"Some Aspects of the Lewisian Geology of the Isle of Barra and adjacent small islands."

A Thesis submitted for the degree of Ph.D. of the University of London.

P. W. Francis
June 1969

Errata

Photograph 25	Lost in processing
Map 6	For "less" in Key, read "more."

ABSTRACT

It is shown that the Lewisian rocks of the Barra area may be divided into a Laxfordian supra-structure characterised by amphibolite facies gneisses and a largely Scourian infra-structure characterised by pyroxene bearing gneisses. Both units contain representatives of the Scourie Dyke suite; in the supra-structure they are highly deformed and folded, in the infra-structure they are relatively undeformed, unfolded and retain original discordant relationships. The infra-structure in addition is characterised by several suites of intrusive rocks earlier than the Scourie Dyke suite, the most widespread of which are dykes of intermediate or diorite composition.

The same sequence of Laxfordian phases of deformation may be recognised in both units. Folding occurred in the supra-structure under amphibolite facies conditions, which continued after deformation ceased. In the infra-structure, evidence for a pre-Scourie dyke granulite facies metamorphism is preserved, and it is suggested that the pyroxene granulite facies assemblages within the dykes themselves were produced by intrusion into hot or dry country rock gneisses.

The Outer Hebrides Thrust in the Barra area is described, and an estimate of its displacement given. The pseudotachylyte problem in general is reviewed, and the conditions leading to its production are discussed.

Acknowledgements

A great many people have helped in a variety of ways to influence the final shape of this Thesis. I would like particularly to express my thanks to those with whom I have been most closely associated:- To Dr. J. Watson for reading and criticising the text, and for her generous help and encouragement over the last three years; to Mike Coward, Rod Graham and John Myers who have provided stimulating and thought-provoking company both in the Islands and in London; to Miss P. Kirk and Miss C. King for their patience in translating the original manuscript into type; and above all to my parents for their unstinted practical help and tolerance.

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I PREAMBLE

(i) General

The island of Barra was selected as a suitable area to carry out fieldwork directed towards the production of a Ph.D. thesis in the spring of 1967. Three reasons determined this choice.

First, Barra and its off-lying smaller islands offered a relatively easily accessible area of well exposed Lewisian rocks about which little was known.

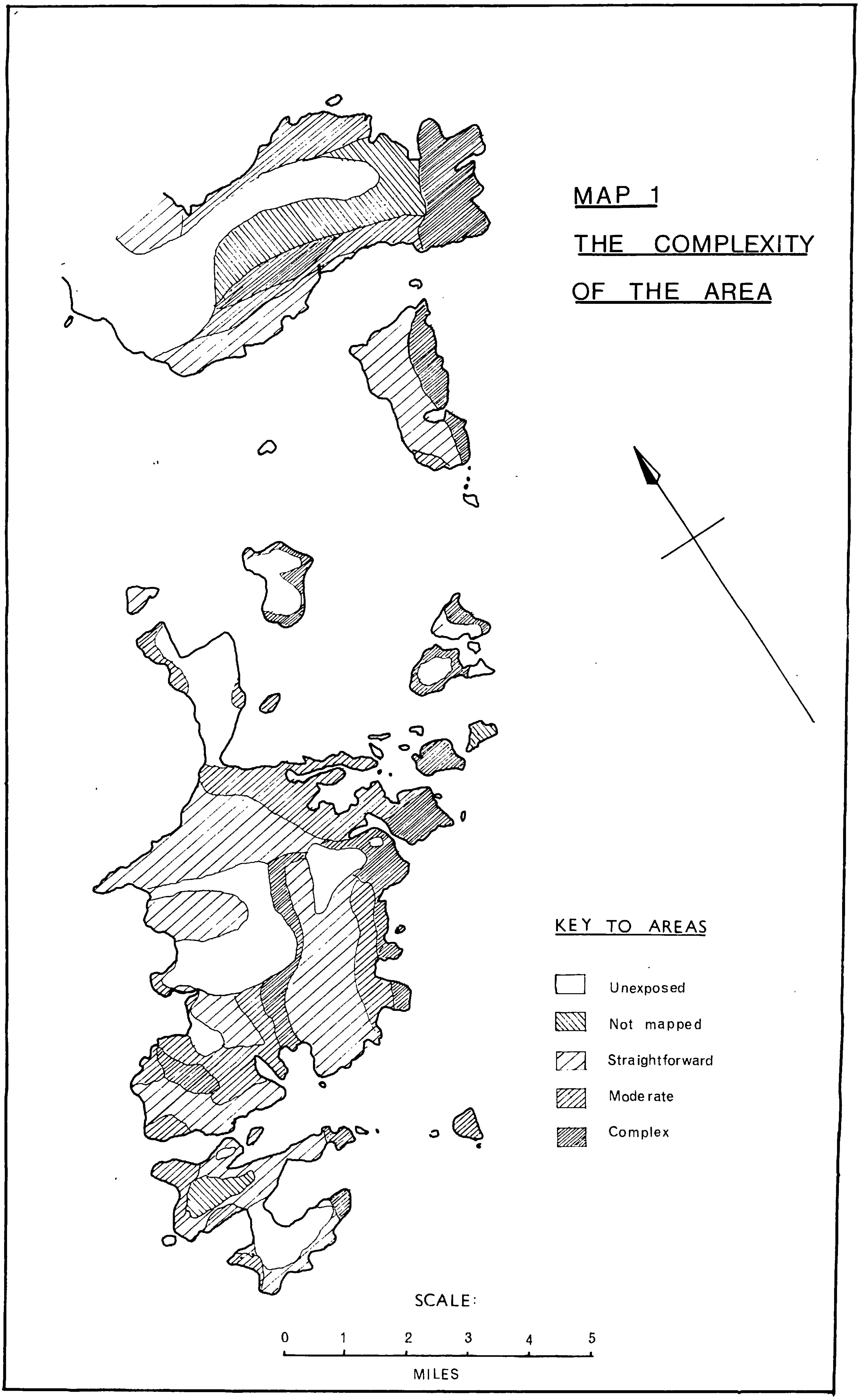
Second, the size of the area was such that it could be adequately covered during two field seasons.

Third, work done on Barra would form part of a larger study on the Outer Hebrides, already being undertaken by other members of Imperial College.

The object of the work was to produce a regional study of the area, to determine its structural and metamorphic histtory, and to relate this as far as possible to that of the rest of the Outer Hebrides and to the mainland of Scotland.

(ii) The Area

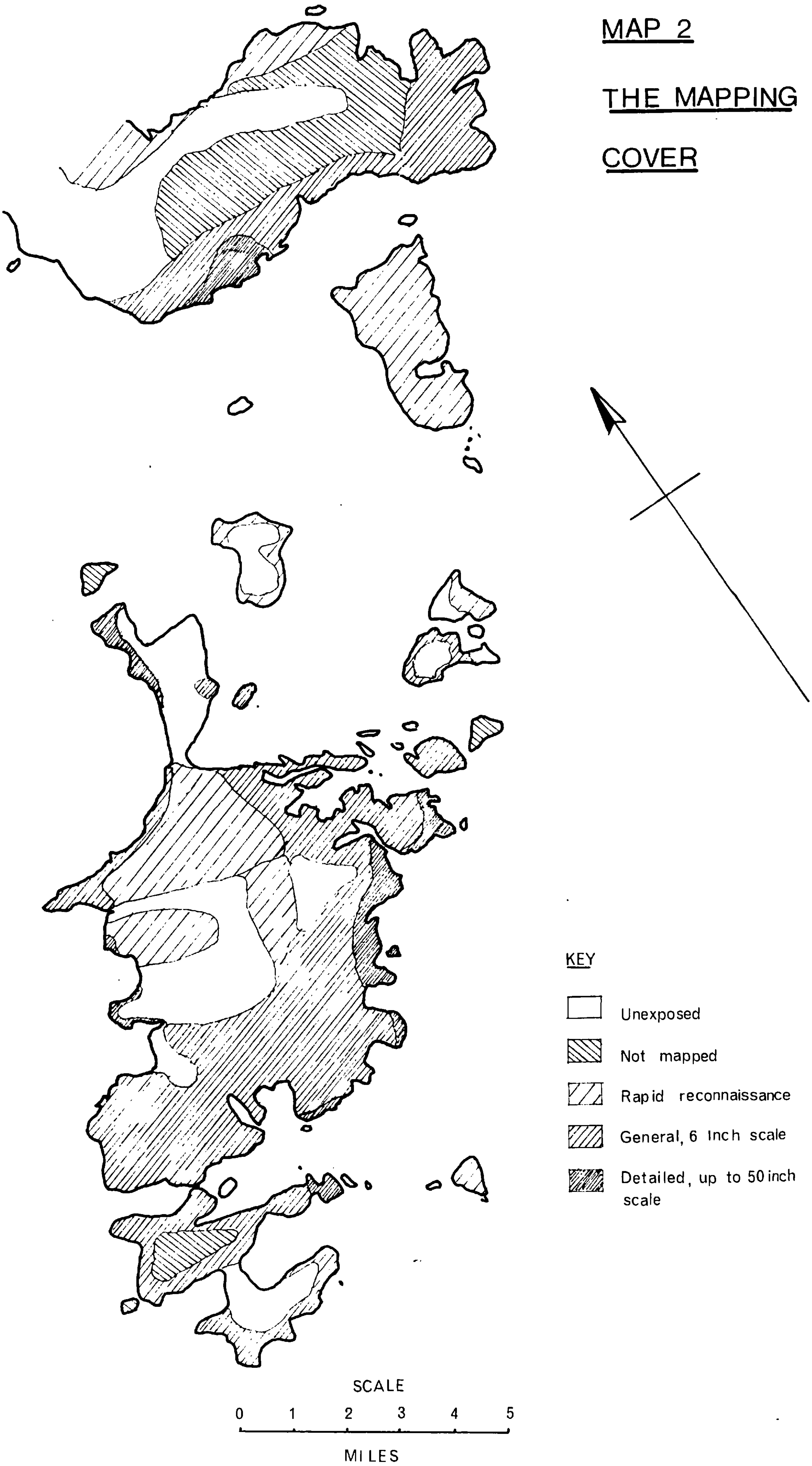
The area ultimately covered was larger than that originally intended, due to the uniformity of large regions in the South and the greater importance and interest of areas north-east of Barra. Maps 1 and 2 show the ground covered, and on them an attempt has been made to indicate the validity of the mapping by defining areas of different degrees of complexity (Map 1) and the degree of detail of mapping



MAP 1 THE COMPLEXITY OF THE AREA

MAP 2

THE MAPPING COVER



(Map 2). Due to combinations of exposure and accessibility, the most complex areas are not necessarily those that have been mapped in the most detail.

In general, the coast line has been mapped in greater detail, thanks to the vastly superior exposures. Inland, not only are there patches of complete non-exposure, but in many of those areas where rocks are exposed, the smooth, slabby lichen covered outcrops make interpretations very much more difficult.

Most of the mapping was done using rather poor quality air photographs on a scale of roughly 6 inches to the mile, and in well-exposed areas on newly-surveyed 25 inch maps. These were enlarged to 50 inches for the coast section on the East of Barra.

A total of nine months was spent in the field, in two seasons. The first season served to provide a rough outline of the problems involved, and was hampered by lack of transport and by typical North Atlantic weather. In the second season, problems and areas of interest delineated in the first were developed and extended, and the mapping was carried over into Eriskay and the southern part of South Uist. Progress was rapid, and was assisted by adequate transport and consistently fine, thoroughly untypical weather.

In addition to the areas mapped, a reconnaissance was made by boat of the islands Sandray, Pabbay, Mingulay and Berneray. Magnificent cliff exposures on these islands gave an excellent idea of the general situation of the southern islands.

(iii) Previous Work

The earliest accounts of rocks in the Outer Hebrides occur only incidentally in the descriptions published by the occasional educated visitors to the Islands, and it was not until 1819 that a work appeared that was largely concerned with rocks. This was Macculoch's "A Description of the Western Islands of Scotland," which contained some reasonably good descriptions of rocks interspersed with comments on the way of life of the crofters and criticisms of their idleness. Perhaps his best observations were concerned with the abundant flinty "trap" veins (psuedotachylyte) which ramify through the gneisses of the islands. Although he mistakenly concluded the "trap" veins to be of igneous origin, he did point their occasional "conglomerated" nature in parts of South Uist. This was certainly the first description of the now well known psuedotachylyte conglomerates and breccias anywhere in the world.

Macculoch's work was not well received in all quarters, however. In 1825 Browne published "A Critical Examination of Pr. Macculloch's work in the Highlands and W. Islands of Scotland." This was devoted primarily to a savage, almost libellous attack on Macculloch and his work, but dealt principally with his social commentary, and contributed nothing to the knowledge of the geology of the islands.

One hundred years passed before the next serious contribution, Dougal's "Observations on the Geology of Lewis" which was naturally chiefly devoted to Lewis, but did draw attention to the zone of flinty-crush rocks, which Dougal recognised as traceable along virtually the entire east coast of the island chain.

In 1925 Jehu and Craig published the initial part of their comprehensive study of the geology of the Outer Hebrides. Of the five parts, only the first two are directly relevant; those covering the Barra Isles, and South Uist and Eriskay.

Although their maps are very generalized and not particularly informative, Jehu and Craig do appear to have covered their ground diligently, visiting all the major islands between Barra and Barra Head, and between Barra and Eriskay. Their petrographic observations are particularly reliable, in that ohly very rarely were occurrences found of the rock types not described and located by them. Their descriptions of the Outer Hebrides Thrust and its associated flinty crush rocks are also very good, although their mapping of the crush zone on Barra was rather haphazard.

Bearing in mind the period and conditions in which they worked, the only criticism that one could fairly make of their work is that they did not carry it as far as they might, saying nothing of their interpretations of the history of the rocks they were concerned with, but contented themselves merely with straightforward descriptions.

Kursten in 1957 mapped an area north of Lochboisdale as one of three he studies as being representative of the "Metamorphic and Tectonic History of parts of the Outer Hebrides." The most interesting aspects of this paper are the very full descriptions of the Thrust Zone in the area near Lochboisdale,,and also in the recognition of two major periods of metamorphism in the Outer Hebrides which are correlated with the Scourian and Laxfordian of the mainland.

The details of this paper do not relate to the present area, as it will not be discussed here in further detail.

An important contribution appeared in 1962 when Dearnley published his "Outline of the Lewisian Complex of the Outer Hebrides in relation to that of the Scottish Mainland." In this paper, Dearnley correlated the three principal zones in the mainland Lewisian (Sutton & Watson 1951) with three similar zones that he recognised in the Outer Hebrides:- a northern Laxfordian zone, a dentral Scourian zone, and a southern Laxfordian zone, in which latter the present area would lie. He then went on to postulate a major wrench fault, the Minch fault, to account for the relative off-setting of the zones across the Minch. Perhaps the most important aspect of this paper was Dearnley's recognition of a suite of intrusive igneous dykes which he correlated with the "Scraris dyke" suite of the mainland.

In a later paper, Dearnley and Dunning (1968) described early, deformed pegmatites in their "central zone," which they suggested might be of pre-Scourian, or Katarchean age, and also described various stages in the deformation and metamorphism of dykes in mobilized Laxfordian migmatitic gneisses, principally in Benbecula and northern South Uist, but also at one locality Pollachar, within the present area. The conclusions of both these papers will be considered elsewhere in the text, when considering the relations between the Lewisian in Barra and elsewhere.

Barra itself has received the attention of only one geologist in recent years, A. M. Hopgood, who, at the time of writing has produced an unpublished Ph.D. thesis and a short paper on dyke deformation.

(Hopgood 1965). A further general paper on Barra is believed to be in press, in addition to a joint paper with Bowes on Mingulay, an island about 12 miles south of Barra (Bull. Geol. Soc. Amer. in press) Since Hopgood's work had broadly the same aim as this present thesis, it is proposed to consider it in some detail here.

Hopgood's thesis is in two volumes, one containing text, the other illustrations. These are 217 pages of text, about 40,000 words, 168 photographs, 84 stereograms, 47 diagrams and 9 rose-diagrams. His aim was to produce a primarily structural study of Barra, and to deduce a sequence of tectonic events by mapping on different scales and by statistical analysis of his field data. A brief summary of his sequence is given here, so that it may be compared with the present interpretation.

