the Laxfordian is post-dyke and the Inverian (Evans 1965) is pre-dyke and therefore the best way to distinguish between the two phases is to decide whether or not the deformation has affected the 'Scourie Dykes'.

Pre-dyke deformation between Loch Gobloch and Pollan Innein (Badnabay zone).

Since the dykes as well as the gneisses of this area are now in the amphibolite facies it can be concluded that the Laxfordian metamorphism has had a pervasive effect.

The pre-dyke structures in the gneisses of this area belong to three ages. An older, poorly preserved, (Sa), banding, found in outcrops of massive 'flecky' acid gneisses, is folded by isoclinal folds (Fb). These folded bands have been refolded and the second generation of folds (Fc), have sub-horizontal enveloping surfaces, and contain an axial plane quartz foliation (Sc). Outcrops of this type of gneiss are not found greater than 5 m wide, and they give way sharply to the well banded acid gneisses with a strongly developed foliation (Sc) produced by the intense shearing of the earlier banding (See Fig. II.4).

Intrafolial folds within the sheared gneisses near to the contacts between Sc and Sb gneisses are not found. This suggests that the deformation was by simple shear. The sense of movement is anti-clockwise, looking from the east. A strong quartz lineation is found within the remnants of the old banding but is present to a much lesser degree in the new banding. Large areas of this older gneiss type have been found where the old rock fabric has been almost totally destroyed by the extreme growth of quartz rods. This lineation is parallel to the fold axes of Fc folds and has a variable orientation. However, within one area it consistently has a higher plunge in a more southerly direction compared with the lineation found in the dykes. Dykes cut across such areas and show no signs of a related deformation. The lineation is therefore considered to be pre-dyke and related to Fc folding and shearing.

<u>The dykes</u>

Three major dykes have been investigated from this area (See Fig. II.5). All have been metamorphosed and exhibit a schistosity to varying degrees and all are in rocks that have an Inverian history (Lambert and Holland 1972). The age relationship of these dykes is:-

1) 'Hyperite' dyke (coarse grained mafic hornblende-biotite rock possibly related to the 'green dykes' of the Geological Survey maps. The 'Fanagmore dyke' of Clough, p 140 in Peach et al 1907).
2) 'Meta-gabbro' (coarse grained, coarse textured rock - 'epidiorite' of Survey).
3) 'Meta-dolerite' (fine grained, showing no relict textures and of melanocratic appearance).

The meta-gabbro and the meta-dolerite both generally show discordant intrusive contacts, although the meta-gabbro is often concordant. The contacts of the 'hyperites' are poorly exposed due to the relatively easily eroded nature of this rock type, but where seen they are concordant to the gneissese banding of the country rock.

The meta-gabbro from Loch Gobloch shows concordant contacts to the Sc foliation (See Fig. II.5) for much of its path but can be seen to cut it by stepwise transgression showing irregular but parallel contacts. The intrusions are always discordant to the earlier (Sb) foliations.

The influence of the later (Sc) foliation increases northwards, as does the Laxfordian deformation of the dykes, for the dykes acquire a WNW-ESE trend by intrusion parallel to Sc and spread laterally into a number of branches. The dykes within this area may be

i) discordant and vertical with a NW trend or

ii) discordant and vertical with a WNW trend or

iii) concordant to Sc with a WNW trend (see Fig. II.6)

The occurrence of (ii) is considered to be due to the small scale, to microscopic, interaction of the use of the Sc foliation and the waning stress control acting to preserve the NW trend (i).

The north-eastern-most branch of the meta-gabbro dyke is exposed on a vertical rock face at NC 1675-5065 where it widens from c.15 m at the bottom to c.25 m at the top, where the horizontal section shows short stubby off-shoots to the bulbous stock-like mass. This probably reflects (as does the intrusion at Creag a Bhaid Choill (Fig. II.3a)) a terminal swelling effect at, or near to, the vertical limit of its intrusion path.

The Laxfordian metamorphism, as stated before, has affected the rocks of this area. The amount of Laxfordian recrystallization of the intrusion varies greatly.

Throughout the area the ophitic nature of the meta-gabbro is preserved to varying degrees, as is, albeit to a lesser extent, the ophitic nature of the 'Hyperite'. Deformation of the dyke textures also varies. At Loch Gobloch short and often curved shear zones cutting otherwise undeformed rocks are found but northwards less distinct shears and a patchy but more pervasive schistosity have been produced in the dykes, the latter parallel to the contacts and especially well developed where concordant. In the area west of Cnoc an Fhir Bhreige crystallization of hornblende in the dykes has occasionally given a lineation (plunge of 20° to SSE). The foliation in the dykes is also very patchy and poorly developed. Where found, it is parallel to the contacts of the body.

Foliations seem to have been produced by recrystallization and/or deformation of feldspar 'blebs' to an oblate shape. A lineation is not always developed.

The extreme effect of metamorphism is to produce a granoblastic texture which tends to obscure the foliation or lineated fabric. It would appear that metamorphism continued well after deformation had been completed, which may have been initiated on the onset of metamorphism.

Loch Gobloch to Scourie Bay (Scourie and Claisfearn Zones)

Pre-dyke History

South of a line from Rubh' an Tiompain (NC 159 498) - Claisfearn (NC 196 461) to Scourie Bay (NC 150 450) the rocks change from the Inver Assemblage to the Scourie Assemblage (Lambert and Holland 1972).

The northern limit of this area falls within a belt of highly deformed gneisses. These gneisses are isoclinally folded and dip steeply to the SW with fold amplitudes of two metres to many tens of metres. This folding (Fc) has folded and boudinaged large masses of basic material (hornblendite). The fold belt dies out southwards on changing from isoclinal to more open folds (see Fig. II.7). Where less intense these folds are asymmetrical over-folds, overturned to the NE, and tend to be intrafolial (see Plate II.1). Such folds are commonly found throughout the area of Inver Assemblage. The highly deformed gneisses generally show a mineral lineation which is parallel to the lineation found in the dykes. (The lineation is considered to be due to the interaction of the pre-dyke structure and the Laxfordian deformation.) The F_c folds die out by Poll an Turrabain (NC161 496) where a banded picrite is seen to cut a large folded basic mass in amphibolite facies. From here to Port Mor (NC 162 484) the gneisses dip steeply to the SW and contain many interfolial overfolds and represent the continuation of the Fc fold belt.

Along the Sound of Handa to c.200 m south of Port Mor the south westerly dipping gneisses are suddenly replaced by sub-horizontal, massive, coarse 'flecky' gneisses which are sometimes poorly banded and contain opalescent quartz. These rocks are gently folded and locally have been sheared into steep SW-dipping belts (?Fc). Early (?Fb) structures are recognised within the flat-lying rocks which produce interference structures with the later (Fc) folding. These earlier folds (Fb) are tight to isoclinal and have an associated axial planar foliation.

The contact between the flat lying and steep gneisses is synformal.

Along the strike of this contact at Loch Laicheard (NC 180 460) and Breac Leathad (NC 183 456), large masses of basic material (picrites and amphibolites) swing from a NE trend (through EW) to a SE trend, lose their 'original' mineralogy and become schistose, hornblende-rich rocks. This deformation folds earlier isoclinally folded gneisses (Fb) into moderately open folds that become tighter and asymetrical and whose axial planes dip to the SW.

From Creag a Bhadaidh Daraich (NC 165 450) a thin dyke (2-3 m) can be traced, despite poor exposure, into the zone of Fc folding. This dyke, referred to on the 1907 Survey maps as a 'rather pale dyke (biotite hornblende dolerite)' is discordant to the generally western-dipping gneisses and is not foliated at Creag a Bhadaidh Daraich. The outcrop of this dyke trends NE-SW and swings through EW to a SE-NW trend as the intensity of the Fc folding increases and acquires a foliation. The dyke is cut by a typical 'Scourie Dyke' at Creag a Bhadaidh Daraich and is considered to be much earlier than the 'Scourie Dyke' suite, and pre-Fc folding. This is apparently the only dyke found on the mainland that is not a part of the 'Scourie Dyke' suite.

The area around Sithean Mor (NC 148 459) north of Scourie Bay, requires some discussion. Teall (1885) described the effect of shears (Laxfordian) on the dyke of Creag a 'Mhail and Sutton and Watson (1962) discuss shear zones which they regard as Laxfordian, which affect the gneisses. All the published work consider the shears found within the dykes and the shear-fold belts, which deform the gneisses of similar orientation, to have a common origin and therefore to be Laxfordian in age. However, field evidence suggests a more complex relationship between the deformation of the gneisses and that of the dykes.

Sutton and Watson (1962) suggest that the shears vary in complexity, the simplest being monoclinal flexures, and conclude that shear folding and the development of an axial plane foliation succeeded flexural folding. The deformation within the dykes is confined to shears, produced by simple shear, that indicate that the movement was sinistral in the horizontal plane. These shears are asymptotic to the dyke margins and have a strike sub-parallel to the shear belts in the gneisses.

Fig. II.8 shows how shears in the gneisses are replaced by two or more shear zones which cut the dykes, strike in a different direction and are asymptotic to the dyke contacts.

However, similar shear zones in the gneisses do not affect the dyke in the same way, for very intense shear belts (c. 15 m wide) can be traced up to a dyke where the deformation of the dyke is represented by a small number of narrow shears (10 cm wide) that cannot conceivably have accommodated the strain shown by the gneiss shears (see Fig. II.9). In such cases shears are found at regular intervals along the dyke whether or not a shear belt is present in the country rock. Thus dyke shear belts are found which, though unrelated directly to pre-dyke shears in the gneisses, may be controlled by their presence.

It is concluded that the shear belts were in existence prior to the emplacement of the dykes, as simple flexures, and that post-dyke (Laxfordian) stresses have reactivated them causing further deformation (the 'shear folding' of Sutton and Watson), and controlling the deformation of the dykes by the transverse shears. This is also found to be the case to the south of Lochinver where there is reactivation of Inverian structures by Laxfordian movements (Evans 1963).

The dykes

Three main dyke lithologies are found in this area. The 'normal' gabbroic-textured rocks, meta-gabbros (epidiorites), the melanocratic meta-dolerites (which may or may not contain feldspar phenocrysts) and picrites. The meta-dolerites have marginal zones without feldspar phenocrysts but the content of these increases towards the dyke centres, and may cause these dykes to resemble the meta-gabbros if the dyke is wide enough (c. 30m). The meta-dolerites are younger than the meta-gabbros. The relative age of the picrites is unknown, but by comparison with other areas they are earlier than the gabbroic dykes.

The NW-SE outcrop trend of the gabbroic dykes of the central block is maintained in this area, often by the alternative use of Sc foliation planes and perpendicular vertical joints in the gneisses. The meta-gabbros show this at microscopic to mappable scales.

To the south of Cnoc Tigh Adhamh (NC 171 488) there are two dykes which have a folded outcrop pattern. The section where the two dykes trend WNW-ESE is highly sheared by Laxfordian movement which has modified to near obliteration the original contact morphology. On the N-S to NW-SE trending sections the dykes are discordant at a high angle to the gneisses, but local concordance does exist. The N-S trend continues over Cnoc Tigh Adhamh to Beachlach Tharbait (NC 170 490) where the meta-gabbro cuts the steep SW dipping gneisses. The same dyke probably continues to Cnoc Cuthaige (NC 168 493) where it is still discordant but is cut off by a Laxfordian shear with high finite strain. This shear displaces the dyke dextrally and the dyke is found again at Rubh' a Tiompain. Here, although rotated by Laxfordian movements, the discordant nature of the intrusion to isoclinally folded (Fc) gneisses is obvious. (See Plate II.2). The southern contact has a number of thin offshoots which can be followed for many metres sub-parallel to the main dyke. These are concordant on their north contacts and discordant by the same amount as the main intrusion (c.20^{o}) on their southern contacts. To the north of the dyke there are discordant offshoots, (see Fig. II-10).

On closer inspection in the field and microscopically, the overall attitude of the margins of these intrusions is found to be due to concordant/highly discordant stepwise transgression of the foliations of the gneisses. Steps in the order of 14 mm along the banding and 7mm across the banding to give an overall angle of discordance of c.26^{o} have been measured from thin sections of the contacts. Intrusion is believed to have been dilatational.

Where contacts of the meta-gabbros are exposed and not sheared, there exists a marked but narrow fine grained marginal zone which grades slowly into the more normal gabbroic textured material, of a grain size of 1-3mm which can reach 4mm in the centre of the wider dykes. These dykes contain xenoliths of basic and acid gneiss (Plate II.3). Acid gneiss blocks are more obvious in the field and are rectangular or rhomboidal in outline. Banding of igneous origin has been found but is not common (see Plate II.3).

The meta-dolerite dykes have a similar trend, and are seen to intrude into the meta-gabbros, often forming composite dykes. A meta-gabbro dyke to the south of Clar Loch (NC 183 472) has a meta-dolerite running along the south margin that eventually cuts through it and out at the northern contact, from where it continues as a separate dyke trending parallel to the meta-gabbro. Fig. II.12.

The dyke at Rubh' a Tiompain shows extremely well the relationship of the two phases of intrusion of basic material, which are also found at Cnoc Tigh Adhamh in the Tarbet dyke. The meta-dolerite has been intruded into the meta-gabbro and forms the central zone and one third of the width of the composite dyke. Tracing the meta-dolerite south eastwards, the dyke splits into two (see Plate II.4) and continually subdivides until it finally admixes with the meta-gabbro (Plate II.5). The contacts between the two dyke types are sharp and it is considered that the meta-dolerite magma was intruded when the central part of the meta-gabbro was semi-consolidated, thus allowing the admixing. This view is strengthened by the occurrence of gneiss xenoliths (which remained solid) that form bridges between areas of meta-gabbro across the intervening meta-dolerite.

As there has been no increase in width of the dyke here due to the added material, the semi-consolidated meta-gabbro must have been forced out by the meta-dolerite magma possibly with a filter press action on the crystal mush. Such filter press action may also have produced feldspar-rich zones in the meta-gabbro at the dyke-dyke contacts, especially in the areas of admixing (see Plate II.5).

The above interpretation has been based on the conception of a separate meta-dolerite magma intruded into the meta-gabbro. The relationships described could just as well be satisfied by the production of a doleritic magma from the filter pressing of the semi-consolidated gabbroic magma, the 'dolerite' magma intruding through and out of the gabbro.

Not more than 4 metres from the northern contact of the composite section of the dyke, another mass of meta-dolerite crops out. Its boundaries are controlled by joints in three orthogonal planes (see Fig. II.11). The set nearest to parallelism with the foliation of the gneiss is often ignored as the dyke tends, in preference, to be concordant to that foliation. It is obvious that intrusion is non-dilatational and that the removed gneiss blocks must have sunk to a lower level. This outcrop is typical of most of these dykes. The use of stoping and forceful intrusion along foliation planes varies between and within dykes to give the outcrop pattern of the dykes at Loch nam Brac (NC177 480) and the boss-like structure of the meta-dolerite at Tarbet (NC 169 486) (See Fig. 11.12).

A weak stress system is inferred to have acted during the intrusion of the meta-dolerite set of dykes. For the meta-dolerites have a mainly non-dilatational origin, do not vigorously maintain their trend, and vary in width haphazardly. Despite being non-dilatational they do not contain xenoliths, whereas the meta-gabbros, which appear to be dilational, do contain numerous gneiss xenoliths, possibly indicating non-dilatational intrusion at another (higher?) level.

This possibly reflects a change in the state of deviatoric stress from moderate to low between the two phases of intrusion. Because of the proximity in time of the intrusion of the two dyke types, this change was probably caused by the intrusion of the earlier dykes reducing the deviatoric stress, since an intrusion will tend to increase the stress normal to the plane of the intrusion, (i.e. σ_3 the lowest principal stress).

<u>Dykes from Port Mor to Scourie Bay (Scourie Zone)</u>

These dykes are only mildly metamorphosed and deformed, include members of the dolerite and gabbro sets (referred to as meta-dolerites and meta-gabbros in the preceding section) and are indistinguishable from dykes of these sets outside this area. They show unaltered igneous mineralogies and textures where they are not cut by shears. Both sets are discordant to the gneissose banding, the dolerites often having rectangular irregularities on their contacts, the gabbros having flat planar contacts with a few minor irregularities due to the dyke following the banding for short distances and crossing back to its normal trend. Irregularities in opposite contacts can be matched and the displacement of conspicuous basic masses across the gabbros fit with a dilatational intrusion mechanism. Both sets show distinct chilling. As to the north, the gabbro contain xenoliths and the dolerites contain feldspar phenocrysts.

Deformation of Dykes

The deformation of the dykes in these two sub-areas between Scourie and Rubh a Tiompain is completely heterogeneous in all aspects. Regionally, there is a discontinuity of deformation which along a line Port Mor to Claisfearn coincides with the limit of the effects of the pre-dyke deformation Dc.

Dykes north of Claisfearn - Port Mor

Dykes within this area, whether originally concordant or not and regardless of orientation, show the production of a foliation (i.e. become an amphibolite schist) parallel to their contacts. This foliation is variable in intensity and extent (i.e. width of foliated zone). It increases northwards and directly indicates the amount of Laxfordian deformation.

The deformation (and metamorphism) that affects the contacts is the result of simple shear of the dyke rock in contact with gneiss which often does not show any deformation that can be linked with the shearing.

The deformation is considered to be dependent on the presence of competence differences between amphibolite gneisses and the dykes of igneous mineralogy at the onset of the Laxfordian deformation.

Shears at the contacts of the dykes to the south of this small area affect only a limited zone to produce amphibolite schists (often only 5 cm wide) and leave the central part of the dykes with their igneous textures and mineralogy unaffected, indicating that the temperature alone, at the times of shearing, was insufficient to cause recrystallization. The foliation is generally well developed and shows a fine hornblende lineation. Going northwards, the degree of the marginal foliation increases and the deformation of marginal gneisses, where they are discordant, becomes apparent.

It is only at Rubh' a Tiompain that the Laxfordian deformation of a dyke approaches homogeneous strain. Here a dyke shows an almost homogeneous foliation parallel to its contacts, which appears across the whole width. The intensity of this foliation decreases into the centre and also on tracing the dyke in a north-westwards direction. The schists are often quite fissile and show a distinct mineral alignment of hornblende needles. The plane of schistosity strikes 115°N and dips c.65° to southwest and the mineral lineation plunges to 145°N at about $30-40^{\circ}$, parallel to the mineral lineation found in the gneisses. Passing into the coarser gabbroic textured parts of the dyke this well developed schistosity is lost and a pronounced oblate shape of the feldspar blebs defines the foliation which contains the hornblende lineation.

The numerous gneiss xenoliths present in the meta-gabbro have a parallelogram shape (see Plate II.3) and show a consistent sense of deformation, assuming an original rectangular cross-section. Their shape indicates a dextral sense of plane strain which gives a λ^1/λ^2 range from 4.8 to 6.4 and gives values of γ max of 0.87 to 1.54. These values are taken from central parts of the dyke, the lower values being calculated from xenoliths nearer to the middle. Values for deformation at the margins are much higher. The deformation has destroyed the original shape to such an extent that calculations cannot be made.

The effect of this deformation on differing dyke types is shown well ½ km south of Cnoc Tigh Adhamh where a late dyke, a meta-dolerite, cuts a member of the meta-gabbro set. (See sketch map Fig. II.14). The earlier dyke shows an igneous texture and mineralogy and is only occasionally affected by internal shear zones. The contact between the two dykes (see insert to Fig. II.14) shows the deformation of the gabbro over a narrow zone in a dextral sense, but the meta-dolerite has been sheared across its width into an amorphous hornblende schist. Joints asymptotic to the contact give the only evidence of movement direction of the schist.

The difference in reaction to differential stresses at the temperatures and pressures of the Laxfordian episode must be related to the fine grain size and texture, and/or to the mineralogy (which is related to its bulk chemistry) of the dolerite causing its extreme instability compared to the gabbro.

At Rubh' a Tiompain the marginal homogeneous foliation is cut by well defined narrow shear zones which are confined to the dyke. (See Plate II.6). Where this relationship can be seen, the foliations are labelled S_e (earlier) and S_f (later). The later, S_f, foliation does not necessarily correlate chronologically with S_f of north of Loch Laxford, although both are the result of heterogeneous deformation post-dating a more homogeneous phase. Here, as to the north of Laxford, the characteristic quartz foliation is produced and is visible in thin sections.

The first deformation can and has produced isolated shears in the dykes.

The well-defined shear zones do not have a unique orientation or sense of movement. They are generally near vertical and dip to the south (none have been found dipping to the north). They can be divided into a conjugate set from the bimiodal distribution of orientation and sense. (Fig. II.15).

The major set has an average strike of c.145°N and dips to the S.W. from 90° to 65° and has a consistent sinistral sense. The minor set, with dextral sense of movement, has a strike mean at c. 45°N and dips up to 65°, here to the south east. A small but significant number of shears between the two modes have been recorded, and occur where the zones of shearing change from one set to the other. This would appear to reflect the ductility of the rocks on shearing.

Some of these shears have been traced out of the dykes and cut the gneisses. However, most are seen to be confined to the dykes and where they approach the dyke margins they gradually change direction and run asymptotically into the margin.

The deflection and thinning of the dykes south of Cnoc Tigh Adamh and the rupturing and thinning of the dyke at Cnoc na Carthaige are both in a sinistral sense. The meta-gabbro dyke at Cnoc na Cathaige has not only been disrupted, for isolated boundinage masses of dyke material have been folded along the new gneiss foliation (S_f) planes and have their own foliation (S_e?) folded. The deformation of the dykes in this manner reflects the competence difference of dyke and gneiss during deformation.

The widespread, sinistral, second-phase, Laxfordian movements of high strain along planes striking NW-SE, with an associated minor set striking NE-SW, indicate a regional stress system where the maximum stress (σ_1) was acting in an east-west direction. The earlier phase, of dextral and more ductile deformation appears to have been completed before the onset of the second phase because stresses needed to produce second phase are of a different orientation. The stresses that controlled the first phase cannot be accurately determined but the oblate form of feldspar blebs, the mineral lineation plunging at moderate angles (40^{o}) and the same movement shown by deflected bands in the gneiss at the dyke contacts give an anticlockwise sense on a steep plane (strike c.120^{o} dip 60 to SW) looking east, and a dextral sense on the horizontal plane. The variation in the amount of deformation seems to increase going into the Laxfordian belt and is greater where a strong Sc foliation is present. It is likely that reactivation of Sc foliation was responsible, in which case stresses were acting at a moderate angle to the Sc foliation. To give the sense of movements observed, the maximum compressive stress (σ_1) need to act at an angle to the Sc planes in an approximately North-South direction.

Deformation of the Dykes south of Port Mor.

Deformation of dykes south of Port Mor is extremely inhomogeneous, affecting the margins of the dykes and producing vertical shear zones within the dykes (striking 50^{o}N) on which sinistral movement* has taken place. They show a dextrally

* The sense of movement quoted are deduced from the relationships between the foliations produced by the shear zones and the limits of the shear zone and refer to the horizontal plane only.

asymptotic relationship to the dyke margins. These shear zones may form in line with folds in the gneisses (e.g. at Creag a' Mhail where one or more shears are concentrated in the area where a single gneiss fold is in contact with the dyke) or alternatively, shears may be equally spaced along the length of a dyke unrelated to the late Scourian shears in the gneisses. All dyke margins seen show a marginal zone of foliation.

An unmetamorphosed dolerite south of Sithean Mor shows deformation and metamorphism of its contact to produce a homogeneous dextrally asymptotic foliation zone about 25 cm wide. The contacts show the common relationship of asymptotic foliation to the contact and the use of angular changes in orientation of the contact to initiate shears (sinistral) which extend into the dyke.

The dextral movement of the margins and the sinistral 50^{0} - trending discrete shears are considered to be contemporaneous. Both 'sets' show a degree of vertical movement and their combined effect is to cause a shortening in a N(W)-S(E) direction. Because of this and because of the relationship between the shears and the late Scourian deformation belts (Sc?), these deformations are considered to be related to De and not Df.

A sub-horizontal shear has been seen which indicates a thrust movement to the north west and must represent the effect of the De deformation where there has been no control by Sc.

A vertical shear zone in a dyke south of Sithean Mor is exposed in all three dimensions and the vertical sense of movement is shown. The lineation produced by the alignment of hornblende crystals on the foliation (schistosity) planes, is parallel to the direction of relative movement, which is the direction of principal extension

(Ramsay and Graham 1970). However, an 'apparent' feldspar lineation is often found normal to the movement direction and this is due to the intersection of schistosity, or fracture, planes with the oblate shape of the feldspar blebs.

Scourie to Loch Poll

This area makes up the northern part of the central zone but excludes the Assynt region where dykes are found unaffected by the Laxfordian events. Most of the dykes of this area have been metamorphosed and deformed, but they can be found with remnants of their igneous mineralogy preserved.

The gneisses of this area are granoblastic, banded to varying degrees and generally amphibole bearing, but patchy outcrops of pyroxene granulites are present. (See Khoury, 1968.)

The gneisses are generally flat lying, especially around Loch Glencoul (NC 25-32), and are often massive with poorly developed banding, but range to finely banded types that often show isoclinal folds. South of Glencoul, at Loch Nedd (NC 140 320) and Unapool (NC 238 325), massive sub-horizontal gneisses show possible cross-bedding.

Bowes and Khoury (1968) and Sheraton (1970) on geo-chemical grounds suggest a sedimentary origin for the gneisses of this area.

At any one position within this area, three styles of pre-dyke deformation can be recognised. Where they are found together, one is always isoclinal and intrafolial to the overall flat-lying gneiss banding. This is seen to be folded by the second phase of close to tight asymmetrical folds which are often overfolds, and tend to be intrafolial where deformation of this, by a later phase, is extreme. The third style of folding is a large scale concentric open warping that affects these earlier phases and accounts for the changes in dip of the flat lying bands.

Only at Farhead Point (NC 149 -410) and Cnoc Garbh (NC 220-357) can all three phases be recognised together and be seen to affect each other.

Because of the similarity in fold style and relative ages, the fold phases are coded as in the area directly to the north:

S_a original banding (? often of sedimentary origin)

F_b early isoclinal, intrafolial similar folds especially well shown by basic bands. These folds characteristically show rounded outer surfaces and angular inner surfaces at their closures. Acid bands take up a new, axial planar, foliation, often to such an extent that folding is obscured.

F_c monoclinal to asymmetrical overfolds that are similar in style and overturn generally, but not exclusively, to the north west. This folding is associated with the boudinage of basic bodies.

F_w gentle warping with S.W.-N.E. axial trace.

All dykes within this area cut across these structures.

Six main dyke types are distinguished in the field:

Picrite

Gabbro

Dolerite (Possibly two types, one producing on metamorphism a black rock, the other a green rock.)

Actinolite-chlorite schist, 'green' dykes, (only found metamorphosed)

Noritic dolerite (only found fresh)

Microcline-mica schist.

The order of intrusion is as shown on previous page, except that the age of the 'green' dykes relative to the dolerites is not known. Dykes of both dolerite types cut the gabbros. No evidence on the age of the noritic dolerites or of the microcline-mica schist dykes has been found.

The picrites are of limited occurrence and have only been seen near Unapool. They are thin, usually not more than two metres wide, impersistent and generally cannot be mapped for any distance because their relative ease of weathering causes poor exposure. They have an E.S.E. - W.N.W. outcrop trend.

The gabbros make up the main dyke type. They are generally very wide, sometimes greater than fifty metres, consistantly follow a N.W. - S.E. trend and individuals can be traced across the whole width of the Lewisian outcrop. Their contacts with the gneisses are discordant and vertical, or nearly so. The contact surfaces are smooth and planar and represent pre-dyke major joint planes. The dykes also follow a minor joint set to give rectangular contacts and narrow (10cm to 70cm) offshoots at right angles to the main dykes. Detached gneiss blocks are not seen, but large blocky protrusions of gneiss are often present. The most probable mechanism of intrusion is by dilatation of the major joint set with subordinate use of a near orthogonal minor set.

These dykes show fine-grained margins and may have a narrow, extremely fine-grained zone adjacent to the gneiss. The grain size increases slowly towards the centre after an initial rapid increase.

Many of the gabbros contain non-gneissic xenoliths (average side length c.40cm), often prismatic in shape, but with a gabbroic texture. These are generally more felsic than the gabbro, but more mafic blocks are also found. These are interpreted as cognate xenoliths. Plate 11.7 shows one such block with sharp contacts to its host and containing a felspar-poor material cutting through the block. This pre-gabbro material may well represent the agent that dislodged the xenolith and may therefore be equivalent to the chilled gabbro, i.e. to the initial intrusion material.

Similar fine grained gabbroic material is found at Cnoc a' Phollain an Beithe (NC 092 322) where it forms thin dykes up to 15 cm wide that lie parallel and at an angle to the main dyke (Plate 11.8). These are cut by an offshoot to the main dyke but also form an anastomosing network at the "end" of the outcrop of a normal gabbro dyke. (See Fig. 11.17). It is not considered that these dykelets invaded along a front to produce a xenolith rich dyke at the limit of the intrusion. For the movement of dyke walls on the intrusion of material has not been perpendicular but centred on some point within the area cross-cut by these dykelets. Intrusion was by dilatation, as contacts can be matched. The material which makes up these intrusions is not found unmetamorphosed but, even so, it is possible to see that they had a narrow, fine-grained, chilled margin, now characterised by biotite and pyrite porphyroblasts, that has a sharp contact with a second intrusive material which increases in grain into the centre.

Close inspection of the contact between the gneiss and the first intrusive shows that the initial injection of material, which opened the joints eroded the gneisses.

The gneiss blocks enclosed by the dyke material are often rounded and appear to be losing their gneissosity. This process has presumably taken place by metasomation where there has been enough energy to destroy the shield provided by the chill. It should be noted that almost totally enclosed blocks, found 100m south in the wall of the dyke, are unchanged and that the alteration is confined to the limit of the intrusion.

Because of the age of these dykelets, their geometry, geochemistry and different injection phases, it is believed that they are the result of the primary stages of intrusion of gabbroic material and are associated with a high energy magma state, possibly due to high fluid content.

The dolerite dykes have an undulating east-west trend, are narrow (often less than 4m wide), and are found within gabbro dykes. They are not common and individuals cannot be traced far but have been recognised from many places within this area, notably north of Kylesku Their contacts are parallel and stepped. The steps can be matched, indicating dilatational intrusion. Dyke-gneiss interfaces are sharp and planar, but are often irregular on a millimetre scale as if the magma had eroded into the planar joint surface. The marginal zones are very fine-grained, the centres are slightly coarser, but still fine-grained, and contain a few plagioclase phenocrysts (1 to 2 mm in diameter). No xenoliths have been found in these dolerites.

A one metre wide green, actinolite-chlorite dyke has been noted from Farhead Point, where it clearly intrudes into a gabbro dyke, follows the margin and bifurcates, sending an apophysis into the centre of this body. (See Fig. II.18). The texture and mineralogy of this dyke are completely different from any other dyke type of this area, but are identical to those of dykes found in other areas.

Although only seen folded, the angular relationship of this dyke and the gabbro indicates that the dyke had a nearly N.-S. trend before folding.

The fine grained norites (See O'Hara 1962) are narrow, only

5 metres wide, are completely discordant and have very straight, planar vertical contacts to the gneisses. At Cnoc an Fhir Bhreige (NC 1460 4180), two outcrops of this dyke type have an en-echelon relationship to each other, both trending parallel to the adjacent gabbro, i.e. N.W.-S.E.

The microcline, mica dykes (Peach et al, 1907 p98) are of very restricted occurrence, being found only around Kylestrome (NC 220 345) in small isolated outcrops. Width measurements quoted on the 6" Geological Survey map are 2 to 6 inches and, in one case 4 feet.

The age of these dykes is unknown but they possess a cataclastic foliation and are therefore thought to be pre-Laxfordian.

All dyke sets are discordant, with near vertical contacts which are sharp and generally planar. Concordant intrusion along gneiss banding has only been recorded at one locality. This is at Loch an Obain (NC 168 400) where a dolerite dyke bifurcates, one limb continuing along its normal trend and the other intruding up into the gneiss, which is dipping at about 45° to the N.W. No indisputable evidence has been found indicating that dyke intrusion has been controlled by pre-dyke folds as Khoury (1968) states.

Fig. II.19, taken from the 6" Geological Survey map, shows clearly the dilatational nature of the intrusion into the gneisses. However, branching and change in thickness of dykes in this area is not common.

The whole series of dykes represents the infill of pre-dyke fissures (joints) of differing strike that were successively rendered liable to opening by a varying stress system. All the intruded material shows marked finer grained margins. Field relations therefore indicate that intrusion was into a rigid and relatively cool environment.

Deformation of Dykes

Deformation of dykes has taken place in three main ways; (a) large scale shearing of dykes and country rocks, (b) the overturning of the vertical dykes to the north and (c) the refolding of the structures of (a) and (b).

The least noticeable phase is the overturning of the dykes to lie sub-horizontally. This is seen at Cnoc a' Phollain Bheithe (NC 092 322), Cnoc Garbh (NC 220 357), Cnoc an Fhir Bhreige and possibly at Farhead Point. At each of these four places, overturning has been to the north, or north-east, on a gently south to south-west dipping surface. There is no evidence for the sub-horizontal orientation to have been intrusive, as features of discordant intrusion can be found.

At Cnoc a' Phollain Bheith (See Fig. II.20) a dyke can be traced North-Westwards from Loch Poll, where the contacts are vertical and flat, to a point 250 metres due south of the summit of Cnoc Phollain a' Bheithe where the contacts have become sheared and are dipping at 16° to the S.W.. The overturned section of this dyke can be traced for 750 metres in a north-east direction, the outcrop being repeated by later folding.

Movement has not been exclusively to the north east as a small flat-lying limb at the south west margin indicates a minor amount of south-westerly movement, possibly on a conjugate shear dipping to the north.

The shearing of the gneiss and dyke here appears to have been confined to a zone outside which little or no shearing has taken place.

The reaction of the gneisses and dyke rock to deformation has been that of two rocks of slightly differing competence. For deformation has been greatest at their mutual contacts. The dyke material shows a well-developed foliation parallel to the contacts that decreases into the centre. In a similar fashion, the deformation of the gneiss banding decreases away from the dyke contact and has produced a tight similar fold beteeen two intrusive sheets, (see Fig. II.20b).

The style of deformation is a direct result of the competence difference between the two rock types involved but direct evidence as to which was more rigid is not shown. From other areas, evidence suggests that the thick dyke sheets as a whole acted in a more competent manner, atleast at the onset of deformation.

As already mentioned, this phase produced a good foliation parallel to the margin forming amphibolite schist.

An asymptotic foliation was produced in the dykelets (See Fig. II.17a) and the differing senses shown on the different limbs of this now folded structure is consistent with their production at the time of overturning. It is important to note that there is no associated deformation shown in the gneisses and this indicates that narrow impersistent sheets of dyke material, isolated in large areas of gneiss, acted as a plane of weakness and have taken all the strain.

At Cnoc Garbh (See Fig. II.21) the gabbroic dyke has had a similar history of overturning and repetition of outcrop through folding. Here, as at Cnoc a' Phollain Bheithe, shearing on vertical planes has taken place, but is seen to affect the overturned sections and the foliation produced by the overturning. The horizontal shearing has produced a common foliation of strike 105°N. dip 30° to the South in both gneiss-dyke contact zones.

At Cnoc an Fhir Bhreige, the gabbroic dyke has been folded over to the north by a number of flat lying, tight, asymmetrical folds that often show axial planar foliation (strike 016°N, dip c.25°W.), which corresponds to the plane of shearing. The shallow plunging fold axes strike 62°N. Folded parts of the dyke show that folding of the contacts has been associated with the production of a narrow zone (c. 10 cm) of amphibolite schist from the normally fine-grained chill. The schistosity plane on the lower limb of the folds typically strikes 130°N, dip 20° to the north east, and contain a mineral (hornblende) lineation that plunges almost North-South (174°N). This hornblende lineation is parallel to the direction of movement.

For most of its length the dyke contacts are extremely planar, smooth, vertical and are undeformed and the whole dyke has retained its igneous texture and mineralogy.

The dykes described above and the one at Farhead Point, all from within the northern part of the Central Zone, show structures that overturn to the north on shallow, south dipping planes and produce amphibolite schists at the dyke-gneiss contacts. The schistosity is dominantly planar and may show a hornblende lineation.

Because of the flat-lying attitude of the foliation produced by this deformation, its occurrence has been limited and its complete three-dimensional geometry can only be described by using minor structures produced adjacent to these zones. These indicate that deformation has been confined to isolated zones about which simple translation has taken place, where an upper block has moved to the north relative to a lower block.

The horizontal shearing pre-dates the vertical shearing and is the first deformation that has affected the dykes; it is coded De.

This deformation has occurred after, or during, the metamorphism that converted the dykes into a hornblende-plagioclase rock. Plagioclase laths have been converted to masses of small, normally zoned, recrystallised plagioclase crystals (An_{50-20}), which may indicate that deformation and recrystallisation has occurred during cooling.

The other major Laxfordian effect (Df) is the displacement of dykes by large transverse shear belts. Within this area deformation is by sinistral shear on near vertical planes and has transformed dykes into amphibolite schists. The shears have high strain values and gradients, i.e. deformation becomes intense very quickly across these isolated zones.

Fig. II.22 shows the distribution of these shear belts across the Lewisian outcrop. The major shears deflect and disrupt dykes and this is used to find the magnitude and sense of movement in the horizontal plane of outcrop. Minor shears show the sense of movement by the asymptotic relation of banding (in the gneisses) and schistosity (in the dykes) to the shears.

The effect on gneisses and dykes is generally confined to the shear belts, for only very rarely is deformation found in the areas between major shears. Where D_f has been weak, strain has been more homogeneously distributed and is shown in the folding of gneiss-dyke contacts (where these are at a high angle to the shear movement,) or by the flexure of the geisses at the contact in accordance with the shear movement of sinistral, down to the north. The flexures in the gneisses are considered by Khoury (1968) to have been pre-dyke and to have controlled dyke intrusion. However where ever a dyke is in contact with such flexures (and this is not always the case) the dyke is foliated and metamorphosed at the margins, the central portions retain their igneous mineralogy and texture. Moreover deformation increases in intensity until the whole width of a dyke is metamorphosed and foliated. For these reasons the flexuring is considered to be Laxfordian.

All the major shears are sinistral and strike in a general east-west direction. There is, however, a consistent change in their strike from 075°N to 130°N from the northern to southern limits of the area, where their effect decreases. They all dip between 75° - 80° to the south. A subordinate set of smaller isolated shears are found that strike around north-south and dip at c.40° to the west. Together they form a conjugate set with a dihedral angle of c.118° about σ_3, which is typical of rocks deforming under brittle conditions, see Fig. II.23. The intersection of this set plunges at 50° to the east. The direction of movement, as given by the intersection of the $\sigma_1\sigma_3$ plane and the movement plane, is 40° to 250°N on the major shears, which corresponds to the field evidence showing a sinistral, down to the north movement and almost horizontal in a due north south direction (i.e. with no vertical component) on the subordinate set.

Movement along the larger shears, in the horizontal plane, can be as great as 1.5 km within a zone only 70m wide. Displacement values decrease away from the Laxford front to Loch Glendhu (NC 240 344) where deformation is less intense but more widespread.

The rocks produced during these deformations vary from fissile schists to rocks with isolated narrow planes of slight modification to the igneous original or relic texture of the dyke (i.e, "hot shears"). The schists are not generally lineated but, where they are, the lineation is parallel to the intersection of the two planes making the conjugate set and is not parallel to the movement direction.

Associated with the D_f shearing is the production of quartz. Quartz is not associated with D_e, except as inclusions, but does form a cross cutting foliation in rocks containing S_e, where it is shown by the alignment ocelli. Quartz crystals and aggregates also help to define S_f schistosities.

The very intense shears which characterize the Laxfordian deformation from Scourie Bay to Kylesku are belts of schistose rocks developed from gneisses and dykes and mark planes of ductile deformation, although their geometry and distribution are characteristic of brittle deformation. Within these belts of ductile deformation, e.g., at Loch an Obain (NC 168 400), the dyke rocks have deformed in a competent manner since they have ruptured and produced boudins whereas the gneisses (especially the basic gneiss) have strained without rupture.

Dyke deformation is homogeneous within the shear belts but at the margins of these belts innumerable minor shears may dissect the dyke. The orientation of these shears is not consistent and they undulate leaving "eyes" of undeformed rock in a matrix of amphibolite schist. Such an arrangement well developed at Rubh 'a 'Bhad Choill (NC 1550 4130) (to the South of Badcall) where the shear belt passes through Farhead Point. Here a number of small dextral shears splay out in an East-West direction from the line of shearing in a manner comparable to that described by Chinnery (1966) and ascribed to fracture by axial compression at high shear stress.

At Loch a' Mhuillin (NC 1630 3970) the Laxfordian deformation has been very brittle. The southern contact of the dyke has in places been sheared into an amphibolite schist zone about 10 cm wide indicating a downward movement to the south west on the NNW-SSE vertical contact. Within 50 m from this contact the marginal shearing is replaced by a breccia of rounded pebbles of metamorphosed chilled gabbro in a fine grained matrix of talc, iddingsite and a carbonate, the typical metamorphic assemblage of the picritic dykes. Both the shearing (ductile) and brecciation (brittle deformation) are considered to be the different results of the same phase of movement (during D_f).

These outcrops show how heterogeneous deformation can be and how near this area was to the conditions that would give brittle deformation. Megascopically the second Laxfordian deformation appears to be brittle but mesoscopically deformation seems to be ductile.

Both S_e and S_f planes are found containing quartz veins which have been folded by a third phase of deformation (D_g). It appears, possibly erroneously, that the presence of D_g at any one point is dependent on there having been a fissile rock present prior to D_g. F_g folds are concentric or chevron in style suggesting a boundary slip mechanism of development. Therefore a well foliated rock may well be a pre-requisite for the development of F_g folds.

Unlike the Southern Laxfordian Zone, the third phase of post-dyke deformation here is not associated with mineral growth.

The axial planes of these folds strike east-west, dip steeply to the south and the fold axes generally plunge to the west.

Pseudotachylite veins have been found cutting foliated dyke rocks at Kylesku. The veins are irregular in shape, impersistent, have not been metamorphosed and appear to have been formed in situ. The age of the pseudotachylites has been placed as late Pre-Cambrian for the southern mainland Lewisian by Park (1961) and as Caledonian for the Outer Hebridges by Francis and Sibson (1973). The proximity to the Moine Thrust at Kylesku, and at other localities where they have been found suggest a Caledonian age for these veins.

Within this area, from Scourie to Loch Poll, and from Loch Poll to Strathan, jointing of the dykes is conspicuous in undeformed or unmetamorphosed dykes.

The joint patterns in such dykes are consistent with those due to cooling. There is one set parallel to the margins which is well developed and a subordinate set which lies orthogonally to these. This system is characteristic of the outer zones of the dyke and may be replaced in the centre by a conjugate set whose acute bisectrix lies parallel to the margin.

Joints are almost absent in metamorphosed dyke rocks of this area and this is explained by low strain energy levels of these rocks as all the strain of deformation was absorbed in the recrystallization and the coeval production of a foliation.

At Loch an Obain the joint system of the undeformed dykes has been filled with quartz which in this area has invaded the shear belt before termination of Laxfordian stresses. It may therefore be concluded that these cooling joints were in existence before this shearing. Quartz veining is very uncommon throughout the northern Lewisian outcrop and its post-dyke production here can only be linked with D_f shearing.

Other examples of joints having been in existence before metamorphism have been found at Cnoc a'Phollain Bheith. For here joints have been found filled with green hornblende which cut through unmetamorphosed gabbro and have a one centimetre wide zone of alteration to amphibolite facies. Even more spectacular is the relation of metamorphosed and unmetamorphosed rocks found at the top of Cnoc a' Phollain Bheith, where alternate parallel bands of brown gabbro and green meta-gabbro crop out. The metamorphosed bands are up to 30 cm wide and lie between c.40 cm wide bands of gabbro. Both dip to E.S.E. at 35°. The thick bands are considered to be wide zones of alteration around joints. As metamorphism to amphibolite facies takes place only around these joints, the agent that produced the change must have emanated from the joints. It is considered that fluid transport along the joints from nearby (less than 5m) metamorphosed and deformed areas which show both S_e and S_f foliations, must be responsible.

Loch Poll to Strathan

It is within this area that are found the greatest variety of dyke types and the type area of the Inverian.

Evans (1963, 65) defined the Inverian as a metamorphism that produced a series of amphibolite-facies rocks from a pre-existing granulite-facies assemblage; that was synchronous with or post-dated the intrusion of a set of pegmatites (Type 1) and that predated the intrusion of the dykes. The Inverian folding, which is cut by the dykes, occupies the same position in time and space.

Evans states : "isotopic dating of these intrusions (Type 1 pegmatities and the dykes) show that they were separated by a time gap barely detectable by present day techniques". The isotopic ages obtained from the pegmatities are 2.20×10^9 years and from the dykes 2.15×10^9 years, which leaves a time gap in the order of 100 million years in which the Inverian metamorphism could have taken place. However this time difference of 0.05×10^9 years is insignificant in relation to the experimental error and to the spread of the dates ($\pm$ 0.04×10^9 years) for each event.

The Inverian metamorphism converted the pyroxene and hornblende-granulite gneisses into amphibolite gneisses with the production of a new texture. The most marked change in mineralogy and the texture coincides with the most intense Inverian deformation which has formed steep belts which strike across the outcrop in a WNW-ESE direction. These are typified by the Canisp Shear Belt and the Strathan Line.

Gneisses of this area range from massive pegmatoid masses and poorly banded massive gneisses to well banded folded gneisses in areas of Inverian assemblages. The massive gneisses contain large lenticulate bodies of ultrabasic material (pyroxenites in Scourie, hornblendites in Inverian and Laxfordian areas) and meta-gabbros, and smaller boudins of these materials. These bodies have been folded and the boudins flattened from an originally blocky or near-spherical shape in areas of Inverian deformation.

Pre-Inverian structures are rare but are found to be isoclinal folds in Inverian refolded areas. Large scale Inverian structures,open NW plunging folds, are cut off by the Canisp Shear belt. These folds can be seen to fold shallowly dipping banded rocks at Badnaban (NC 081 209), and at Port na Alltan Bradhan (NC 054 260) where they, (F_b), fold early isoclinal closures (F_a) and are associated with cuspate folds. (See Plate II.9).

Inverian folds are characteristically tight and have a NW-SE striking axial planes that are steeply dipping to the north-east. These folds are cut by dykes.

The Canisp Shear Belt, the type Inverian, that has been modified by Laxfordian deformation deserves detailed description.

Because of the Laxfordian deformation unmodified Inverian structures are difficult to find in the centre of the belt. The belt is bounded to the south by the Lochinver anticline and marks the position of a synformal structure, as rocks to the south and north dip into the belt and gradually increase in dip (See Fig. II.24). The rate of change of dip with distance is higher in the north. The southern margin is characterised by an increasing number of geniculate folds, that step down to the north, until the gneisses dip sub-parallel to the steep limbs of these folds. The folds change in style and become tight to isoclinal and have steep (c.80°) south-westerly dipping axial planes with shallowly eastward plunging axes. The fabric of these intensely deformed Inverian gneisses is planar without a distinct mineral lineation. Randomly oriented hornblende needles lying on the gneissosity planes often characterize the Inverian deformed rocks. A schistosity, rather than a gneissosity, is often developed in the hornblendites and in black biotite schists. A coarse pre-Inverian gabbro on the northern edge of the belt has been deformed to give a mild foliation.

Minor folds are rare and where seen are parasitic to large Inverian folds on the edges of the belt.

The chronology of dyke intrusion given by Tarney (1963) is in general agreement with relations shown on the 6" Geological Survey maps. However, inspection of critical areas found dyke/dyke contact exposure poor or non existent. The relationships of the picritic and epidiorite (meta-gabbroic) dykes on these maps show the picrites to be both pre-gabbro (NC 175-225), and post-gabbro (NC 151-225), see Fig. II.25. Relationships similar to those reported by Bridgwater and Coe (1970), where one dyke protrudes into, but does not cut, another, suggests that the gabbros were stoped into by the picrites. However, there is no evidence that the picrite intrusion was by stoping and it is therefore suggested that the gabbros were intruded after the picrites, but before total consolidation. If this was so the picritic magma would be able to move into the space made by the extension due to gabbro intrusion.

Major rock types found as dykes include picrites, gabbros (and meta-gabbros), norites (metamorphic equivalent not recognised), olivine gabbros and dolerites (meta-dolerites) with or without plagioclase phenocrysts.

The complete intrusion history, as far as can be determined is as follows:-

1) Mela-diorite (andesine dolerite) trend ENE-WSW
2) Picrites (including peridotites) trend ESE-WNW and olivine gabbro of Badnaban.
3) Gabbros (trend NW-SE)
4) 'green' actinolite - chlorite dyke trend SE-NW (unmetamorphosed equivalent not recognised)
5) Dolerites, with or without phenocrysts (trend NW-SE or E-W) and the norites (trend NW-SE) - those have an uncertain age.

The outcrop trends given for the various dyke sets are their average, for their trends are variable but the mutual relationships of one area are the same, e.g., the picrites always lie nearer to due east-west than the gabbros.

The gabbros and norites show a decrease in grain size to the contacts and extreme chilling at the contacts. In the centre of a norite veins of pegmatoid norite have been found. The dolerites also have finer grained margins and their contacts are glassy, show flow banding and contain rounded gneiss and gabbro xenoliths under a microscope. The 'green' actinolite dyke has only been seen with its metamorphic mineralogy but shows remnants of a coarse igneous texture.

Any change in grain size has not been observed because of its metamorphic mineralogy.

The contacts of the picrites are invariably not exposed but there is a variation in grain size which is characterised by the increase in size of pyroxene crystals to the centre, but all picritic rocks are coarse grained.

All dykes, except the dolerites and the meta-dolerites which are about 10 metres wide, are of a similar width, i.e. 20-50 metres. Most dykes can be traced across the width of the Lewisian outcrop and only a few are seen to end.

The thin dykes are rare and of the thicker dykes the 'green' dykes and the norites are the least abundant followed by the picrites, the gabbros being the commonest.

All of the dyke types are more abundant just to the north of the Canisp Shear Belt.

Poor exposure of the mela-diorite, picrites , norites and 'green' dykes excludes detailed description of their intrusive morphologies. All that can be said is that they are large bodies that have parallel sides, do not contain xenoliths, maintain their intrusive widths and have probably been intruded by a dilatational mechanism.

The abundant gabbros (and meta-gabbros) provide enough outcrop for a more detailed discussion of their intrusion. They, as a set, have a well defined consistent NW-SE trend. They sometimes branch, but the branches quickly return to the NW-SE trend.

Dyke contacts are planar, straight, and discordant, cut across Inverian folds and other earlier structures, and follow orthogonal (i.e. NE-SW) joints for short (c.50 cm) distances.

However, where pre-dyke foliations are well developed the intrusion may follow them for short distances. A section of unmetamorphosed and undeformed dyke at Leathad an Lochain (NC 076 206) is concordant to a zone of fissile schists (sheared gneisses) striking 100°N (Inverian), whereas the rest of the dyke has a NW-SE trend which cuts through NE-SW folds and NE-striking gneisses. A similar example of local control is shown at Poll nam Muc (NC 152 254) where an undeformed gabbroic dyke runs east-west and still shows many discordant and irregular blocky contacts. The reason for this abnormal trend is again the presence of strong E-W pre-dyke shearing which has been faulted after dyke intrusion.

The best developed control of intrusion by pre-dyke foliations is found within the Canisp Shear Belt on the north side of Achmelvich Bay (NC 05 25) where the steep ESE-WNW striking isoclinally folded gneisses are concordantly intruded by gabbroic dykes. The northern contact of one dyke faithfully follows the banding of the gneisses. The southern contact is also concordant to the gneissosity but steps across it using vertical joints which are perpendicular to the Inverian foliation. The result is that the dyke thins going westwards until it dies out. The stepping across the foliation is interpreted as an attempt to keep the intrusion parallel to the trend of dykes outside the shear belt, and would therefore produce an en-echelon outcrop of dykes around the Canisp Shear Belt.

The gabbros contain many cognate xenoliths which are more felsic, or in some cases more mafic, than their host. Their sides are smooth and sharp and suggest that they were rigid and fully consolidated when they were prised off. At the contact of a large (9m x 3m x 4m +) xenolith the minerals of the gabbro alone are aligned to show a faint foliation which runs asymptotically upto the xenolith. This sense of movement indicated is of the felsic xenolith moving downward relative to the host. This is the result of the last sinking movement of this large block in the crystal mush of the gabbro just prior to total consolidation. Another xenolith, with a flat lying oblate shape, has accumulated feldspar crystals on its upper surface in excess of the normal content of the gabbro. This points to feldspar settling during the early stages of crystallization.

The dolerite dykes show extreme irregularity of their contacts. These dykes have a generally NW-SE trend but may have a near east-westerly trend which only locally show control by pre-dyke shear zones.

At Bealach Lochan Mhic Leoid (NC 1510 2525) parallel minor dykes combine to form the main dyke and are connected by thinner dykelets (See Fig. II.26). This shows well the use of the major NW-SE joint set and the minor N-S set which are also intruded by the gabbro dykes. On tracing this dyke into the area of E-W shearing, the minor set becomes more important and the dyke outcrop swings to become north-south before entering the shear. The contacts of this section are very irregular, blocky and eroded because of the almost equal use of two joint sets before the N-S set became dominant. Xenoliths are not found, except for the small rounded gneiss masses in the glassy chill.

These dolerites contain feldspar phenocrysts that are few in number and are widely scattered throughout their matrix.

The dolerites, like the gabbros, have a dilatational origin using the same joint sets and the E-W foliations but as elsewhere the stress controls on the resultant trends are much weaker.

<u>Deformation of Dykes</u>

The deformation of the dykes is generally associated with metamorphism. However, at Cnoc a Mhuilin (NC 086 203) a system of joints has been formed in unmetamorphosed gabbro. These joints (see Fig. II.27 and Plate II.10) are short, have an open 'Z' form and are closely spaced. They lie in bands that vary in trend from ENE-WSW to SSW-NNE but generally lie N-S. The sense of kinking is sinistral.

These joints may have been caused by the release of strain energy imposed in these rocks during the phase of deformation that produced oblique shear zones in metamorphosed dykes.

All other deformation of dyke material has been accompanied by mineralogical changes. In many cases metamorphism is only confined to zones of deformation, the undeformed material retaining its igneous mineralogy, in others it is pervasive, altering dykes whether deformed or not. Alteration produces amphibolite schists or epidiorite from the gabbros and dolerites and talc schists from the picrite dykes.

Extreme Laxfordian deformation occurs in areas that have undergone intense Inverian deformation. Deformation is generally weak but is present over the whole of the north of the area. The limit of metamorphism of the dykes is poorly defined but appears to run east-west through Lodge Assynt to Clashnessie, the dykes south of this line being unmetamorphosed if undeformed.

Production of a foliation may be best developed in the picritic dykes that produce a "soft" talc, actinolite schist from the whole width of the intrusion. Metamorphism again appears to be closely related to deformation since a picrite dyke that has retained its igneous features has joints that have been altered in a zonal manner with talc, actinolite and quartz (Plate II.11). This mineralogy is the same that is developed in the sheared picrites but here must have been produced by fluids emanating from the shear belt.

Thin section inspection of altered picrites suggests that the growth of new minerals began before shearing, with olivine being the last to recrystallize, and continued for some time after shearing had stopped.

Deformation features can be best studied in the gabbros because of their abundance, good exposure and distinctive coarse texture.

Outside the Canisp Shear Belt, deformation is confined to narrow marginal zones (c. 50cm wide) of asymptotic foliation that indicated a north side down and dextral sense of movement that is mirrored in the deformation of the contact gneisses. The zone of affected gneisses is roughly as wide as the zone in which the dykes are foliated. Occasionally shear zones cut across the trend of the dykes and have a sinistral sense of movement.

The gabbro dykes on the north side of Achmelvich Bay shows well how deformation varies from within to outside areas of Inverian deformed rocks.

Here, to the south of the Canisp Shear Belt, a gabbro dyke shows how a single dyke can react differently to a single stress system in a small area. The intrusion is 16 to 20 metres wide and the contacts are straight and planar, although rectangular deviations are characteristic which result from the use of the minor joint set. The dyke contains many feldspar rich cognate xenoliths and shows a gradual increase in grain size away from the contacts, the majority of the increase being realized in the first 2 metres. The dyke was intruded through shallowly dipping, gently warped gneisses that show intrafolial isoclinal folds.

Zones of strong shearing of the gneisses flank the dyke see Fig. II.28. These zones, which are about $1\frac{1}{2}$ metres wide, are of recrystallized schistose gneisses that have been deflected into parallelism to the contacts of the dyke. The deflection of the gneissose banding, which is not destroyed, indicates a dextral movement in the horizontal and a north side up-south side down movement in the vertical. The dextral displacement in the horizontal plane is the greater. The lineation produced in the schistose gneiss is normal to the movement direction and is parallel to the axis of folding.

The deformation of the gneiss is confined to the dyke contacts and is not found in areas outside the centre of the Canisp Shear Belt.

The control of the dyke/gneiss contact as an initiator of strain is shown well at the north contact of this dyke (see Fig. II.29). Here the dyke contact steps by about 3 metres to leave a number of 'hanging' xenoliths. This abnormal intrusion path has provided a number of near vertical contacts which are parallel to the major contacts. All these planes are sheared and deformation passes from them following the major contacts into the dyke.

The deformation of the dyke along its length shows a great variation in style, whilst the style and degree of deformation of the gneisses does not. For most of the length of the dyke strain has been taken up in the formation of a mild foliation shown by the modification of the ophitic texture. This foliation is present for about 3.5 metres from both contacts, but the exact limit is difficult to locate.

The foliation has a dextrally asymptotic relationship to the contacts. The foliation furthest from the contact is at about 26° to the contact (shear strain γ of c.1.0) and is about 10° - 15° near to the contacts (shear strain γ of c. 3.5-4.5) which represents a shear gradient of just over 1 per metre. These values show that the centre of the dyke has moved, relative to the point on the contact by about 10 metres. Therefore taking both contacts and assuming that the contacts were at the exact centre of the marginal shears, then the gneiss to the north of the dyke has been moved to the east by about 40 metres relative to the gneiss to the south.

Along the length of the dyke the style of deformation changes. The marginal foliation zone decreases in width and the strain is taken up in narrow, high strain, sinistral shears that cut across the width of the dyke. Very few shears are present in the centre and individual shears cannot be traced across the whole width but occur on both sides of the centre. The number of shear zones increases towards the contact but individual shears do not show any change in amount of displacement along their length. As the shears approach the contact they slowly change in trend and merge to form a zone of highly deformed amphibolite schist, approximately 30 cm wide, adjacent to the gneiss. Due to the increase in number of the shears and to their change of attitude, the area of undeformed dyke between them rapidly decreases and individual shears wander, merge and cross each other to leave elongate eyes of undeformed dyke rock.

The gneiss in contact with the dyke shows the same amount of dextral deflection and the shears, like the 'mild' foliation, approach the contact dextrally, but the isolated transverse shears have a clear and constant sinistral sense of movement.

Since these shears replace the more homogeneous deformation they are considered to be coeval and to indicate optional deformational styles which are not dependent on the orientation, composition, or texture of the dyke nor on the structural position as these do not vary.