<u>Outline of Hopgood's Sequence</u>

Phase (1) Formation of original banding

(2) Isoclinal folding and regional metamorphism

(3) Shear folding

(4) Various igneous phases at Leenish:-
- (a) Early phase. Large basic intrusives
- (b) Middle phase. Ultra-basic intrusives (Hornblendite dykes and coarse hornblende pegmatites)
- (c) Late phase. Basic Sills (Biotite gneiss)

(5) First North-East phase F , plus migmatisation and formation of pegmatites.

(6) Agmatization and boudinage.

(7) Later dyke emplacement:-
- (a) Early phase. Acid and intermediate dykes (biotite gneiss)

(b) Middle phase. Basic dykes (biotite gneiss)

(c) Late phase. Basic dykes (hornblende/pyroxene granulite).

(8) Pyroxene granulite regional metamorphism

(9) F_2 folding trending 345° and accompanied by pegmatite injection. Preceded by first thrust period.

(10) F_3 folds and pegmatites, trending 145°

(11) F_4 folds and pegmatites, trending 100°

(12) F North-Easterly warps.

(13) Thrusting

(14) Jointing and fault development trending 070°

(15) Post - Lewisian dykes and faulting.

After carefully reading Hopgood's thesis, andof course, going over the same ground, it appears to me that two of Hopgood's observations are of value. First, and most important, his recognition of dykes earlier than those of the Scouri dyke suite on the east coast of Barra, although his interpretations on the number and sequence of early intrusives differ drastically from the present work.

Second, his observations that folds of (his) F_2 age are the dominant structures on Barra and in the southern part of the Hebrides as a whole. Recent work in the Hebrides has demonstrated that the regional structures is controlled by folds that Hopgood would correlate as F_2 , although these are now considered to be F_3 in age.

In my view, however, Hopgood's thesis fails to give a convincing account of the geology of Barra for the following reasons:-

First, he makes no distinction between the rocks above and below the Outer Hebrides Thrust. The differences between these rocks are very striking, and of fundamental importance to the geology of the area. Hopgood makes only the most oblique reference to this, and consistantly ignores the contrast across the Thrust, to the extent of continuing foliation trends across it on his map.

Second, he relies mainly on orientation as a criteria for correlating phenomena. If, for example, a fold has an axial trace 145° , then any other fold with the same trend is the same age, and any pegmatitic trending 145 is also of the same age.

Third, he makes extensive use of statistical analysis of his structural data for interpretations. Such analysis is potentially very valuable, but Hopgood's use of it is well beyond the limits of validity, and he tends to prefer such analysis to interpretations made in the field. Also, the data he uses is mainly of foliation orientation, whereas data on linear elements in multi-folded areas is much more useful.

Fourth, his thesis contains many obvious errors in logic and observation. It is not proposed to detail them here, but they may be illustrated by an example:- Hopgood mapped in on his 6 inch map a thrust-plane, outcropping over some 2 miles on the hill Ben Tangaral in Southern Barra. These is no evidence whatsoever for such a thrust.

Many of the shortcomings of Hopgood's thesis were apparent when reading it in London, and consequently it was decided that it did not form an adequate basis to work on, and thus a fresh start was made, ab initio.

II DESCRIPTION OF THE GEOLOGY OF THE AREA

INTRODUCTION

In writing this thesis three aims have governed the methods used. These are brevity, simplicity and objectivity. This approach is partly the result of reading several theses in geology which are so long and complex as to be infinitely tedious and extremely difficult to follow through and understand as a whole. Also, when dealing with material as inherently complex as basement rocks, it is impossible to make progress in understanding them without making a sequence of subjective assumptions which too often turn up later as facts in discussions. Consequently an attempt has been made to separate observations from interpretations, although of course, it is impossible to be fully objective in making even the simplest observation.

The geology will be described under four principal headings:- Western Gneisses, Eastern Gneisses, the Oitir Mohr Zone, and the Thrust Zone. The Outer Hebrides Thrust on Barra separates two main groups of rocks which differ from one another in many respects, the Western and Eastern Gneisses:-

The Eastern Gneisses are petrologically very varied, and contain several sets of intrusive igneous rocks of distinct ages and compositions. These are extensively deformed and migmatised in the South-East of Barra, but are relatively undeformed in Eastern and North-Eastern Barra, where they cross-cut the country-rock foliation. The metamorphic grade of the gneisses also changes north-eastward from amphibolitic to pyroxene granulite grade.

The Western Gneisses, which form much the largest group in terms of area, are very uniform petrologically, and contain only one set of undoubted intrusive igneous rocks, which are discordant only within the Oitir Mohr zone, which forms a distinct unit and will be described separately. The Western Gneisses outside the Oitir Mohr zone show a very rapid decrease in deformation and an increase in metamorphic grade towards the boundary of the zone, but in all other respects they are a rather monotonous series of acid gneisses with occasional concordant amphibolitic bands.

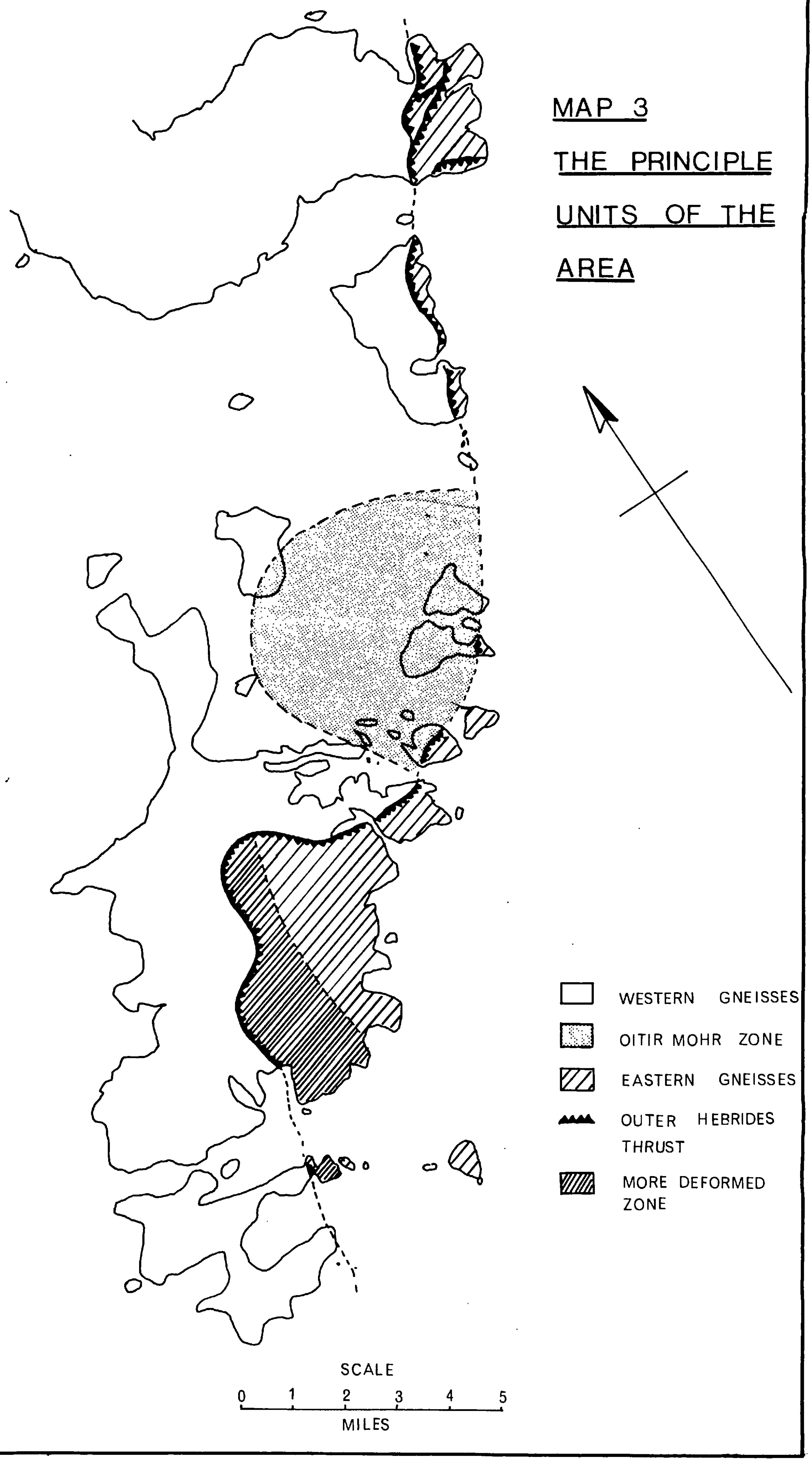
The Oitir Mohr zone itself is of great importance to this thesis, but unfortunately the rocks are only indifferently exposed on a few small islands. The rocks within the zone are in all respects similar to the Eastern Gneisses; they contain a series of intrusive igneous rocks of distinct age and composition and are characterised by the presence of orthopyroxene in rocks of almost all compositions. The last of the intrusive igneous suites forms a set of discordant dykes with pyroxene granulite mineralogy which cam be traced across the transition into the Western Gneisses into concordant amphibolites.

The Outer Hebrides Thrust forms a single, simple easterly dipping plane in the southern part of the area, thrusting uncrushed rocks over one another, but above the Thrust on Eriskay and South Uist, the rocks are extensively crushed, and instead of a single plane, several are present on South Uist at least. One of these thrusts, at Marulaig, introduces a completely new type of rock into the area, a wedge of "Eastern Gneisses" of the type exposed east of the Thrust in the rest of South Uist. This will be described briefly in the section on the Thrust.

The psuedotachylyte associated with the Thrust forms a distinct and important topic which will be discussed at some length.

The positions of the principal units described are illustrated on Map 3. A loose map, Map 4, shows the principal localities referred to in the text.

MAP 3 THE PRINCIPLE UNITS OF THE AREA



THE EASTERN GNEISSES

General

The rocks east of the Thrust described here should not be confused with the "Eastern" gneisses of South Uist or elsewhere, which are significantly different.

Two important zones have been recognised within the Eastern Gneisses; a more deformed zone and a less deformed zone, with a sharp transition between them (Map 3). In both zones, a very varied and distinctive set of rocks is present, in strong contrast to the uniform rather monotonous Western Gneisses. This contrast is naturally most striking in the less-deformed zone, and it seems remarkable that Hopgood did not draw attention to it.

THE LESS DEFORMED ZONE is characterised by a wide variety of intrusive igneous rocks which still show consistently cross-cutting relationships with the country-rock foliation. The sequence of intrusions is summarized in Table I. To avoid confusion, the last, most important suite of intrusive dykes will be referred to as the "Scourie Dyke Suite", although the evidences for this correlation will be discussed much later in the text. The Scourie dykes of the less-deformed zone are almost always of pyroxene-granulite mineralogy, while the country-rock gneisses also commonly contain orthopyroxene.

THE MORE DEFORMED ZONE.. In this zone, rocks of most of the types recognised in the less deformed zone can be identified, but in a deformed and migmatised state. Dykes which were cross-cutting are now folded and boudinaged, a new fabric is developed in the rocks, and amphibole appears in rocks which were previously pyroxene bearing.

It is proposed to describe briefly the rocks of the two zones, then the structures that have affected both zones and finally their metamorphic history.

TABLE I

Summary Sequence of Intrusive and later events in the Eastern Gneisses

MORE DEFORMED ZONE	EVENT	LESS DEFORMED ZONE
Weak. No folds identified	F_{3E} deformation	Weak. A few minor folds
Regional Structure	F_{2E} deformation	Regional Structure
Folding	F_{1E} deformation	No folds, but extensive flattening
Dykes wholly or partially amphibolized	Scourie Dyke Intrusion	Dykes have granulite mineralogy
Deformed and foliated	Pegmatites	Non-foliated, discordant.
Deformed and foliated	Granites	Non-foliated, discordant.
Not recognised as dykes, but as large homogeneous masses	Early dyke suite	Cross-cutting dykes of three sets recognisable.
A few dubious representatives	Early Intrusive bodies	Large homogeneous masses
	Formation of original complex	

The Less Deformed Zone

(i) Introduction

Because of its considerable interest, this zone was examined in some detail. A strip of coast, starting from the transition into the deformed zone, was mapped on a scale of 50 inches to the mile, giving a section nearly a mile long across the strike (Map 5). Since the coastal fringe of exposure is so narrow, it was not possible to extend detailed mapping inland, and so the poorly exposed inland areas and the remaining coastal exposures were mapped on a 6 inch scale only.

The dominant features of Map 5 are the Scourie dykes, and it is immediately obvious that these form regular, planar, bodies over much of the map, but as one moves south-westwards they become progressively more deformed. The inset shows the area which might be called the boundary between more and less deformed zones:- here the dykes still show occasional discordant relationships, but they are extensively deformed and boudinaged and show incipient amphibolitization. The area of the inset is very nearly on strike from the south-western tip of Leenish Point, where the main map commences.

(ii) Gneisses

Although the zones of more and less deformation have been separated principally on the basis of dyke deformation, there are also some important differences in the gneisses of the two zones. The acid gneisses of the deformed zone are rather uniform, monotonous hornblende-biotite gneisses, but in the less deformed zone two differences are apparent.

First, the gneisses are much more varied in appearance, and in particular they contain a lot more included material. This usually consists of blocks or lumps of coarse amphibolitic material, often with an early foliation in them. Sometimes this foliation defines folds, and the blocks appear to represent the noses of folds whose limbs have been sheared off. In other localities, blocks of intermediate composition occur in large numbers, forming an assemblage resembling an agmatite, except that the matrix is gneissose rather than quartzo-feldspathic. In these assemblages the blocks themselves are often foliated and this foliation can be used to show that blocks have been completely disorientated relative to one another (Photo 1). It is considered that this occurred very early in the geological sequence of events, since in some places these block assemblages can be seen clearly cut by dykes of the early suite. It is not impossible, however, that in some instances the disruption occurred much later. The general appearance of these rocks is strongly reminiscent of other areas of low deformation in basement rocks, particularly in Greenland (Bridgwater 1968).

The second, and perhaps more important distinction, is that orthopyroxene appears in the gneisses and becomes abundant north of the Alt Heiker. Where pyroxene is most abundant, the rocks have a very distinctive rusty brown colour, and large, conspicuous pyroxene crystals can be seen with the naked eye. The rocks contain many quartzo-feldspathic stringers, and the general appearance is very similar to that of brown weathering metasedimentary gneisses. Under the microscope, one sees quartz, biotite, orthopyroxene, plagioclase

1. Early, foliated blocks in a gneissose matrix, Eastern Gneisses of Bruernish Point. NF 726007

2. "Mottled" Amphibole bearing body, Leenish Point. Note the light coloured intermediate dyke in the centre of the photograph. NL 703987

and orthoclase feldspars, with a little hornblende and ore. The rusty brown colour in outcrop appears to be due to pale yellow-brown rims of presumably ferric iron material around all of the grains. Typically, the orthopyroxene occurs as large single crystals which are frequently corroded and altered to fine grained material, possibly biotite, and other partly crystalline material. This break-down of pyroxene may in part be responsible for the brown-stained rims to grains in the rock. Only a few pyroxene grains are sufficiently fresh to show well the typical pleochroism from delicate pink to pale green.

There seems to be a complete transition from these brown-weathering rocks containing much pyroxene to gneisses perfectly free of pyroxene, containing only hornblende and biotite. It was not found possible to map out these variations, since there seemed to be no regular distribution of pyroxene rich and pyroxene poor material.

One interesting aspect of these rocks is that in all those sections examined, there was a complete absence of clinopyroxene. It is suggested that this may be due to the original chemical composition of the rocks.

Early intrusive bodies Two curious and rather interesting rock types will be described under this heading. They are superficially dissimilar, but it is hoped to show that they may in fact be related: the first to be described is characterised by orthopyroxene, the second by hornblende.

Orthopyroxene bearing bodies These were first recognised near the hamlet of Balnabodach, whence they acquired their polysyllabic field name "Balnabodashites." They are very poorly exposed, and hence very difficult to map, but they do appear to form a chain of more or less discrete bodies arranged along the strike.

In outcrop, they look very much like the brown gneisses, but they are homogenous, lacking banding and fabric. They are rather coarser grained, and are studded with conspicuous brown pyroxene crystals. Their poor exposure makes it difficult to comment on their relations with the gneisses, but contacts seem to be diffuse rather than sharp, and the body appears to have been formed by in-situ recrystallization, rather like a granite, and not be forceful intrusion. This point is significant, and will be referred to in a later section.

In this section, orthopyroxene is conspicuous as large, often altered grains. Brown rims around grains are observed, and this feature, coupled with the tendency for hand-specimens to be excessively crumbly seems to be typical of orthopyroxene bearing rocks, and is presumably a result of the break down of the pyroxene.

Biotite is abundant, and appears in some instances to be replacing the pyroxene. Some hornblende is also present in varying amounts. Sections taken from the most homogenous bodies contain very little, if any quartz, a plagioclase near oligoclase constituting the bulk of the rock, while a little potassium feldspar is also present. Sections from other localities, however, show wide variations in amounts of quartz, which becomes extremely abundant in places. This variation obviously presents considerable problems.

Two possibilities seem to be indicated:-

First, that these bodies of homogeneous pyroxene-biotite-plagioclase rock represent originally basic or intermediate igneous rocks, which have been metamorphosed, possibly with the introduction of quartz in places.

Second, that they represent metasedimentary rather than originally igneous rocks. This is undoubtedly the conclusion that one would reach considering only their field of occurrence, since they so closely resemble the brown gneisses and biotite-rich metasedimentary rocks of other areas in the Hebrides. The almost entirely quartz free composition of many of these rocks seems to argue against this possibility however.

Amphibole bearing bodies. Rocks of this type are found at several localities along the coastal section, and at one or two poor exposures inland, principally near Lochan nam Fooilean. They are of basic to ultramafic composition and are distinguished by the presence of very large hornblende crystals, up to 1½ inches across.

In outcrop, they occurr usually as irregular masses or lumps in a granitic or pegmatitic matrix. Sometimes, as at Leenish, ball-shaped masses are caught up in granite; elsewhere a large mass is broken up into blocks by a network of pink pegmatitic veins, producing a "net veined" texture.

Occasionally, large, massive bodies occurr. One such is at the S.E. tip of Leenish Point, where two textural extremes may be rec

At the northerly end of the outcrop, very striking large hornblende crystals are set in a matrix of feldspathic material. As one traces the rocks southwards, the hornblendes appear to give way to clots or masses of mafic minerals which are drawn out into lenses, giving the rock a distinctive mottled appearance. (Photo 2)

Thin sections of the variety containing large hornblendes reveal a variety of minerals. Hornblende is of course abundant, occurring in the matrix as well as in large crystals, together with the biotite, clinopyroxene, orthopyroxene and plagioclase. The clinopyroxene shows signs of conversion to hornblende. The mottled variety contains only hornblende, biotite, fresh clinopyroxene, plagioclase and a little quartz, and in many respects are similar to the orthopyroxene bearing bodies described above, except for the presence of clinopyroxene.

This body as a whole has a very sharp margin against the country rock gneisses, just possibly cross-cutting at one locality. Similar sharp margins have been observed elsewhere, at Brevig for example. It is suggested, therefore, that these bodies represent basic or ultrabasic intrusive igneous rocks. The assemblage in the varieties containing large hornblende crystals may approximate to the original igneous texture, assuming that complete uralitization of the original pyroxenes had occurred, whereas the mottled variety represents its deformed and metamorphosed equivalent, perhaps with a new crystallization of clinopyroxene.

Three factors suggest a correlation between these rocks and the pyroxene bearing bodies.

First, the extensive development of amphibole bearing rocks at Brevig and Leenish is directly along strike from the pyroxene bearing bodies further inland.

Second, although there is a wide variation, the overall minerology is similar, except for the occurrence of clinopyroxene in the amphibole bearing rocks.

Third, they appear to have the same time-relations to the county rock and to later dykes. In photo 2 a dyke of the early suite can be seen cutting the mottled rock. A dyke of the same suite has also been observed cutting a pyroxene bearing body at one locality, so it would appear that both types are of broadly the same age.

Hornblende from the bodies at Leenish has been dated by Moorbath at 2,585 m.y. (K/Ar), while biotite from the same bodies gave an age of 2,010 m.y. (K/Ar).

(iii) The Early Dyke Suite

Three sets of dykes have been recognised, distinguished by their age and composition:-

Youngest set.	Leucocratic, granodioritic
Intermediate set.	Intermediate composition
Oldest set	Melanocratic, basic to ultrabasic

OLDEST SET These are the most basic and least abundant of the early dykes, only 3 having been recognised. None is more than 9 inches thick. At one locality, by great coincidence, one of these dykes can be observed cross-cut by members of both later sets (Fig. 1), and it

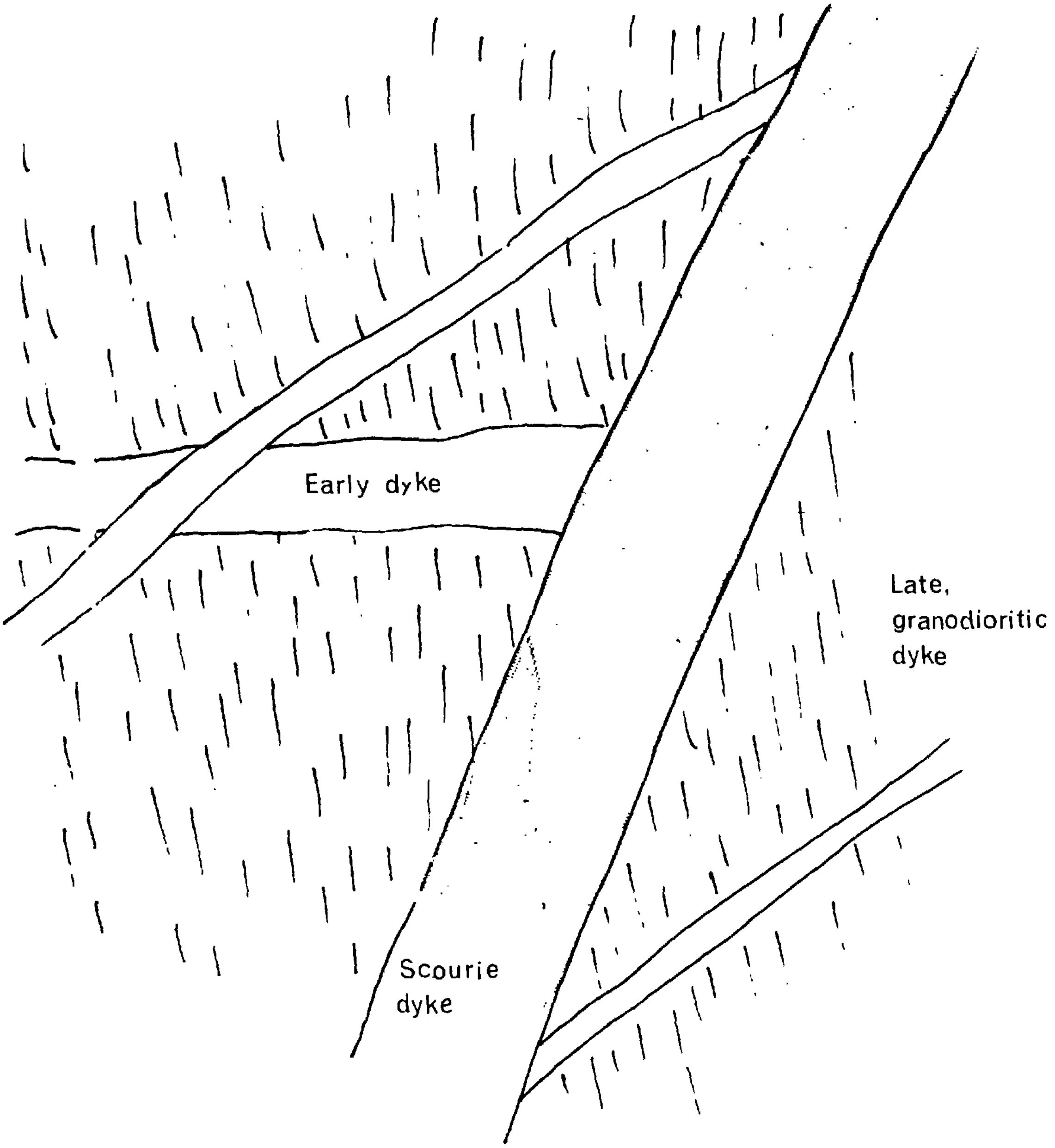
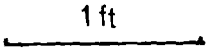


Fig.1 Dyke relationships at Leenish Point

Note offset along Scourie dyke



is largely on this evidence that these dykes are assigned to the oldest end of the series. All three recorded dykes are strongly discordant, one of them nearly perpendicular to the plane of the foliation (Photo 3).

Their mineralogy is rather varied. The dyke in Fig. 1 for example contains mostly hornblende with a little biotite and plagioclase (An 30), while the dyke in Photo 3 contains only hornblende and clinopyroxene with a little quartz. These compositions indicate an origin as basic to ultrabasic intrusives. It is also clear that they closely approximate in composition to the amphibole bearing bodies just described, and that therefore one might be justified in correlating them.

INTERMEDIATE SET. These are extremely abundant, and examples may be found over the whole of the less deformed zone. They range in thickness from 3 feet down to a couple of inches, and cut the county rock foliation at varying angles. One very distinctive feature of these dykes is their tendency to wander across the foliation, rather than cut across it in a regular, dyke like fashion. These dykes tend to merge into the gneisses, and diffuse themselves vaguely through it, earning themselves the field term of "ghostly" dykes. Many of the dykes in this set, however, are planar, regular bodies, and it is suggested that there may be a contrast here between dilational and non-dilational dykes; the irregular dykes being of originally non-dilational origin, and therefore formed partly in situ.

The mineralogy of all these dykes is very simple and uniform. Point-count analysis of five different dykes was undertaken, and the

3. Highly discordant dyke of the Early set, Brevig. NL 704994

4. Discordant dyke of the Intermediate set. Note the foliation parallel to its margins defined by clots of hornblende and biotite. Brevig. NL 706994

results are presented in Table 2, which shows that despite small variations in mineral quantities, the bulk composition is fairly uniform. The texture also is very simple, with perfectly clean, fresh minerals forming simple, equant, grains. Plagioclase boundaries with plagioclase are particularly simple, and when 3 crystals meet, each crystal has a 120 degree interfacial angle.

Although there is no fabric apparent under the microscope, the dykes seen in outcrop sometimes show distinct fabrics revealed by the segregation of mafic minerals into elongated streaks or clots, (photo 4). The interest in this fabric is chiefly in its orientation, which is parallel to the dyke margins, and not to any fabric in the gneisses. This point is discussed later.

The position in time of these dykes is easily fixed. They cross-cut all the rocks so far described, and are frequently cut by Scourie dykes and can also be seen in the process of digestion by the early granite to be described shortly.

The consistent time relationships, the uniformity of composition and the abundance of these dykes strongly suggest the presence in the Eastern gneisses of a distinct suite of intrusive rocks of dioritic composition, which is in Barra at least, as important as the Scourie Dyke suite.

YOUNGEST SET. Dykes of this set are scarce, only some half dozen being found. Their relative age may be established at the locality of Fig. 1, where a typical member cuts dykes of both earlier sets. Dykes are typically about 9 inches wide, and are always regular,

TABLE 2

Point Count Analyses of Intermediate Dykes

Specimen	Locality (Grid. Ref.)	Biotite %	Hornblende %	Plagioclase %	Opaque %	Apatite %
47	NF726007	18.4	24.9	52.3	3.6	0.7
56	NF734006	15.0	23.5	51.6	4.0	1.0
54	NF736013	12.1	39.1	46.7	0.9	0.9
86	NF716003	14.2	24.4	57.7	2.8	0.8
95	NL704987	13.7	27.1	56.6	2.7	0.8

Specimen 56 contained about 5% scapolite. The plagioclase composition was consistently about An 30.

planar bodies. They are distinctly leucocratic by comparison with the earlier dykes of this suite. Their mineralogy is distinctive:- they contain abundant quartz, a variety of feldspars, principally oligoclase with microcline and some orthoclase. Biotite is the chief mafic mineral, with a little second-hand orthopyroxene. As usual with orthopyroxene, there is a strong brown staining of the mineral grains, producing a rather rusty appearance in the outcrop.

Compositionally, these rocks are much more acid than any of the intrusive rocks so far described, and must be well within the field of granodiorites.

(iv) Early Granites

These are not extensively developed within the less deformed zone, although much larger bodies are found within the deformed zone. However, on the shore at Brevig, splendid fresh pink granites may be seen invading and replacing country rock gneisses. Some bodies show very sharp junctions with the gneisses, while others have distinctively gradational boundaries. Blocks of easily recognisable material such as those of the early intermediate dykes are often seen as rafts or xenoliths in the granite clearly establishing their mutual time relationships. The granites are also convincingly cut by Scourie Dykes.

In this section one sees clear, fresh quartz, foxy red biotite, abundant orthoclase and some microcline. Plagioclase is definitely subordinate to potash feldspar. The feldspars show some perthitic textures, and all in all these are very fine, typical granites.

Apart from these relatively large bodies at Brevig smaller examples of granites do occur elsewhere. At Leenish, for example, a slightly foliated granite has invaded an amphibole bearing body with the result that rounded lumps of amphibolite are caught up in a pink granite matrix, making a very conspicuous rock. A similar situation occurs at two or three other localities along the coast, but here the invading material is pegmotitic rather than granitic, and forms the net-veining relationship mentioned earlier.

At two localities along the coast a rather different granite/ amphibolite relationship is seen. Instead of breaking up the amphibole bearing body into discrete lumps, a continuous transition between homogeneous granite and homogeneous amphibole bearing body may be clearly seen, particularly well at an outcrop directly beneath the outfall of the sewer of the croft at NL 705995. Here it appears that the granite is digesting the earlier body, and is acting as a definitely replacive rather than intrusive body.

The larger areas of granite have been indicated on Map 5. There must be a considerable element of subjectivity in this, however, for it is clearly very difficult to draw a line between granite and partially granitized gneiss.

(v) Early Pegmatites

Pegmatites are fairly common in the less deformed zone, but only rarely can their age be confidently established.

At Leenish Point, however, three undoubted early pegmatites are exposed, and are convincingly cut by Scourie Dykes. Two of these pegmatites are relatively small, only about 18 inches wide, but the third is a very large body many feet wide and very conspicuous (Map 5). The two smaller bodies consist of pink K feldspar, with minute amounts of quartz and biotite, whereas the larger body consists of a core of mossive white quartz surrounded by an outer zone of large pink feldspar crystals well over a foot in size. This large body seems to be situated in an early, minor, shear zone, and is a little odd in that it peters out abruptly at one point, and suddenly re-appears a little further on with the same thickness as before. The crucial point of this gap in the pegmatite is of course not exposed, being under water in a small sloc.

Moorbath has dated the K feldspar from these pegmatites and has obtained a value of 2620 m.y. (Rb/Sr), the data falling on a particularly good isochron.

(vi) Scourie Dykes

These are very abundant indeed and are present in all sizes from very large, branching dykes traceable for over a mile, to tiny apophyses. They represent the last important intrusive event in the Eastern Gneisses, and they form a vital time marker for correlations with the deformed zone and with the Western Gneisses.

Petrographically, these dykes are beautifully simple. Nearly all the dykes over one foot thick are excellent two pyroxene granulites, while narrower dykes and the edges of large bodies are amphibolites. Two textural varieties may be distinguished; a uniform fine grained variety and a maculose variety.

FINE GRAINED VARIETY. In the field, these rocks are remarkably homogeneous, with no sign of fabric nor banding, and have a "salt and pepper" appearance caused by the regular mixture of different coloured minerals of uniform grain size. These rocks also furnish remarkably elegant thin sections. Orthopyroxene, clinopyroxene, plagioclase and ore are the chief minerals, together with a very little hornblende. The texture is that of a classic granulite - all the minerals form equant grains of roughly the same size and have regular boundaries with one another, while triple points between mineral often show 120° interfaces.