In the centre of the Canisp Shear Belt, where Laxfordian deformation has been much greater, the dykes continue to show both styles of deformation. Where a dyke has deformed to give a homogeneous foliation, the foliation is more intense and pervades the width of the dyke. Sections of dykes that are deformed by shear zones now show dextral shears that are sub-parallel to the dyke contacts, and are slightly asymptotic to the contacts in a dextral sense. The orientation that they take up is the natural one of maximum shear stress and again they show marginal deflection.

These shears are generally dextral but conjugate sinistral shears are occasionally found. They are ubiquitous and intersect (even when all are dextral) to leave large eyes (c. 4m x 0.7m) of undeformed dyke rock. Their strike is about 115°N (ESE-NNW) which is sub parallel to the dyke contacts and they show low-plunging hornblende lineation (14° to 115°N).

Both styles of deformation are accompanied by the deflection and shearing of the contact gneisses. It is important to note that where dykes are not present in the centres of the Canisp Shear Belt the gneisses have been intensely sheared in belts 2-10 metres wide.

Therefore it would appear that the Laxfordian shearing has been concentrated in zones of strong Inverian folding where the pre-dyke attitude of the gneisses was near to that of the final Laxfordian foliation. Within this area, i.e. the Canisp Shear Belt, the deformation has been focussed on the gneiss/dyke surfaces and only if these are not present has deformation been confined to the gneisses.

In contrast to the gabbro dykes the picrites have been deformed to very soft and fissile actinolite-chlorite-carbonate schist across their widths. The difference in degree of foliation and pervasion must be due to differences in chemistry and therefore mineralogy. The occurrence of carbonates may point to the presence of a fluid phase during metamorphism which would weaken the rock and tend to 'lubricate' deformation. Because of the mobility of such fluids they would move from areas of deformation and possibly weaken undeforming picrite areas and thus cause the wholesale alteration of the picrite dykes.

It is within the metamorphosed picrites that a second phase of Laxfordian deformation is shown as the folding of the schistosity in an almost chevron style. This folding is with coded Dg as it folds an earlier Laxfordian foliation.

As the shearing is dextral (with a minor sinistral conjugate) and not associated with a foliation that contains quartz it does not appear to be linked with the Df deformation found to the north. Its movement direction (dextral with north side down vertical movement) is similar to the movement associated with De deformation found to the north of Scourie Bay, where there has also been the development of strong pre-dyke vertical structures (? Inverian). Deformation of the dykes of this area is therefore assigned to the first Laxfordian deformation, De.

<u>Area around Gruinard Bay</u>

The area investigated lies to the south of the Gruinard River and includes the northernmost limit of the Laxfordian effects on the rocks of the Southern Zone. It has been recently described by Crane (1973).

<u>Pre-Dyke History</u>

The country rock to the dykes is rarely banded nor does it show a good penetrative foliation. 'Xenoliths' of banded gneisses are occasionally found in the host gneisses which are generally granitic, or granodioritic rocks. A pre-dyke metamorphism has produced agmatities from these rocks and masses of basic rock (now hornblende-plagioclase-biotite schists) to produce a coarse two- feldspar, biotite quartz neosome and an amphibole (hornblende) rich palaeosome. This process has led to the production of large tracts of outcrop of rock which is mainly feldspar and quartz in which there are innumerable rounded pods of basic (hornblende) material. Crane (1973) shows that this rock has a folded outcrop pattern.

Within the area investigated, besides the locally preserved banded gneisses, foliations in the gneisses are almost non-existent except for a sparsely developed penetrative foliation which postdates their agmatization origin. This area provides a "control" in assessing the extent to which the pre-dyke foliations controlled intrusion.

Little or none of the rocks of this area have escaped metamorphism during the Laxfordian episodes, as all the dykes now possess a metamorphic mineralogy and texture. In this respect they closely resemble the dykes found in the central zone, and especially in the area from Loch Poll to Scourie and around Lochinver.

Despite their metamorphosed nature relict textures in some cases are well enough preserved to compare the dyke types with those of the central zone. Three dyke types have been recognised.

1) Meta-gabbros (coarse grained relict textures, green in colour)
2) Meta-dolerites (fine grained relict textures, black to greenish black in colour, often with phenochrysts)
3) Actinolite-chlorite rocks(seldom foliated)

The age relationships between dyke types are as follows:

1) Actinolite-chlorite rock (the 'Green' dykes of the Geological Survey) trend NW-SE to NNW-SSE.

2) (or pre-1) 'Early' meta-gabbro. The 'early' meta-gabbro is indistinguishable in the field from the 'later' meta-gabbro but is seen to be cut by it.

3) Meta-dolerite, trend in two sets NW-SE and NNW-SSE. (Cuts 'early' gabbro)

4) 'Late'-meta gabbro strike NW-SE. (Cuts dolerite)

The actinolite-chlorite dykes are poorly exposed due to their soft nature. Mapping shows that they are variable in width, ranging 2 metres to over 50 metres, and in trend, although individual intrusions maintain their width and trend. Variations in grain size, i.e. chilling, or mineralogy have not been seen due to their poor exposure and intensive recrystallization.

The fine grained dolerite dykes vary greatly in width from 1 metre to over 50 metres and outcrop in a conjugate set, which apparently are not mutually cross-cutting. Those which trend NW-SE (parallel to the outcrop of the meta-gabbros) are wider than those which trend NNW-SSE. They may or may not contain phenocrysts. In many cases they form the outermost part of a multiple or composite dyke, the inner part being formed by the later meta-gabbros.

At Torr Morr (NG 9565 9130), Can Na Criche (NG 9555 9047) and at NG 9770 8757 members of the dolerite set of dykes are found in contact with gneisses on only one side of a gabbro intrusion. The contact between the meta-dolerite and the later meta-gabbro are often transitional whereas these dykes have chilled margins against the earlier meta-gabbros.

At Can Na Criche a 15m wide intrusion of meta-dolerite (phenocrystic) is in contact with the south side of a 40 metre meta-gabbro. The contact is gradational, the dolerite becoming richer in feldspar phenocrysts, but can be determined to fall within a metre wide zone. Because of this asymmetrical relationship, it is considered that dolerite intrusion was much wider and that the gabbroic material has 'digested' a proportion of the dolerite intrusion, i.e., at least the northern contact. Fig. 11.31,(NG 9770 8757), shows a meta-dolerite occupying the eastern marginal zone to a multiple dyke, of early and late gabbro, and its contact relationship shows that it has intruded into the 'early' gabbro and that a second intrusion of gabbroic material ('late' gabbro) has stoped off dolerite and gabbro to leave such a complex outcrop. It must be pointed out that the dolerite chills asymmetrically against the enclosing gneiss and early meta-gabbro, being coarser against the gabbro. Thus the gabbro was still a heat source at the time of intrusion of the dolerite.

These dolerite dykes are fine grained containing only few small phenocrysts of feldspar, if any, at their margins and show a slight increase in grain size and in phenocryst content to their centres. Only at Can Na Criche has their grain size and appearance approached that of the meta-gabbros.

Xenoliths have not been found and this together with other evidence suggests that intrusion was dilatational into a conjugate set of fractures, the NNE-SSW set being more numerous but the NW-SE set containing the greater volume per dyke of doleritic material. This suggests that the availability of previously formed fracture planes was balanced against the prevailing stress system acting on intrusion, i.e. NW-SE vertical fractures lying nearer to the $\sigma_1\sigma_2$ plane although being less common. The meta-dolerite-gneiss contacts were used for the intrusion of the later gabbroic material and the outcrop pattern at Can Na Criche suggests that this was not long after consolidation of the margins of the larger dolerite dykes.

Once again the larger and more common gabbroic dykes offer more information for study, although the 'early' and 'late' meta-gabbros cannot be distinguished in the field.

They are very wide, often 85 metres or more, have straight parallel contacts that are steep (vertical or dipping 70° - 80° to the SW or NE) and may be in contact with meta-dolerites to form multiple dykes. The 'late' meta-gabbros cut across meta-dolerites and the 'early' meta-gabbros.

Few irregularities of contacts have been observed. One dyke, at NG 9760 8785 divides into three branches to leave two lenses of enclosed gneiss. One of these lenses is cut by innumerable small dyklets that trend 114°N and are made up of fine grained gabbroic material. Their average width is approximately 5 cm and thirty have been counted cutting an outcrop only 3 metres wide. Their 114°N trend is parallel to the wider meta-dolerites suggesting that between the time of intrusion of the meta-dolerites and the 'late' meta-gabbros, the priority between the two intrusion planes, i.e. NW-SE and NNE-SSW, has been reversed.

100 metres south of this outcrop, see Fig. II.31 the gneiss/ meta-dolerite/gabbro (later) relationships show that a degree of stoping of the meta-dolerite must have taken place by the late gabbroic intrusion. Perhaps a degree of stoping may be characteristic of the late gabbroic intrusions.

Xenoliths in the gabbroic dykes are common, although they are more common in some than in others. Rock types distinguished are acid and basic country rock and more mafic and more felsic dyke rock (possibly cognate xenoliths or possibly 'early' meta-gabbro in 'late' meta-gabbro).

Some gneiss xenoliths have a narrow band of mafic minerals (now hornblende) around their bottom surfaces, but not on their sides or tops, and are enclosed by the normal dyke rock. From this it is thought that the xenoliths were sinking through the magma and collected crystals present at that time on their under surfaces. These crystals are thought to have been pyroxenes.

There are also large feldspar rich gabbroic 'xenoliths' as well as large 'xenoliths' of feldspar-poor gabbroic material. These bodies have an orthorhombic shape and are flat lying. Typically these masses are greater than approximately 60 m^3 (i.e. 6x3x5: metres).

A number of these volumes show horizontal igneous banding (see Plate II.12) which is associated with the second phase of intrusion of gabbroic material.

The large gabbroic xenoliths may be detached masses of the 'early' meta-gabbro in the 'later'. But if igneous banding is confined to the second intrusion these feldspar rich, feldspar poor or banded masses must represent cognate xenoliths of the second meta-gabbro or spaces in the first gabbro infilled and probably cut by the second phase. As horizontal banding has been found in situ it strongly suggests that these volumes are indeed undisturbed masses of the 'later' meta-gabbro within the 'earlier'. If this is the case it helps to explain the banding as the tunnels and shelves cut by the second intrusion which would provide areas where quiescent conditions could be maintained to allow the solidification and sedimentation of crystal phases without interference. With such conditions and with a steady current the banding could have been produced.

All the dykes of the Gruinard River area have been completely recrystallized during metamorphism but also they all conspicuously lack any degree of foliation. Thus it can be assumed that the Laxfordian episode was essentially a metamorphic, non deformational event in near hydrostatic pressure conditions.

From Loch Maree to Gairloch

Pre-Dyke History.

Areas investigated in this region of the mainland are those around Loch Tollie (NG 840 785), Creag Mhor Thollaid (NG 86 77) and Sithean Mor (NG 812 716). The pre-dyke history of each of these areas is far from obvious.

Loch Tollie

The structure of the Loch Tollie area has been described by Clough (1907a) and Park (1970b). At Loch Tollie the gneiss banding and the dykes form a non-cylindrical antiform which dies out to the south east. Park considers two models to explain the geometry of the dykes. In the first, the gently dipping dykes of the central part of the antiform are interpreted as having been partly dragged and partly flattened into their present position. In the second the dyke intrusion is envisaged as taking place when the banding was already in a sub-horizontal orientation and that magma followed low lying bands and cut across them vertically to climb the south in a step-wise fashion. Subsequently (Park & Creswell, 1972, 1973) the second model was preferred.

Pre-dyke deformations of the gneisses of the Tollie Antiform are those to produce intrafolial isoclines (Db) and the tight folding of banding and Fb folds (Dc). Both Fc and Fb axial planes are now shallowly dipping to the North East. These correspond to D_2 and D_3 of Park (opcit.)

Creag Mhor Thollaidh (NG 86 77)

/This area is described by Clough (1907), Park (1970b) and referred to by Park and Cresswell (1972, 1973) as showing special dyke intrusion relationships to pre-dyke deformation structures.

It consists of an isolated fault bounded block of high ground to the north east of Loch Tollie. Because of this and its complex history it cannot be directly related to the surrounding areas.

The gneisses are generally acid and show varying degrees of banding with their main mineral constituents being quartz, plagioclase and hornblende. Large masses of basic material, now hornblende rich with minor plagioclase, biotite and quartz, are also found. These large masses form part of the pre-dyke gneiss complex, some are massive and agmatized by quartz-plagioclase veins, whilst others have been foliated, folded and boundinaged. The origin of these bodies is not obvious, but in all cases they are discordant to the gneiss banding and represent a phase of Scourian basic intrusion that was at latest pre-D_c.

The dominant structure of this area prior to the intrusion of the 'Scourie Dykes' appears to have been a NNW-SSE striking foliation in the gneisses dipping steeply to the east. This foliation contains isoclines, (Fb), that refold earlier isoclines (Fa?). Where the later folding, Fb, has not affected the rocks relict areas of gneisses with Sa foliation are seen. The present orientation of Sa is E-W and steeply dipping. The E-W striking Sa and the NNW-SSE striking Sb describe large geniculate folds.

Fa corresponds to F_1 and Fb to F_2 of Park (1970b).

Superimposed on these folded gneisses is a fold phase of high intensity folds, (Fc), that is locally developed. This folding produces areas of intensely plicated rocks with a penetrative foliation that strikes WNW-ESE and dips to the south.

Da, Db have only folded an earlier gneissosity but Dc has produced a new foliation, Sc. Dc probably corresponds to D_3 of Park (1970). Similar structures were described by Crane (1973) in the area directly north west of Creag Mhor Thollaidh and are assigned to the Inverian.

Sithean Mor (NG 812 716) This area comprises folded acid gneisses and amphibolite schists that strike NW-SE and dip steeply to the north east. The schists are considered by Park (1964) to have been basic lavas or intrusives. Both rock types are tight to isoclinally folded, and with fold amplitudes of c. 15m. The acid rocks are poorly banded and contain few basic bands.

These folds that are cut by members of the 'Scourie Dyke' suite and are considered by Park (1970b, 1973) to be of Inverian (ID_1) age. The style of folding and the local development of a new foliation of this deformation is similar to the Dc structures of Creag Mhor Thollaidh and the Tollie antiform.

The dykes and their deformation in the area from Loch Maree to Sithean Mor

Within this area the main dyke lithologies known from other areas can be recognised, but cross cutting relationships between the dyke types have not been found.

The types distinguished are 'normal' (meta) gabbro which are biotite rich at Loch Tollie, banded (meta) gabbro, 'green' actinolite dykes, (meta) dolerite and banded ultra-basic dykes which are similar to the banded picrites. The dolerites are black, fine grained and include the scapolite rich dykes at Creag Mhor Thollaidh.

Dykes of Creag Mhor Thollaidh

The dykes of Creag Mhor Thollaidh (see Fig. II.32a) are generally discordant to the gneissosity or schistosity but minor control of intrusion by pre-existing foliations exists, e.g., Fig. II.32b The intrusion fissures appear to have been mostly joints, e.g., Fig. II.32b,A. and faults, for the dykes often mark boundaries between areas of differing structural histories. Intrusion is thought to have been dilatational.

The small intrusions that are found in the N.E.-S.W. zone do not significantly differ in their relationships with the gneisses. They are discordant by 20° and show only minor use of gneissosity planes for intrusion, see Fig. II.32c.

The gneisses within this belt are not noticeably different to those nearby, except that metamorphic crystallization has been granulitic in nature and post-dates a phase of deformation that has deformed and boudinaged the pre-dyke agmatized basic bodies. Both the basites and the dykes have been recrystallized and now possess granulitic textures that may describe a faint foliation. As this phase has affected the dykes it must be of Laxfordian age. The foliation produced in the dykes is parallel to the dyke-gneiss contacts but the already foliated basic bodies have become highly plicated. The folds are chevron in style and have vertical axial surfaces that strike N.E.-S.W. The dyke foliations are parallel to the contacts which lie in the unusual N.E.-S.W. trend.

Park (1970) considered that the N.E.-S.W. zone existed prior to dyke intrusion since there was no evidence of rotation of the pre-dyke foliation. However the writer believes that the presence of anomalous N.E.-S.W. trending dykes and dyke foliation, together with the gradual loss of this foliation as the trend changes to N.W.-S.E., indicates that the change in trend is due to post-dyke deformation.

The outcrop pattern of the dykes, gneisses and basic bodies can be explained by Laxfordian simple shear along a N.E.-S.W. trending zone. The sense of movement is dextral, which is shown by the deflection of trend going from N.W.-S.E. at Tollie Farm to N.E.-S.W. and back to N.W.-S.E. on Creag Mnor Thollaidh. This zone is assigned to the first post-dyke deformation of this area, De and ante-dates two other deformations.

The movement direction (a) of this shear has been calculated to plunge by 70° to 070°N in a plane striking 025°N dipping 77° to S.E. using the variation of L_c in this zone (Ramsay 1966). There is a large vertical component, as shown by the plunge being steep in the shear, and the sense of movement of down to the south-east is shown by the change in the south plunging antiform between Sc and Sb which has been 'opened' by the movement within the shear zone. Metamorphism continued after the D_e deformation to produce the metamorphic assemblages found in all the dyke rocks and the recrystallization of the gneisses of the N.E.-S.W. shear zone.

Later metamorphism and deformation occurred together. The fold phase Fg characteristically produced a quartz lineation parallel to fold axes and is especially noticeable in the De deformation zone. The folds are concentric in style and often cuspate at dyke-gneiss contact indicating that the dyke was more competent. Occasionally an axial planar foliation has been developed. These Fg folds are found on all scales, plunge to the E.S.E. by 60° and have near vertical axial planes. They correspond to F_4 of Park 1970b, i.e., the second Laxfordian deformation, LD_2 (Park 1973).

The shallow north-east dipping orientation of the gneisses and dykes, due to D_f, seen in the south-west corner of Fig. 11.32 provide a link between Creag Mhor Thollaidh and the Tollie Antiform across the Allt an Leth-chreige Cush Belt (between NG 860 776 and NG 862 771).

Dykes of the Tollie Antiform

Within the Tollie Antiform the dykes commonly possess a strong foliation. The gneisses record at least two pre-dyke phases of folding (Fb & Fc) and now the dykes, F_c folds and S_c in the gneisses now lie with a shallow north-easterly dip at Loch Tollie.

Dykes are generally seen to be discordant to the flat lying gneisses (See Fig. 11.33). They are thin, their width being now less than 10m and are less frequent in the south-west part of the fold. The overall parallelism of the dykes to S_3 (S_c), thickness and branching was interpreted by Park and Cresswell (1972, 1973) to be due to structural control by the pre-existing foliation. Although a degree of control has been exercised by S_c foliation on the intrusion of the dykes, the mechanism of intrusion was similar to that proposed for other areas discussed, i.e., dilatational emplacement along fractures that are not necessarily parallel to the S_c foliation.

The dykes now possess a granulitic metamorphic texture that is typically rich in biotite grains that lie parallel to any foliation present. The dyke rocks are not always foliated but where found the foliation is generally found at and parallel to the contacts. However, the foliation may run asymptotically to the contact from further in in the dyke where it is nearly horizontal. See Fig. 11.34 A,B,C.

Both marginal and central foliations contain a lineation that plunges at low angles to the south east.

This sub-horizontal foliation is thought to take up the orientation of maximum shear while the marginal foliation shows the effect of flexural slip along the plane of competence difference of the gneiss dyke intersurface. The foliation is not associated with any deflection of the gneissosity, suggesting that, at the pressure and temperature conditions prevailing during deformation, the gneisses were relatively rigid.

The deflection of the dyke foliation up to the dyke-gneiss contact (Fig. II.34) suggests that flexural slip was due to the upper surfaces of the dykes moving to the south or west relative to the lower surfaces.

It is this deformation that may have led to the limited formation of early Laxfordian folds, for minor recumbent folding of dyke-gneiss contacts are seen. It is believed that the deformation associated with the development of this foliation had the overall effect of deforming vertical dykes and gneiss foliations into a general moderately north-east dipping attitude (see Fig. 11.35) and causing attenuation. This is as proposed in the first model of Park 1970b.

If this interpretation is correct, this phase of low angle shearing is comparable with the D_e phase of the northern part of the central zone, but is geometrically the mirror image of it. For here deformation has been 'up and over' to the south on northerly dipping planes compared to 'up and over' to the north on southerly dipping planes in the central zone. By reference to Park (1970b - plate 20) the area affected by the deformation D_f is shown in Fig. II.35. (Df corresponds to D_{3a} of Park (1970b)).

A later phase of folding affects the dykes and gneisses producing the structure of the Tollie Antiform. These F_g folds are concentric, see Fig. 11.34d, and have axes and an associated quartz lineation that plunge to the south east. The intensity of this folding increases in a south west direction until the gneisses and dykes are deformed into a steeply dipping attitude that strikes N.W.-S.E. and forms the southwest limb of the Tollie Antiform.

The dykes here are lineated to such an extent that the new foliation marked by rotated biotites and recrystallized quartz occelli is subordinate. This excellent lineation is due to the intersection between Sf and Sg and is of variable intensity over the whole of the Tollie Antiform.

It is possible that the change in Lg lineation (L_4 of Park) plunge value and direction of the gneisses at Meal Airigh Mhic Criadh (NC 832 774), (Park 1970b, Fig. 8) marks the limit of the effect of Dg on Df deformed gneisses.

Fig. 11.35 shows a structural interpretation of the Creag Mhor Thollaidh and Loch Tollie areas in terms of a gently dipping Laxfordian shear zone affecting originally steep dykes and pre-dyke gneisses. This interpretation is similar to that of the first model of Park 1970b and is preferred to Park's second model of his 1970 paper and the papers of Park and Cresswell (1972, 1973).

The Dg deformation is concentrated in the south west limb of the antiform. The structurally lowest part of the antiform near the shore of Loch Tollie shows a steep pre-dyke foliation which has not been so severely affected by the sub-horizontal foliation as the structurally higher zones. This suggests that the zone of D_f deformation is limited downwards as shown in Fig. II.35. The upper limit of the zone is seen in the south of Creag Mhor Thollaidh.

Post D_f events include the intrusion of granite sheets and pegmatites and their boudinage. The retrogression of metamorphic assemblages of De and Df took place during Dg.

<u>Dykes of Sithean Mor</u> (NG 812 716)

This area has been previously described by Clough 1907 and Park 1964. The dykes of this are are very closely spaced and occur in the highest concentration seen on the mainland. Within the 250m section investigated eight separate bodies were found which represented about 50% of the outcrop. All the dykes are vertical, strike N.W.-S.E. are discordant and possess metamorphic mineral assemblages. They have been intruded by dilatation into highly sheared and folded gneisses and basic bodies that dip to the north east and are now in amphibolite facies. The style of folding suggests that the gneisses have passed through deformation D_c.

Although all the dykes now have metamorphic assemblages, deformation has only been pervasive in the southernmost intrusions. The northernmost dyke has a mild contact parallel foliation and contains a few isolated narrow, dextral shears of low γ-distance profiles. The boundaries of these shears have a north easterly trend and contain schistose rock, the schistosity striking north south. The schistosity possesses a lineation that plunges to the south by 70°. Going south-westwards the effect of the marginal, more homogeneous shearing increases and affects more of the width of the dykes so at a position south-west of Sithean Mor the dykes are foliated across their whole width.

In one of these intrusions that still shows its sharp and blocky discordant contacts, the homogeneous deformation of the gabbroic material has taken place in two different ways. At the north contact deformation has produced a foliation that is parallel to the contact and decreases in intensity towards the south. This foliation affects about three quarters of the dyke width. However the foliation at the southern contact is also parallel to that contact but slowly changes its orientation until it strikes north south and dips to the east. The swing of this foliation is thus sinistral to the contact. This relationship is similar to that found at Achmelvich Bay, but there the different types of deformation were found adjacent to one another on both sides of the intrusion, and the asymptotic foliation was confined to separate zones of simple shear. Partly because of this and the microscopic appearance of the asymptotic penetrative foliations from other areas, the foliations on the south side of this dyke at Sithean Mohr probably had a strain-slip mechanism of origin.

The general increase in deformation going south across this small area begins to affect the gneisses and tends to leave both the dyke margins and the gneissosity dipping to the north-east. The relative amounts of vertical and horizontal movements associated with the reorientation of the dykes and gneisses cannot be estimated, but the horizontal sense was sinistral while the variation in dip values for the gneissosity suggest that the north east side may have moved down relative to the south west side.

Evidence for more than one phase of post dyke deformation is not seen.

The metamorphism of the dykes appears to be contemporaneous with the deformation but may have continued after the deformation had ceased, causing slight plagioclase blastesis.

The area around Loch Torridon

Members of the "Scourie dyke" suite have been studied between An Ruadh Mheallan (NG 836 615) and Loch Torridon and south of Loch Torridon at Shieldaig (NG 820 540). The geology of the whole of this area was described by Clough (in Peach et al 1907) Sutton (in Sutton and Watson (1951)) and more recently the northern part, from An Ruadh Meallan to Loch Torridon, by Cresswell (1969, 1972, 1973).

The Pre-Dyke History

Cresswell (1972) distinguishes five episodes of pre-dyke deformation which affected massive quartzo-feldspathic gneisses, basic and ultra basic gneisses. Large areas of the gneisses are made up of agmatized basic and acidic bodies that still show an original banding. The rocks of Shieldaig are very similar, but may be very pink in colour due to potassic feldspar phenoblasts of Laxfordian origin.

The most extensive deformation took place immediately prior to dyke intrusion, and produced steep E.S.E.-W.N.W. zones of shearing that refold isoclinal folds and produce belts of strongly foliated and banded gneisses. This deformation phase is referred to here as D_c and corresponds to D_4 of Cresswell. Ths S_c foliations strike E.S.E.-W.N.W. and dip to the E.N.E. by about 60°. They are often cut by dykes that are not deformed. The prece ding deformation Db (D_3 of Cresswell) produced folds with an associated axial planar foliation that now has a N.E.-S.W. trend. This folding affected rocks that now trend N.W.-S.E. and contain intrafolial folds produced during D_a (D_2 of Cresswell).

At Shieldaig the pre-dyke structures are far from obvious because of the strong Laxfordian reworking. However evidence does point to this area having been made up of homogeneous acid gneisses and agmatites which only possess a faint foliation. The attitude of this foliation is moderately steeply dipping to the N.E., similar to S_c north of Loch Torridon, or near vertical and striking E-W, similar to S_b north of the Loch.

No evidence for post-Dq, pre-dyke deformation have been recognized in the areas investigated. However Cresswell (1972) describes a phase of folding late in the pre-dyke history (D_5) at Meall nah'Airde (NG 790 590), which throws gneisses into a moderately shallowly N.E. dipping attitude.

Dykes Relations

Due to the intense Laxfordian metamorphism of this area very little is known of the original mineralogy of the dykes. However, they can be subdivided into the following groups which are listed in their order of intrusion:

i) gabbroic dykes

ii) doleritic dykes

and iii) 'green' dykes.

(A number of ultrabasic dykes (meta-picrite) and late dykes, (probably Tertiary) have been found.)

The order of intrusion is the same as set up by Cresswell (1969) who coded the dykes TD (gabbroic types), TB (doleritic types) and TU ('green' types).

The Gabbroic Dykes

The Gabbros are found over all the area and have a N.W.-S.E. trend irrespective of how much Laxfordian deformation they have suffered. They are found upto about 75m wide, but dykes of this thickness are confined to areas of low Laxfordian deformation, suggesting that deformation was involved in shortening in a N.E.-S.W. direction. The outcrop thickness of most dykes is about 20m, but at Shieldaig, where they are highly deformed, the majority are only about 2m wide. Also at Shieldaig there is a large fault bounded block of metamorphosed and foliated gabbro that if it was derived from a N.W.-S.E. trending body, must have been over 150m wide. The complex nature of the intrusion of the gabbros can be seen in all parts of the area, although locally relationships may be modified or obliterated.

Where undeformed, or only mildly deformed, gabbro/gneiss contacts are sharp, planar and often blocky (see Figs. II.36 and II.37) and may show strong evidence of dilational intrusion along brittle fractures, faults and joints (see Fig. II.36).

Where igneous textures are preserved they show an ophitic texture. However, completely undeformed contacts are only rarely exposed but show a narrow (c.1cm) extremely fine grained chilled margin that grades almost instantly into 'normal', albeit fine grained, gabbroic rock. Within the gabbroic dykes, rapid variation in grain size or composition is not common. The grain size, after a rapid increase, from the margin shows only a slow increase to the centre which only becomes obvious when hand specimens are compared.

In one section of the dyke at Loch na Beiste (NG 812 584) a variation in the feldspar content describes a faint vertical banding, but this is impersistent. In the same intrusion at NG 8138 5832 there is a 12cm wide band devoid of feldspar that can be traced for a distance of over 2m parallel to the contact. This band does not have sharp contacts with the surrounding gabbroic material and may indicate a temporary change in magma composition rather than a later intrusion phase.

It is obvious from the inspection of the geological map of the area north of Loch Torridon that there is a concentration of the number of dykes present in areas where the gneisses have suffered D_c deformation. These areas flank blocks that show only earlier deformation and where the number of dykes present are fewer. Park and Cresswell (1972 and 1973) suggest that the well developed N.W.-S.E. foliation produced during D_4 (here called D_c) took a controlling role over the intrusion of the suite of dykes to cause the formation of sills. Detailed examination of a number of dykes at the edges of belts of Dc deformation confirms Park and Cresswell's observation that the dykes outcrop parallel to the N.W.-S.E. S_c foliation and can invariably be seen to cut and therefore post date it. The branching dyke at Loch na h'Umhaig (NG 826 616) is described by Park and Cresswell (1973, fig. 4). This dyke complex shows branches broadly parallel in strike to the Sc gneisses but dip in the opposite direction, see Fig. II.36. This example and that at Loch na Beiste (Fig. II.37) suggests that although the zones of D_c deformation appear to have controlled the availability of magma, the intrusions have filled a set of joints or faults that cut the S_c foliation.