The colour of the pyroxenes in these rocks is striking. The clinopyroxene is a distinct pale apple green colour, while the orthopyroxene is almost violently pleochroic from pink to green. The plagioclase composition averages about An 35.

MACULOSE VARIETIES. Dykes with this texture are always large bodies, and usually this texture is found at the centre, with a gradual transition from the more common fine grained textures inwards away from the margins, which are themselves amphibolites.

In the field, the texture is very conspicuous as an even "spotting" in the rock, produced by the mafic minerals clustering together in the spots, leaving patches of feldspar between. Under the microscope this arrangement is confirmed. The clear patches consist of groups of plagioclase crystals meshed together in equant grains, while the dark spots consist of crystals of ortho-and clino-pyroxene usually with a little hornblende, also in simple equant grains.

Although the bulk composition of these rocks must be much the same as that of the finer grained variety, the plagioclase is different in two respects; its composition appears to be much more calcic than the invariable An 30 found almost everywhere else in the rocks of the Eastern Gneisses. Values of up to An 45 have been measured. Also, some of the plagioclase grains show a very strong zonation, revealed by the sweep of extinction outwards from the centre of the grain. No sharply zoned or layered crystals were found, the zoning is always of a gradual, regular type.

It is suggested that the distinctive texture of these rocks is a relict ophitic texture. Discussion of this and of the mineralogy and its significance in these dykes as a whole will be reserved until later.

(vii) Younger Pegmatites

In many places, small pink pegmatitic bodies, sometimes with cores of white quartz, are found cutting Scourie dykes and producing local amphibolization of them. Moorbath has dated K feldspars from these pegmatites and obtained values of 1680 m.y. (Rb/Sr).

These younger pegmatites occasionally reach large sizes, particularly in the Bruernish area, and locally they contain large nodules of magnetite. At NF 720010 some particularly fine magnetite specimens were obtained, in large amorphous masses up to 6 inches across.

The More Deformed Zone

In this section, the deformed representatives of the rocks in the less deformed zone will be described, and some significant differences will be demonstrated. Map 6 shows the distribution of rocks within this zone, which has been divided into three fairly sharply defined sub-zones:- a zone of acid gneisses, a zone of meta-diorite gneisses, and a zone of mixed granite, meta-diorite and acid gneiss. These zones are of course most easily identifiable on the coast, but it is considered that they extend inland in the poorly exposed ground, reaching right up to the Thrust.

(i) The Zone of Acid Gneisses

This zone is nearly one mile wide. Its extreme margin is artificially defined as the boundary between more and less deformed zones - in other words, where Scourie dykes cease to cross-cut. Its western margin is defined by a rapid transition into homogeneous meta-diorite. This transition is not sharp, but diffuse.

The rocks within the zone are a monotonous series of acid gneisses with occasional small fragments of early amphibolitic material. A good banding is developed, which in places is so regular as to produce "striped gneisses". The banding is defined by layers of gneiss of slightly different composition, with occasional bands of pink pegmatitic material. The mineralogy of these rocks is very simple. Fresh biotite and hornblende form the only matrix minerals, while quartz, K feldspar and plagioclase make up the rest of the rock. The texture is usually rather coarsely granular.

This belt of acid gneisses seems to lack any evidence of intrusions earlier than the Scourie Dyke suite (described shortly) and forms a very distinct lithological unit which may also have considerable structural significance as we shall see later.

(ii) The Meta-Diorite Gneiss Zone

No distinct, cross-cutting dykes of any of the three sets of early intrusive dykes of the less deformed zone can be recognised in the more deformed zone, but there are very large quantities of rocks almost identical in composition with the intermediate dyke set. These occur as bands of all widths up to hundreds of yards, and their presence defines the zone of meta-diorites. The eastern margin of this zone is marked by the passage into acid gneisses, which contain no meta-diorite but the western margin is rather vague and is rather loosely drawn where increasing amounts of granites and acid gneiss material appear.

The rocks of this zone are remarkably homogeneous. One can walk for many yards over rocks of perfectly uniform grain size, without banding, and with only a very slight foliation. Such foliation as there is present is defined by single hornblende and biotite crystals or by streaked out clots or segregations of hornblende and biotite. The largest bodies seem to grade into acid gneisses in places, but smaller bodies show consistently knife-sharp contacts against both granite and acid gneiss.

The petrography of these rocks is simple and consistent. Hornblende, biotite, plagioclase, orthoclase and a little microcline are the principal minerals, with accessory apatite. There was very little variation in either mineralogy or texture in any of the slides examined, except that scapolite was observed in one slide, and a little clino-pyroxene in another. There is one locality, however, near NL 676972 where two significantly different rocks are found, separated by a granite band. One is a very coarse biotite schist, very soft and crumbly. The other is less rich in biotite but contains abundant visible brown pyroxene crystals. Sections show them to be orthopyroxene, surprisingly fresh in appearance, with biotite, hornblende plagioclase and orthoclase. It is considered that these two rocks represent minor variations of the usual composition, which, it is suggested, is dioritic.

These rocks then are compositionally very similar to the intermediate dykes, and it seems reasonable to suggest that they are of the same period of intrusion, despite their much bigger size. The only differences between these rocks and the cross-cutting dykes of the less deformed zone is in their feldspars. Potassium feldspars, principally orthoclase with a little microcline, are definitely more abundant in the meta-diorites, and the plagioclase composition in them is somewhat more albitic than in the cross-cutting dykes. To a certain extent, some differences are visible in hand-specimen, for the feldspars in the meta-diorites have a distinctive purple colour, but it is not known whether this reflects the composition of the feldspar. It is also impossible to say whether these differences in feldspar composition represent original variations, or metamorphic effects.

(iii) The Mixed Zone

Within this zone, acid gneisses, meta diorites and granite rocks are all found together. The zone has a rather vague boundary against the meta-diorite zone, and includes the small area of Eastern gneisses on Vatersay, as well as the area on the mainland.

The most distinctive units in this zone are granites, which occurr as sheets up to about 50 yards across. Mapping out of individual sheets is not possible, due to the poor inland exposures, but on the coast, good sharp contacts between granite and meta-diorite may be frequently observed. The granites have a good fabric, usually planar but, sometimes, approaching linear, which is defined by oriented biotite flakes.

Contacts with acid gneisses range from sharp to gradutional, recalling the situation at Brwig. The mineralogy is also very much the same as in equivalent rocks of the less deformed zone, and it is concluded that these rocks are indeed the more extensive, deformed equivalents of the granite bodies of the less deformed zone and have the same time relationships.

The only other noteworthy rocks in this zone occurr on Vatersay, where a small band of biotite-orthopyroxene rich rock is exposed, exactly similar to that already mentioned in the previous section.

(iv) Early Pegmatites in the more deformed zone

Pegmatites as a whole are scarce in the deformed zone, except in the acid gneiss zone where they are considered to be relatively young. A few pegmatites are found within the meta-diorite zone which are parallel to the regional foliation, and themselves have a strong planar fabric. It is considered that these may be the deformed equivalent of the early pegmatites of the less deformed zone.

(v) Scourie dykes in the more deformed zone

Attention has already been drawn to the contrast between dykes in the two zones of the Eastern gneisses; as one moves from the less into the more deformed zones the dykes which were previously regular, continuous bodies become progressively more disrupted, boundinaged and folded. Looked at in more detail, however, two interesting factors emerge.

First, the deformation, which is accompanied by migmatisation and amphibolitization is most strongly developed within the acid gneiss zone. Dykes here are completely concordant, completely amphibolitized and extensively folded, boundinaged and migmatised. Photos 5 and 6 illustrate this. Within the meta-diorite and mixed zones, although dykes are still deformed, folds are less common, and only partial amphibolitization is observed. A planar fabric is often observed in partially amphibolitized dykes, but none is visible in completely amphibolitized dykes. Fig. 2 shows a particularly interesting situation where a very strong axial plane fabric is preserved in an isoclinally folded Scourie Dyke. The fabric is defined partially by new hornblendes and partially by large plagioclase phenocrysts which appear to represent original plagioclase laths which have been re-oriented into their present position. The foliation in the gneisses in this figure may represent the original gneiss banding, S_o, or a new fabric, since it is axial planar to the fold. To decide which

5. Thoroughly amphibolitized and folded Scourie dyke, at NL 689977 (Near Rudha Mor)

6. Agmatized Scourie dyke at same locality.

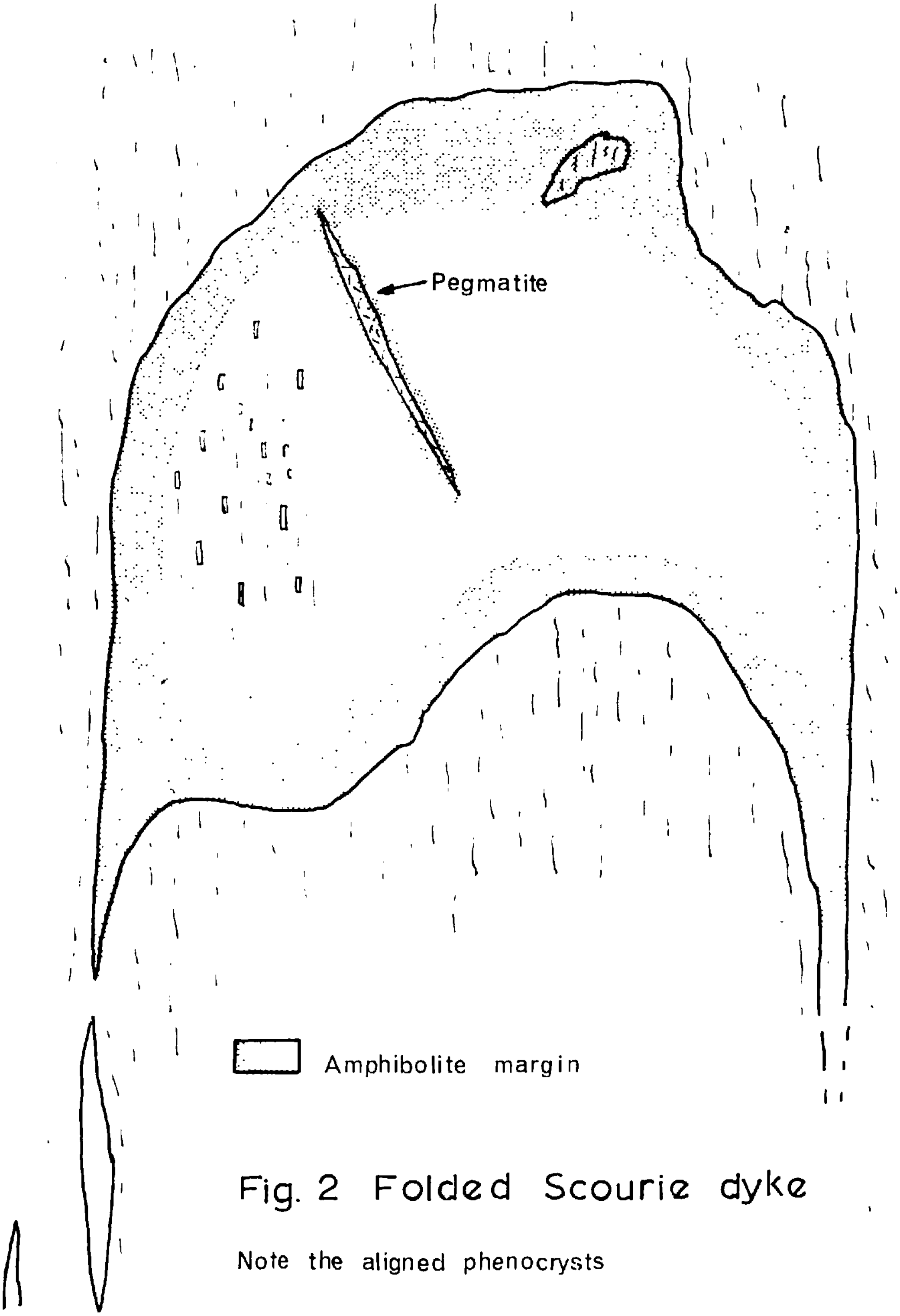


Fig. 2 Folded Scourie dyke

Note the aligned phenocrysts

it is, it would be necessary to know the original orientations of the dyke and the gneiss foliation.

Second, original cross-cutting relationships are fairly common in the mixed zone, which also contains some particularly large dykes. A pair of these dykes can be traced more or less continuously behind Castlebay village right up to the Thrust. Study of these deformed dykes in the mixed zone raises some interesting questions on their original shape. The dykes in the less deformed zone are regular, planar bodies, although some branch occasionally and send off apophyses. In the more deformed zone, however, there is a distinct tendency for dykes to be much more irregular in shape. This is demonstrated by large dykes stopping abruptly, branching irregularly and often changing radically in thickness along their length, and generally giving the impression of total disorder. Some of this is undoubtedly due to later folding and boudinage, but in many localities, such as Creag Mhor on Vatersay, it is clearly an original feature. This contrast between the original shapes of the dykes in the more and less deformed zones is significant, and will be discussed later.

The mineralogy of dykes within the deformed zone is identical to that of the less deformed zone, except of course for the introduction of hornblende and absence of orthopyroxene in the most affected dykes. The metamorphic history of the dykes will be considered later.

The Structural History of the Eastern Gneisses

(i) General

At first sight, the structural pattern within the Eastern Gneisses appears quite simple, with large areas of uniform foliation. The interpretation is very difficult, however, particularly within the less deformed zone, since one is faced with the problem of distinguishing early folds from later, in an area where folds are conspicuously scarce. Also, within the deformed zone, one has to distinguish between old and new fabrics in the gneisses, which can be very difficult. Thus it should be emphasized that what follows is an interpretation, and not a statement of facts.

The structural sequence is summarised in Table 3, and the structures will be described in the same order. It should be noted that intrusion of the early dyke suite seems to have occurred after the early folding events, and before the early shears, but the evidence is not conclusive.

(ii) Original Gneiss Banding, S_o

This is identifiable throughout the less deformed zone, where it is frequently cut by Scourie Dykes. It is a planar fabric, defined by layers or bands of different mineralogy in the gneiss, some layers being richer in mafic minerals than others. The texture is that of a typical granite gneiss. Within the gneiss there are often blocks of amphibolite showing a definite foliation not related to that in the gneiss, and this indicates that the S_o banding itself is the result of a long and complex history. Within the more deformed zone, the

TABLE 3

The structural history of the Eastern Gneisses

More Deformed Zone	Event	Less Deformed Zone
Not identified	F_{3E}	Small folds with axial trend 100°
Large scale, regional folding	F_{2E}	Large scale, regional folding, asymmetrical warps
Scourie dykes folded, boudinaged, new fabric developed, S_1	F_{1E}	General flattening, some folds in gneisses
	Scourie Dyke Intrusion	
	E. & N.E. trending shears, some with pegmatite	
Not recognisable	Early fold phases	Recognisable in places
Observed locally	Production of original gneiss banding, S_0	Regional

original banding can be identified occasionally when it is cut by Scourie Dykes, but, as we shall see, it can be confused with the new fabric, S_1.

(iii) Early Fold Phases

These are not easy to confirm in the field, and a slight deviation is required in order to explain the problems involved.

Examination of any of the maps of the Eastern Gneisses will reveal the predominantly north-south, very regular foliation trend. This trend, which is rather more irregular in the extreme north-east due to later folding, is common to both more and less deformed zones, and is the result of the F_1 deformation phase which has tended to align all the elements in both zones.

The important result of this is that the cross-cutting dykes of the less deformed zone have been brought towards parallelism with the XY plane of the F_1 finite strain ellipsoid, and as a rule the majority of dykes of both the early suite and the Scourie Dyke suite are within 10-20° of the trend of the gneiss foliation. Since the dykes are nowhere folded, one may deduce that their original orientation lay within the extensional rather than the contractional field of the strain ellipsoid. Examination of dyke discordances suggests no more precise original arrangement of the dykes - for example there are about as many dykes which are clock-wise to the foliation as anti-clock-wise.

Now we have to examine what was the effect on the orientation of the gneiss foliation of the F_1 strain. Clearly, this will depend on the original orientation - where it lay in the extensional field it would merely tend towards parallelism with the XY plane of the strain ellipsoid, and therefore towards parallelism with the dykes. Where, however, it lay in the contractional field, buckling would occur, (assuming of course that layers of different competence were present), and the folds that resulted would have axial planes parallel to the XY plane of the ellipsoid.

If we consider the further case where the gneiss was already folded before the F_1 deformation, it is clear that some folds, those with axial planes nearly perpendicular to the XY plane would tend to be suppressed, while those with axial planes nearly parallel to the XY plane would be flattened and amplified. This is a very generalised interpretation of what is in fact a very complex process, but it shows that one has to take care in distinguishing genuinely early folds in the gneiss from F_1 folds.

Photo 7 illustrates this problem very well. The sharp edge of a Scourie dyke is seen in the left of the photograph while a very narrow apophysis runs parallel to it. This apophysis cuts a fold structure in the gneiss, and is almost axial planar to it. At first sight, this would appear to be a clear case of an apophysis cutting an earlier, pre-dyke fold, but it is equally possible that the fold was produced during F_1, if the gneiss foliation was originally at a high angle to the XY plane of the strain ellipsoid.

Early folds are therefore very difficult to identify positively. Completely objective proof is occasionally found, however, where both

7. A Scourie dyke (left) a narrow apophysis (centre) and gneisses at Leenish Point. Note the rather feint fold cut by the apophysis, whose axial plane is parallel to the dyke. NL 703986

8. An isoclinal F_{1E} fold in Eastern Gneisses, shore of Brevig bay. NL 695988

limbs of a minor fold are cut by Scourie dykes, a situation which it would be impossible to produce by post-dyke deformation. A great many early folds can, however, be recognised in the field if one is prepared to rely on intuition rather than proof, since most of the early fold structures have a very distinct style, and tend to occur in material containing a great many quartzo-feldspathic stringers and rods, and also to have a rodding lineation which is very uncommon in later structures.

No attempt will be made here to separate early fold phases from one another, but complex interference patterns can often be found, for example at NF 717010, near the Bun an t-Sruith, demonstrating the presence of several early phases. An example is illustrated in Fig. 2′ from a locality at Ard Rudha Mohr NL 700977, on the fringe of the less deformed zone.

(iv) Early Shears

In some localities, minor shear zones running easterly or north-eesterly may be observed to be cut by Scourie dykes. At Leenish, such a shear is occupied by a large early pegmatite which has been dated (see earlier); elsewhere, they are barren. They are usually steep to vertical structures with a dextral sense of movement. Their only significance seems to be that they represent the only tectonic event which separates in time the early dyke suite and the Scourie dyke suite. This important point is worth re-stating:- there is no major episode of deformation separating the principal suites of intrusive rocks in the Eastern Gneisses.

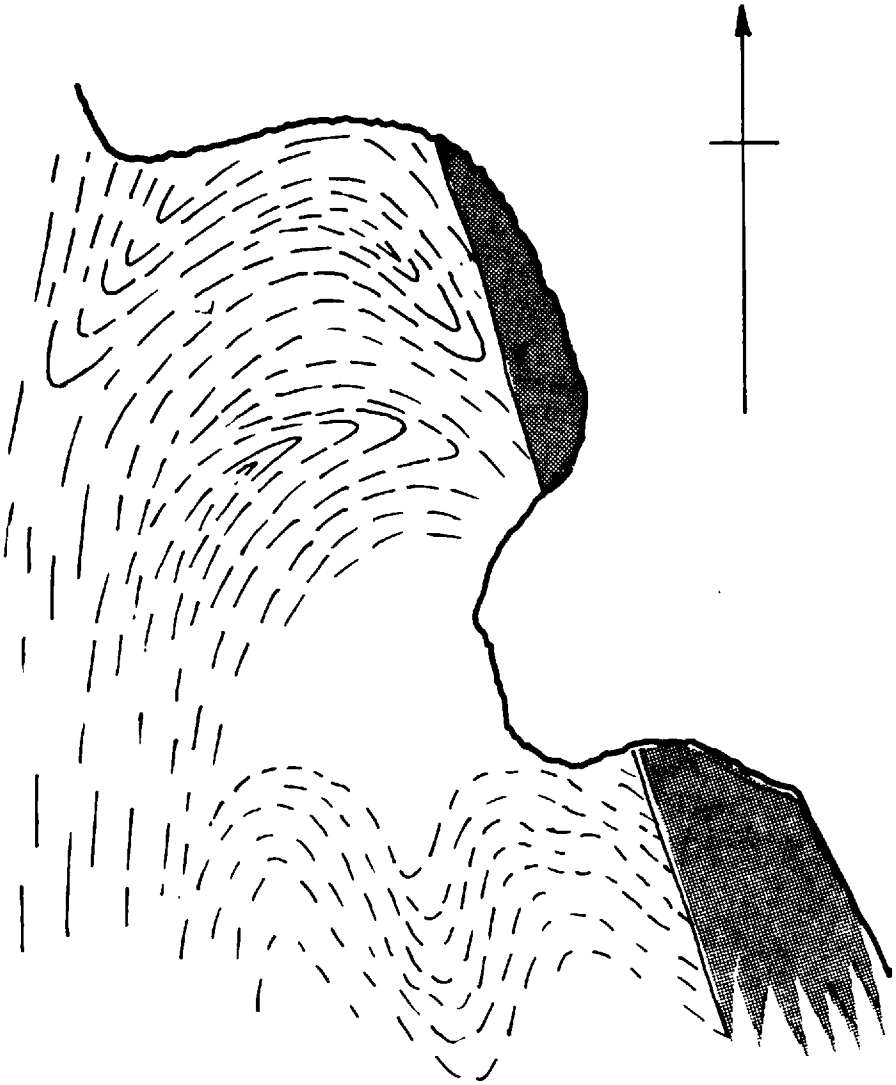


Fig. 2' Early, preScourie dyke folds at Rudha Mohr

10 ft

(v) First Fold Phase, F_{IE}

Although folds of this phase are by no means common, deformation during F_{IE} was of prime importance in its effect, since it was responsible for deforming an original series of variable, folded gneisses cut by two main suites of dykes into a more or less regular parallel series. The variations in amount of F_{IE} deformation which were responsible for the resulting zones of more and less deformation are of considerable interest and will be discussed later. Since, however, F_1 produces folds and boudins only within the more deformed zone, discussion will be confined here to the rocks of that zone.

F_{IE} FOLDS. Folds of F_{IE} age are found affecting both acid gneisses and Scourie dykes, but they are not observed within the homogenous meta-diorite. In folds affecting the acid gneisses only one has of course to decide whether they are in fact F_{IE} folds and not earlier folds. This problem is particularly acute in the transition zone between more and less deformed zones. Photo 8 shows such a fold at Brevig, which re-folds earlier, presumably pre-Scourie dyke folds.

Folded Scourie dykes are first found at Rudha Mohr (Nl 696 974), about half a mile into the more deformed zone, and from there on, folded dykes are found occasionally as far as Vatersay, where the last remnant of Eastern Gneiss is preserved. Throughout this area, only one phase of folding can be seen to affect the dykes. There are none of the complex interference patterns that will be described in the Western Gneisses, and hence it is clear that no folds earlier than F_{IE} have affected the dykes, nor are there any significant minor folds of later generations, and we shall see that the only later structures are in fact very large indeed.

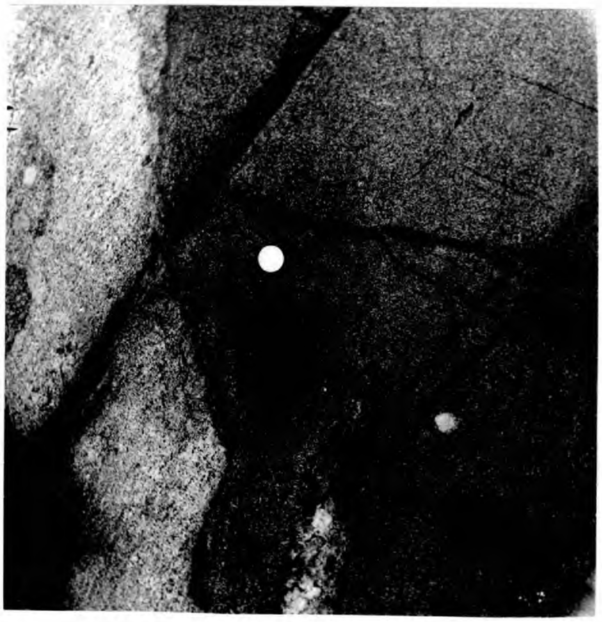
STYLE OF F_{IE} FOLDS. The folds present are too variable and too few for any useful comment to be made on this topic. The range of styles extends from rather open, irregular structures, particularly in the most migmatitic areas, to straightforward, regular isoclinal folds. It should be noted that the present geometry of F_{IE} folds is not necessarily their original geometry. It is very probable that their present style is the result of F_{2E} modification of their original F_{IE} style. This interesting topic will be considered at some length in relation to the Western Gneisses, where much fuller data are available.

ORIENTATION. The axial planes of all F_1 folds are parallel to the regional gneiss foliation and trend roughly N-S. The dip of the axial planes is vertical or very steeply to the East. Plunges, where they can be measured, are rather variable, but generally seem to be at low to moderate angles to either north or south. Considerable variations may be measured even on individual folds (such as that in Photo 8) and it is considered that this is probably the result of an inhomogeno F_2 strain on the F_1 fold.

BOUDINAGE IN F_{IE}. Boudinage of Scourie dykes is the first effect to be noticed on leaving the less deformed zone for the more deformed zone. Its interest here lies in the different styles of boudinage. Two extremes are observed:- rather lumpy irregular barrel shaped boudins with abrupt terminations and much longer, thinner boudins which taper out into a point. The latter variety is illustrated in Photo 9. The more barrel shaped boudins are found in the most migmatitic areas of the zone of acid gneiss, the elongated variety outside this zone. This distribution is significant in that it indicates different competence relationships, and we shall be returning to it again.

F_{IE} FABRICS. F_{IE} fabrics are widely developed in the rocks of the deformed zone, in rocks of all compositions. The acid gneisses are perhaps the most difficult to deal with, since one has to separate new from old fabrics, and one can find all transitions between the original foliation and the new. Within the zone of acid gneisses, . where migmatisation is most extensively developed, the problem is particularly acute, since here the gneisses have a very strong new fabric, yet the deformed and migmatized Scourie dykes which are completely amphibolitized show no fabric at all, and where one sees a Scourie dyke in the gneisses, it may appear to be discordant (Photo 10). This effect is presumably due to the ease with which amphibolitic material can lose a tectonic fabric on later, static re-crystallization, and is a problem which will be discussed again in the section on Western Gneisses. It is important to emphasize here that F_{IE} planar fabrics are found only in partially amphibolized Scourie Dykes. Dykes which are totally granulitic show no fabric, nor do those which are completely amphibolitic, and thus it is often only the amphibolitic margins of large dykes in the more deformed zone which show any fabric.

9. Boudinaged Scourie Dykes, Ru-fear-Vatersay. Note the distinctive lens shape. NL 684970



10. A completely amphibolitized Scourie dyke showing complete absence of any tectonic fabric (Note however the conspicuous jointing) NL 68977

(vi) Second Fold Phase, F_{2E}.

This is a very difficult topic to describe, since all the F_{2E} structures are large, and there is a complete absence of minor folds. The bulk of the Eastern Gneisses consists of very regular, steep N-S trending foliated gneiss, which swings round in the north-east of the area and becomes much more gently dipping and develops large, open asymmetrical warps which are best developed in the Bruernish area.

It is considered, though it would be difficult to prove, that the regional structure of the Eastern Gneisses is a large asymmetrical F_{2E} antiform, with an axial trace roughly N-S. The steep limb of this structure is expressed in the regularly striking, steeply dipping gneisses and its gentle limb by the area of low dipping gneisses in the north-east of Barra, where the large, open asymmetrical folds form second-order folds on the limb of the major structure. If this interpretation is correct, then we have in the Eastern Gneisses a very large, asymmetrical antiform which plunges gently to the North.

We have seen that the zone of acid gneisses in the more deformed zone is distinct in several ways - it contains no evidences of intrusion by members of the early dyke suite, the Scourie dykes within it are more deformed and migmatised than in any other area, and that even the style of boudinage is different. It is suggested here, very tentatively that this zone of acid gneisses may represent a very tight synformal unit, a counterpart to the large F_2 antiform. There is no direct structural evidence for this synform, however, so there must be grave doubts as to its validity. As a structure, however, it would be very important, as we shall discover when considering the relationships between the Western and Eastern Gneisses.

While F_{2E} deformation does not seem to have produced any minor folds of consequence, it almost certainly led to the modification of earlier F_{1E} folds, particularly in areas of high deformation such as in the zone of acid gneisses. There appear to be two reasons why no F_{2E} minor folds were produced:- first, since F_{1E} and F_{2E} were roughly co-axial, then one might expect modification of earlier folds rather than production of new ones. Co-axially refolded folds, however, were not observed.

Second, conditions during F_{2E} may have been such that only folds of a large order could be produced, with no lower orders.

(vii) Third Fold Phase, F_{3E}

Only a very few folds of this phase were identified, principally at Leenish and one or two other localities. They have steep to vertical axial planes, steep plunges and axial trends roughly east south east. Their only importance is in making structural correlations with the rocks west of the Thrust. A section across the Eastern Gneisses is illustrated in Fig. 12.

THE WESTERN GNEISSES

General

The term "Western Gneisses" was first introduced by Dearnley (1962) to describe the ubiquitous grey gneisses west of the Outer Hebrides Thrust. Such uniform acid gneisses form the majority of rocks West of the Thrust in the present area, with the exception of the rocks of the Oit a Mohr zone which will be described separately. In this section it is proposed to describe the rocks of the Western Gneisses themselves and then to discuss their structural history.

The following two tables present a brief summary of the principal rock types and their structural history.

Principal Rock Types

Four principal rock types have been recognised and will be described:- acid gneisses, metasediments, early amphibolites and Scourie Dykes.

(i) Acid Gneisses

Every visitor to the Islands will be thoroughly familiar with these rather monotonous rocks. They are coarsely foliated hornblende/biotite acid gneisses with frequent quartzo-feldspathic veinlets and stringers parallel to the foliation. The only visible variations are in grain size, which tends to become coarser to the South, and in the degree of foliation or banding in the rock. Photo 11 illustrates a gneiss with particularly well developed banding, defined by bands of quartzo-feldspathic material alternating with bands of mafic minerals.

11. Particularly finely banded Western Gneisses in a clean, freshly blasted exposure, Quarry, Bagh-nan-Clach NF 696086

12. Early, pre-Scourie dyke interference patterns, Orosay, South Uist. NF 731174

TABLE 4

Rock Groups in the Western Gneisses

Rock Group	Mineralogy	Distribution
Acid gneisses	Quartz, oligoclase, microcline ∓ orthoclase biotite, hornblende.	Ubiquitous
Metasediment	Quartz, plagioclase ∓ microcline, garnet, biotite.	Scurrival Point only
Early amphibolites	Variable, usually hornblende + plagioclase, sometimes with garnet. Plagioclasites occasionally.	Scurrival Point and Orosay S.U. only
Scouric Dykes	Hornblende, clinopyroxene plagioclase in small bodies. Orthopyroxene in some large bodies in North.	Found everywhere as concordant bands in the acid gneisses

TABLE 5

Summary of Events in the Western Gneisses

Event	Fabrics	Orientation	Distribution
F_4	Some minor mineral growth. Axial plane pegmatites.	Axial planes strike c.100°, dip 65° to N.	Minor folds abundant everywhere.
F_3	Few. Much Recrystallization obliterating earlier fabrics.	Axial planes strike 140°, dip 30° to N.	Regional structures in Hebrides, many minor folds.
F_2	Some linear fabrics, most lost by later recrystallization.	Axial planes originally N.N.E., plunges to N.	Folds restricted to northern part of the area.
F_1	New Regional, S_1, foliation in gneisses. Some planar fabrics in dykes.	Not known. Possibly co-axial with F_2.	Rare, best evidence at Scurrival Point.
—	—	—	—
Intrusion of Scourie Dykes.	Dykes cut original gneiss foliation S_0 now preserved only in modified form.	Possibly N.W.-S.E.	Found all over area as concordant amphibolites.