The Dolerite Dykes

Many of the gabbroic dykes have been intruded by finer grained dolerite dykes. These are found with sharp contacts against the gabbros and show signs of having chilled against them. Their contacts are often straight but may show irregularities that can be matched from one side to the other. Although often seen less than a metre wide they may be upto 30m across.

At NG 829 603 dolerite magma has cut into a gabbro dyke to form a multiple intrusion and has cut out part of the gabbro in order to use the gabbro/gneiss contact. Such multiple dykes have the dolerites trending in the same direction as the gabbros. However, where found isolated, they may have a more W.N.W. - E.S.E. trend and appear to be much narrower. Intrusion of the dolerites was probably dilatational, e.g. see Fig. 11.38.

The 'Green dykes' are not common but are seen cutting members of the gabbros and a member of the dolerites at Loch a'Mhullaich (NG 8090 5985) and Meall Ceann na Creige (NG 8040 5955) respectively. Where exposed the contacts to these dykes are straight and flat and are generally discordant to the gneissosity. Again the country rocks on opposite sides may show different structural histories, indicating intrusion along faults. The geometrical relationship between a 'green' dyke and the dolerite dyke at Meall Ceann na Creige, Fig. 11.38 cannot be explained by dilatational intrusion alone but must be due to intrusion along a fault that displaced the dolerite and gneisses prior to the intrusion of the 'green' dyke. This shows that faulting continued during the emplacement of the 'Scourie Dyke' suite. These dykes are found up to c. 50m wide and have N.N.W.-S.S.E. outcrop trend and are only found to the south-west of Loch Diabaig.

Deformation of Dykes

The dykes that occur to the south-west of a line from Meall Ceann na Creige to Loch na Beiste show relationships between the gneiss foliation and intrusion contacts that are open to two interpretations. The exposures from Shieldaig to Meall a'Choire Bhuidhe (NG 819 548) show the problem well. In 600 metres twenty thin dykes crop out and all strike N.W-S.E. They are less than 5m wide, are strongly sheared parallel to their margins and have near concordant contacts with strongly sheared shallowly (30°) north-east dipping gneisses. However, where the gneisses are not sheared the dykes are relatively undeformed and much wider (15m to 30m). They are also discordant.

The amount of deformation shown in the gneisses is variable, and where the gneisses are strongly sheared a thin dyke is sure to be found and for most of the 600 metres no dykes have been found in undeformed gneisses.

Inhomogeneity is shown not only by some areas having been unaffected but also by the strains having been concentrated in areas that contained lithological inhomogeneities, i.e. areas containing dykes. (c.f. the Laxfordian in the Canisp Shear Belt). This explains why the zones of the strongest foliations are found around well foliated thin dykes.

It could be argued that the bulk of the deformation (of the gneisses) was pre-dyke (S4, folded by F_5 after Cresswell) and that the intrusion of basic magma produced sills parallel to the well developed foliation S_c, where the fissility of the foliation would channel the magma into many thin sheets. Material intruded into areas of low D_c would therefore be discordant, wider and steeper. Following this the effect of the Laxfordian reworking would be concentrated in the sills and would have little effect on the gneisses, c.f.Cresswell 1972, Park and Cresswell 1972, 1973.

The second possible interpretation is that near vertical dykes with a N.W.-S.E. trend and of similar width (15-30m) were intruded into areas that may or may not have had a steep S_c orientation. Since the Laxfordian deformation was inhomogeneous it might have foliated the dykes and gneisses alike with the deformation being initiated at the dykes. During the shearing, or afterwards, the rocks that had been foliated were then rotated to dip to the north east. This is essentially the model used by Sutton & Watson 1951.

If the second interpretation is correct the strong shallowly dipping foliations would be of essentially Laxfordian age and the present concordance, or near concordance, would be due to Laxfordian deformation.

Some guidance may be had from comparing the two sets of strain indicators in this section, the dykes & basic pods found in the gneisses. The dykes, where nearly concordant with the shallowly dipping gneisses, are highly sheared and have planar non-blocky contacts that dip at low angles to the north east. Outside the zone of sheared shallowly dipping gneisses the contacts are near vertical, discordant and blocky and the dykes are hardly foliated.

Within the gneisses the basic pods vary in shape. In the relatively undeformed gneisses they are near spherical but in the sheared shallowly dipping gneisses they are flattened. By assuming a perfect spherical shape to these pods and no volume change, an estimate of the amount of shortening in the horizontal plane in a N.E.-S.W. direction may be calculated and compared to the thicknesses of adjacent dykes. This shows that, if the shearing of the gneisses post-dated the dyke intrusion and if the strain was of equal magnitude for the dykes and pod containing gneisses, the original widths of the dykes would have been comparable.

The pod shapes are oblate ellipsoids that have their long axes plunging to 060°N by c.40°, which is parallel to the lineation on the schistosity planes of the dykes.

There would therefore seem to be a case for regarding those intrusive sheets that have a shallow dip to the north east as being rotated and thinned by a Laxfordian deformation. Furthermore, the variation in gneiss and dyke orientation between Shieldaig and Loch nam Beiste could be explained by shallow north east dipping zones of Laxfordian shearing.

The deformation of the dykes has been extremely heterogeneous over the whole of the area under consideration, but as a general rule the amount of dyke deformation and the extent to which a schistosity has been formed in the dykes increases to the south.

As elsewhere, the post-dyke deformations can be subdivided into the phases, D_e, D_f, D_g etc.., by their effect on previous structures. The first phase, D_e, that affects the dykes is characterized by the production of a contact parallel foliation. The width of dyke that shows this foliation varies within a given small area from zero to two metres or more in areas of 'low' deformation to the north of Loch Diabaig. As a general rule the width affected increases southwards and is especially wide in areas of strong D_c (pre-dyke) deformation.

The foliation trends are N.W-S.E. and dip steeply, generally to the north east. The orientation of the contacts has had great control on the production of these foliations, for in many areas they faithfully follow irregular and rectangular contacts. This is shown well in the dykes at Loch nam Beiste where an isolated (although possibly attached) rectangular block of gneiss has a contact parallel foliation on all sides.

In areas of strong D_e deformation and in wide dykes this foliation may run asymptotically to the margin from a more E.N.E.-W.S.W. direction and this indicates that the foliation was probably produced by a dextral movement. This is shown well in the 'green' dyke to the south of Loch Diabaig at NG 8090 5963, where a foliation has been produced across the whole width of this 'soft' body.

The production of this contact foliation may or may not be associated with an equivalent deformation in the gneisses. In some areas, e.g. Shieldaig, the gneisses may have suffered deformation equivalent to that shown in the dykes, but in other areas, e.g. Meall Ceann na Creige, the foliation in the dykes may be widespread while the gneisses at the contacts of the dykes are unaffected. The reasons for this are not obvious but may be related to the total strain experienced in one area, for areas showing low total strain the deformation seems to be concentrated in the dykes.

In many relatively undeformed dykes a contact foliation may be present together with parallel narrow shear zones. These have a N.W.-S.E. strike and have a steeply north-east dipping or vertical orientation showing dextral or vertical movement. In such cases the contact foliation zone is narrow and has not developed sufficiently to be asymptotic.

The boundary between the gneisses and the dyke rocks has initiated the production of foliations but dyke/dyke, e.g., gabbro/dolerite, contacts have remained passive.

As already stated the production of this foliation has been variable throughout the area. Within smaller areas the deformation has also been extremely variable. For instance the north-western-most branch of the dyke complex shown in Fig. II.36 is highly foliated, whereas the southern branches are not.

Zones of D_e shearing, which produce rocks having foliations that strike N.W-S.E. and dip at high angles to the N.E. are often found in, although not exclusively confined to, areas that have undergone the pre-dyke deformation D_c. D_c deformation also produced sheared gneisses of a similar orientation. It would therefore appear that the D_e deformation phase was primarily concerned with either the activation of the dyke margins or the reactivation of S_c foliations. However where deformation forces were strong, belts of shearing were developed that are not confined to such pre-existing planes and cut across massive gneisses and dykes alike. This relationship is similar to that found in the centre of the Canisp Shear Belt in the Laxfordian deformation episode, D_e, of that area.

The relative components of vertical and dextral movement cannot be ascertained, but individual outcrops suggest that vertical movements, possibly with north side down, have been more important.

Two outcrops, at NG 8120 5841 (Fig. II.39a) and at NG 8270 6050 (Fig. II.39b), show F_f folding of discordant dyke contacts. These folds have a sub-horizontal axial surfaces and fold the contact parallel foliations, S_e. The folds of Fig. II.39b, have been folded by a later deformation, Dg. Because of the degree that the S_e foliation follows irregularities in the dyke contacts it cannot be confidently stated that the folded nature of the contacts are the result of a post-dyke deformation. These folds are therefore only tentatively assigned to a post-D_e deformation phase, D_f.

The third phase of Laxfordian deformation, D_g, increases quite markedly to the south. The most northern position where it has been found is just to the north of Loch Diabaig at the locality for Fig. II.39b. This deformation characteristically deforms the S_e dyke foliations, the dykes and gneisses into a moderately shallowly (c.30°) north easterly dipping orientation. Where its effects are least obvious, narrow low-lying shear zones are formed that may affect previously undeformed dyke rock. The curving of the F_f fold shown in Fig. II.39b shows that the movement couple around the D_g planes of shearing was 'up and over' to the south.

Going south the effect of D_g becomes greater and is shown to be so in both the gneisses and the dykes.

At Meall Ceann na Creige dykes that show a strong Se foliation are folded by this deformation Dg. Their margins and contact-parallel foliations have locally been brought into a shallowly north-east dipping attitude to produce a set of similar folds that have axes that plunge by 30° to 080°N, an amplitude of c.30 cm and a wavelength of c.40 cm. In vertical section the 'new' sub-horizontal and the 'old' vertical orientation of the Se foliation describe a set of 'steps' that climb to the south west. In vertical plan they describe an 'S' shape.

This therefore indicates a general movement of the upper "block" moving up and over towards the south (south west).

On the south shore of Loch Torridon, north of Shieldaig, the effect of Dg has been to foliate gneisses and dykes together to produce a locally homogeneous shallowly dipping set of rocks. The amount of rotation of early post dyke foliation (Se) cannot be determined. The area between the summit of Meall a' Choire Bhuidhe and the road (i.e. NG 8195 5420) is thought to represent one zone of intense Dg shearing that waxes and wanes. By the road, dykes show possible remnants of De foliation that has remained in its original orientation (strike 120°N, dip 70 to N.E.) but is cut by zones of Dg shearing of variable width that are spaced at c.25 cm intervals. These zones deflect, and in some cases cut off, the Se foliation to produce asymmetrical folds that where seen are overturned to the south. Their axes plunge by 31° to 106°N.

The sense of movement shown on this S.E.-N.W. trending vertical outcrop, that is almost parallel to the strike of S_g, indicates that there was a slight component of movement displacing rocks above the zone of Dg shearing to the north-west. All through the sequence similar folds are seen in the gneisses and in plan they all describe a 'Z' shape with their longest limb lying sub-parallel to Sg. It therefore appears that the overall sense of horizontal movement has been sinistral. Fold axes and elongation direction of the basic pods in the gneisses all plunge to the east or north east. In some places a well developed mineral elongation that resembles slicken slides is present on the Sg schistosity planes of the dykes. This plunges down the dip of Sg (i.e. at 30° to 40°) to the northeast or more to the east. If this indicates the movement direction then the movement has been 'up' the dip of Sg.

In the dykes at Shieldaig the Sg foliation formation is associated with the growth of microcline and metamorphic segregation to give a banding. Microcline pegmatites and epidote veins are seen cutting across rocks that possess a Sg foliation.

Quartz veins and foliae lying parallel to the Sg foliation of a 'green' dyke and a nearby meta-gabbro at Beall Ceann na Creige, south of Loch Diabaig, are affected by folds which are assigned to F_h. S_g, S_e and the trend of the dykes are folded by this phase of deformation which appears to have taken place under less ductile conditions than previous phases. The structures produced are found scattered over all the area, cut across dyke/gneiss contacts and include small scale shear zones, kink bands, concentric and chevron folds.

Kink bands have been found in a conjugate set. The bands of kinking strike 164°N and 045°N, showing a sinistral and a dextral sense of movement respectively. They indicate an overall extension in a north-south direction due to east-west compression. The folding of Se foliations, found at the same exposure as the kink bands is associated with the folding of the dyke into an 'S' shape. The axial planes of these folds strike 046°N and are almost vertical. Elsewhere axial planes to the folds are found striking from 030^{o}N to 062^{o}N in the dykes and gneisses. The F_h folds have wavelengths ranging from 4 cm to 80 cm and amplitudes that range from c. 1½cm to 30cm. Their fold axes generally plunge to the north east suggesting that their axial planes dip to the south east. This agrees with the few cases where the folds are exposed well enough for their axial planes to be measured.

These folds (Fh) are best developed in highly schistose rocks, as in the case elsewhere for the last folding phase of the Laxfordian events, seem to be dependent on a boundary slip mechanism for formation, thus explaining why the best development is confined to schistose rocks.

A mile to the west, south of Balgy (NG 846 545) (see Sutton and Watson 1951 p260) both gneisses and dykes have been folded and describe and 'S' shape, but Sutton and Watson consider these fold to post-date the microcline blastesis and the thrusting and are therefore thought to belong to the Dh deformation.

Cresswell (1969) sub-divided the Laxfordian into three main phases. The first phase, D_6, was found only in a few dykes and was associated with the initial stages of metamorphism of the dykes that produced hornblende rims to pyroxenes and the foliation of garnets. This deformation produced a contact parallel foliation. D_7, the second Laxfordian deformation again produced a foliation parallel to the dyke margins, and co-axial to S_4, but was associated with metamorphism that transformed the dykes into amphibolite schists and caused exsolution in hornblendes. D_7 occurred with the stages of metamorphism 2, 3, 4 and 5 of Sutton and Watson (1951a). D_8 deformation produced buckle folds in areas of high D_7 deformation and was associated with the retrogression of biotite to chlorite.

Subsequently Cresswell (1972) inserted an extra phase before

D_6 that was responsible for the formation of 'hot shears' oblique or parallel to the margin of the dykes in the north of the area. In Cresswell and Park (1973) LD_1, LD_2 and LD_3 are used instead of D_6, D_7 and D_8 respectively.

From the description of the deformations mentioned above the following observations are made. The 'hot shears' and S_6 foliation are thought to have originated at the same time and to correspond to S_e foliations. Structures similar to D_f folds are not recorded by Cresswell. D_7 corresponds to D_g and D_8 to D_h, although some of the folds attributed to F_8 by Cresswell could be F_f folds.

The pre-dyke folding of Cresswell, F_5, that rotated S_4 into a shallowly NE dipping orientation prior to concordant 'dyke' intrusion is considered to have been post-dyke in origin (D_g) and to have transposed S_4 and the dyke contacts into parallelism with the S_g foliation produced in the dykes.

Chapter III PETROLOGY

The petrographic characteristics of the members of the 'Scourie Dyke' suite have been described by Teall (1885), Peach et al (1907), Sutton and Watson (1951 and 1951), Bailey (1951), O'Hara (1961, 1962) Tarney (1964), Dearnley (1973), Park and Cresswell (1973) and others.

Five main distinct rock types have been recognised and these are gabbro, dolerite, norite, a 'green' actinolitic rock and ultrabasic picrite.

Gabbros

This rock type is the most common of the rock types which together are called the 'Scourie Dykes'. The term gabbro is used to indicate a coarse grained basic igneous rock and to separate it from the easily distinguishable dolerite which is of a much finer grain size.

When unmetamorphosed these rocks may be grey, brown or green and have an even texture where the mafic mineral grain areas may be up to c.3 mm in diameter and the areas felsic minerals may be up to c.4 mm in diameter (see Plate III.1).

In hand specimen the texture is hypidiomorphic, or more commonly allotriomorphic. This gives the rock a characteristic mottled appearance which is especially prominent in the metamorphosed specimens.

Since very few dykes are found unaffected by metamorphism little can be said about the variations in the petrography of these rocks.

The minerals which form these rocks include plagioclase (of variable composition), pyroxene (both orthorhombic and monoclinic), green hornblende, biotite, ore, apatite and quartz. Olivine and kaersutite are only very occasionally found in these rocks and the ortho-pyroxene content is extremely variable. The average model proportions of the main mineral phases are approximately; plagioclase 40% pyroxenes 45%, hornblende 8%, ore 5%, biotite 2%. The plagioclase and pyroxene content is extremely variable and both may range from 20% to 60%.

Plagioclase Crystals are found as isolated laths in the samples of finer grained margins of the gabbroic dykes. However the laths generally lie together with random orientation to form the felsic areas of the rock (plate III.1). Individual crystals have a length to breadth ratio of about 5:1, occur up to about 3.5 mm long and are allotriomorphic or hypidiomorphic. The smaller grains (< 0.2 mm) show a tendency to be more allotriomorphic, or even idiomorphic, and when found in the fine grained contact material they are isolated in a mafic 'matrix' (pyroxenes and hornblende) to give an ophitic or subophitic texture.

The plagioclase compositions generally fall between An34 to An55 (andesine-labradorite). The majority are andesine. The plagioclase invariably shows 'normal' compositional zoning of within the range mentioned above. The centres of some of the larger crystals have a bytownite composition. Albite, Carlsbad and pericline twinning is ubiquitous.

Inclusions of small laths in larger plagioclase laths are rare. Clouding of the feldspars due to thermal metamorphism has been described by MacGregor (1931) for members of this set of rocks. Clouding of unmetamorphosed plagioclase crystals may occur to different degrees within one crystal and may be concentric to any zoning present.

Inclusion of minute pale green acicular crystals of what may be hornblende, similar to that which grows in the last stages of crystallization, are common and the longer crystals may be aligned parallel to the [010] cleavage planes.

The rims, which are of a more sodic plagioclase, are often free of inclusions. This may be because they are the result of orthocumulative growth or, alternatively, the result of late stage alteration which occurred at the same time as the hornblende crystallization.

Pyroxene - grains are generally anhedral and are found grouped together forming 2mm diameter patches. In the finer grained gabbros of the margins of these bodies the pyroxenes may be euhedral.

The freshest pyroxenes are augites with faint brown pleochroic colour that are generally clouded by minute brown crystals that are often aligned parallel to (100). Elsdon (1971) has recently ascribed similar inclusions in pyroxenes to iron-titanium oxides.

O'Hara (1961) suggests that the zoning that is often found in the pyroxenes is of pigeonite cores to ferroaugite rims and that the clouding is due to the exsolution of ferropigeonite and ferroaugite (see Plate III.2). Some dykes show these pyroxene mantled by fibrous pale green pyroxene and in other dykes this is the only pyroxene. The lamellae (fibres) are well ordered parallel to and twinned on (100) but may be chaotic to give a 'symplectitic' appearance, (see Plate II.3). The clouding due to the brown inclusions is not found in these pyroxenes. O'Hara (1961) describes the same features and shows that these are intergrowths of a host clinopyroxene with composition Ca_{39} Mg_{32} Fe_{29}, and an orthopyroxene, that have been produced by exsolution.

Occasionally pleochroic (pale red to pale green) enstatite may be present as individual euhedral crystals that may also contain the brown inclusions. The modal content of orthopyroxene is extremely variable but rarely exceeds one tenth of the mafic phases present. The crystals are euhedral and of similar size to the other pyroxenes in the same rock. Clinopyroxene rims may surround orthopyroxene.

Hornblende - this mineral occurs in two forms:
(1) as interstitial plates and rims to pyroxenes, see Plate II.2, and (2) as plates forming an ophitic relationship with plagioclase laths (sometimes kaersutitic-see Tarney 1973). See Plate III.4.

The poikiloblastic plates are associated with the finer marginal facies of dykes and are uncommon. These hornblendes have a pleochroic deep green colour. The interstitial hornblende is pleochoic green to olive green and occurs in the interstices between earlier formed grains (plagioclases and pyroxenes) or mantling opaque ores (magnetite with minor ilmenite) or associated with biotite. It also occurs around the pyroxenes. In rocks where the clinopyroxenes have wide hornblende rims the hornblende rims on the orthopyroxenes are very narrow or absent. It has also been noticed that the exsolved pyroxenes have extremely wide rims.

This hornblende is considered to have been formed during the last stages of crystallization during or after the final stages of plagioclase (andesine) growth, after pyroxene growth had ceased and before the growth of the ores and biotite. Samples which show this primary development of hornblende may also have hornblende crystals as inclusions in the centres of plagioclase grains. These are considered to have formed at the same late stage as the interstitial hornblende.

Opaque ores, biotite and garnet _ The ore minerals, generally magnetite with ilmenite intergrowths, found in the gabbroic dykes occur exclusively in the interstices between plagioclase and pyroxene crystals, where they are generally surrounded by hornblende (see Plate III.2), sometimes by biotite and occasionally by garnet. Their form is often euhedral.

The occurence of garnet as coronas to the ores, or as interstitial clusters, is confined to dykes rich in biotite, lacking in primary hornblende and possess pyroxenes without exsolution textures. The garnet coronas are made up of minute colourless grains that slightly overgrow the plagioclase with which they are generally in contact.

Small quantities of euhedral apatite (upto 0.5 mm long) are present in some rocks and interstitial quartz may represent upto 5% of the mode, this is often associated with micro-graphic quartz-alkali feldspar intergrowths.

The order of crystallization of the mineral phases in the gabbros relative to plagioclase are summarized in Fig. III.1 (c.f. Park and Cresswell, 1973). Because of the relative age of growth of the hornblende and plagioclase it is suggested that crystallization took place under low (less than 2 kbar) water pressure (Yoder and Tilley 1962).

The presence of pyroxene exsolution, hornblende, garnet, biotite and anorthitic plagioclase points to an interesting cooling history of these rocks. The formation of all these phases appears to be confined to the last stages of crystallization and reflects the temperature conditions of the country rocks, (see O'Hara 1961).

The exsolution of pyroxenes suggests that the rocks cooled slowly past the inversion temperature. Although the gabbro bodies are wide, and therefore cooling would be relatively slow, the marginal gabbroic rocks show the same characteristics as the centres. Therefore it is assumed that the heat flow from these bodies was not entirely responsible for the slow cooling rate. The amphibolite facies mineralogy was considered to indicate a temperature range for the country rock of between 300 and 500^{o} by O'Hara (1961) and to be due to autometamorphism. Sutton and Watson (1951) and Tarney (1963) also entertained this possibility.

The presence of the exsolved pyroxenes indicates a slow cooling rate but whether or not biotite or hornblende are formed seems to be dependent on the chemistry of the interstitial liquids.

Dolerites - fresh, unmetamorphosed, specimens of dolerite are more rare than fresh gabbros.

Grain size varies from below 0.1mm to 1.0mm. The rocks are even-textures but may contain plagioclase xenocrysts up to 4mm in diameter. The xenocrysts are invariably so highly sericitized that estimation of their composition is impossible. However some show evidence of oscillation zoning. These plagioclase may well have originated from gabbroic bodies similar to those already described.

Plagioclase - unlike those in the gabbros, the crystals produce an ophitic texture. They occur up to c. 0.8m long and show extreme zoning from An_{52} (low labradorite) cores to An_{32} (low andesine) rims as found in the gabbros. Up to 65% of the rock may be plagioclase.

Pyroxene, subhedral augites of c.0.5mm diameter, show simple twinning about (100) and polysynthetic twinning to give a herringbone structure.

Concentric zoning may be present in which case the edges are deep brown in colour (titanaugite). As found in the gabbros, these augites contain brown inclusions. Euhedral orthopyroxene crystals are sometimes present. The pyroxenes can represent between 25% to 45% of the rock.

Hornblende -- this mineral may occur as thin 0.05mm rims or as poikilitic plates associated with the growth of the ore minerals (magnetite). Some samples show no hornblende, in which case biotite occurs instead.

The ores found in the dolerites are mostly skeletal or have grown exclusively with hornblende or biotite in interstices. Biotite with inclusions of ore is also found as partial rims to clinopyroxenes. This suggests that these biotites are the result of the reaction between the clinopyroxenes and the magma.

Small quantities of garnet rim the interstitial ores or occur on their own between plagioclase laths. The garnets have only been found in biotite rich rocks.

Quartz is generally found as a late stage growth phase but is apparently not associated with graphic intergrowths. Pseudomorphs, upto 0.3mm in diameter, after olivine of chlorite and opaque ores, are found.

The dolerites, although separable from the gabbros in grain size, texture and intrusion width show the majority of the features that characterize the gabbroic rocks with the exception that they have not been found to contain exsolved pyroxenes. In view of this and of their similar geochemistry, their origin and history is considered not to have been significantly different from that of the gabbros. Their special features can be ascribed to the general narrowness of the intrusions allowing rapid freezing and possibly rapid intrusion.

The intrusion of the dolerite dykes is therefore considered to be due to crustal tension, after initial intrusion of the gabbros, allowing further intrusion of basic material from magma chambers that were fractionating plagioclase (suggested by the plagioclase xenocrysts). These magma sources were probably those that supplied the gabbroic dyke material.

It is possible that the dolerite dykes were intruded into a cooler crust. However, the occurrence of gabbros that post date the dolerites at Gruinard Bay, the close association in time of dolerite and gabbro at Rubh a Tiopain and the presence of garnet coronas in the dolerites suggest that the crustal temperatures were not significantly different during the intrusion of the dolerites.

Norites only two fresh dykes have been sampled, one described by O'Hara (1961) at Badcall and the other found to the east of Tumore Lodge (Loch Assynt) described by Peach et al (1907) as a hyperite or enstatite diabase.

These dykes show a rapid increase in grain size and texture from margin to centre. The margins contain ophitic plagioclases (An_{45}) that are small (less than 0.5mm long), may be flow aligned and surround euhedral, prismatic phenocrysts of enstatite (1-2mm long). See Plates III.5 and III.6. Both the plagioclase and the enstatite are strongly zoned with the outer rims of the orthopyroxene being very brown in colour. Towards the centre, the grain size increases and plagioclases may reach 0.8mm in length and the enstatites up to 4mm x 1mm. The texture is the same as at the very edge. Interstitial phases are enstatite, clinopyroxene, biotite, ores, and in some cases quartz and hornblende. In both dykes investigated there is a minor amount of clinopyroxene which occurs interstitially or as discrete grains that show extreme exsolution as in the gabbros. The plagioclase and pyroxenes occur in about equal volumes. In the dyke at Tumore the amount of clinopyroxene increases towards the centre and is found as thick (0.5mm) mantles to the enstatite.

The orthopyroxenes of the centre of the Badcall dyke have had their euhedral shape destroyed by alteration at their edges to very pale green hornblende and biotite. There is only a faint suggestion of this having happened in the Tumore norite.

In the centre of the Tumore norite, which is much wider than the Badcall dyke, the plagioclase becomes more sodic (c.An30) and occurs as large (1cm) poikilitic plates enveloping the mafic phases, apatite, biotite and quartz. The pyroxenes are much larger. Most important, however, is that bands up to 5cm wide are found almost entirely composed of poikilitic plagioclase plates showing a symplectitic relationship with brown enstatite or exsolved clinopyroxene, (see Plate III.7). This indicates that the growth of the plagioclase and the brown enstatite were synchronous, but also that enstatite continued to grow with the clinopyroxene until very late.

Since the reaction rims to the orthopyroxenes of the gabbros and dolerites are very narrow, their restricted occurrence in these norites is not thought to indicate a significantly different cooling history. The marked difference is that norites show a gradual increase in grain size from margin to centre, unlike the gabbros and dolerites where the increase in grain size is quickly realized. This may reflect their width, the temperature of the gneisses at the time of intrusion or an inherent difference in the cooling rates of gabbroic and noritic magmas.

Picrites The picritic dykes have been described in great detail by Tarney (1964, 1973) and in Peach et al (1907). Once again occurrences of these dykes in an unaltered state are rare and only found in the central area. There is great variation between dykes and within dykes. These variations are due to variation in the proportions of the main constituent minerals olivine, orthopyroxene and plagioclase. Olivine content ranges from 5-50% and pyroxene content from 50 - 75%. Plagioclase, biotite and ore (chromite and picotite) may represent up to 10% of the rock.

Olivines Olivine grains (Fa 12% - Tarney 1964, 1973) occur in all the rocks and may be rounded to euhedral. They often occur as small inclusions (0.3mm) in large orthopyroxene crystals (see Plate III.8). In this position they are very well rounded and cracked but do not show any reaction across their interface. The olivines of the areas between the orthopyroxenes are larger (c. 1mm) and may be euhedral and are found here surrounded by poikilitic plagioclase (An 55). These crystals are crowded into the interstitial areas and surrounded by the late stage, possibly intercumulus, growth of plagioclase, biotite and ores.

Orthopyroxenes Crystals are generally large (up to 8 mm) phenocrysts that contain the small rounded olivines. They typically have a pale pink to pale green pleochroism and are reported by Tarney (1964, 1973) to be bronzite (c. Fs12) with their edges being more iron rich (c. Fs 16) and of a darker colour. The large pale-coloured plates have near circular cross-sections. Some samples that show small amounts of olivine also contain smaller euhedral and browner (iron rich) orthopyroxene crystals in the matrix.

Clinopyroxenes - these are rare and occur in isolation, or as exsolution lamellae in orthopyroxenes or growing epitaxially with orthopyroxenes (Tarney 1969). Tarney (1973) gives the composition of the pyroxenes as Ca:Mg:Fe=42:46:12 (augite) and the exsolution lamellae as being diopsidic augites.

Some olivines have been completely replaced (probably on cooling) by ore and chlorite. This is not a metamorphic feature, for on metamorphism the olivines are the last phase to recrystallize.

Olivine Gabbros - these occur immediately to the south of Lochinver and have been described by Tarney (1964, 1973). There is a great variation between the margins and the centres of these bodies. The constituent minerals are euhedral clinopyroxene, augite (c. 0.8mm), rounded prismatic orthopyroxene (0.3 x 2.0 mm), olivine, chlorite pseudomorphs after olivine, poikilitic plates (up to 1cm in diameter) of plagioclase (c. An35) and interstitial kaersutite, biotite and ore (titanomagnetite) (see Tarney 1973). Plate III.9 shows a typical texture. Pyrrhotite is found as the replacement product of the olivines. The orthopyroxene, bronzite, has the same form and optical properties as those found in the norites, and the clinopyroxenes are as found in many gabbros and dolerites. The overall appearance of the mafic phases, except for the quantity of olivine present, is similar to some of the dolerites.

Tarney (1973) describes these dykes as having augite-rich margins and (Tarney 1964) states that the composition of the minerals is olivine (Fa25), augite (Ca:Mg:Fe=40:37:23) and orthopyroxene (Fs25).

At the edges of these dykes, the clinopyroxene occurs generally as separate or touching grains but in the centre they are larger and tend to form patches of hypidiomorphic crystals. Unaltered olivines do not exist in the centre. The euhedral to rounded olivines of the edges, where they form upto 30% of the rock, show up to three coronas of a fibrous amphibole, but in the centre they have been completely replaced by actinolite-tremolite and pyrrhotite. In the centre olivine pseudomorphs represent 10% of the rock. The recrystallization of olivine to amphibole is considered to reflect an increase in water vapour pressure. Other variations in mineral content from the margin to the centre are that of biotite and kaersutite which increase and orthopyroxene which decreases.

It would appear that olivine and orthopyroxene were the two original magmatic phases and that the olivine was replaced by amphibole and ore after the crystallization of the plagioclase.

As the recrystallization of olivine has occurred in situ and has completely removed the olivine in the centre but not at the edge, it could be that water vapour pressure increased with the progressive consolidation of the dyke from the margin to the centre.

Petrogenesis of the dyke types

Study of the set of rocks that have been found in a non-altered state showing similar, but variable, texture suggests that they form a differentiation sequence:

PICRITES - OLIVINE GABBROS AND NORITES - DOLERITES AND GABBROS.

Differentiation processes that have caused this appear to have been initiated by olivine and orthopyroxene fractionation as indicated by the earliest phases of the picrites. It is believed that this differentiation was replaced by series differentiation to give the range of rocks which eventually produced the gabbros and dolerites. A possible scheme is given in Fig. III.2.

The fractionation of early orthopyroxenes is favoured at higher pressures, when the orthopyroxenes are likely to be rich in alumina (Green and Ringwood 1967). This would cause the series differentiated rocks to be aluminia poor. Olivine fractionation, possibly with minor low-alumina orthopyroxenes, would lead to high-alumina rocks. There are common external relationships between the norites and those gabbros and dolerites which have garnet and biotite coronas. These may be the rocks that have resulted from early olivine fractionation.

These two trends, assuming a common parent, could have developed either due to differences in crustal level where fractionation began, following the ideas of Green and Ringwood (1967), or due to the mechanical separation of the two earliest phases, olivine and orthopyroxene, leaving the magma portions rich in either orthopyroxene or olivine. Further differentiation would give either opx picrites-norites-two pyroxene gabbros or olivine picrites-olivine gabbros-one pyroxene gabbros - two pyroxene gabbros.

Autometamorphism of the Scourie Dykes

Sutton and Watson (1951) and O'Hara (1961) suggested that the garnet and hornblende coronas around ores were due to autometamorphism. The rocks in which these occur with replaced olivines show no sign of other reactions that might be expected to occur as a result of metamorphism. This strongly suggests an autometamorphic origin. O'Hara (1961,62) argues that the dykes of the mainland were intruded into hot country rock, and Tarney (1963), that the area gradually cooled during the period of intrusion. Moreover since many examples of dyke intrusion can be found throughout the mainland to prove that jointing and faulting of Inverian deformed rocks occurred before dyke intrusion it is believed that the country rocks had cooled down to some extent after the Inverian metamorphism and before dyke intrusion.

It is possible therefore that relative heating up of the Lewisian rocks before, or at, the time of intrusion of the Scourie dykes was an isolated event unconnected with either Laxfordian or Inverian metamorphism. Since evidence of jointing in the dykes can only be found in areas of no or little Laxfordian metamorphism, the heating of the complex could possibly have heralded the Laxfordian in the northern and southern Laxfordian belts, although the evidence for this is purely negative.

O'Hara (1961) suggested a temperature of the country rock of between 300 and 500°C. The present work shows that the autometamorphic coronas show the following sequences; andesine- garnet-ore, andesine-hornblende (or anthophyllite) - (biotite)-ore, and andesine-hornblende-pyroxene. All three may occur in the same specimen. The occurrence of both amphiboles and garnet may help to suggest the conditions at which the coronas grew.

The presence of amphibole suggests high water vapour pressure, for in low water vapour pressure conditions the continued growth of pyroxenes would be expected. This continued growth of pyroxenes has taken place in norites but not in the dolerites and gabbros.

Hamilton and Anderson (1967) show how basaltic melts of at least 1% water will have increasing water vapour pressure on crystallization. Possibly the magma from which the norites developed was so poor in water that the water vapour pressure would not increase.

Since any temperatures below 1150°C (the approximate crystallization temperature of tholeiite dolerites) can be achieved on cooling, only the pressure conditions of the country rock can be accurately indicated.

Jaeger (1957) calculated that the relationship between contact temperature (Tc), country rock temperature (Tr) and the liquidus temperature of intruded magma (Tl) would be $Tc = (Tl-Tr)f+Tr$, where the function, f, is about 0.5. For a tholeiitic magma Tl would be c. 1150°C.

At any considerable depth a temperature could be reached and held for long enough to cause the melting of acid contact gneisses. This melting is not seen. Using this equation and taking the minimum melting point of acid rocks at 650°C and maximum at 750°C then the country rock would need to be below 150°C and 350°C to advoid the temperature of the contact reaching above 650°C and 750°C respectively.

Following this it would be expected that for melting of acidic contacts not to occur the dyke would need to have been emplaced at depths less than 6 to 14 km, depending on the composition of the contact gneisses. (This assumes that the geothermal gradient was 25°C km^{-1}.)

Hsu (1968) established the stability relationships of almandine under hydrothermal conditions at different oxygen fugacities. This work shows that, for low fluid pressures (up to 5 kbars), almandine will be stable with amphibole at almost any temperature down to $500^{\circ}C$ for any fluid pressure (see Fig. III.3) and at oxygen fugacities less than c10^{-15} bars (data for amphibole from Yoder and Tilley (1962).

Oxygen fugacities of basaltic magmas are much higher than this (about 10^{-7} bars) but decrease rapidly on crystallization and quickly approach 10^{-15} bars (Hamilton and Anderson 1967) when almandine garnet could be formed.

Whether or not garnet would be formed may have been dependent on the chemistry of the interstitial liquids or whether oxygen fugacities reached less than 10^{-15} bars. The fact that hornblende and garnet are not found together supports the second suggestion. The time when a given interstice became a closed system, by the continued growth of plagioclase, would control whether or not oxygen fugacities fell below 10^{-15} bars.

It is therefore concluded that the environment of intrusion was that of a country rock which was cooler than 150° to $350^{\circ}C$ and that the presence of hornblende and/or garnet does not help to make a more precise estimate of either the temperature or pressure pertaining. However since hornblende is seen to have crystallized after plagioclase crystallization took place at less than 2 kbar water vapour pressure.

Metamorphism of Gabbros and Dolerites

The metamorphic alteration of these basic dykes has been described by Sutton and Watson (1951a,b) who recognized seven stages of progressive change.

1) Autometamorphic changes with retention of the original textures to give amphibole, garnet coronas to the pyroxenes, oligoclase coronas to the original feldspar, and biotite, amphibole and garnet coronas to the magnetite. (See Plate III.2).

2) Formation of large aggregates of hornblende with the disappearance of the pyroxene and the coronas, followed by the formation of hornblende into poikilitic plates with quartz inclusions. Production of sphene.

3) Recrystallization of feldspars to andesine and formation of epidote, see Plates III.10 and III.11. Darkening of hornblende colour. The rocks become foliated at this stage, by the modification of the original textures.

4) Recrystallization of the quartz-hornblende aggregates with complete destruction of the original texture, with the assemblage amphibole- (epidote) -oligoclase.

5) Appearance of biotite.

6) Development of green augite.

The development of the corona structures, considered to be an autometamorphic feature, has already been discussed and the effects of the Laxfordian metamorphism are assumed to be stage 2 onward.

The earlier stages of metamorphic changes can only be seen in undeformed dykes and cause the further growth of the coronas. The hornblende rims of the pyroxenes become wider by growth into the pyroxene and plagioclase. The rim of one patch of pyroxene may be in optical continuity or may be made up of small crystals growing out from the pyroxene. The growth of hornblende to replace the pyroxene may proceed in two ways. Firstly, the pyroxene may be completely taken over by hornblende, either in continuity with the outside rim or in a mass of small, often acicular, grains. In both cases silica may or may not be released during the transformation to leave inumerable small rounded quartz inclusions. The presence or absence of quartz inclusions probably reflects the original composition of the pyroxene. Pyroxenes that have exsolution intergrowths show conversion of one of the intergrowth set to hornblende, while the other remains unaffected and the hornblende produced may itself contain exsolution lamellae. These pyroxenes form quartz free hornblende masses. Orthopyroxenes in the same samples show little sign of alteration and it is therefore concluded that the clinopyroxene of these masses are converted to hornblende first. Comparison of the chemical composition of hornblende (SiO_2 - 45%), augite (SiO_2 - 49%) and enstatite (SiO_2 - 58%) suggests that orthopyroxenes are more likely to produce the quartz-rich masses. (Data from Deer, Howie and Zussmann 1963).

The boundary between the hornblende rims and the hornblende produced by conversion from pyroxene remains well defined. Some pyroxenes are completely taken over by single hornblende crystals and these typically retain the dusty zones of small brown inclusions. As these are not associated with quartz production such hornblendes may be formed from clinopyroxenes. At this stage the feldspars remain intact, but become increasingly sericitized and saussuritized and biotite and apatite remain unaltered. The ores may be recrystallized from the outside to sphene or may remain, keeping their euhedral shape.

The growth of hornblende continues by overgrowing plagioclase and quantities of small idioblastic grains of epidote grow in the feldspars. This marks the release of calcium from the plagioclase lattice. At this stage calcite crystals (c. 0.5mm) can be formed. The growth of hornblende over plagioclase is often preceded by a narrow zone where the feldspar is clear and is more albite-rich. In one example this zone has composition An23, where the original crystal was An44. Also some feldspar laths have been zoned about the cleavage fractures and here the areas next to the cleavages are more sodic. This suggests that there has been some mass transfer of calcium from the plagioclase to epidote, hornblende and calcite.

In a small number of rocks, the growth of clear euhedral garnets (0.05 mm) occurs. The samples that show this come from the margins of dykes (cf O'Hara (1961)). This may be a reflection of the geochemical composition of the edges of the bodies. The garnets may form with quartz, ores and hornblende but are also found as a corona to distinct feldspar laths now in contact with hornblende. In this situation the garnets have grown over the plagioclase-hornblende (or possibly plagioclase-pyroxene) boundary and this edge is marked by a sharp difference in the appearance of the garnets for the garnet that has grown in place of the plagioclase is free from quartz inclusions.

The next stage is where the feldspar becomes recrystallized to polygonal andesine-oligoclase grains. This recrystallization begins at the touching ends of plagioclase laths and finally replaces the whole lath. This recrystallization leaves a mosaic of small (0.1 mm), equidimensional polygons that have straight crystal boundaries, see Plate III.10. The majority are six sided with almost perfect 120^{o} triple grain boundary intersections. This texture is typical of annealing recrystallization (Burke and Turnbull, 1952 and 1960)and has been described by Sturt (1969) and Bondensen and Henriksen (1965) from gabbroic rocks metamorphosed under amphibolite-facies conditions.

At this stage epidote, biotite and apatite crystals begin to disappear and the ores continue to be replaced by sphene. The hornblende-quartz texture also changes considerably. The quartz coalesces to form larger grains (c. 0.1mm) in a mosaic of idioblastic stubby prisms of hornblende that are growing and may be found up to 0.1 mm long. The hornblende rims also recrystallize and are no longer easily recognisable as being separate from the interiors. Epidote may remain to this stage and is found between the polygonal plagioclase grains. The polygonization of the plagioclase laths that characterises this stage indicates straining of the plagioclase laths although deformation of the texture is not necessarily shown.

The further stages of metamorphism are confined to rocks that are deformed. Deformation is initially recognised from the distortion in shape of the plagioclase areas. These areas become elongated and the irregularities in their shape are smoothed out and achieve an ellipsoidal cross section, see plate III.12. The polygonal grains become smaller, and these, quartz and hornblende grains are now about the same size, see plate III.13. The hornblende crystals are more idoblastic and lie within the foliation planes. They may be aligned to define a lineation.

The alteration of ores to sphene may have gone to completion in which case separate grains are strung out parallel to the foliation. However, in some samples no signs of sphene are found, in which case ore grains are distributed throughout the rock. Occasional large plates of hornblende (that may still contain the minute brown inclusions) remain surrounded by the equidimensional planar fabric. With increased deformation these are 'broken' up and lost.

The stretching and flattening of the original fabric continues until the feldspar areas are only recognisable as thin sheets and the rock becomes a homogeneous foliated and lineated rock where the schistosity is defined by the hornblende crystals.

During these last stages of deformation and metamorphism to an amphibolite sohist biotite growth occurs parallel to the foliation. Biotite crystals are generally very small. Epidote may still exist in these fissile schists.

Further metamorphism beyond this stage results in the destruction of this schistosity by a growth of all the mineral phases. Hornblende becomes darker and larger (up to c.1 mm), plagioclase grains, generally oligoclase or andesine, grow in size and may show albite twinning.

As stated by Sutton and Watson (1951 a, b) green pyroxene (augite or diopside) may be found in dykes that have suffered the highest grade of metamorphism. This augite occurs as small (c. 0.5 mm) xenoblastic grains replacing hornblende in rocks where the plagioclase is andesine (c. An35) and where epidote and quartz form symplectites.

Textural changes associated with stages 4 to 6

The growth of crystals give rise to subtle changes in the microscopic texture of the rock. The end result is a granulitic-textured rock, often with a poor foliation. Quartz, epidote, biotite and sphene play only minor roles in this process and it appears that the "pressure" of growth of hornblende and plagioclase are responsible.

With increasing grain size, presumably controlled by the time spent under metamorphic conditions, the following changes take place. From an initial state where the rock texture is fine grained and almost equigranular, the plagioclases are polygonal and the hornblendes are sub-idioblastic, see plate III.13, hornblende becomes euhedral and less acicular and the plagioclase becomes clearer (i.e. not sericitic) and shows albite twinning. The idioblastic shape of the slightly larger hornblendes tends to control the grain boundary relationships, but quartz-plagioclase and plagioclase-plagioclase boundaries are curved.

In the next stage, plagioclase crystals become larger by grain boundary migration until they are bigger than the coexisting hornblendes(see Plates III.14, III.15 and III.16). The plagioclase is dominant and the grain relationships are plagioclase- plagioclase curved boundaries and plagioclase-hornblende are embayed boundaries. Thus the texture is formed by xenoblastic plagioclase and hornblende, the hornblende often taking an 'interstitial' form.

Plagioclase growth continues (up to 3 mm diameter) but does so without the formation of crystal faces. At this stage quartz crystals (0.3 mm diameter) are globular and are excluded from the areas of plagioclase growth (plate III.16). They occur with the hornblende, often being bounded by two or more hornblende crystals, or as inclusions in hornblende. Biotite is xenoblastic and may contain quartz inclusions.

The above changes take place with the increases of crystal size in plagioclase from 0.1 m to 3 mm and in hornblende from 0.2 mm to 2 mm, in quartz from 0.1 m to 0.3 mm. Most of the increase in quartz grain size is achieved quickly after which quartz does not grow, but takes a completely passive rôle.

Dyke rocks that develop granulitic textures have been found north of the Ben Stack line, around Loch Tollie and to the south of Loch Diabaig. Of these areas pyroxene growth has only been recorded from around Rhiconich, north of Loch Laxford. This represents the highest grade achieved by the Laxfordian metamorphism. The coarsest textured dyke rocks collected are from Durness. Lambert and Holland (1972) show that the closure of the radiogenic systems occurred later at Durness than at Loch Laxford and it is believed that the coarser grain size of the mineral phases at Durness, relative to Loch Laxford, reflects this later cooling.

Post-tectonic plagioclase blastesis has been noted from the Tarbet, Torridon and Gairloch areas. These spherical blasts, up to 3 mm in diameter, are now represented by highly sericitized or saussaritized plagioclase grains, (up to 0.5 mm in diameter). The surrounding rock to these areas are conspicuously lacking in plagioclase, for the foliation is defined by an extremely fine quartz, hornblende banding. This form of feldspar growth is geographically linked with presence of garnets in the dykes and basic bodies in the gneisses. The development of garnets in the Torridon area was placed during the first period of post dyke metamorphism by Cresswell (1969). This

This is also the case at Tarbet.

Epidote and biotite appear to be mutually exclusive. Metamorphosed dykes seldom contain both epidote and biotite. It is considered that this is due to the bulk chemistry of the dykes, with biotite indicating a high potash content. Since within one area dykes rich in biotite are found with dykes rich in epidote, the variation in biotite content is considered to be controlled by the composition of the dyke before metamorphism.

Biotite growth starts after hornblende and is generally late-syntectonic to post-tectonic in the more granulitic dyke rocks. The biotite plates, generally brown and often up to 3 mm long, grow across hornblendes and help to define the foliation. Later crystal growth of the hornblende and/or plagioclase causes the biotite plates to be bent and to kink. Biotite growth pre-dated the folding phases (Dg, Dh) which are related to retrogression and which convert them to chlorite (including penninite). In a sample of metamorphosed dyke from Durness, biotite containing quartz inclusions forms a symplectitic texture.

Colourless epidote is sub-idioblastic in the more granulitic textured rocks (i.e. to north of Loch Laxford) and in these rocks characteristically forms symplectites with quartz. (See Plate III.16). Euhedral apatite grains (less than 0.2 mm long) have been found in the granulitic textured dykes of Durness and the highly sheared dyke at Rubh a Tiompain (Tarbet). Quartz crystals in the most highly metamorphosed dykes are large (up to 1 mm in diameter) and contain minute lines of inclusions that may have been inclusion bubbles.

The relationship between sphene and the ore minerals is complex and can only be briefly dealt with in this study. The conversion of the original igneous metalliferous ores takes place at various stages in the progressive metamorphism and deformation. In some rocks all the ore has been replaced by sphene, while in others sphene and ores coexist in the same sample, or only ore occurs. At the limits of metamorphic growth either sphene or large ore (magnetite) crystals may be present so that no general scheme linking sphene/ore relationships with extent of metamorphism has been noticed. The controls that might dictate the variation described are multiple. Bulk chemistry, ore chemistry, temperature, pressure and deformation may all play a part.

Metamorphism of the dolerites does not differ from that shown by the gabbros except that, because of their fine-grained nature, the original igneous texture is more quickly destroyed by recrystallization and the opaque ores and biotite are found in greater quantities.

The metadolerites of Creag Mhor Tollaidh are unique in that they contain meionitic (Ca rich) scapolite. The texture of the dykes of this area is granulitic and the scapolite grains play the same texture-forming rôle as plagioclase. These textural characteristics, together with the fact that the plagioclase composition is An 45 (andesine), and that the plagioclase crystals contain symplectite growths of epidote and quartz, suggests that the grade of Laxfordian metamorphism is equivalent to that found at Rhiconich, where pyroxenes are found in the metamorphosed dykes.

Hietanen (1967) found that rocks containing meionitic scapolite and andesine belonged to the sillimanite-muscovite subfacies of the upper amphibolite facies.

Metamorphism of the Picritic dykes.

The metamorphic changes in the picritic dykes of the Assynt area have been described by Tarney (1964 and 1973) as follows:

Stage 1) Development of a small amount of chlorite between olivine and plagioclase,

Stage 2) Formation of tremolite coronas around olivine in contact with plagioclase,

Stage 3) Exsolution of magnetite from biotite before being transformed to Mg chlorite,

Stage 4) Complete replacement of plagioclase by tremolite,

Stage 5) Beginning of the break down of sub-calcic augites to Mg-tremolite and haematite,

Stage 6) Recrystallization of tremolites and reduction of haematite to magnetite. No augite remains.

Stage 7) Slight replacement of orthopyroxene to tremolite,

Stage 8) Further recrystallization of tremolite and appearance of Mg chlorite, olivine and orthopyroxene remaining relatively stable.

Stage 9) Local replacement of orthopyroxene by anthophyllite.

Stage 10) Replacement of olivine and with high CO_2 partial pressure, dolomite may appear.

The first two stages are here considered to be autometamorphic since they appear in olivine gabbros in areas where the gabbros show autometamorphism but no other signs of 'normal' metamorphism.

Tarney argues that metamorphism must have taken place at temperatures greater than 480°C for the olivines to remain stable and not to have been converted to serpentine. Martin (1971) puts the temperature range for the serpentinization as between 200° - 450°C.

Experimental data of Greenwood (1963, 1971) on the stability of anthophyllite indicates, for P_{H_2O} 1 to 4 kb., that a temperature of greater than 670°C was reached, whereas the presence of talc with anthophyllite gives an upper temperature limit for the metamorphism of about 700°C for the Assynt area.

Metamorphic textures developed in these rocks are extremely variable and may be described as generally chaotic. The listed stages of alteration (after Tarney op. cit) provide a good brief description of general textures. New crystal phases, except early-formed chlorite and dolomite, are idioblastic and occur within one sample over a great size range. Large crystals typically are not aligned and have grown over earlier textures. This is especially true of tremolite, talc and the dolomitic carbonate.

Metamorphism has taken a place along joints in otherwise unmetamorphosed picrite dykes. This has been found about 100 m north of the Canisp Shear Belt at Clachtoll (NC 045 267), where metamorphism up to stage 8 has taken place leaving orthopyroxenes and olivine stable. The centre of the symmetrical zone of alteration is rich in talc and dolomite (stage 10).

These relationships strongly suggest that fluid phases leaving the Canisp Shear belt were the direct cause of localized metamorphism, and that jointing of the picrite had occurred before metamorphism.

Meta-picrites found near Creag Mhor Thollaidh are composed of interlocking idiomorphic to sub-idiomorphic hornblende crystals

(0.01 to 1 mm in diameter). These rocks are at the highest grade found and show that metamorphism had gone beyond stage 10 of Tarney (op. cit.) and passed across the immiscability gap between hornblendes and actinolitic amphiboles (see Klein 1969). This suggests that the temperature of metamorphism at Creag Mhor Thollaidh was greater than 700°C.

Schistosity in these rocks is confined to the area near to the Canisp Shear Belt, where folding of this schistosity has also taken place. The schistosity is often defined by alignment of chlorite and talc crystals but in many cases it is a fracture cleavage. This fracture cleavage is not associated with any homogeneous deformation because the areas of concentration of ores produced on the breakdown of augite are not deformed. Chlorite growth within the fractures is parallel to the fractures but talc is seen to grow across this schistosity. Tarney depicts tremolite growth taking place after schistosity formation.

The schistosity produced is roughly parallel to the margins of the picrite dykes but the angular relationships cannot be exactly defined because of the almost total absence of meta-picrite gneiss contacts.

Tarney (1973, p 116) considers that the margins of some early basic dykes had suffered deformation under amphibolite-facies conditions before the picrites were emplaced because a basic dyke picrite dyke contact shows a foliated basic dyke in contact with an unfoliated picrite (Tarney op. cit. plate 1). The foliation of the basic dyke is at 15° to the contact. However since extensive post-tectonic recrystallization has taken place in the picrites and that deformation of the margins of basic dykes often produces an oblique foliation then the post-deformation intrusion of the picrites cannot be proved by the relationships described by Tarney. For the relationship shown can be explained by a picrite/basic dyke contact which has been deformed and metamorphosed with the metamorphosis of the picrite alone continuing after the deformation had ceased.

'Green' Dykes

Members of this set of dykes have been recorded from the whole length of the Lewisian of the mainland. Peach et al (1907), Crane (1972), Cresswell (1969) and Tarney (1973) have all described them.

The unmetamorphosed equivalents of these rocks have not been recognised, but their normative composition suggests that they may have been norites with c.35% plagioclase. As the norites have only been recognised where unmetamorphosed they could be equivalent to the green dykes.

In their unfoliated form these pale green rocks may show remnant patches of plagioclase (oligoclase) and biotite which are now overgrown by a mat of interlocking idioblastic and subidioblastic laths of actinolite and hornblende. Cresswell (1969) shows that the amount of biotite increases towards the centre of the bodies. The amount of chlorite is variable and may form up to 30% of the rock, amphibole may form up to 95% and plagioclase varies upto 15%. Opaque ores are very occasionally found and sphene is found in accessory amounts.

Any foliation present is defined by the alignment of the amphibole laths and the micas. Where sufficient plagioclase remains after amphibole growth, it has recrystallized into polygonal grains and the plagioclase areas are flattended parallel to the foliation.

In areas of high amphibolite facies Laxfordian metamorphism this species of rock no longer exists as an actinolite-chlorite rock but is transformed into a coarse grained (c. 2mm) hornblende rich rock which has a granulitic texture, where the amphiboles are idioblastic to subidioblastic. The hornblendes have very high birefringence (c. 0.025) and show exsolution lamellae of another amphibole, parallel to (100) and ($\bar{1}$01). Any micas present are now green or brown biotite. The change between the two is rapid and the intermediate stages have not been recognised. Rocks that show this new texture have been found at Durness and Rubha Ruadh. A sample from Loch Diabaig shows two amphiboles coexisting with biotite. The two amphiboles are cummingtonite and hornblende.

The three stages in the amphibole development are as follows:

1) Actinolite(and chlorite)

2) Cummingtonite and hornblende ($\pm$ chlorite, actinolite) (Transitional)

3) Hornblende (with exsolution lamellae - possibly cummingtonite)

Stage (1) indicates greenschist facies conditions, although adjacent gabbroic dykes are at amphibolite facies. This assemblage is therefore regarded as being near to the greenschist - amphibolite facies transition, probably low amphibolite facies. Between the actinolite and hornblende groups of amphibole there is a miscibility gap (Shido and Miyashiro 1959) and the transition from stage 1 to stage 3 marks this gap with the breakdown of chlorite providing Al^{3+} for the change of actinolite, $Ca_2(MgFe)_5(OH)_2(Si_4O_{11})_2$, to hornblende, $Ca_2(Mg,Fe,Al)_5(OH)_2\left[(Si,Al)_4O_{11}\right]_2$.

The metamorphic changes described are attributed to the earliest and most widespread metamorphism which accompanied the earliest and most widespread metamorphism which accompanied the earliest deformation and may have continued to take place during later deformation. These later deformations are essentially those involved in the folding of the schistose dyke sheets where the accompanying metamorphism causes the segregation of quartz to produce large (c. 5 mm long) multi-granular occelli. These occelli are aligned parallel to D_f shear planes to the north of Loch Laxford, at Tarbet and Cnoc Phollain Beithe and now form a lineation parallel to F_g fold axes around Loch Tollie.

Retrogression of earlier metamorphic assemblages has taken place during the last deformation (folding) phases in the south. However, apart from the conversion of biotite to chlorite and the growth of an epidote parallel to (001), no other effects have been established.

Metamorphic Grade

Except for the late stage retrogression of metamorphic assemblages under greenschist-facies conditions, the metamorphism of the dykes has been uniformly under amphibolite-facies conditions. In the eentral region amphibolite facies conditions of pressure and temperature prevailed, but in the northern and southern areas of greater Laxfordian activity the metamorphic conditions were those of the upper limit of the amphibolite facies.

The highest grade seen in the area studied were found to the north of Loch Laxford, where the grade is near to the granulite facies. However, since only a small amount of clinopyroxene is present with the dark green hornblende and sphene the rocks must be considered to be within the amphibolite facies (see Engel and Engel 1960). The assemblage cummingtonite and hornblende found in the 'green' dykes at Torridon points to the silliminite-almandine-orthoclase subfacies of the Barrovian amphibolite facies (Winkler 1967), and a temperature of c. 650-700°C at 8 to 9 kbar pressure. The metamorphic assemblages found in the meta-picrites and the 'green' dykes of the central region are those found in the staurolite and kyanite zone of the amphibolite facies of New Hampshire as described by Lyon (1955).

Because of the absence of "grade indicating" minerals in the metamorphosed dykes little more than the general statement that grade increases away from the central region can be made. Textural variations provide a subjective indication of grade for the earlier phases of metamorphism, but these are often destroyed by later deformation. However, these show that the metamorphic gradient at the Laxfordian fronts, especially the norther front, are high and that there is very little variation on either side of these fronts. For example the change in grade of metamorphism around the Ben Stack line changes from the characteristic low amphibolite facies to near granulite facies in about 5 km. Because of the presence of the tectonically isolated block of high grade rocks of around Loch Tollie it appears that the metamorphic gradients have been increased by the relative uplift of the areas of lower grade rocks by zones shearing and tight folding. Since planar structures developed at Laxford and Tollie dip towards the central block a reverse fault movement is suggested (cf Beach et al 1974).

Apart from the evidence provided by Fyfe and Beach (1972) of biotite-kyanite assemblages found in Laxfordian shear zones at Scourie, only indirect evidence points to metamorphism having taken place at medium pressures (> 5 kbar).

The appearance of anthophyllite and talc suggests that temperatures may have reached about 670°C in the central block whereas in the northern and southern Laxfordian belts the occurrence of sillimanite-almandine-orthoclase subfacies suggests temperatures of 650° - 700°C (at 8-9 kbar).

Nature of Metamorphism

The central region, where metamorphism has been lowest, provides the exposures that offer information about the nature of the Laxfordian metamorphism of the dykes. Since the higher grades of metamorphism and greater deformations of the areas behind the Laxfordian fronts would tend to destroy similar evidence, the conclusions derived from the central region can only be inferred to have acted in those areas.