The banding is not usually so conspicuous on weathered surfaces.

In thin section, the principal minerals are seen to be quartz, oligoclase and microcline, with occasional biotite, hornblende, and orthoclase. Muscovite on the whole is very rare, contrary to the observation of Jehu and Craig, as indeed it is throughout the area mapped as a whole.

(ii) Metasediments

On the shore at Bagh-nar-Clach (NF696085), bands of garnet bearing biotite gneisses are exposed, up to about 50 ft. in width and traceable discontinuously for nearly half a mile. Jehu and Craig first distinguished these rocks from the acid gneisses and gave a very brief description of their petrography, but made no observations on their origin.

The metasediments here are, superficially at least, very similar to those on South Uist and elsewhere in the Outer Hebrides. They are recognisable in the field as rather coarse, rusty weathering rocks with abundant biotite and quartz, and particularly fine large pink to lilac coloured garnets up to ½ inch across. Two different varieties may be readily distinguished:- a smooth, uniform fine grained variety and a much coarser variety containing a great many quartzo-feldspathic stringers, which are intensively ptygmatically folded. The second is much the commoner type, the first running only as a single 6-10 ft. wide band traceable for some 150 yards.

Thin sections add little extra information. Quartz, plagioclase, biotite garnet and a little microcline are found. Orthoclase and hornblende, both common in the adjacent acid gneisses, are conspicuously scarce, and muscovite is lacking. The mineral textures are simple and granular, giving no evidence of the development of successive fabrics.

The contacts between ordinary acid gneisses and metasediment are mostly fairly sharp, but on the extreme north-west coast of Scurrival Point, rocks occur which are transitional between the two. The metasediment here also shows intimate relationships with early amphibolites, and we shall consider the significance of this after describing the amphibolites.

(iii) Early Amphibolites

This term has been introduced to cover a group of rocks much more widely distributed in South Uist than in the present area. They are distinguished from amphibolites of the Scourie Dyke suite by their very coarse, migmatitic textures, their tendency to contain large garnets, and their occurrence as large masses rather than thin, more regular sheets. They also have an early banding or foliation which is not found in Scourie Dykes.

Only two early basic bodies within the present area are sufficiently large to be mappable; one on the island of Orosay off South Uist, and the other at Scurrival Point on Barra.

Exposure of the Orosay body is unfortunately confined to a narrow fringe round the coast of the island, but it does seem that this body comprises a single highly irregular sheet about 200-300 feet thick which has been much affected by later F_4 folding. The body as a whole is extremely variable in composition, and appears to consist of bands of rocks of widely different mineralogy and thickness. Three principal types may be recognised:-

First, and most abundant, is a simple hornblende-plagioclase rock containing locally some quartzo-feldspathic material as clots and stringers, elsewhere it is homogeneous.

Second, and also fairly abundant, is a garnet-hornblende-plagioclase rock, in which the garnets sometimes reach very large sizes and become so abundant as to constitute the dominant mineral. Some beach pebbles approaching garnetite composition were also found.

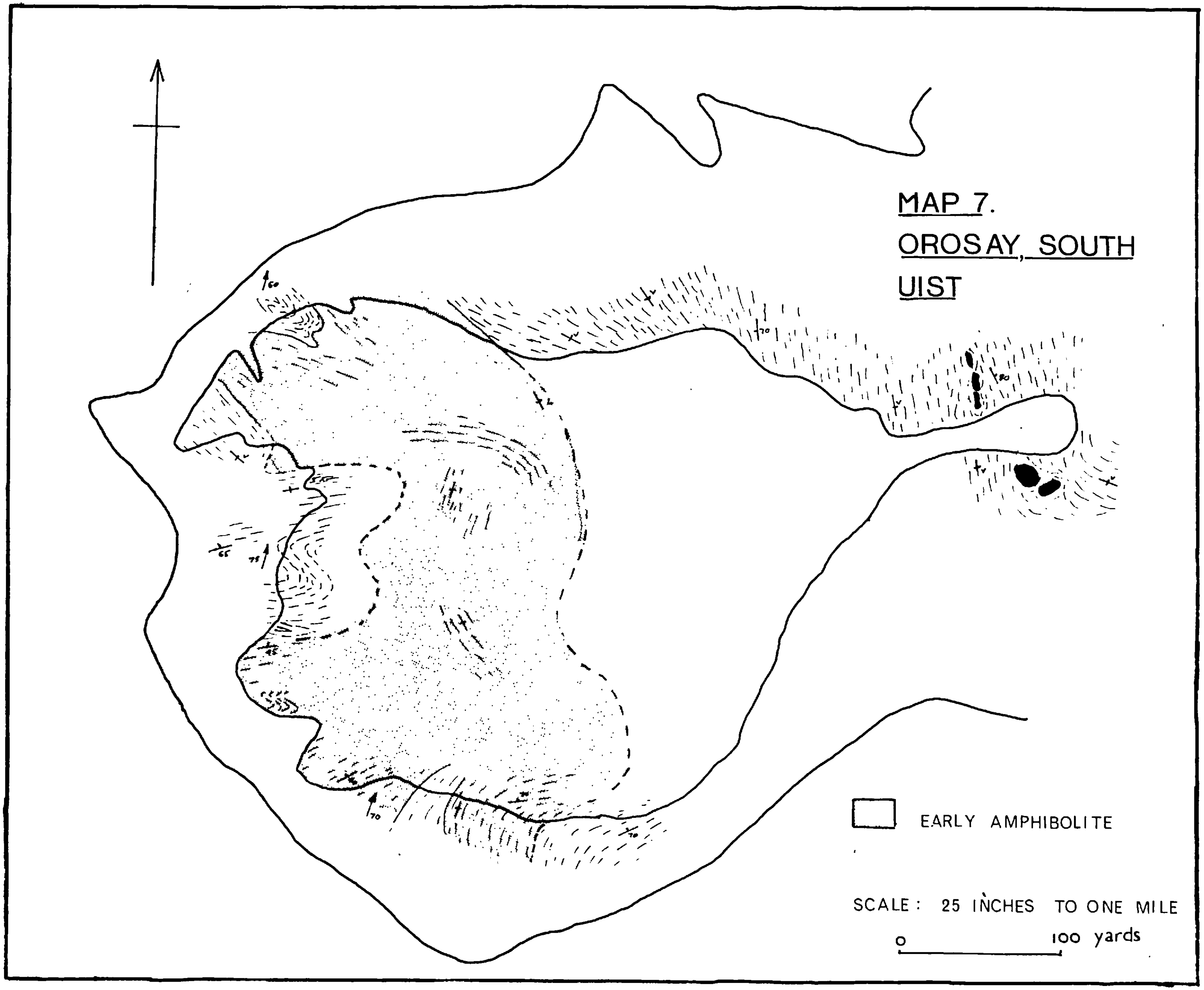
Third, an uniform, white sugary textured rock consisting entirely of plagioclase, which must approach anorthosite in composition.

In a few places the gneisses near the large body are rich in garnet and biotite, and approach metasediment in composition.

Although this suite of rocks would richly deserve further study, it is proposed here only to consider briefly the origin of the body and its compositional banding. Two opposed hypotheses are suggested:-

First, that the body was an originally banded or layered igneous rock, such as a gabbro-anorthosite, which has suffered later metamorphism.

Second, that the body was an originally homogeneous mass of igneous or supra-crustal origin, and that the present compositional



MAP 7. OROSAY, SOUTH UIST

banding was produced by metamorphic segregation.

The presence of anorthositic layers is perhaps the most significant aspect of this problem. Anorthosites are not common rocks, although they do occur at three other localities in the Outer Hebrides;- north-east Lewis, South Harris, and at another small locality in South Uist (M.P. Coward). It seems likely that the first two, which are both fairly large bodies, may be of igneous origin, but the occurrence in South Uist seems to consist merely of small segregations of plagioclasite in a larger hornblende-plagioclase amphibolite, the whole outcrop covering only a few feet.

The small size of the Orosay body, the small proportion of anorthosite relative to amphibolite, the lack of any igneous textures and the clear evidence of profound later migmatisation in this part of South Uist - to be described later - strongly suggest that the compositional banding is a product of metamorphic segregation rather than an original igneous feature. The original nature of the body as a whole is open to the same questions as those to be raised in discussion of the body at Scurrival.

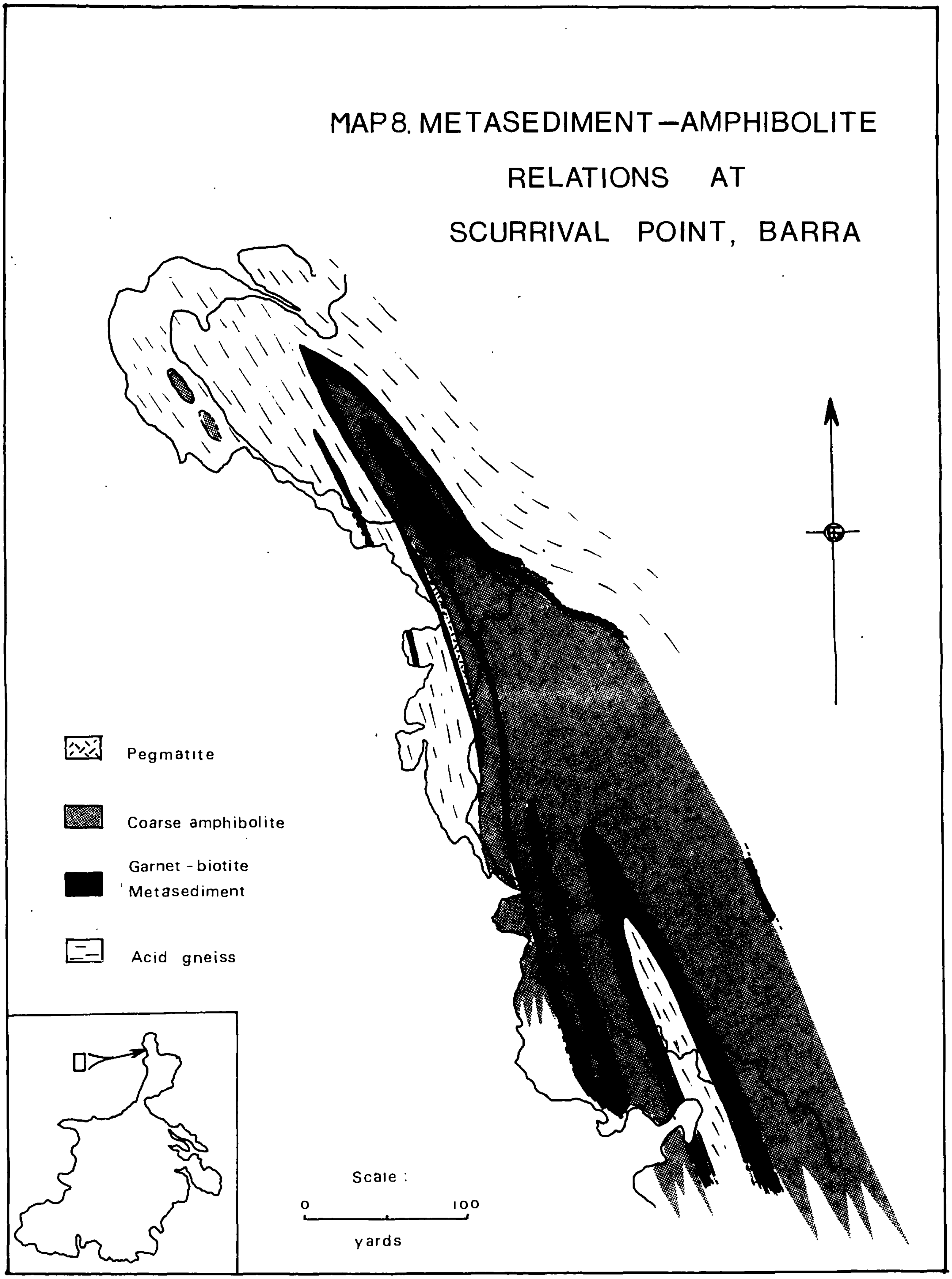
(iv) Early Amphibolites at Scurrival Point

There are very large quantities of early amphibolite material in the area of Scurrival, in sheets of various thicknesses from hundreds of feet down to a few inches. The rock is usually very coarsely crystalline, containing much quartzo-feldspathic migmatic material as clots, stringers and veinlets, and does in places have a distinct foliation or banding defined by layers of lighter colour. The mineralogy is extremely simple, since hornblende and plagioclase (oligoclase) with a little clinopyroxene are the only minerals present.

Some of the smaller bodies, which are merely boudins about two feet thick, contain very large, dark red garnets, which are locally regressed to feldspars and biotite. This is the only locality within the area mapped where garnet shows such textures.

The most interesting aspect of the amphibolites at Scurrival is not their mineralogy, however, but their relations with the metasediment there. Map 8 illustrates this relationship at Bagh-nan-Clach, where the amphibolites and metasediments are tightly interfolded together. Such close associations are by no means rare; they have also been observed on a smaller scale on the island of Muldoanich, on Orosay S.U., and at several localities on South Uist, and it is suggested that this association indicates that the amphibolites themselves are of supra-crustal origin.

A second possibility exists however. If the amphibolites represent an early phase of igneous intrusion, then the intimately associated garnet-biotite gneisses may not in fact represent metasediments per se, but might represent the results of metamorphic or metasomatic processes taking place in the neighbourhood of large igneous bodies. Such processes could have produced changes in the surrounding country rocks, which, after later deformation and metamorphism, gave rise to rocks of metasedimentary appearance.



MAP 8. METASEDIMENT – AMPHIBOLITE RELATIONS AT SCURRIVAL POINT, BARRA

If, for example, a large igneous mass were to produce an aureole of hornfelsing in the rocks surrounding it, it seems reasonable that this might result in the hornfelsed rock constituting a closed system during later metamorphic activity, so that it retained its original composition, and therefore after much later metamorphism, migmatisation and deformation it still retains some differences from the ordinary acid gneisses. It is interesting to note that the largest areas of metasediment in the Outer Hebrides, the Langavat and Leverburgh belts happen to flank the largest igneous body, the South Harris Igneous complex. This in itself is a striking association which has never been accounted for.