The occurrence of zones of metamorphosed dyke rock adjacent to joints within otherwise unmetamorphosed rock, both gabbroic and picritic (see Plates III.17a and III.17b) indicates that the dykes had cooled down sufficiently to fracture and were at a relatively high crustal level at some time before the onset of the Laxfordian metamorphism. Moreover these joint centred areas of metamorphism suggest that, for some areas, temperature and pressure conditions alone were not sufficient to metamorphose the dykes, but that fluids were important.

Fyfe and Beach (1972) describe Laxfordian shear zones in the gneisses from Scourie and conclude that these shears were the sites of "massive fluid flow, the fluids rising up" an "inverted thermal gradient" to cause oxidation in the zones. Petrographical and geochemical evidence (see chapter IV) suggests that the movement of material between unsheared and sheared metamorphosed dyke rock has taken place.

The presence of metamorphosed contacts and unmetamorphosed centres to dykes also deserves discussion. Many wide, and some narrow, dykes show metamorphosed, amphibolite margins although their centres remain unaffected by metamorphism. The metamorphism can be attributed to the presence of the zones of deformation. These generally narrow shear zones may have promoted the flow of hot fluids which could have provided the activation energy to allow metamorphic reaction, or may have produced sufficient frictional energy to trigger the reaction or even to have caused a rise of temperature to amphibolite facies conditions. The presence of pseudotachylites associated with these narrow shear zones suggests that great quantities of frictional heat were produced and that this heat provided the activation energy needed for metamorphic reactions in areas where the pressure and, more importantly, the temperature was only just sufficient to allow reaction to proceed.

Fabric of sheared dykes

Heterogeneous deformation has been recognised in four main aspects. These are:-

a) Large shear belts that cut across dykes and result from Df deformation of the Kylesku - Scourie area.

b) Narrow zones of shearing at dyke margins.

c) Narrow shear zones confined to dykes (found throughout the central region) that are asymptotic to the dyke margins.

d) Microscopic, closely-spaced shear planes that are confined to a dyke (generally only small, c. 10 cm dykes) and where the gneiss at the contacts is unaffected.

In each case the unsheared dyke rock may be at stage 2 or 3 of Sutton and Watson (op. cit.).

Shear belts

a) The example taken to show this type is taken from Loch am Obain and shown in Plates III.18a and III.18b. The undeformed dyke is at the stage when the plagioclases are hardly sericitized and are not recrystallizing. However, they may be bent. The pyroxenes have been completely replaced by hornblende but apatite, ores and micrographic intergrowths remain.

In the shear the dyke has been converted into a fissile schist. The plagioclase areas have recrystallized into zoned oligoclase polygons and extremely flattened. Elongate hornblende crystals (up to 0.8 mm long) are subidioblastic and aligned to define the foliation but a few hornblende plates with the dusty inclusions still exist. Ores, sphene and apatite are present. Biotite plates lie parallel to the schistosity but in many cases have been retrogressed to chlorite. This retrogression and the separate growth of chlorite is post-tectonic (post Df).

b) Contact shearing. An example is taken from a gabbro dyke at Tarbet where a chilled gabbro has been deformed by simple shear about the contact, see Plates III.19a and III.19b.

The undeformed rock still contains original, albeit highly saussuritized, plagioclase laths (1.5 mm long) in a matrix of hornblende, quartz and opaques. Areas of quartz and hornblende crystals, each c. 0.01 mm in diameter, and relic mafic minerals (up to 2 mm long) are separated from the plagioclases by coarser hornblende, ore (and minor quartz) aggregate, (hornblende c. 0.05 mm diameter). Idiomorphic epidote is found growing in the feldspar.

As the amount of strain increases towards the margin, the following changes take place. At $\gamma^* = 3.0$ the plagioclases laths begin to recrystallize but are extremely saussuritized. The finer quartz-hornblende masses become less distinct and coarser (0.08 mm). The plagioclase areas are still distinctly lath-shaped and lie nearly parallel to the foliation. However, the surrounding areas have been elongated parallel to the foliation. Deformation is concentrated in

*(Shear strain measurements (γ) calculated as described by Ramsay and Graham (1970) from the angle between the foliation and zone boundaries)

the hornblende-quartz-ore areas.

Recrystallization of the plagioclase areas into polygonal grains is complete when $\gamma = 7.0$. At this stage they have lost their lath shape.

At $\gamma = 10$ the grain size of hornblende is (0.1 mm) and the hornblende, quartz and opaques are evenly distributed. The plagioclase polygons remain together and the foliation is defined by the elongation of the plagioclase areas and the alignment of subidioblastic grains.

At $\gamma \simeq 35$ the plagioclase areas are very thin (0.1 mm) and almost imperceptible, being shown by a train of single crystals. Plagioclase is found mixed with the hornblende-quartz matrix, and epidote is no longer present.

c) Intra-dyke shear zones

An example from south of Tarbet shows that the undeformed dyke at the edge of the shear contains no pyroxene and the central areas of the mafic minerals is now quartz and hornblende. Plagioclases are sericitic and are red in hand specimen. Perfect igneous textures remain, with hornblende and ore being interstitial between the plagioclase crystals.

At $\gamma = 3\frac{1}{2}$, the plagioclase crystals are partly recrystallized into highly sericitized plagioclase polygons and large crystals of carbonate are present. Where polygonization of the feldspar has occurred, the whole rock shows a parallelism of textures due to the elongation of the original fabric. However, in the areas where polygonization has not occurred the plagioclase areas have apparently remained sufficiently rigid to prevent change in shape of the texture. Here the deformation is brittle and has taken place by fracturing with the formation of pseudotachylite veins.

At the lowest strains the quartz-hornblende masses are elongated but the remaining hornblende is deformed by the crystals breaking into cleavage fragments and shuffling. With increasing shear strain, hornblende becomes mixed into the plagioclase areas which become more elongated, the hornblende grows, the quartz-rich zones disappear and then hornblende is seen growing within the plagioclase blebs.

At the highest strains ($\gamma > 11$) the hornblende crystals have grown to 1 mm in diameter and obliterate the previous texture. Up to these strains, homogenization had continued by the stretching of the plagioclase blebs and the increased growth of hornblende in these areas. The mafic areas are at this point made up of idiomorphic to subidiomorphic hornblendes aligned parallel to the foliation.

Another pair of samples of a shear zone and the adjacent undeformed dyke rock show the following features, see Plates III.20a and III.20b. In the undeformed material the plagioclases have almost been replaced by innumerable minute epidote crystals. This is the only alteration product of most of the igneous plagioclases that have not recrystallized into polygons. However, some of the plagioclases have recrystallized. The replacement of the mafic minerals to hornblende is complete.

The sheared material is almost homogeneous with thin lines of small plagioclase laths, and the alignment of the b-axes of the subidioblastic hornblendes defining the schistosity. No epidote is found in the schists.

d) <u>Pervasive shears in dykelets (see Plate III.21)</u>

The fabric may best be described as ribbons of epidote, quartz, plagioclase, and hornblende aggregates (0.05 mm grain size) between zones of coarser (0.1 mm) material. The fine zones are homogeneous and 1 to 2 mm wide. The coarse zones show deformed relict ophitic textures and contain large plates of hornblende with the quartz or dust inclusions produced by the static replacement of pyroxene to hornblende.

The finer grained ribbons represent zones of movement and become more closely spaced nearer to the dyke/gneiss contact. Therefore the area of relatively undeformed material almost disappears, the only relics of the original metamorphic texture that remain are the occasional "rolled" hornblende plates. These slip planes meet the dyke contact at 25°, but the gneiss remains undeformed.

Annealing Recrystallization of Feldspars

At stage 3 of metamorphism (Sutton and Watson 1951a), after the replacement of pyroxenes by hornblende has been completed, previously sericitized and saussuritized plagioclase laths (An_{35-50}) are transformed into a mosaic of small, regular, straight-sided polygons of plagioclase (andesine and oligoclase). These polygons, although small (< 0.1 mm diameter), are frequently zoned often in an oscillatory manner.

The 'polygonization' of the feldspars occurs with the retention of the original texture of the dykes but may also be associated with the development of a foliation, in which case the deformed shape of the feldspar masses is made up of these grains. Recrystallization may occur at the ends of two touching plagioclase laths which suggests that the iniation of recrystallization is due to strain.

This style of recrystallization is described as 'annealing recrystallization' when found in metals, and is associated with the release of stored strain energy. Here the strain energy is taken to have originated from tectonic stresses whether or not deformation has taken place. Recrystallization is dependent on two variables; temperature and amount of strain. Because of this, the poiht at which annealing recrystallization takes place may or may not represent a single temperature but may occur over a range of temperatures (Reed-Hill, 1964).

The problems of oscillatory zoned polygons, as shown in Plate III.24, has been discussed by Cresswell (1969) who considers the concept that the zoning reflects changes in grade during crystal growth. This is readily applicable since the zoning is often centred in the middle of the crystals.

However Byerly and Vogel (1973) suggested that, during recrystallization of plagioclase, impurities (including Na or Ca) that were not needed in the plagioclase stable at a given set of conditions would diffuse to high energy areas within a crystal,i.e. grain boundaries. This may explain why in most crystals there is a narrow zone of different composition at the crystal edge. If this was the case 'normal' zoned crystals suggest that the centre was in equilibrium with conditions and that the edges were enriched in Na by diffusion. This requires the original feldspar before polygonization (which occurs after epidote formation) to have contained more Na than needed. This suggests an increase in grade from before to after recrystallization. Conversely, reverse zoning would show that the pre-polygonization plagioclase lath had an anorthite content higher than the ideal crystals that grew on recrystallization,in which case the excess Ca would diffuse to the crystal boundaries. This suggests either a decrease in grade or that polygonization affected a plagioclase whose igneous composition had not been greatly altered by the earliest stages of metamorphism.

Evidence supporting the diffusion model is that the oscillatory zoning, which is often marked by a sharp increases in anorthite content, has a polygonal outline. Such a zone may represent the old edge of the crystal in which case the surrounding area marks, a later, rapid, stage of crystal growth. Using this model the cutting off of zones of one grain by another can be explained by the growth of an adjacent crystal. Larger grains are characteristically not zoned, except for the very edge. Since larger grains suggest slower growth, probably due to less pre-recrystallization straining, their lack of zonation may be because diffusion, to exclude impurities, kept pace with growth.

Oscillatory zoned crystals with An_{20} cores and An_{10} rims (compositions determined by Schuster's method) have been found in deformed and undeformed samples from near Cnoc Phollain Beithe where the metamorphism is associated with the heterogeneous D_e deformation. Assuming isobaric conditions and that the crystal composition reflects changing metamorphic conditions, then the zonation indicates a decrease in temperature as the polygonal grains grew from points of nucleation. Recrystallization therefore took place with cooling after deformation. Oscillatory zoned polygonal grains with an overall 'reverse' zonal scheme have been found in a sample, from Achmelvich Bay, that has been affected by D_f shearing. The central parts of the grains are c. An_{20}, the edges are c. An_{30}. Reverse zoning of this nature would represent the increase in temperature after the end of straining.

As the variation in composition of the feldspars is within the oligioclase range, the metamorphisms associated with D_e and D_f are in amphibolite facies. Taking the evidence from both localities it suggests that the complex cooled between D_e and D_f.

The composition of the centres of crystals from samples from the two areas are both An_{20} and in one case the edges are An_{30}, and the other they are An_{10}. Then according to the diffusion model the grade of metamorphism of both areas during both deformations was identical and the 'reverse' and 'normal' zoning reflects the amount of pre-polygonization loss of Ca.

Forty one dyke rocks have been analysed for major and trace elements. The rocks were taken from 32 intrusions from localities from Tarbet (Sutherland) to Loch Diabaig (Ross). Samples were chosen to include the main dyke varieties, gabbro, dolerite, picrite and 'green' dykes and to represent, as far as possible, the centre and chill of the intrusions. One sample, Ø 31, is from an igneous xenolith of an intrusion that was sampled at intervals from one contact to the centre (Ø 29-Ø 32).

Few of the samples analysed show an igneous mineralogy and many are foliated. Some foliated and unfoliated pairs of samples were chosen from the same intrusion in order to determine whether any chemical variations are due to metamorphic redistribution.

The samples analysed are listed below, with relevant details of mineralogy. (unmet-unmetamorphosed, met-metamorphosed, fol-foliated)

Gabbroic Dyke Samples.

SCM - Scourie Bay (unmet).

14 - Dyklet from Cnoc Phollain Beithe - (met and fol).

35a - Multiple intrusion - Rubh an Trompain - (met and fol).

Ø 14 - Tarbet - (minor met).

Ø 17 - Loch an Obain (minor met).

Ø 18 " (fol).

Ø 25 - Tarbet (minor met).

Ø 27 - Achmelvich Bay, contact (met and fol)

Ø 28 sh " " (met and fol)

Ø 28 op " " (met) adjacent to Ø 28 s

Ø 29 - Achmelvich Bay, contact (met and fol).

Ø 30 - Achmelvich Bay, (met).

Ø 31 " " xenolith (met).

Ø 32 " " centre (met).

Ø 36 - Unapool (unmet).

Ø 198 - Loch Assynt (met).

Ø 199-Loch Assynt (met) (described as 'green dyke' in Survey Memoir).

Ø 246- Badnaban (unmet. olivine bearing).

Ø 262 - Badnaban (unmet).

Ø 366 - Loch Diabaig (met).

Ø 384 An Ruadh Mheallan, Torridon (met).

Doleritic Dyke Samples

335b Ruhb an Tiompaign (met and fol).

Ø 13 - Tarbet (met).

Ø 28 - Tarbet (met and fol).

Ø 35 - Achmelvich Bay (met and fol).

Ø 114 - Tarbet (met and fol).

Ø 182 - Loch Assynt (met).

Ø 227 - Loch Assynt (met).

Ø 234-Loch Assynt (unmet)

Ø 304-Creag Mhor Thollaidh (met, scapolite bearing).

Ø 344 - Gruinard River (met).

Ø 384f - An Ruadh Mheallan, Torridon (met)

Ø 391-An Ruadh Mheallan, Torridon (met and fol).

Picritic dyke samples

391 - Achmelvich Bay (met and fol).

Ø 113 - Tarbet (cumulate, unmet).

Ø 192 - Loch Assynt (met).

Ø 228 - Loch Assynt (unmet).

Ø 376-An Ruadh Mheallan, Torridon (met)

'Green' dyke samples

Ø 328 - Gruinard River (met).

Ø 375 Loch Diabaig (met).

For each element the mean content of each rock group will be given, followed by the standard deviation. As only two 'green' dykes have been analysed only the average of the two results obtained for each element can be given,

The geochemistry of the dykes analysed is compared to the average composition of twenty-seven Precambrian dykes of similar mineralogy, composition and age (post 2,5 x 10^9 yrs) from Wyoming that have been described by Condie et al (1969). Trace element concentrations are compared to the average concentration of tholeiitic basalts given by Prinz (1967).

For each trace element measured by X.R.F. the lower detection limit (L.D.L.) will be given.

Major Elements

Silica, (SiO_2)

The rocks analysed contain between 39% and 55% silica. The gabbroic, doleritic and 'green' dykes have between 45% and 55%. The picritic rocks have a 12% range in SiO_2 content from 39% to 51%. This shows that although ultramafic, the picrites are not necessarily silica poor.

This may be directly related to pyroxene content since the silica-rich picrites are those that contain, or are thought to have contained, relatively small amounts of olivine and large amounts of orthopyroxene.

Fig. VI.3 shows that the vast majority of the dolerites, 10 out of 12, have silica contents between 48½% and 50%. This is considered to be significant because of the large range in silica contents of the other groups.

The average and standard deviation in the SiO_2 content of the rock groups are:-

gabbros	49.81% (2.07%)
dolerites	49.89% (1.71%)
picrites	45.88% (5.22%)
'green' dykes	48.88%
Wyoming diabases	49.0% (0.61%)

<u>Titanium, (TiO_2)</u>

gabbros	1.68% (0.62%)
dolerites	1.56% (0.72%)
picrites	0.38% (0.15%)
'green' dykes	0.68%
Wyoming diabases	1.44% (0.61%)

The titanium concentration decreases with increasing solidification index ($MgOx100/MgO+FeO+Fe_2O_3+Na_2O+K_2O$) and the highest value of 3.04% TiO_2 is in a gabbro. The lowest values are from the picrites and 'green' dykes (0.16 to 0.56% and 0.53 to 0.82% respectively). The gabbros and dolerites contain similar amounts of TiO_2, between 1.0 and 3.0%.

The curve showing a smooth decrease of TiO_2 content with solidification index, shown in Fig. IV.1a, does not include two samples Ø246 and Ø199, which contain more TiO_2 than the other rocks of similar solidification index. Ø246 contains titanaugite and possibly Ø199, (a meta-gabbro), did also. The general increase of titanium contents with differentiation, which is indicated by decreasing solidification index, is explained by the increase in ore (Ti in ilmenite) and hornblende content (Ti^{4+} substitute for Al^{3+}). These minerals are the last to crystallize in the gabbros and dolerites.

Alumina (Al_2O_3)

gabbros	13.02% (1.56%)
dolerites	13.14% (1.99%)
picrites	6.07% (1.49%)
'green' dykes	8.61%
Wyoming diabases	12.7% (1.2%)

Alumina shows a gradual increase from the picrites (c. 5%) to the gabbros and dolerites (c. 16%). The dolerites tend to contain more alumina than the gabbros. The gabbroic xenolith (Ø31) contains 17.60% Al_2O_3, which reflects the high plagioclase content of this rock. Alumina content decreases from S.I. (solidification index) = 30% to S.I. = 10%, i.e. with increasing differentiation, and the high aluminium content in the cognate xenolith may indicate that fractionation of alumina-rich phases has taken place (c.f. Wager and Brown 1968)

Iron (Fe)

Total iron, expressed as Fe_2O_3, for all rock types is variable and falls between 12% and 22%. The highest values belong to those rocks (gabbros and dolerites) which have lower values of solidification index.

gabbros	16.60% (2.58%)
dolerites	15.81% (2.95%)
picrites	14.60% (2.31%)
'green' dykes	14.73%
Wyoming diabases	15.0% (2.0%)

Individual samples of the gabbros and the dolerites contain over 20% iron and therefore the rocks of the 'Scourie dyke' suite belong to a series where strong iron enrichment has taken place. The plot of alkalis, iron and magnesia (i.e. A'.F'.M'., Fig. IV.4) shows that the iron enrichment trend followed is similar to that shown by the Skaergaard intrusion.

The nine rocks that hold positions furthest along the course of differentiation come from dykes that lie outside the 'central zone'. No reason for this can be given.

Manganese (MnO)

The concentration of manganese in the rocks analysed shows very little variation. MnO makes up between 0.14% and 0.19% of the picrites, 0.21% and 0.28% of the 'green' dykes and between 0.16% and 0.27% of the gabbros and dolerites. The proportion of manganese shows an increase with differentiation, as shown by decreasing S.I.

Fig. IV.1a.

gabbros	0.22% (0.02%)
dolerites	0.22% (0.03%)
picrites	0.18% (0.03%)
'green' dykes	0.25%
Wyoming diabases	0.23% (0.03%)

Magnesia (MgO)

Magnesia content shows great variation. The picrites, which contain or contained olivine and orthopyroxene, contain between 16% and 28% MgO. The olivine gabbro contains over 13% MgO. The 'green' dykes, that only show possible relics of olivine are also magnesium rich (c. 16% MgO). The dolerites and gabbros are relatively poor in magnesium. They contain between 3% and 10% MgO.

gabbros	6.26% (2.03%)
dolerites	6.00% (1.62%)
picrites	23.3% (4.31%)
'green' dykes	15.7%
Wyoming diabases	7.07 % (1.72%)

Calcium, (CaO)

gabbros	9.60% (1.20%)
dolerites	9.90% (1.27%)
picrites	2.23% (4.81%)
'green' dykes	8.13%
Wyoming diabases	9.43% (1.30%)

In the same way as for iron, the calcium content of the picrites falls within a wide range of 2% to 11%. This probably reflects the original modal content of calcic pyroxenes. The calcium contents of dolerites and gabbros are similar and show only a diffuse trend against solidification index with a maximum calcium content of c.11% at S.I. = c.25% decreasing at higher and lower values of S.I. Because the igneous petrology of the basic dykes is not fully known, the reasons for this increase and decrease with S.I. is not clear.

It is most probably the result of interaction between plagioclase content and the An content of the plagioclase present. The plagioclase xenolith, Ø31 which has probably formed by plagioclase accumulation, is not rich in CaO but has a high Na_2O content, suggesting that the plagioclases were albite rich.

Specimens taken from and adjacent to a narrow shear zone, (Ø28 sh and Ø28 op) have CaO contents of 9.52% and 11.2% respectively. Other dykes from the close vicinity (Ø29, Ø30, Ø32) and Ø27 which is from the same intrusion, have almost identical chemistry as Ø28 sh and Ø28 op but contain between 9.80% and 10.80% CaO. The apparent increase in CaO in the unsheared sample, and the decrease in the sheared sample is believed to be due to the movement of calcium out of the shear zone.

Soda (Na_2O)

As expected soda is low in the picrites (between 0.25% and 1.68% Na_2O). The 'green' dykes contain between 0.58% and 2,00% and the gabbros and dolerites contain similar concentrations of soda from 1.6% to 3.5%. The dolerites have a lower average soda content than the gabbros. The xenolith Ø31 has the highest concentration measured of 3.78% Na_2O. This points to the major sodium carrying phase being plagioclase which is concentrated in this xenolith and in the normal gabbroic dykes compared to the dolerites.

gabbros	2.33% (0.38%)
dolerites	2.12% (0.54%)
picrites	0.82% (0.56%)
'green' dykes	1.33%
Wyoming diabases	2.18% (0.41%)

Potash (K_2O)

Potash content of the set of rocks analysed is extremely variable and reaches a maximum of 1.8% in a sample of dolerite. The picrites contain the least amounts of potassium, between 0.09% and 0.8% K_2O. The sample (Ø228) that contains 0.8% K_2O shows an igneous mineralogy and contains interstitial biotite. The potassium-carrying phase of the picrites is therefore assumed to have been biotite. The 'green' dykes show similar amounts of potassium as the gabbros, which have between 0.3 and 1.2% K_2O. The dolerites, however, tend to contain more potassium than the gabbros.

gabbros	0.68%	(0.27%)
dolerites	0.89%	(0.38%)
picrites	0.34%	(0.29%)
'green' dykes	0.61%	
Wyoming diabases	0.95%	(0.44%)

An increase of about 0.5% K_2O is shown in a sheared rock (Ø28 sh) compared with of the undeformed surrounding rock (Ø28 op), which contains c. 0.4% K_2O. It appears that either there has been a concentration of potassium in the shear from a large 'catchment' area or potassium-rich fluids have passed through the shear zone.

Phosphor (P_2O_5)

Like TiO_2, total iron, and MnO, phosphorous increases with decreasing solidification index. P_2O_5 concentrations of between 0.02% and 0.05% are found in the picrites, 0.05 and 0.06% in the 'green' dykes and 0.04% and 0.28% in the gabbros and dolerites. The increase in phosphorous with differentiation is directly related to the amount of apatite which is common in the unmetamorphosed, and often in the metamorphosed, gabbroic and doleritic rocks.

gabbros	0.13%	(0.06%)
dolerites	0.12%	(0.06%)
picrites	0.03%	(0.01%)
'green' dykes	0.05½%	
Wyoming diabases	..... not determined	

Trace Element Geochemistry

Group IA elements

Lithium, Li

The lithium contents of the twelve rocks (gabbros and dolerites) analysed range from zero to 25 p.p.m. and show a positive correlation with solidification index. The relation between Mg (here indicated by solidification index) and Li is well known (see Heier 1962) and is due to their similar ionic radii (Li^+ 0.68 Å, Mg^{2+} 0.67 Å)

The average content of the rocks analysed is 9.9 p.p.m. - very close to the average Li content of tholeiite basalts given by Prinz (1967) as 10 p.p.m.

Rubidium Rb, (L.D.L.= 0.6 p.p.m.)

Rubidium concentrations of the rocks analysed are below 25 p.p.m. except for one rock, a dolerite, which contains 69 p.p.m. This anomalously high concentration is in a rock of unusually high potassium content.

gabbros	8.0 p.p.m.	(7.4 p.p.m.)
dolerites	15.5 p.p.m.	(17.6 p.p.m.)
picrites	5.9 p.p.m.	(7.2 p.p.m.)
'green' dykes	12 p.p.m.	
Wyoming diabases	45 p.p.m.	(29 p.p.m.)
tholeiitic basalts	17 p.p.m.	

After taking into account the very high Rb content of one of the dolerites, there is no marked difference between the Rb contents of the different groups of rocks and within each group certain individuals contain less than the lower detection limit.

The variation in Rb content appears to be the direct result of metamorphism, which has reduced the amount of rubidium present, often to below the lower detection limit of 0.6 p.p.m. All the rocks that contain less than 0.6 p.p.m. (i.e. effectively zero Rb), have been metamorphosed. Some metamorphosed rocks (often foliated) contain similar concentrations of Rb to the unmetamorphosed rocks. This may be explained in the following way (see Fig. IV.5). Those rocks that contain measurable amounts of rubidium, and are metamorphosed, contain biotite (or retrogressive chlorite). The K:Rb ratios of the unmetamorphosed rocks are similar (c. 500). It would appear that on weak metamorphism without deformation, where biotite is not formed, rubidium is greatly depleted causing very large K:Rb ratios. This is probably because no mineral phases are present to retain Rb^+ ions. Therefore the presence of an Rb^+ accepting mineral (i.e. biotite, where Rb^+ substitutes for K^+)on metamorphism determines whether rubidium will remain the rock or will be lost.

There is only one rock (Ø29) that does not obey the rule that metamorphosed rocks with biotite will contain large amounts of Rb and vice versa. Like all the other rocks taken from this dyke it contains 'zero' rubidium but it does contain biotite whereas the others do not. However in this sample (which comes from the margin of the dyke) the biotite is post-tectonic, having grown across the schistosity. It may therefore be concluded that Rb was lost on the metamorphism that was accompanied by deformation and was unavailable during the later growth of biotite, which could have grown in response to the influx of potassium from the adjacent gneisses.

Group IIA elements

Strontium, Sr (L.D.L. = 0.8 p.p.m.) and Barium, Ba (L.D.L. = 6 p.p.m.)

	Strontium		Barium
gabbros	238 p.p.m.	(114 p.p.m.)	196 p.p.m. (31 p.p.m.)
dolerites	213 p.p.m.	(108 p.p.m.)	190 p.p.m. (52 p.p.m.)
picrites	74 p.p.m.	(40 p.p.m.)	167 p.p.m. (45 p.p.m.)
'green' dykes	58 p.p.m.		167 p.p.m.
Wyoming diabases	186 p.p.m.	(58 p.p.m.)	320 p.p.m.(214 p.p.m.)
Tholeiitic basalts	450 p.p.m.		244 p.p.m.

Strontium (Sr) The majority of samples analysed contain less than the average Sr content of tholeiitic basalts. Two rocks, Ø31 and Ø199, have anomalously high values of 600 and 655 p.p.m. Sr respectively.

The other gabbroic and doleritic dyke rocks produce a diffuse trend when plotted against solidification index. At S.I. = 28% the Sr content reaches a maximum of about 300 p.p.m., but at higher and lower values of S.I. the Sr content falls to below 100 p.p.m. The picrites and 'green' dykes contain less than 100 p.p.m. Sr. This relationship is similar to that shown by Ba and Ca.

As strontium is concentrated in the earliest, high temperature plagioclases (of high anorthite content) the above variation can be attributed to the increase in plagioclase content with differentiation (causing the increase in Sr content from the ultra-basic to basic dyke rocks) and the subsequent decrease in Sr content due to the decreasing anorthite content of the plagioclases on further differentiation.

Sr:K ratio plotted against K, Fig. IV.6, shows a 'strontium depletion fractionization trend' as found by Condie et al (1969) for the Wyoming diabases and postulated by Green and Ringwood (1967). The Sr depletion trend is unusual for continental tholeiites but is typical of submarine tholeiites and of the Antarctic and Tasmanian tholeiites.

Following Condie et al, the marked Sr depletion could be due to plagioclase fractionation from a tholeiitic magma (Ca-Al rich). If this is correct for the 'Scourie Dykes', and the Wyoming diabases, vast quantities of plagioclase must have crystallized and been removed from the magma. A figure of c.75% (of the plagioclase content) was suggested for the Wyoming diabases. Many 'Scourie' gabbroic dykes show that plagioclase crystals were early to crystallize from the magma and were often segregated into bands. Moreover many of the dolerite dykes contain plagioclase phenocrysts that have rounded outlines and are of different composition (more calcic) from those plagioclases that are found in the surrounding dolerite. Most important of all is that xenoliths, often very large, of plagioclase rich gabbroic-textured rocks are often found in the gabbros. These xenoliths (e.g. sample Ø31) contain about 75% plagioclase and may well represent blocks of consolidated or semi-consolidated plagioclase cumulate brought up from the differentiating magma chambers where the dyke material originated.

The analysed samples of plagioclase-rich xenolith Ø31 does show a K/Sr ratio normal for continental tholeiites and may therefore have formed as suggested. Sample Ø199 from the actinolitic meta-gabbro, although now not obviously plagioclase rich, may have contained large quantities of plagioclase. This rock,that is chemically similar in many respects of Ø31 and often very dissimilar to the 'normal' gabbroic and doleritic dykes, therefore may well represent the rock with a composition nearest to the primary tholeiitic magma before extensive plagioclase fractionation had taken place.

Condie (1973) has linked crustal thickness and chemistry of igneous rocks (notably Rb and Sr). Plotting Rb v Sr (Fig. IV.7) and using Condie's fields for different crystal thicknesses, the majority of the analysed samples that have not obviously been depleted in Rb during metamorphism fall in the field where crystal thickness is between 15 and 20 km. It is considered that during the intrusion of the 'Scourie Dykes' the crust was under tension (see Chapter VI) and since the 'Scourie Dykes' are of an obvious continental origin, it is strange that they show Sr depletion trends similar to those seen in submarine tholeiites. The statement of Condie et al that "such a coincidence of trends may indicate a genetic relationship between submarine tholeiites and Sr depleted, continental tholeiites" may be countenanced for both the submarine tholeiites and the 'Scourie' dykes have been intruded through a crust that was under tension.