(v) Scourie Dykes

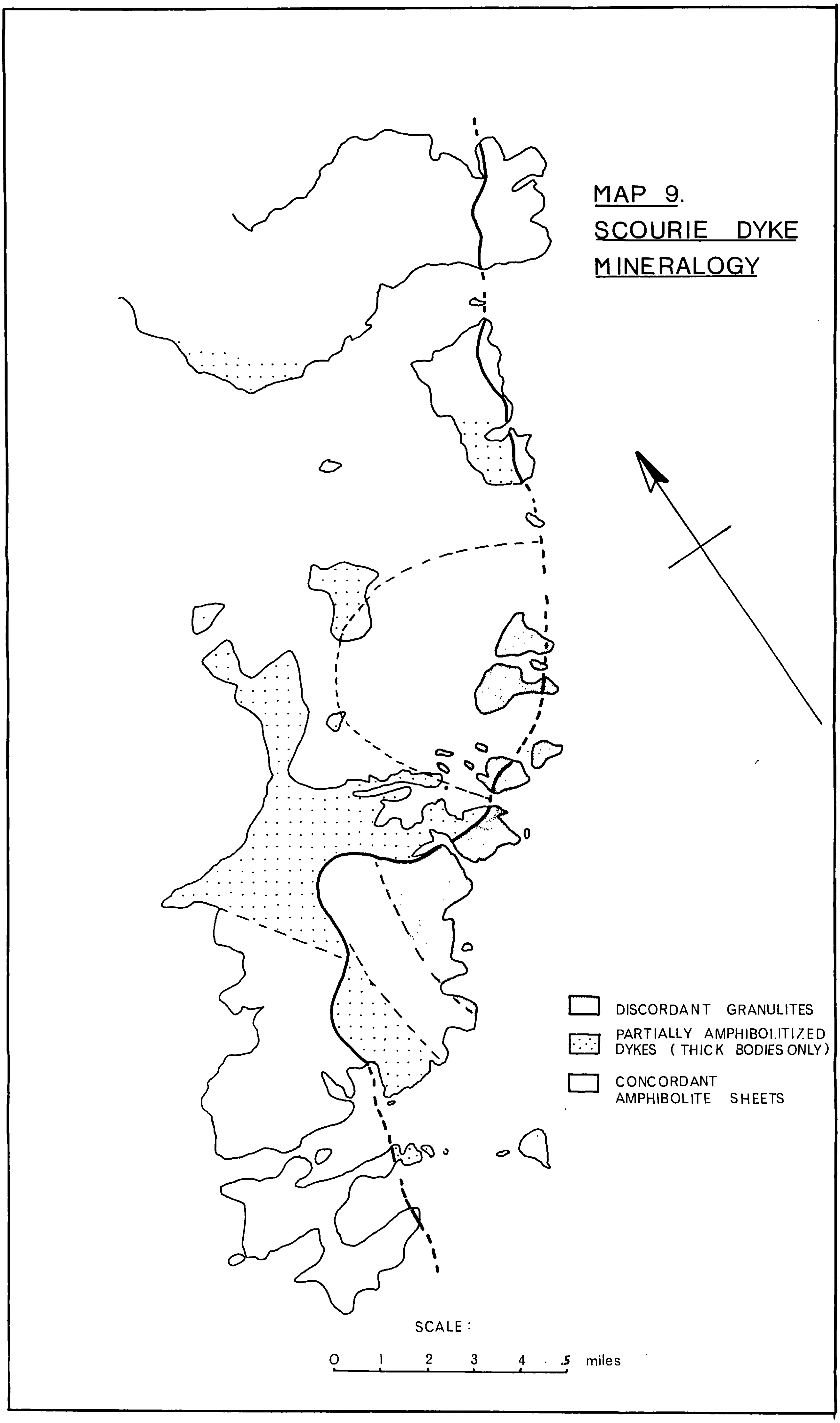
These are abundant in the Western Gneisses as concordant amphibolite sheets. They are fundamental to the elucidation of the structural and metamorphic history of the area.

On the islands in the Oitir Mohr (Great Sound) basic bodies of dyke-like form cross-cut the gneiss foliation at angles up to 90°. The area in which these indisputably intrusive bodies occur is sharply defined and has been called the Oitir Mohr zone (q.v.). The boundary to this zone runs through the islands of Fuday and Orosay E. and on both of these islands the transition from discordant dykes to concordant sheets may be observed.

An equally important but much more gradual transition may be observed in the texture and mineralogy of these bodies, although this is complicated by the effects of varying thickness. Within the Oitir Mohr zone, the dykes are characterised by the assemblage orthopyroxene/clinopyroxene/plagioclase/opaque and by relict opitic textures, with amphibolitic margins. As one moves away from this zone, so this pattern becomes more rare and becomes confined only to large bodies; eventually it gives way even in the thickest bodies to hornblende/clinopyroxene/plagioclase assemblages, with typical coarsely granular textures. These changes are schematically summarized on Map 9.

It is one of the principal assumptions of this thesis that the contrast between the dykes in the Oitir Mohr zone and those in the Western gneisses is analagous to that between the Scourian and Laxfordian zones on the mainland; namely that the abundant, discrete, concordant amphibolite sheets within the Western Gneisses represent the metamorphosed and deformed equivalents of the discordant dykes within the Oitir Mohr zone. In view of the transition which can be traced, this is considered to be a valid assumption.

The amphibolite sheets thus interpreted as originally intrusive igneous bodies therefore include sheets of all thicknesses, reaching a maximum of about 50 feet, and from all parts of the area mapped. The history of folding and metamorphism of these bodies will form an important part of this thesis.



MAP 9. SCOURIE DYKE MINERALOGY

Structural History of the Western Gneisses

(i) General

In recent years, progress in structural geology has led to great advances in understanding mechanisms of deformation of rocks and has produced new techniques for interpreting complex geological structures. These have made it possible to extend into the Lewisian detailed [1] structural mapping of a kind not previously attempted.

The methods, however, are only as useful as the rocks allow, and there are some considerable problems in this respect. Granite gneisses and amphibolites, with which we are almost exclusively concerned, are by no means ideal for detailed structural analysis principally because they are rather coarse grained, homogeneous rocks which lack the delicacy of structure of rocks of lower metamorphic grade.

Two problems stem directly from the nature of the rocks:-

First, erosion produces outcrops with smooth, often rounded surfaces. The relief on these surfaces is usually not more than a few millimetres (the average grain size) and this makes it very difficult to judge the sense of direction of foliation dip or fold plunges on flat surfaces, let alone to make more accurate measurements.

Second, widespread late re-crystallization has obliterated nearly all earlier fabrics in the area particularly in amphibolites of the Scourie dyke suite, which could have been informative. A summary of the structural events to be described is given below, in the order of description.

EARLY FOLDS AND FABRICS. pre Scourie dyke age. Not well preserved, mainly seen in metasediments and early amphibolites. Earliest foliation, S_0 probably produced at the same time as these early structures.

F_1 FOLD PHASE. Probably a very important phase, but little direct evidence preserved. Believed to have produced the regional gneiss foliation S_1 and to have folded Scourie dykes.

F_2 FOLD PHASE. Produces conspicuous folding of Scourie dykes in northern part of the area, does not appear to have produced new fabrics in gneisses, may have done so in dykes, but these now lost, Possibly co-axial with F_1.

F_3 FOLD PHASE. Very important, controls the overall structure of the area, large asymmetrical folds overturned towards the south west. The gentle limb of these folds produces the large areas of uniformly low dipping gneisses.

F_4 FOLD PHASE. Very common minor folds, but few larger. Regular axial trend 100°-110°.

(ii) Early, pre-Scourie Dyke Folds and Fabrics

In the Oitir Mohr Zone, Scourie dykes cut foliated gneisses which occasionally exhibit minor folds older than the dykes. In the Western Gneisses, however, evidence for pre-dyke tectonic activity is hard to find, especially as one has to distinguish early folds from later, F_1, folds which are themselves difficult to identify.

The most likely early folds occur within the Scurrival metasediments (Map 8), which lie in isoclinal folds believed to be F_1 in age (see later). Now the metasediment in the limbs of these isoclines contains numerous migmatitic, quartzo-feldspathic stringers which are intensely ptygmatically folded, and these ptygmatic folds do not have any consistant relationship to the larger structure, nor to any later structures. Complex interference patterns indicate that more than one phase of early folding occurred. It is interesting to note that metasediments characteristically retain evidence of early structures in many parts of the Outer Hebrides.

Some rather more conclusive evidence is found at a tiny outcrop on the island of Orosay S.U. where early folds can be seen truncated by Scourie dykes, which are themselves buckled by F_1 folds. Complex early interference patterns are observed again here (Photo 12). This is the only locality within the Western gneisses of the area mapped, outside the Outer Mohr zone, where a discordant dyke was observed. The gneiss foliation cut by the dyke here is the original gneiss foliation, S_0.

(iii) The F_1 Fold Phase

This fold phase is rather difficult to deal with, since few folds are preserved, but it is considered that the present foliation in the gneisses, S_1, was largely produced by F_1 deformation. This belief is based on the observation that F_2 folds, which are the most conspicuous and most impressive folds in the area, all fold the gneiss foliation - there is no new axial planar fabric developed, (see below). Also, in some localities Scourie Dykes may be observed with a foliation in them folded by F_2. This foliation is believed to be an F_1 foliation.

Further evidence may be seen in the Scurrival metasediments. The large isoclinal folds involving metasediment and early amphibolite at Bagh-nan-Clach (Map 8) have an axial planar fabric which is parallel to the regional foliation in the acid gneisses. Here, however, this fabric in the metasediments can be seen to be a new. one. The large basic core to the fold in Fig. 3 has an early foliation (S_0) which is folded round in the fold, while the new fabric in the metasediment is perfectly planar, and in a few places can be seen superimposed on an earlier banding in the metasediment.

The sequence of events summarized is thus:-

(4) F_2 folding, folds S_1 foliation in dykes and gneisses.

(3) F_1 folding, production of new foliation in gneisses metasediments, and Scourie Dykes, S_1

(2) Scourie Dyke intrusion.

(1) Early folding, and production of early foliation in gneisses and metasediments, S_0.

In the early amphibolites, one can see occasionally the S_0 foliation folded by F_1 and with the new, S_1, fabric growing across the earlier. In the acid gneisses, however, it is probable that what is termed the "S_1" foliation may be partly pre-Scourie Dyke in age for two reasons:- First, the folds in metasediment at Scurrival which we are calling F_1 may not necessarily be of the same episode as F_1 folds in Scourie Dykes elsewhere, since it is very difficult to correlate these very early structures. Second, while F_1 folding may have obliterated all earlier fabrics in the noses of F_1 folds, it

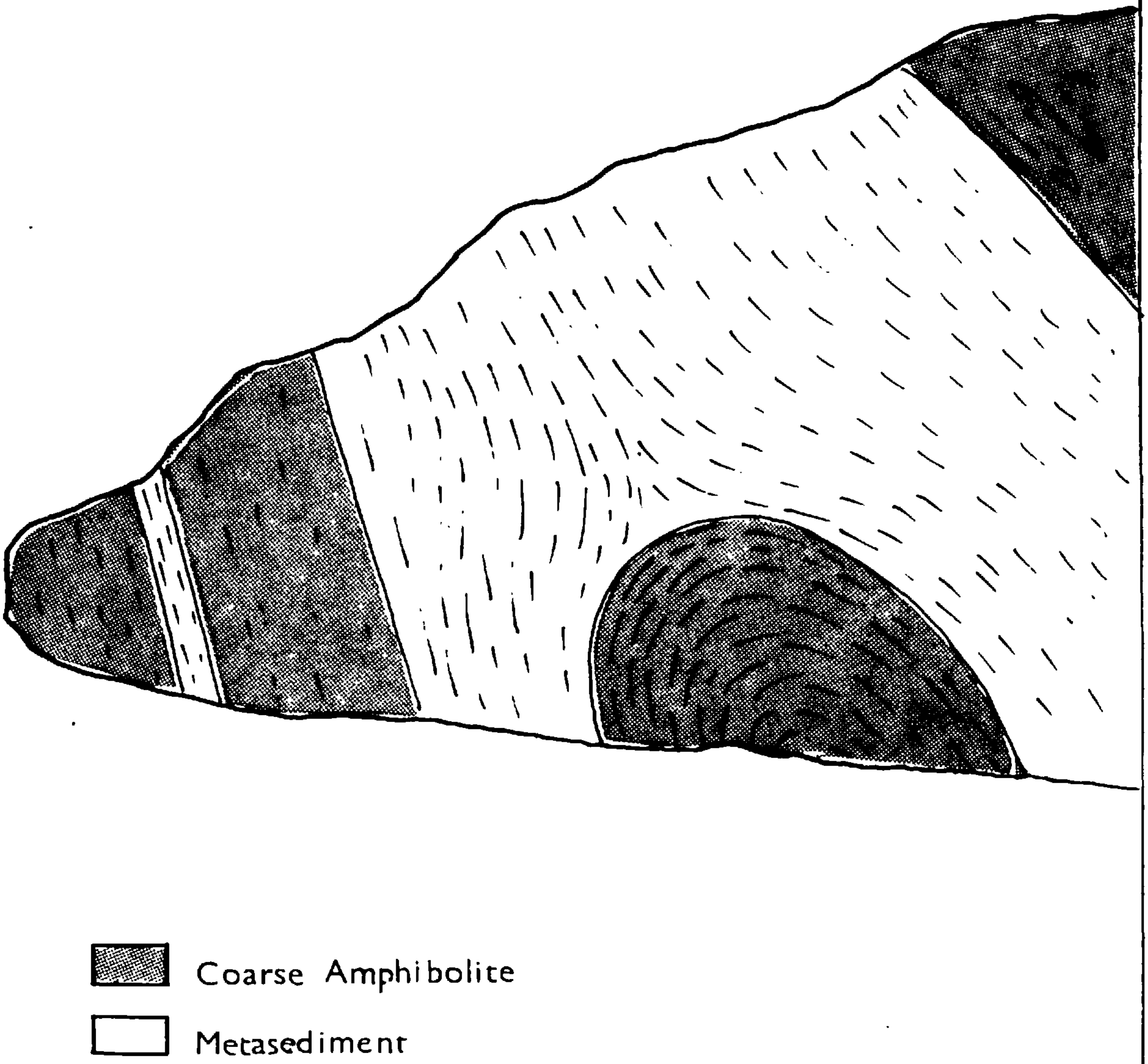


Fig 3 Nose of early fold at Scurrival Point Note the fabrics

is unlikely to have done so on the limbs of these folds, where the earlier foliation will be simply re-emphasized and modified.

Perhaps the most convincing evidence for the F_1 fold phase comes from those localities where F folds refold earlier folds in complex interference patterns. Figures 4 and 5 illustrate such patterns in refolded Scourie Dykes. These figures also show two interesting aspects of F_1 folds.

First, in Fig. 4 a family of small branching dykes is seen splitting off from the larger dyke. It is clear that a simple branching dyke could in some circumstances be mistaken for an isoclinally folded dyke.

Second, in two of the figures the F_1 and F_2 folds are co-axial yet in the third, Fig. 5 this is not the case. The situation in this case, however, is very complex, and it would not be wise to draw conclusions on the original orientation of the F_1 folds relative to F_2.

(iv) The F_2 Fold Phase

F_2 folds are the earliest structures which can be consistently recognized in the Western Gneisses. While both acid gneisses and Scourie Dykes are involved, it is folded Scourie Dykes that are the most interesting and informative, and with which we shall be mainly concerned. Four headings will be used in describing these folds:- Age, Fabrics, Style, and Distribution and Orientation.