Barium Ba

The rocks analysed contain between 110 and 300 p.p.m. Ba and when plotted against solidification index they show a trend that is similar to that shown by CaO. (Fig. 2a)

Barium content of the adjacent sheared and unsheared rocks, Ø28 sh and Ø 28 oph, show an apparent increase in barium in the sheared rock from c. 200 p.p.m. to c. 300 p.p.m. Plotting Sr/Ba ratios against %K the rocks analysed fall within or near to the field of continental tholeiites of Condie et al. (1969). See Fig. IV.8, although the plot K/Sr v %K (Fig. IV.6) places them outside this field.

Group IIIA

Gallium, Ga

The content of Gallium in the rocks analysed (gabbros and dolerites) are similar to those found in basaltic rocks generally, i.e. they range between 13 p.p.m. and 25 p.p.m. The average gallium content for tholeiites basalts is 19 p.p.m. (Prinz 1967).

Group IVB

Lead (L.D.L. 13 p.p.m.)

All except one of the rocks analysed have concentrations less than the lower detection limit.

Group VIIB

Fluorine and Chlorine F & Cl

Analysis of F and Cl was kindly carried out by Dr. R. Fuge on a number of samples. Values for chlorine range up to 2500+ p.p.m. for the scapolite-bearing meta-dolerite. However, non scapolite-bearing rocks only contain up to 1150 p.p.m. When plotted against S.I. they show a slight negative correlation (see Fig. IV.2a and Fig. IV.2b).

It is notable that rocks retaining their igneous mineralogy have a very low Cl content (c50 p.p.m.) whereas metamorphosed rocks always contain greater amounts. Moreover unfoliated rocks contain larger amounts of Cl (c800 p.p.m.) and sheared rocks less (c.350 p.p.m.). Also chlorite bearing or saussaritic rocks (usually unfoliated) contain greater amounts of chlorine than the biotite (foliated) rocks. Thus it is possible that the variation in chlorine in metamorphosed dyke rocks is mineralogically controlled.

The fluorine content of the rocks analysed fall between 100 p.p.m. and 400 p.p.m., show a negative correlation with S.I. and seem to vary sympathetically with chlorine (Fig. IV.9).

The concentration of fluorine seems to follow the same pattern as that of chlorine in the metamorphosed rocks. Thus the concentration of both halogens seems to be dependant almost wholly on the state of deformation, i.e. it would appear that the physical state of the rock (whether foliated or not) determines how mich chlorine or fluorine is retained. Foliated rocks are considered to offer easier passage for these gases to pass through and out of the rock.

Transition Elements

Group IIIA Scandium, Sc (L.D.L. = 1.5 p.p.m.) and Yttrium, Y (L.D.L.= 6 p.p.m.)

	Scandium		Yttrium	
gabbros	33 p.p.m.	(4.5 p.p.m.)	27 p.p.m.	(11.1 p.p.m.)
dolerites	34 p.p.m.	(5.7 p.p.m.)	29 p.p.m.	(11.6 p.p.m.)
picrites	19 p.p.m.	(4.9 p.p.m.)	11 p.p.m.	(4.3 p.p.m.)
'green' dykes	22 p.p.m.		18 p.p.m.	
Wyoming diabases	36 p.p.m.	(4 p.p.m.)	not determined	
tholeiitic basalts	31 p.p.m.		30 p.p.m.	

Scandium

Scandium content decreases smoothly with increase in Solidification Index from c.20 p.p.m. for the picrites to c.35 p.p.m. for the gabbros and dolerites. The xenolith Ø31 contains little Scandium (20 p.p.m.).

Prinz (1967) states that scandium is concentrated in pyroxenes, amphiboles and to a lesser extent in biotite, but is almost lacking in olivines. This is in accord with the scandium contents of the rocks analysed, the olivine bearing rocks containing the least amounts and the pyroxene-bearing dykes the greater amounts of scandium.

Yttrium

Yttrium varies in a similar way to V and Zn (other transition elements) by showing a decrease with increase of Solidification Index. The picrites may contain as little as 5 p.p.m. and the highest content of yttrium of 50 p.p.m. is found in the rock which has the lowest solidification index. Wilkinson (1959) points to apatitie as the main yttrium carrier (where it substitutes for Ca^{2+}), but Cornwall and Rose (1957) find abundant Y in ilmenites and magnetites (Y substituting for Fe^{2+}). Such a concentration of yttrium in the late minerals of basaltic differentiation would explain the trend in the rocks analysed.

The close relationship of yttrium with vanadium and zinc (see Fig. IV.10) which are contained in high concentrations in magnetite and illmenite respectively, suggests that these oxides rather than apatites contained the yttrium in the 'Scourie Dykes'. The plot Sr v Y (see Fig. IV.11) shows a negative correlation for the gabbros and dolerites and separates these from the ultrabasic rocks (picrites and 'green' dykes) which have low Y (and Sr) contents.

Group IV A

Zirconium (Zr) (L.D.L. 9.4 p.p.m.)

gabbros	92 p.p.m.	(25 p.p.m.)
dolerites	87 p.p.m.	(55 p.p.m.)
picrites	26 p.p.m.	(22 p.p.m.)
'green' dykes	39 p.p.m.	
Wyoming diabases	128 p.p.m.	(53 p.p.m.)
Tholeiitic basalts	108 p.p.m.	

The zirconium content of each rock type shows a great range (as shown by the standard deviation) and when plotted against S.I. shows that there is a general decrease in Zr content with S.I.

Zirconium is concentrated in pyroxenes and in residual magmas where zircons may be formed (Prinz 1967). As zircons have not been found in the rocks analysed it must be assumed that zirconium has been incorporated in the pyroxene.

The variation of zirconium and titanium (Fig. IV.12) is that which would fall in the fields "B" and "D" of Pearce and Cann (1973) which are identified with ocean floor basalts (and possibly low potassium tholeiites). This, as does the strong Sr depletion of these dyke rocks, suggests a strong resemblance to submarine basaltic rocks.

<u>Group VA</u> <u>Vanadium, V</u> (L.D.L. = 32 p.p.m.) and <u>Niobium, Nb</u> (L.D.L.=2.7 p.p.m.)

	Vanadium		Niobium	
gabbros	424 p.p.m.	(87 p.p.m.)	17 p.p.m.	(8 p.p.m.)
dolerites	412 p.p.m.	(150 p.p.m.)	13 p.p.m.	(6 p.p.m.)
picrites	147 p.p.m.	(72 p.p.m.)	3 p.p.m.	(2 p.p.m.)
'green' dykes	259 p.p.m.		below L.D.L.	
tholeiitic basalts	251 p.p.m.			

Vanadium content is lowest for the picrites (highest Solidification Index) at c50 p.p.m. and greatest (c500 p.p.m.) in the gabbros and dolerites of lowest Solidification Index, showing a similar relationship as Zn and Y. Vanadium will substitute for Fe^{3+} and is therefore found in high concentrations in pyroxenes and especially in magnetite (Naumor and Gurin 1967) but does not appear in olivines which tend to concentrate chromium. Because of the similarity to yttrium in particular, it is thought that the vanadium is held in magnetite to a greater extent than pyroxenes. Fig. IV.13 shows that there is a close relationship between vanadium and titanium, especially at low values of both. The trend, well defined at low levels on this plot, shows at higher TiO_2 levels a broad scatter which varies between

a) constant $V:TiO_2$ ratio, and

b) constant V, at c. 230 p.p.m. with increasing TiO_2 (decreasing $V:TiO_2$ ratio with increasing TiO_2.

Since the main phases containing these elements are oxides (i.e. Ti in titanomagnetite and ilmenite; and V in magnetite) the reasons for their concentrations may be due to the physical conditions (PO_2 and T) causing precipitation when Ti and V concentrations were at different levels. Buddington and Lindsley (1964) state that at the same temperature an increase in oxygen fugacity results in a decrease in percentage of TiO_2 in magnetite and an increase in the Fe_2O_3 of the ilmenite in the solid solution series Fe_3O_4 - Fe_2TiO_4, (magnetite, ilmenite). If the amount of vanadium closely follows Fe^{3+} then it would be expected that an increase in oxygen fugacity would cause the $V:TiO_2$ ratio to increase. Therefore it could be that the variation on the V - TiO_2 plot is an indicator of the variation in oxygen fugacity during development of these oxides, with high $V:TiO_2$ ratios indicating high oxygen fugacities.

Niobium

Niobium concentrations are low for these rocks, some being below the detection limit. Despite the low values a general increase in Nb content can be detected from the ultrabasic rocks (picrites and 'green' dykes), of around 7 p.p.m., to the basic (gabbros and dolerites) around 30 p.p.m.

There is a well defined geographical control on the Nb distribution, for the highest values are found in basic dykes from around Achmelvich Bay (i.e. around the Canisp Shear Belt). This is shown well in Figs. IV.13 and IV.14 where all the gabbros of Achmelvich Bay fall in one isolated field. Pearce and Cann (1973) point to the ratio Y/Nb (Fig. IV.14) being an indicator to the tectonic setting of volcanic rocks, and argue that the variation in Nb is due to differences either in degree of partial melting or in Nb content of the source rock. Either of these explanations may account for the marked difference shown by the rocks of Achmelvich Bay. (see discussion of zinc concentrations)

Group VIA	Chromium Cr, (L.D.L. = 4.8 p.p.m.)	
gabbros	201 p.p.m.	(177 p.p.m.)
dolerites	202 p.p.m.	(193 p.p.m.)
picrites	2400 p.p.m.	(368 p.p.m.)
'green' dykes	1547 p.p.m.	
tholeiitic basalts	160 p.p.m.	

Chromium content shows a very smooth variation with Solidification Index, (Fig. IV.2a) increasing, almost exponentially, from below 10^2 p.p.m. (dolerites and gabbros) to over 10^3 p.p.m. (picrites) with increasing S.I. values. As Cr is concentrated in chromite ores of the ultra-basic rocks and in early pyroxenes, which deplete the Cr content of the magma (McDougall and Lovering (1963)), this variation is readily explicable.

The variation between Cr and TiO_2 (Fig. IV.15) shows a negative correlation (cf Rivalente and Sighinolfi 1971). However, the variation from basic to ultrabasic rocks is not simple, as there are two converging trends.

The steeper trend (i.e. more rapid decrease in Cr with TiO_2 increase) is almost completely confined to the ultrabasic rocks and suggests that these rocks contain quantities of chromite ores associated with the presence of olivine. The majority of the rocks, that show a slow decrease in Cr content with TiO_2 content, show the 'normal' variation, presumably due to the continuing pyroxene crystallization whereby the amount of Cr in the pyroxenes and in the magmas falls with the gradual increase in TiO_2 during differentiation.

Group VIII Cobalt, Co and Nickel, Ni (L.D.L. = 3.4 p.p.m.)

	Cobalt		Nickel	
gabbros	55 p.p.m.	(9 p.p.m.)+	122 p.p.m.	(137 p.p.m.)
dolerites	52 p.p.m. ++		91 p.p.m.	(63 p.p.m.)
picrites	-		1353 p.p.m.	(425 p.p.m.)
'green' dykes	-		798 p.p.m.	
Wyoming diabases	-		143 p.p.m.	(91 p.p.m.)
tholeiitic basalts	39 p.p.m.		85 p.p.m.	

\+ average from eleven gabbros only

++ one dolerite analysed for Co

Cobalt Cobalt concentrations for the few dyke rocks analysed (all except one belonging to gabbros) are between 46 and 68 p.p.m. The xenolith Ø 31 contains 37 p.p.m. cobalt.

Nickel Like Cr and Mg, nickel concentrations increase with Solidification Index (S.I.> 30%) with some picrites containing over 2000 p.p.m. Ni. All rocks containing olivine and those thought to have contained olivine have high Ni contents and because of this the picrites, the 'green' dykes and the olivine gabbro are separated on plots of nickel contents, especially log Ni v log Cr and log Niv log MgO (Figs IV.16 and IV.17).

The Cr/Ni ratio, of Fig. IV.16, is not constant as Turekain (1963) suggested it should be for basalts. However, the Ni/Mg ratio (see Fig. IV17 and Fig. IV.1a) show that there is a closer correlation of Ni with Mg than there is for Ni and Cr. This relation may be simply explained by the fact that both Ni and Cr are concentrated in olivines and later in pyroxenes, Cr is discriminated against in olivines, and Cr is also found in chrome spinels where Ni is nearly absent.

It is important to note that the rocks from different areas, notably Achmelvich Bay, where a sufficiently large number of samples were collected, contain differing but fairly constant Ni and Mg concentrations, see Fig. IV.17.

Group IB Copper, Cu (L.D.L. = 29 p.p.m.)

gabbros	128 p.p.m.	(81 p.p.m.)
dolerites	120 p.p.m.	(58 p.p.m.)
picrites	38 p.p.m.	(30 p.p.m.)
'green' dykes	34 p.p.m.	
tholeiitic basalts	123 p.p.m.	

The picrites and 'green' dykes contain little Cu, but the gabbros and dolerites contain much greater amounts, up to 200 p.p.m.. In a similar way to Zr, copper content plotted against S.I. shows a convergence of two trends in the gabbros and dolerites, one trend showing 'high' and the other showing 'low' Cu content.

The reason for the variation of copper is not obvious because little work has been carried out on the concentration of copper in silicates. In the Shaergaard intrusion(Wager and Brown 1968) copper is either present in copper sulphides or concentrated in the ferrogabbros (and granophyre) where it is mostly found in the pyroxenes (clino) and plagioclase. When compared with the norm. percentages of the analysed rocks it appears that the low values of copper are associated with rocks of low normative plagioclase and rocks with high normative hypersthene. Fig. IV.18 shows that in the field of olivine normative rocks the two trends are distinct. This suggests that differentiation in the Ol-Hy-Di(-Pl) field took place by either pyroxene (high Cu content trend) or olivine (low Cu content trend) crystallization.

<u>Group IIB</u> <u>Zinc Zn</u>, (L.D.L. = 2.4 p.p.m.)

gabbros	92 p.p.m.	(25 p.p.m.)
dolerites	95 p.p.m.	(31 p.p.m.)
picrites	81 p.p.m.	(12 p.p.m.)
'green' dykes	93½p.p.m.	

Zinc varies with S.I. in a similar way to V and Y. With increasing S.I. it decreases from c150 p.p.m. to c70 p.p.m. at S.I. 30%, it then increases slowly to about 80 p.p.m. for the picrites and 'green' dykes at S.I. of 60%. Goldschmidt (1954) states that zinc follows Fe^{2+} in oxides (and Mg and Fe^{3+} in silicates) and points to ilmenite, magnetite and especially chromite ores in olivine as the zinc containing phases in gabbroic rocks. The close association with V and Y (found in ilmenites and magnetites) suggests that the concentration of these two elements and zinc is due to the amount of these ores in the rocks. It would be expected, from the plots of these trace elements against S.I., for ores to be more abundant in the ultrabasic rocks and the more highly differentiated (and iron rich) basic rocks. This does not conflict with the petrographical evidence, However, the unusually low values for zinc in the rocks from Achmelvich Bay (c50 p.p.m.) reflects either a different source for these rocks or that an unusual differentiation path has been followed.

The rocks from Achmelvich Bay are also low in Y, which varies in sympathy with Zn. Wedepohl (1963) suggests that Zn is concentrated in garnets of peridotic rocks and Pearce and Cann (1973) point to Y being contained in garnet at higher concentrations than most of the other mantle phases. It could therefore be that the gabbroic rocks of Achmelvich Bay were derived from a source rock that contained little or no garnet. Green (1969) suggests that such a source rock would be mantle material at pressures less than 20 kb, i.e. nearer to the earth's surface. It is suggested in Chapter VI (see Fig. VI.12) that the asthenosphere was nearer to the surface here (c.f. the rest of the northern Lewisian) at the time of dyke intrusion. If this was so it would account for the peculiarities in the chemistry of the Achmelvich Bay dyke rocks.

Lanthanides and Actinides : Niodinium, Nd(L.D.L.=38 p.p.m.)
Thorium, Th (L.D.L.=2.5 p.p.m.) and Uranium, U (L.D.L.=3.3 p.p.m.)

	Niodinium	Thorium	Uranium
gabbros	-	7 p.p.m. (3 p.p.m.)	-
dolerites	-	5 p.p.m. (3 p.p.m.)	-
picrites	-	5 p.p.m. (3 p.p.m.)	-
'green' dykes	-	2½p.p.m.	-

Niodinium was found to be below the detection limit (38 p.p.m.) for all samples. Uranium was found to be less than the lower detection limit of 3.3 p.p.m. except for one sample (Ø 246), the olivine gabbro, which contains only 4 p.p.m. which is not considered to be significant.

Thorium content (Fig. IV.2b) varies from the lower detection limit of 2.5 p.p.m. to 13 p.p.m., but shows no significant variation with rock type.

Normative Composition of the Scourie Dyke Suite

Since very few of the rocks analysed or collected in the field have retained their igneous mineralogy the use of the normative composition of these rocks offers a way of understanding the differentiation of this suite of rocks.

All the rocks analysed fall either in the olivine tholeiite group or the tholeiite group of Yoder and Tilley (1962) as normative nepheline has not been recorded, see Fig. IV.19. The dolerites are generally quartz normative although a few lie very close to the plane of silica saturation. Therefore the dolerites are considered to be saturated to oversaturated tholeiites. The gabbros also generally fall into this group except for two rocks: Ø36, a specimen from the margin of a gabbro, and Ø246, the olivine gabbro, that fall in the field of undersaturation and are therefore olivine tholeiites. The picrites do not form a distinct group and are found to be either undersaturated or just in the field of silica saturation. This is also the case for the two 'green' dykes.

Except for four samples Ø376 (picrite), Ø328 ('green' dyke) and Ø344, Ø114 (dolerites) the normative components of the rocks analysed fall together on a plot of Ol, Hy, Di, Qz. (Fig. IV.19). Over half the dolerites and gabbros are grouped together around Qz 15% - Di 50% - 35% Hy (Ol-zero), the position C. The others describe an arc A-B, which runs from Di 25%, Ol 75%, through the field where Di > Hy to Hy 90%, Qz 10%, cutting the Hy-Di line at Hy 50%, Di 50%. There is no clear break between the samples that plot along A-B and those that are grouped together (C).

Fig. IV.20 is a plot where the abscissa is obtained by the projection from the Di corner of the base of the 'expanded basalt tetrahedron'. The position of a rock on this projection will give an indication of the degree of saturation of each rock and can be used for undersaturated, saturated and oversaturated rocks. The relation between the normative plagioclase content of a rock (plotted on the ordinate) and this index therefore gives an indication of its position within the 'expanded basalt tetrahedron' of Yoder and Tilley.

This plot shows that the rocks that group at C and the rocks of the arc, AB, that lie near to the Di-Hy line have the highest concentrations of normative plagioclase (Pl). Of the other rocks that fall on the arc, the Ol rich rocks show increasing Pl content with decrease in Ol and the Hy rich rocks increase in Pl with increase in Di content.

The relationship of the rocks within the basalt tetrahedron therefore describes two arms stretching up from the position of Picrite Basalt and Bronzitite to the majority of the rocks that lie halfway to the Pl apex above the position where Di$\triangleq$Hy. Therefore two distinct trends in differentiation to one point are indicated.

Following Coombs (1963), the form of the plagioclase surface has been projected onto the base of the expanded tetrahedron (Fig. IV.21). The approximate position of the five phase point R (plagioclase, olivine, diopside, hypersthene - liquid) is marked on Fig. IV.19. Its position on Fig. IV.20 would be at An + Ab 40% and just to the right of the Hy-Di line. The point R lies near to the 'arc' (AB) and the 'group' (C) and all but two rocks that describe the arc AB fall on or near the boundary olivine, plagioclase-pyroxene, plagioclase. The spread of points within the tetrahedron either fall along the position of the olivine-pyroxene (diopside or hypersthene) phase boundary surface or group around the five phase point. Since the points follow the inferred positions of these boundary surfaces the spread of points on Fig. IV.20 about the position of the five phase point may well mark the approximate position of the plagioclase phase boundary surface.

As the majority of analysed rocks fall within the trend A-R-C, Fig. IV.19, the differentiation of the suite along these lines seems to be more 'normal'. Thus it would appear that differentiation of the magma has moved to the Ol(Pl), Di(Pl) boundary surface, travelled along this to the plagioclase surface, from there to the five phase point R, and from there towards the minimum melt five phase point of the QZ-Pl-Di-Hy-liquid eutectic (see Fig. IV.22).

This trend would produce picrites, olivine basalts, saturated tholeiites and finally oversaturated tholeiites. This is the trend expected from the fractionation of olivine from an olivine tholeiite liquid at low pressures of depths less than about 15 km (Green, Green and Ringwood, 1967).

The minor trend BR that appears to follow the Ol-Pl, Hy-Pl boundary surface up to the five phase point, R, where both Hy and Di would be expected, would give rise to a series of noritic gabbros that would move towards R from B and then follow the differentiation of the other series towards Qz.

Since the trace element geochemistry of the rocks of both trends are almost identical, different positions of origin within the mantle for each set are not envisaged. The cause of the initial divergence in trends could be due to position of the isotherms in the Ol, Hy, Di field of the tetrahedron. For if the initial magma-composition was near to the thermal ridge of this field then differentiation could pass towards either the olivine-clinopyroxene phase boundary to give A,R,C or towards the olivine-orthopyroxene boundary to give the trend B, R, C. At depths with pressure greater than 6kb the olivine-orthopyroxene boundary acts as a thermal divide (Yoder and Tilley 1962), and therefore at pressures greater than 6kb the composition of the magma would follow the boundary with the crystallization of olivine and orthopyroxene to give rocks whose composition would be close to the phase boundary.

Green (1967) states that the fractionation from either olivine tholeiitic or picritic liquids at pressures greater than 20 kb (possibly at 10 kb) would produce orthopyroxene, not olivine, and this would lead to relative silica depletion in the liquid and may result in nepheline-normative rocks instead of a series of quartz-normative rocks as shown by the two trends A, R and B, R. It would seem that the trend A,R belongs to rocks fractionated at less than 6 kb (c. 15km) the rocks on B,R must have developed by differentiation initiated at pressures between 6 kb and c.20 kb (i.e. between c. 15km and 50 km).

This agrees with the view of Green, Green and Ringwood (1967) who suggest that fractionation between 4.5 - 9 kb, (c. 11 to 23 km) of an olivine tholeiite will essentially involve only increase in plagioclase content.

It would therefore seem most likely that the two trends are formed because of the fractionation of an olivine-normative magma within two separate depth intervals, trend A,R at depths less than 15 km and trend BR between 15 and 50 km. Further evidence suggesting the presence of two distinct groups is the plot Na_2O+K_2O v SiO_2 (Fig. IV.3) which divides the analysed rocks into two converging groups. In one group SiO_2 increases with total alkalis within the field of High Alumina

Basalts from the picritic rocks to the basic rocks. The other trend passes from low to high alkali content without much variation in silica. This group of rocks includes the 'green' dykes.

It is possible to calculate the chemical changes on removing and accumulating different crystal phases from a parent rock chemistry if we can determine, or assume, the chemical composition of the mineral phases. The changes in alkali and silica content due to the addition and removal of 9 wt% and 17 wt% of olivine (Fa 14) and orthopyroxene (bronzite) and 9 wt% of clinopyroxene (subcalcic ferroaugite), bytownite and andesine, from a 'parent' rock are shown in Fig. IV.23. Mineral compositions are taken from Deer, Howie and Zussman (1963) and have been chosen to correspond as closely as possible to the mineral phases recognised in the 'Scourie Dykes". The composition of the 'parent' rock is taken as that of Ø25 (a chilled margin of a gabbro) although the changes in chemistry will be similar for any basic parent rock.

It appears that the changes are almost totally controlled by the silica content of the minerals compared to that of the 'parent' rock and can be summarized as follows. The continued accumulation of a mineral phase will tend to move the composition of the resulting rock towards the composition of the mineral, the removal will move the composition away from composition of that mineral and the 'parent'.

From this, the fractionation effects of olivine and plagioclase are seen to be opposite, but both change the composition within the 'high alumina basalt' field. Petrological study of the dykes suggests that olivine fractionation is more likely to have occurred in the silica-poor rocks. Pyroxene fractionation will give rise to a decrease in alkalis with (a) an increase in silica (orthopyroxenes), or (b) without a change in silica (clinopyroxenes). Therefore it is possible that the spread of analyses that show alkali increasing with little change in silica can be attributed to clinopyroxene fractionation alone or to orthopyroxene (and olivine or plagioclase) fractionation. Moreover the petrography of the dyke rocks points to orthopyroxene and olivine being important in fractionation of the ultra-basic rocks and to pyroxenes (with or without plagioclases) controlling the variation in the basic rocks.

(It is worth noting that the supposed plagioclase cumulate, Ø31, falls between the composition of Ø25 and labradorite-andesine.)

The course of differentiation as shown by an A.F.M. diagram (Fig. IV.4) is one of strong iron enrichment, up to c.20% total iron (as FeO). The trend begins with the picrites and 'green' dykes and continues with the gabbros and dolerites which both show similar amounts of iron enrichment, although there are more dolerites than gabbros with high iron content.

It has been suggested from the norm. data that the depths where the two trends were initiated could be less than 15 km, probably with the crust, and greater than 15 km and upto 50 km, probably confined to the mantle. It can be argued that these two levels of origin of the rock series were controlled by whether or not the magma bodies produced by mantle melting did or did not pass quickly into the crust.

Field and petrographic evidence suggesting fractionation in the dyke bodies is limited to the ultrabasic and a number of the larger gabbroic dykes. This evidence, together with the similarity in trace element geochemistry of gabbroic and doleritic dykes that occur together, suggest that the processes of differentiation continued as the magma was moving towards the surface and in many cases up to the point of total crystallization of the bodies.

Watterson (1968 pp 60) defined the two ideal types of fractional crystallization differentiation as "series differentiation" and "phase differentiation". In terms of these two types of differentiation the variation in the chemistry (and therefore petrography) of the main 'Scourie dyke' groups would be due to "series differentiation", that is the continual separation of the major phases that varied within discontinuous and continuous reaction series to form the picritic 'green' and basic (gabbroic and doleritic) dykes. Whereas "phase differentiation", the separation of different mineral phases, has only been effective within the dyke bodies and probably after mass movement of magma had stopped and as the magma was consolidating.

Geochemical effects of metamorphism and deformation

The dyke samples for analysis were chosen mainly to obtain a representative petrographic and geographic range and not with a view to obtaining quantitatively accurate evidence of any geochemical changes resulting from metamorphism. However the available analyses are sufficient to give a qualitative account of such effects.

The most obvious effect of metamorphism seems to have been on rubidium content (see Fig. IV.5). It has been argued earlier that rubidium has been removed from the rocks on metamorphism, but that certain quantities of rubidium are retained if biotite was present as metamorphism occurred. Similarly chlorine content appears to be dependent on metamorphism since metamorphosed rocks contain many more times the amounts of chlorine than are found in unmetamorphosed dyke rocks, see Fig. IV.21.

The effect of synmetamorphic deformation on the chemistry of the dykes can be assessed from the comparison of the samples Ø17 with Ø18, and Ø28 op with Ø28 sh and Ø30. Sample Ø17 is from the centre of an undeformed and only slightly metamorphosed gabbroic dyke from Loch an Obain and Ø18 is from the centre of the same dyke that has been sheared by an E-W, 100 m wide shear zone. The deformation of the dyke is homogeneous. The compositions of the two samples are not significantly different except that there is a relative loss of Rb and Li in the deformed section (See Fig. IV.24). This suggests that homogeneous deformation of a dyke may be isochemical.

Sample Ø28 sh is from a 30 cm wide shear zone in the centre of an inhomogeneously deformed dyke from Achmelvich Bay. Sample Ø28 op is from the undeformed dyke rock adjacent to the shear zone and Ø30 is from the centre of a nearby undeformed dyke with almost identical chemical characteristics.

The changes in composition due to the shearing are summarized in Fig. IV.24. Potassium, barium and possibly rubidium have been enriched in the shear zone without the apparent decrease in these elements in the adjacent undeformed rock. The copper content of the zone has been reduced. Lithium and calcium are enriched in the undeformed rock.

By reference to the ionic radii of the elements which have been enriched or depleted it is seen that the addition of material to the shear zone, probably from outside the system, involves those elements with the large ionic radii (i.e. K^+, Ba^{2+}). The smaller ions, Li^+, Cu^+, Ca^{2+} have been involved in relative depletion in the shear zone and increase in the surrounding rock.

Burns (1966) shows a decrease in magnesium content in the dykes during the Laxfordian metamorphism between Scourie and Loch Laxford.

The present study has not been exhaustive enough either to support or refute this.

However the increase in potassium shown by Burns to have occurred on metamorphism due to metasomatism is confirmed, but for deformed rocks only. Beach and Fyfe (1972) discussing the effect of Laxfordian shears cutting gneisses show that potash, water and oxygen have been added to the system by passing fluids. This is believed here to be the cause of the variation in chemistry of the inhomogeneously deformed dyke rocks, although evidence for similar conditions in the homogeneous deformation of a dyke in a large shear zone does not show these effects.

Beach and Fyfe show that the ratio $\frac{2Fe_2O_3}{2FeO_2+FeO}$ is increased in the sheared rock and that oxidation had therefore occurred. No such variation is shown by the rocks Ø17, Ø18, and Ø28 op, Ø28 sh.

The evolution of the 'green' dykes

By using the geochemical results of other workers it is possible to investigate the composition and origin of the 'green'dykes. Thus the geochemical analyses of 'Scourie Dykes' determined by Cresswell (1969), Crane (1972), O'Hara (1961) and Park (1966) have been used in the Figs. IV.25, IV.26, IV.27. From these plots it can be seen that the 'green' dykes show little variation in amount of 'iron enrichment', Fig. IV.27, but produce a distinct field within the basalt tetrahedron, as shown in Figs. IV.25 and IV.26. This field lies almost entirely within the Di, Ol, Hy, Pl volume (the olivine basalts), shows a decreasing Pl content with increased saturation and that the 'green' dykes are poorer in Pl and Di than the other members of the 'Scourie Dyke' suite.

Following Green (1969) the low plagioclase (Pl) content probably indicates that these rocks occurred due to the fractionation of olivine and aluminium rich orthopyroxene from a magma that was a product of high percentage partial melting of pyrolite mantle at higher pressures than those rocks of higher Pl and aluminium content.

However, Kushiro (1969) has shown that the phase boundaries within the basalt tetrahedron shift with varying pressure and water vapour pressure conditions. Fig. IV.21 attempts to summarise Kushiro's results. By comparing Figs. IV.21 and IV.25 it can be seen that the 'green' dykes lie along the position of the olivine-pyroxene phase boundary for high pressures (20-30 kb, anhydrous). This, with the work of Green (op. cit.), suggests that the 'green' dykes may result from a 'dry' magma that differentiated at a deeper level and higher pressures in the mantle than the other rocks.

It may be surmised that the 'Scourie Dyke' suite includes rocks whose sites of initial differentiation range from very deep in the Earth (c. 75 km) to very shallow (c. 15 km).

Chapter V Notes on the MECHANISM OF DYKE DEFORMATION

The behaviour of the 'Scourie Dykes' during the Laxfordian deformations is essentially that of the straining of layers of one material (the dykes) in a material of a different competence (the country gneisses).

Due to the range in pressure and temperature conditions under which the dykes were deformed the strain patterns developed vary from one area to another depending on their position relative to the two Laxfordian fronts, time spent under stress and whether or not deformation of the dyke had previously taken place.

As a general rule, within the Central Zone the deformation of the dykes and gneisses has been inhomogeneous, with the dykes acting as the less competent material. Within areas of higher grade Laxfordian metamorphism the deformation of the dykes and gneisses has been more homogeneous with the dykes and gneisses acting as if they had similar physical properties. At the highest grades of metamorphism the dykes behaved as the more competent rock.

The orientation of the Laxfordian stress axes that can be determined from the deflection of the gneiss banding against the dykes and the sense of movements shown on shear zones that cut through the dyke rocks show that the maximum principal stress generally acted in a north-south direction and therefore at a moderately high angle to the NW-SE trending contacts of the dykes. Because of this the net effect of the Laxfordian stresses is to rotate the dykes into parallelism to the plane perpendicular to σ_1 direction.

With the increase in grade of metamorphism the style of deformation appears to vary from brittle to ductile. Where little or no metamorphism has occurred the Laxfordian elastic strains have been stored and released to produce joints, see Fig. II.27. In regions where metamorphism has been weak, i.e. in most of the Central Zone, the deformation has been heterogeneous and ductile. Here the deformation is confined to narrow (30 cm) zones of simple shearing of the contacts of the dykes. The shears, which are often found only in the dykes, may form conjugate sets with a set found within the dykes and at a high angle to the dyke contacts. The sense of movement on any shear is shown by the asymptotic nature of the foliation to the centre of the shear. Typical shear strain gradients of such zones are c.7 cm^{-1}.

The dyke contacts, which represent an intersurface between two materials of differing competence, are nearly always the site of such shearing and the position and orientation of the contacts show a large control on the production of these shears. For example a shear will often continue in the orientation of the contact for some distance into the dyke at a stepped contact, and if an irregularity in the contact has an orientation near to that of the 'conjugate' set a shear of that orientation will be initiated (see Fig. V.2).

These shear zones are concentrated at the contacts and may exist alongside a more homogeneous deformation style which produces a penetrative foliation in a zone at the contact of the dyke. The width of this zone is often insignificant compared with the total width of the dyke and the centre is unaffected. As the zone of deformation becomes wider the dykes seem to have acted more like a Bingham body, i.e. where the viscous component of deformation became greater. Typical shear strain gradient values are 1 m^{-1}.

In the areas of moderate to high Laxfordian metamorphism, the deformation of the dykes has occurred across the whole width of the dyke bodies to produce a contact asymptotic or contact parallel foliation. In such areas the subsequent folding of the dykes and gneisses at the high grade of metamorphism produced similar fold shapes suggesting that there was a low viscosity contrast between the dykes and the gneisses.

The later phases of folding, associated with retrogression, that affect already foliated dykes, tend to produce concentric folds and these may be cuspate at the dyke contacts. These cuspate folds show that the metamorphosed dykes were more competent than the gneisses

It would appear that the first phases of deformation and metamorphism alter the physical properties of the dykes in such a way that they act as the more competent rock, relative to the gneisses, after deformation and metamorphism. It is considered that the properties of the dyke rock change on metamorphism and this could be a function of the change from an igneous to a metamorphic assemblage. Alternatively it could be because the later phases affect a previously strained dyke. Certain evidence points to a change in properties resulting from the preceeding deformation. Narrow shear zones, that cut across dyke rock locally foliated in a previous phase of deformation, show an asymmetric strain profile (see Fig. V.1), with the previously deformed rock showing a higher strain/distance gradient. This suggests that during the second deformation the previously deformed rock was less viscous, i.e. less competent.

<u>Geometrical relationships of the narrow zones of shearing relative to the contacts of the dykes.</u>

The physical properties of the dykes may be such that the narrow shear zones and the wider zones of marginal foliation form side by side, as found at Achmelvich Bay and Sithean Mhor (Rosshire). In both of these cases narrow zones of shearing run asymptotically upto the contact from the middle of the dyke and the sense of movement of these shears have a consistant relationship to the sense of deflection shown by the gneisses and the zone of marginal foliation (see Fig. II.28).

A similar style of deformation has been found in the dykelets of Cnoc a Phollain Bheithe where closely spaced shears cut across the dykelets from one contact to the other. They do not pass into the gneisses and the angle between these shears and the contact is less at the contact than in the centre.

At neither the smaller scale nor the larger scale is the 'deflection' of the shears thought to be due to a second phase of movement. Nor is it thought to be due to variation in grain size of the rock since the increase in grain size away from the contact at Achmelvich Bay takes place closer to the margin than the position where the curving of the shears stops. Moreover the shears in the dykelets of Cnoc a Phollain Bheithe cut across the contact between two intrusive phases without showing any marked refraction.

In the examples just cited, the number of shears increases towards the contact and in the centre of the dykes the shears are straight and are considered to mark the orientation of a plane of maximum shear stress (τ_{max}).

Similar shapes of zones of failure have been previously described by Max (1970), Berger (1971), Watterson (1968) and Allaart (1967) in dykes, by Kranck (1961) and Greenly (1919), where the failure planes are joints, and by Chinnery (1966) where second order faults describe these sigmoidal shapes.

Using the results of Chinnery (op. cit.) the orientations of the planes of shearing, or "second order shears", can be accounted for. Although unlike the problem of faulting used by Chinnery the dyke/gneiss intersurface can be at any angle to the principal stress directions of deformation and the stresses are concentrated at irregularities of the dyke contacts instead of at the end of a master fault. Since shear stress concentration will only occur at an irregularity their limited occurrence is explained.

It has been noted that the narrow shears are almost always confined to the dykes and are only rarely found in the gneisses. This shows that the dykes had a lower shear strength during deformation.

Using the classification of secondary shears (faults) of Chinnery the observed examples can be explained. See Fig. V.4. The secondary shears shown in Fig. II.29 belong to type A, those shown in Fig. V.2 shows a secondary shear of type B(C). Examples of shears of high curviature have been found and are of type C.

As the displacements about the dyke contacts (NW-SE strike) are dextral and have resulted from a general north south compression the types which might be found in the gneisses would be of types E and F only.

Strain patterns within shear zones of dykes

A shear zone in a dyke north of Scourie Bay is expressed in three dimensions and the precise sense of movement can be deduced. The lineation produced by the alignment of hornblende crystals and the elongation of feldspar blebs on the schistosity planes is parallel to the direction of principal extension (c.f. Ramsey and Graham 1970). However an 'apparent' feldspar lineation is often found normal to the movement direction and this is due to the intersection of the schistosity planes with the oblate shape of the feldspar blebs. This is more likely to be so in the field of flattening where the schistosity plane is tangential to or cuts the cones of no finite longitudinal strain.

Measurements of the shape of the feldspar volumes across a single shear zone in an apparently otherwise undeformed dyke show k values confined to the field of flattening, with k = 1 at $\gamma = 11.0$ and the decrease in strain being shown by a decrease in x/y only. See Fig. V.3.

This suggests that deformation by simple shear was either accompanied by a certain amount of pure shear or that the simple shear deformation was subsequent to, or followed another deformation which affected the final shape of the strain ellipsoid.

The shape and orientation of the strain ellipsoid of this other deformation will determine whether or not the lineation shown on planes parallel to the boundary planes of the zones of shear will be parallel to the movement direction.

Chapter VI DYKE DENSITIES AND DISTRIBUTIONS

Using the 6 inch to 1 mile Geological Survey Maps the whole of the autochthonous mainland Lewisian outcrop was divided into 1 km squares corresponding to the Ordnance Survey grid system. From within each kilometre square the area of outcrop of the dykes was measured by measuring their width and their length within each square. The dyke density is quoted as a percentage of the total outcrop. Because of the simple subdivision of rock types into ultrabasic (picrites) and basic (gabbroic and doleritic) that was used by the Survey workers, the data could only be split into these two groups. A rectilinear grid was used because of its convenience. This procedure is considered to be statistically accurate because of the excellent exposure.

The percentage outcrop of the dykes was plotted and hand contoured. (See Figs. VI.1, VI.3, VI.5, VI.7).

The outcrop trend of the dykes of each kilometre square was also measured. The trend was taken from the widest dyke as it may be assumed to represent the declination of the σ_2, σ_1 plane. The normal to the outcrop trend (σ_3 direction) is plotted in Figs. VI.2, VI.4, VI.6, VI.8.

The only previous work of this nature in the Lewisian is that of Lisle (note to a paper by J.S. Myers 1971). This shows that the density of outcrop of the 'Scourie Dykes' of Western Harris is low, most of the area containing less than 3% dyke material, and that the areas containing more than 3% trend N.N.E.-S.S.W. (South of West Loch Tarbert) or occur in isolation between belts of low density outcrop that trend N.N.E.-S.S.W. and N.W.-S.E.

On the mainland Lewisian the outcrop density of the dykes is much higher. From Loch Laxford to Durness the outcrop of dyke material is minimal. Very few dykes are recorded on the maps and inspection of the ground reveals only narrow isolated dykes. However it is considered that the absence of dykes from this area is real and not due to the destructive nature of Laxfordian reworking. From Loch Laxford south to the end of the continuous Lewisian outcrop near Enard Bay, the average outcrop density is c. 7½% reaching a maximum of just over 20%.

In the southern half of the area, Gruinard Bay to Loch Torridon, the average outcrop density is c.15% and reaches over 40% to the south of Loch Gairloch. It is important to note that some kilometre squares in the southern half contain no dykes at all, but this is not the case in the northern half of the mainland outcrop.

Area North of Loch Broom

Dyke densities of the basic dykes appear as belts of high and low concentrations that are parallel to the trend of the dykes. This is also the case for the southern region. The belts are evenly spaced over the region and the separation between the belts is c.3½ km. However, to the north of the Canisp Shear Belt (a Laxfordian deformation zone of dextral movement) the outcrop density, although still showing N.W.-S.E. trending zones of high concentration, also shows NNE-SSW trending highs. To the south across the Canisp Shear Belt the dyke concentration pattern returns to a well developed system of NW-SE trending highs.

The block between the Canisp Shear Belt and Loch Glendhu has been moved from the west, relative to the rest of the outcrop, since to the north of Loch Glendhu all the Laxfordian shears show sinistral movements. This block has a similar density pattern to that of a part of the area investigated by Lisle (op. cit.) for a part of the Outer Hebrides.

The dyke trends show very little deviation from the general NW-SE trend. Only in the 10 km square NC 20-30, do they show any marked variation in trend. Here the trend is more E-W and coincides with an area of low density dyke outcrop (less than 2½%). This may be due simply to the lack of fissures with the 'normal' NW-SE trend in this region.

The ultrabasic dykes of this region occur around the Canisp Shear Belt where they, and the zones of high concentrations, trend NNW-SSE. The average density of the ultrabasic dykes for this region is between 2½% and 5%. However, there is a belt of conspicuously high density that lies obliquely to the trend of the ultrabasic dykes in a more EW direction and runs into the Canisp Shear Belt. Dyke densities in this 'high' region reach over 10%. The termination of this 'high' and its associated 'lows' is due to the Laxfordian movements that have taken place in the Canisp Shear Belt. The distance between the belts of high ultrabasic dyke concentrations on either side of this structural break is c. 3 km. This may be the lateral displacement on the shear.

If the concentrations of the basic and ultrabasic dykes are added together the net result is to smooth out the 'topography' of the density surface to the north of the Canisp Shear Belt, but it enhances the 'ridges' to the south where the trend of the two dyke types are almost identical.

Area south of Loch Broom

Because of the extensive areas which are covered in peat and the great numbers of lochs in the region south of Loch Broom the outcrop of the Lewisian rocks is poor compared to the area further north and a complete survey of the Geological Survey maps is not possible.

The concentration of the basic dykes in this southern region is much higher than in the north and reaches over 40% (just to the south of Loch Gairloch). Also, compared to the north, the belts of high dyke concentration reach higher values and areas of low dyke density can have much lower values. This is shown well around Loch Gairloch. South west of the southern limb of the Tollie antiform the dyke density is very low with some kilometre squares containing no dyke material. Where as immediately south east of Gairloch there is a belt of extremely high (greater than 40%) dyke density. On average the dykes represent between 10% and 20% of the outcrop.

As in the northern region, the dyke density waxes and wanes parallel to the trend of the dykes and the distance between the highs and lows is similar to that of the north. The distances range from between 2.1 to 3.9 km.

Two areas of high dyke concentration that do not have the usual NW-SE trend occur around the Tollie antiform (Square 70-80). Their more EW trend is most probably due to the folding that produced the antiform.

The variation in the trend of the dykes from the NW-SE can be frequently attributed to Laxfordian folding, e.g., in the Tollie area. But around the Gruinard River the trends are variable and the variation cannot be explained by Laxfordian deformations.

The ultrabasic dykes are not common and are only found in any great concentration to the south of the Gruinard River where they represent just over 5% of the outcrop. The shape of the area of outcrop swings from NW-SE to EW going from East to West, see Fig. VI.7.

This bend coincides with the change in strike of the basic dykes from NW-SE to EW. When the concentration of the ultrabasic dykes that trend EW is added to that of the basic dykes their high values reinforce each other. The NW-SE trending area of high ultrabasic dyke concentration coincides with the belt of high values of basic dyke concentration (20-40%) which ends near to where the ultrabasic dyke density contours bend.

This shows that the intrusion of the two dyke types here tends to maintain the periodicity of density values and that the intrusion of both types has been affected by whatever caused the anomalous EW trends.

Periodicity of Dyke Outcrop Concentrations.

The most noticeable feature of the outcrop density maps is that the areas of high, and low, density of dyke material run in belts that are parallel to the dyke trends and the spacing of these belts is regular. (See Fig. VI.9).

The spacings i.e. wavelengths between the 'peaks' and 'valleys' in the dyke densities going from south to north are

Wavelength (km).

Maxs.	4.1	3.4	2.3	3.1	3.4	2.7	3.1
Mins	4.1	-	2.1	3.1	-	2.1	2.7
Maxs.	3.6	2.1	2.3	-	3.9	3.4	
Mins.	3.6	2.3	2.3	3.4	3.4	4.2	

Combined Average = 3.1 km

The values of dyke density of c 15%, for the south, and c 8%, for the north, represent a crustal extension of 17.6% and 8.7%

respectively. Extension of these magnitudes could not have been brought about by uplift. For if we consider a sector of the crust that is uplifted by an amount δR where R is the radius of the Earth the relationship between the extention, δl, and δR is $\delta l = \frac{l.\delta R}{R}$. (See Fig. VI.10). Then the uplift to give 17.6% and 8.7% extension, assuming the Earth's radius to have been 6,400 km, as now, would need to have been 1126 km and 557 km respectively. Therefore extension by uplift is impossible as crustal material would not exist at these depths, but must have been caused by relative tension due to externally applied forces. The forces concerned in this stretching of the crust would have acted in a NE-SW direction and are analogous to the crustal spreading forces postulated to be driving the present day plate system.

It must be assumed that the pattern of the outcrop density of the dykes is due to controls which acted below the present level of erosion. The controlling forces could be attributed to fractures spaced at c. 3km intervals in the lower crust.

Since the spacing of fractures produced in a slab under tension is proportional to the thickness of the slab (Hobbs 1967) the spacing of the belts of high dyke rock concentration may be low above a thin crust. Conversely the belts may be widely spaced above a thick crust. An hypothetical cross section through the crust at the time of intrusion of the 'Scourie Dykes' is shown in Fig. VI.11.

The marked difference in dyke density between the northern and southern areas of the mainland Lewisian suggests that a structural break may exist beneath the Torridonian between Enard Bay and Little Loch Broom.

The greater variation in dyke concentration in the south may point to the south having been at a deeper structural level than the north during dyke emplacement. However the crustal extension, as represented by the dykes, of the southern area is approximately double that of the north. Therefore the two areas may represent two, once more widely separated, areas of crust that suffered different amounts of extension. If the crustal spreading model is accepted and if the crustal spreading model can be applied to the Archaean, it might be expected that the southern Lewisian was positioned nearer to the spreading axis and that the overall northwards decrease in dyke density implies a north-eastwards movement of the northern area away from this axis.

Chapter VII CONCLUSIONS and ACKNOWLEDGEMENTS

Conclusions

The pre-dyke complex

The study of the pre-'Scourie Dyke' deformation has shown a basic similarity in the Scourian history of the mainland Lewisian from Durness to Loch Torridon. The last of the deformational events distinguished in this work, Dc, is considered to be equivalent to the Inverian deformation of the Loch Inver area.

Between Loch Laxford and Loch Torridon the deformation phase Dc has produced characteristic overturned folds and/or zones of shearing. Both of these types of structures dip towards the middle of the Lewisian outcrop, for the planes of shearing and the axial surfaces of the folds of the northern part of the Central Zone dip to the south and those of the southern part dip to the north.

Petrogenesis of the dykes

The evolution of the magma before crystallization from petrographical and geochemical investigations appears to have followed one of two main paths. One path, produced by olivine fractionation, gave olivine picrites, norites and gabbros (and dolerites). The other, produced by orthopyroxene fractionation, gave orthopyroxene picrites, olivine gabbros and gabbros (and dolerites). Both sets show strong iron enrichment and correspond to tholeiitic, high-alumina basalts. It is believed that both sets were developed from a common parent of olivine tholeiitic composition and that the level in the lithosphere at which material was held determined which differentiation path was to be followed to produce the quartz-normative basic dyke material. The magmas held at a deep level (presumably in the mantle) produced the orthopyroxene picrite magmas and magmas held at a higher level (probably in the crust) initiated differentiation that produced the olivine picrite-gabbro set.

The 'green' dykes , which are of limited occurrence do not seem to belong directly to either of these differentiation trends. They are normatively feldspar-poor, olivine tholeiites that are probably the result of differention of 'anhydrous' olivine tholeiitic material at extreme depths in Earth, followed by their rapid rise into the crust.

For the non-'green' dykes the differentiatioh processes probably continued upto the time of their final intrusive movements.

The order of intrusion of the different dyke materials varies from one area to another and, if the theory of magma evolution at differing depths at the same time is correct, some variation would be expected. However the order of intrusion of the main dyke types recognised show a degree of consistency: thus the usual sequence is either Picrites, Gabbros, Dolerites, 'green'dykes or 'green' dykes , Gabbro (I), Dolerite, Gabbro (II), the latter sequence being confined to the area around the Gruinard River. However the age relationship between the gabbros and the picrites is often reversed.

Although for most areas it would appear that the intrusion of one rock type occurred before the total consolidation of the previous type, this does not mean that the intrusion of the whole suite was quickly completed. For the intrusion of any one type was probably protracted and overlapped in time with other types.

The rocks found have been split into four main types which belong to one, or more, series, although it is likely that one type may grade into another type. This seems highly probable for the picrites, olivine gabbros and the norites, and for the gabbros and dolerites.

Conditions of emplacement

The 'Scourie Dykes' were intruded after the Inverian deformation and metamorphism and before the Laxfordian deformation and metamorphism (by definition) and the dykes investigated show that in many cases the intrusion of basic material has taken place along joints and faults that cut Inverian deformation structures, although intrusion parallel to Inverian fabric planes has also taken place.

Widespread evidence of dilatational emplacement suggests that intrusion of basic and ultrabasic material, of probable mantle origin, into the acidic gneiss crust took place under overall tension. The extension of the crust as indicated by the amount of 'Scourie Dyke' material is calculated to have been about 9% in the northern Lewisian and about 18% in the south.

Many of the larger dykes may account for the whole of this extension in any one area and may represent fissures that tapped the mantle. In other areas the extension is shown by many thinner intrusions which could have been fed by larger bodies at depth. Often the areas that show the thinner and more abundant dykes are those that had suffered intense Inverian deformation. In such areas the presence of the steeply dipping fabrics of similar strike to the dykes is considered to have provided increased probability of bifurcation of dyke channels going up through the crust.

It is suggested that variation in dyke density may be linked to variations in the thickness of the crust at the time of intrusion. The difference in the amount of intruded material found in the northern part of the mainland Lewisian compared to the south may indicate different positions relative to the spreading axis of crustal extension.

The stress regime at the time of intrusion of each of the rock types shows no marked change in orientation, for each set has a general NW-SE trend. Only minor branching, en echelon intrusion and 'stepping' has been found and therefore sufficient joints and faults near to the $\sigma_1\sigma_2$ plane must have been available to the magma at the time of intrusion.

With time there has been a minor change in the orientation in which σ_3 acted from almost N-S, during the intrusion of the early phases, to NE-SW, for the gabbros and dolerites.

The mechanism for the intrusion of the picrites and gabbros has been, as far as can be deduced, dilatational. However the gabbros commonly contain gneiss and cognate xenoliths. The intrusion of the dolerites at many localities has occurred by non-dilatational mechanisms. The change from dilatational to non-dilatational intrusion can be explained by a change in the magnitude of the deviatoric stress from high to low and this change could be the direct result of the intrusion of the earlier gabbros which would tend to increase the value of σ_3.

Although many dolerites tend to be stock-like and to be formed by the 'plucking off' of gneiss blocks, they do not contain gneiss xenoliths, whereas the gabbros do. It therefore seems possible that the xenolithic gneiss blocks produced by the intrusion of the dolerites could have moved by gravity to a different level and that the gneiss xenoliths found out of place in many of the gabbroic dykes may have originated in a doleritic intrusion at a different (higher) level.

The conditions directly before, during and directly after intrusion changed little, for faulting and jointing seen occurred at all of these times. This suggests that the pressure and temperature conditions remained such as to allow brittle deformation to take place. These conditions would have been of low temperatures and/or low confining pressures and/or high strain rates. However the autometamorphism of the gabbros and dolerites indicates that cooling was slow. This may be due to an already warm country rock or to the protracted movement of magma through the dyke fissures causing the warming up of relatively cool country rocks.

Direct evidence concerning the temperature and pressure of the gneisses on intrusion is not provided by the autometamorphic mineralogy. For this mineralogy can be produced on cooling at any 'low' fluid pressures and most oxygen fugacities. Following Dearnley (1973) the absence of melted country rock at the contacts of dykes allows the temperature of the country rock to have been less than 150 to 350°C, given a model of rapid intrusion and consolidation without the flow of hot material through the dyke fissures. Since the dykes (gabbros specifically) show evidence of many pulses of magma flow (e.g. eroded chills) and of long lived magma flow (e.g. 'inch-scale' layering) the temperature of the gneisses prior to the intrusion could have been much cooler than suggested above and therefore at a high level in the crust.

However evidence used has been collected from areas hardly affected by the Laxfordian events. If other conditions prevailed in now Laxfordian reworked areas, which had generally undergone Inverian reworking, they would have stood little chance of preservation.

Laxfordian deformation and metamorphism

After the consolidation and jointing of the dykes the Laxfordian events of metamorphism and deformation took place, with the metamorphic changes continuing from where the autometamorphism ended to produce hornblende, plagioclase rocks of upper greenschist to low amphibolite - to high amphibolite (-possibly granulite) facies rocks.

The initial stages of metamorphism, which may be the only stages reached in the Central Zone, were often dependant on deformation to initiate recrystallization. The areas north of Loch Laxford and around Loch Tollie show granoblastic rocks and textures which suggest that the areas of highest grade of metamorphism saw the growth of metamorphic minerals that outlasted the main and initial stages of deformation.

In the northern half of the Lewisian outcrop four distinct phases of dyke deformation have been recognised. The first of these has tended to deform the dykes into a sub-horizontal attitude as a result of low angle over-thrusting to the north on southwards dipping planes. The stress system that produced these movements had the maximum principal stress acting in a N-S, roughly horizontal, direction and the minimum stress acting in a near vertical direction. It is this phase that may have been responsible for the present day orientation of the gneisses directly to the north of Loch Laxford and is the deformation phase De of the area between Scourie Bay and Loch Poll.

The second phase of deformation has been recognized over all of the northern Lewisian. The deformation has tended to produce S.W. dipping foliations due to a shear couple of 'NE side up SW side down' with a dextral component in the horizontal. It is this phase that has reactivated Dc (Inverian) structures and the dyke/gneiss intersurfaces to produce marginal schistosities and second order shears in the dykes, and the flexure of the gneisses at Durness and within the Central Zone. The high strains around the Ben Stack Line and of the Canisp Shear Belt belong to this deformation. This phase has been coded De over most of the Central and Northern Zones and Df for the area between Scourie Bay and Loch Poll.

The stress system responsible could have been of the maximum principal stress acting in a N-S (or NNW-SSE), almost horizontal direction, and the intermediate stress acting almost vertically.

In the area between Loch Laxford and Loch Poll the third phase structures are vertical, sinistral shear belts that strike NW-SE (to E-W in the south) and a minor, dextral, conjugate set of shears of WNW-ESE strike. The spacing between the belts of shearing decreases northwards as the amount of displacement decreases. Near to the Laxford Front the schistosity produced is characterized by quartz foliae. Directly to the north of Loch Laxford, this phase has caused upright folding, and to have acted at the time of formation of the segregation foliation at Durness. This phase has been coded Dg for the area between Scourie Bay and Loch Poll.

The formation of the deformation styles noted can be explained by a stress system where the maximum principal stress acted in a E-W direction and the intermediate stress acted vertically.

The last deformation phase was responsible for the minor E-W folds of Durness, the large scale warping directly to the north of the River Laxford and the upright folds found south of Scourie Bay.

Therefore the Laxfordian deformations can be accounted for as being the result of a changing stress system whose axes remained orientated N-S, horizontal - E-W, horizontal and vertically.

Moreover by considering the areal extent of each phase and the associated metamorphic textures the second phase is seen to mark the hiatus of the Laxfordian metamorphism of the Central and Northern Zone.

The deformation structures of the southern zone suggest that four distinct Laxfordian deformation phases occurred. However, unlike the rest of the mainland, the amount of Laxfordian deformation shows a less well ordered increase away from the southern end of the Central Zone.

The area around Gruinard Bay and the Gruinard River is notable for, although complete recrystallization of the dykes has taken place, next to no deformation of the dykes has been observed. This may reflect the lack of a strong Inverian grain in this area.

The earliest phases recognized in the area between Loch Maree and Gairloch produced the NE-SW trendihg belt of Creag Mhor Thollaidh (De) and possibly the minor shears of that orientation of Sithean Mor. The vertical sense of movement about this zone of dextral shearing is thought to have been SE side down. However the first deformation phase to affect the areas either side of Loch Torridon was associated with the production of a marginal foliation and minor shears that indicate a dextral sense of movement about the contacts of the dykes that may have resulted from a N-S compression.

The second phase affecting the area around Loch Torridon has only been recorded twice and has folded the dyke contacts about sub-horizontal axial planes.

There is one style of deformation structure that may help to link these two areas, for both around Loch Tollie and and Loch Torridon a phase of simple shearing has produced planar structures that dip to the NE at low angles and are the result of over-thrusting of material to the south. This phase, Df of Loch Tollie and Dg of Loch Torridon, is a mirror image of the first deformation to affect the northern Lewisian, where it occurred before the hiatus of metamorphism. In the southern Lewisian the metamorphic hiatus occurred at the time of the over-thrusting.

The last deformation of the two areas, i.e. Tollie and Torridon, also differ. Around Loch Tollie the last deformation phase (Dg) is characterized by WNW-ESE folding and shearing which moved the rocks north Loch Tollie up relative to the south. However, further south around Loch Torridon the last deformation recognized (Dh) has produced conjugate sets of folds that indicate extension in a general N-S direction. Fortunately one other linking feature does exist. In both areas the last phases are associated with retrogressive metamorphism.

Although such a short distance of no exposure separates the northern and southern halves of the mainland Lewisian outcrop their Laxfordian histories cannot be correlated easily. Common features that exist are that, for both areas a phase of over-thrusting was followed by a phase of vertical shearing and then by crustal shortening. If these deformations correlate in time then the peak of metamorphism is diachronous, occurring later in the north than in the south (see Fig. VII.1). However if metamorphism occurred at a similar time in both the northern and southern Lewisian then the Laxfordian tectonic history may have been of metamorphism reaching a climax at one time and of tectonic pulses, producing similar structures, passing from north to south, but showing minimal effects in the areas of zero, or little, metamorphism.

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