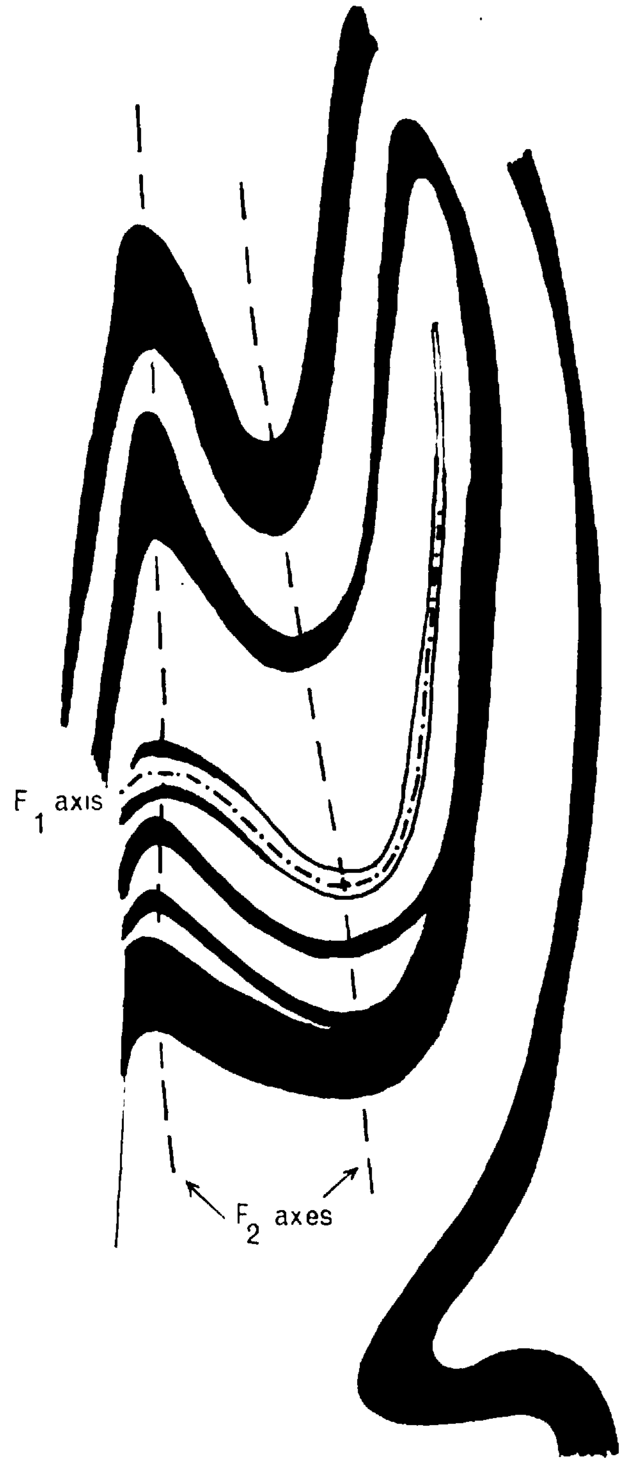
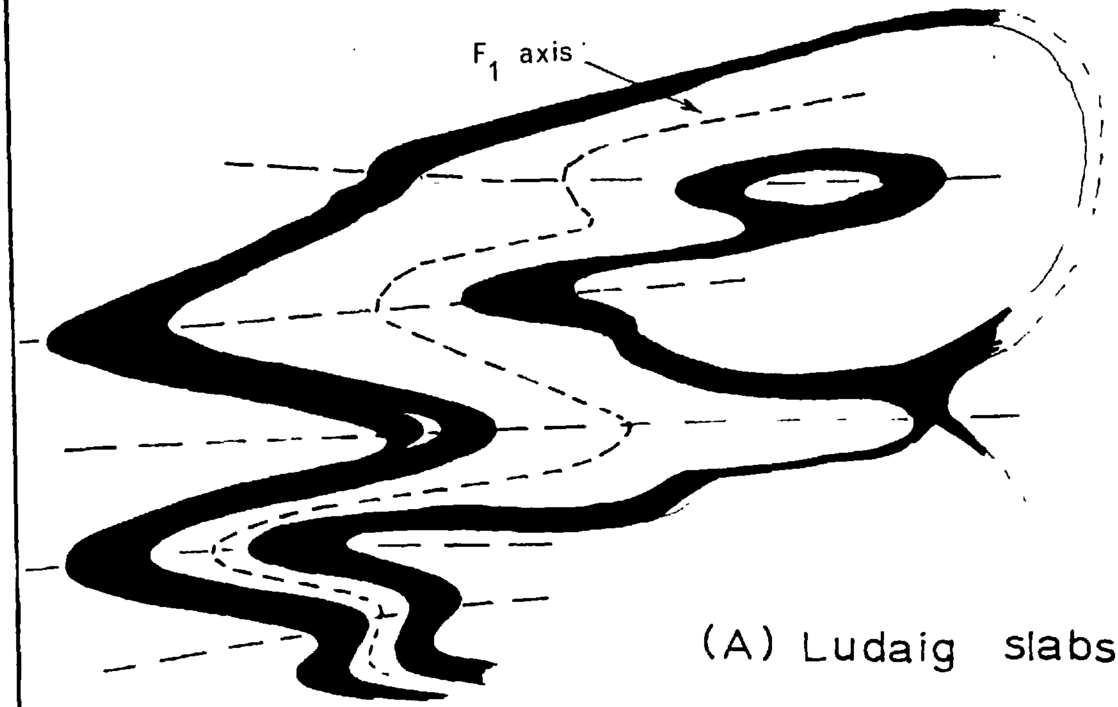
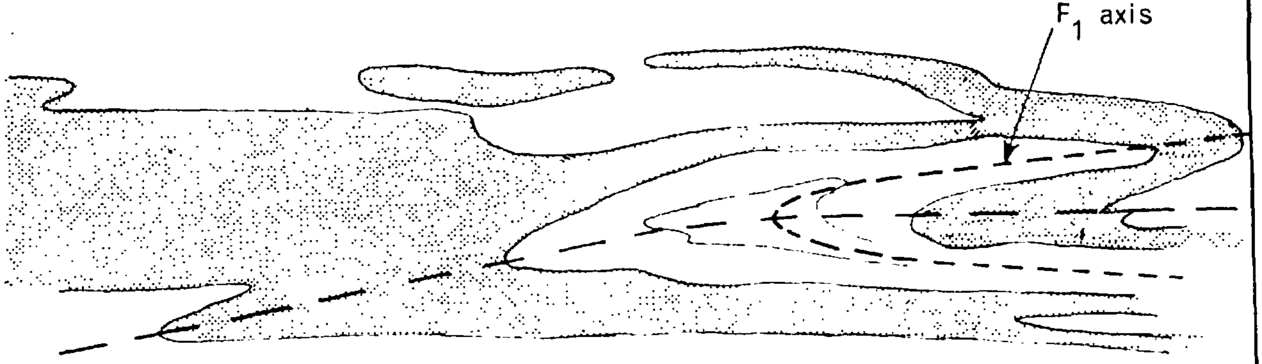


Fig. 4 F_2 refolding F_1. Ludaig slabs

Note the small branches



(A) Ludaig slabs



(B) Orosay S.U.

Fig. 5. F_1/F_2 Interference patterns

AGE OF F_2 FOLDS. In most localities, F_2 folds can be identified by their characteristic style and orientation, but sometimes more positive evidence is available. Figures 4 and 5 for example show F_2 folds affecting earlier F_1 structures, while Photo 13 shows an F_2 fold refolded by an F_3 fold, a relationship which may be observed at many localities in the northern part of the area.

FABRICS. F_2 folds consistently fold the S_1 foliation in the acid gneisses without producing a new axial plane fabric. This is clearly illustrated in Photo 14. In some areas however, the S_1 fabric has been obliterated by later recrystallization, a topic which will be considered further. Where Scourie dykes are folded by F_2 , no fabric is found, but in view of the intensity of deformation, and by analogy with other areas of folded dykes, it is considered that fabrics were in fact originally developed, but have since been destroyed by subsequent re-crystallization. A rather coarse planar fabric is found in some dykes, in the southern part of the area, which is parallel to the regional foliation. There are no F_2 folds in these areas, however, and this fabric could therefore be thre result of either the F_1 or the F_2 fold phases.

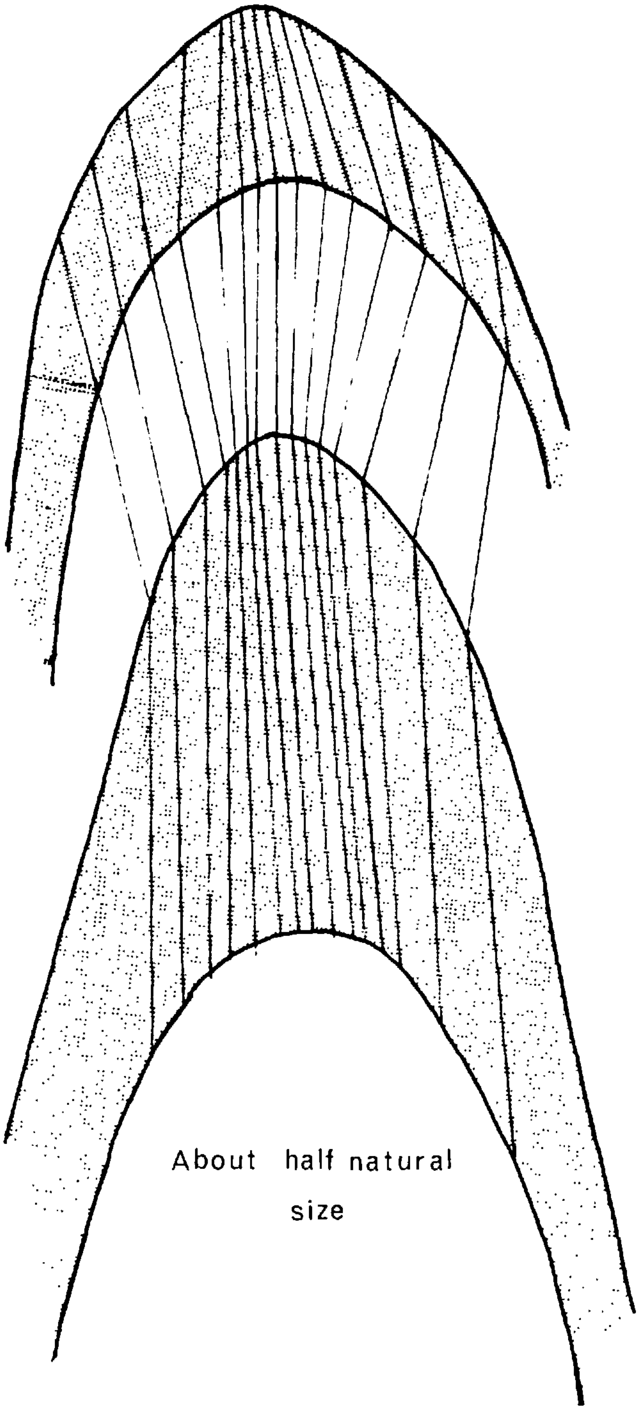
STYLE OF F_2 FOLDS. F_2 folds are very distinctive. They are small folds, with amphitudes never greater than 30 feet, and are usually almost isoclinal, with axial planes parallel to the regional gneiss foliation. Their appearance in the field suggests that they could justifiably be described as "similar" folds.

13. F_2 Fold refolded by F_3, Scurrival Point. Amphibolite layer probably represents a Scourie dyke NF 697095

14. F_2 Fold in acid gneisses, Scurrival Point. See also isogon plot, Fig. 7. NF 694092

Isogon plots were made of a few folds to check more carefully on the style. Predictably enough, it was found that folds on the whole closely approached the parallel isogon (Class 2) similar fold type of Ramsay's classification (Ramsay 1967). When broken down into individual layers, minor variations in style between layers of different composition were found. Figures 6 and 7 illustrate typical plots. Figure 6 is particularly interesting because it shows a pair of amphibolite layers, believed to be of Scourie dyke origin, which are tending towards the Class 3, convergent isogon type of fold. This is a commonly observed feature, and it is significant in that it does have implications concerning the original competence differences between layers, the amphibolite layers being the less competent at the time of folding. We shall be returning to this point later, but it should be emphasized here that care should be taken in interpreting isogon data, because original variations in dyke shape would drastically modify the resulting fold isogons.

Ramsay has shown (Ramsay 1962a) that perfectly similar folds may be envisaged as parallel folds (class IB, orthogonal type) which have been subjected to an infinite compressive strain. This is a mathematical concept, but it is useful in looking at natural folds. Ramsay has derived an expression which relates the thickness of a folded layer at a point with the strain ratios at that point, and has summarized this expression **graphically**. This graph can be used to obtain very rapidly the strain ratios required to produce the fold in question from **an original** parallel fold (Fig 8). The strain ratios used on this graph are the square roots of the ratios of the quadratic elongations $1 + e_1$ and $1 + e_2$ in the two-dimensional strain elipse.



About half natural size

Fig. 6. Isogon plots of folded amphibolite layers

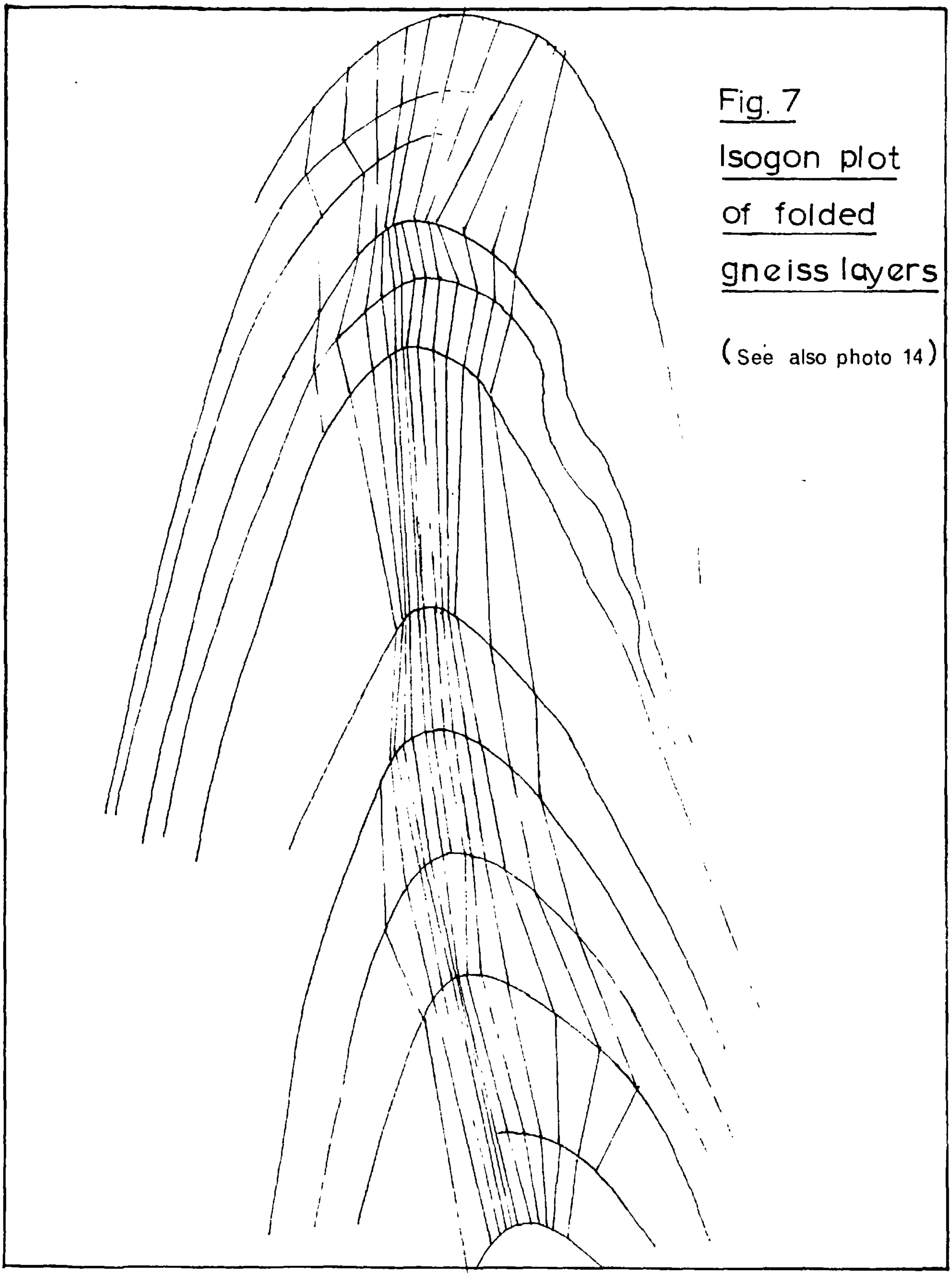


Fig. 7

Isogon plot of folded gneiss layers

(See also photo 14)

Data from a few typical folds in the Ludaig area of South Uist were plotted on this graph, and the results indicated strain ratios in the region 0.3 - 0.2, values which are fairly common. When the same technique was applied to folds from the Scurrival region of northern Barra, however, it was found that all the data fell on the line $T^1 = 1$, indicating nearly infinite strains. This could well be of far-reaching significance, since, for the F_2 folds measured from South Uist lie on the gentle limb of the regional F_3 structure, whereas those from Scurrival are on the steep limb, and therefore this gives us a guide to the states of strain on the limbs of the major F_3 fold structure.

In the case of the Scurrival folds, where we are dealing with very high strian ratios, the isogon method is rather insensitive, and an empirical method has to be used to obtain an approximate value of the strain ratios. The fold in question is simply drawn out on a grid, and then "unstrained" by re-plotting the grid with different co-ordinate ratios until the fold approximates to the parallel model. Figure 8 shows a particularly flattened fold unstrained by a ratio of 15:1, and it is clear that the result is an acceptable approach to a parallel fold. (The folded layer is an amphibolite, probably a Scourie dyke, illustrated in Photo15).

Several folds which could not be treated by the isogon method were examined in this way, all involving folded Scourie Dykes, and it was found that the amount of unstraining required varied between 10:1 and 15:1. Both this method, and the isogon method, however rely on the assumption of homogeneous compressive strains and this

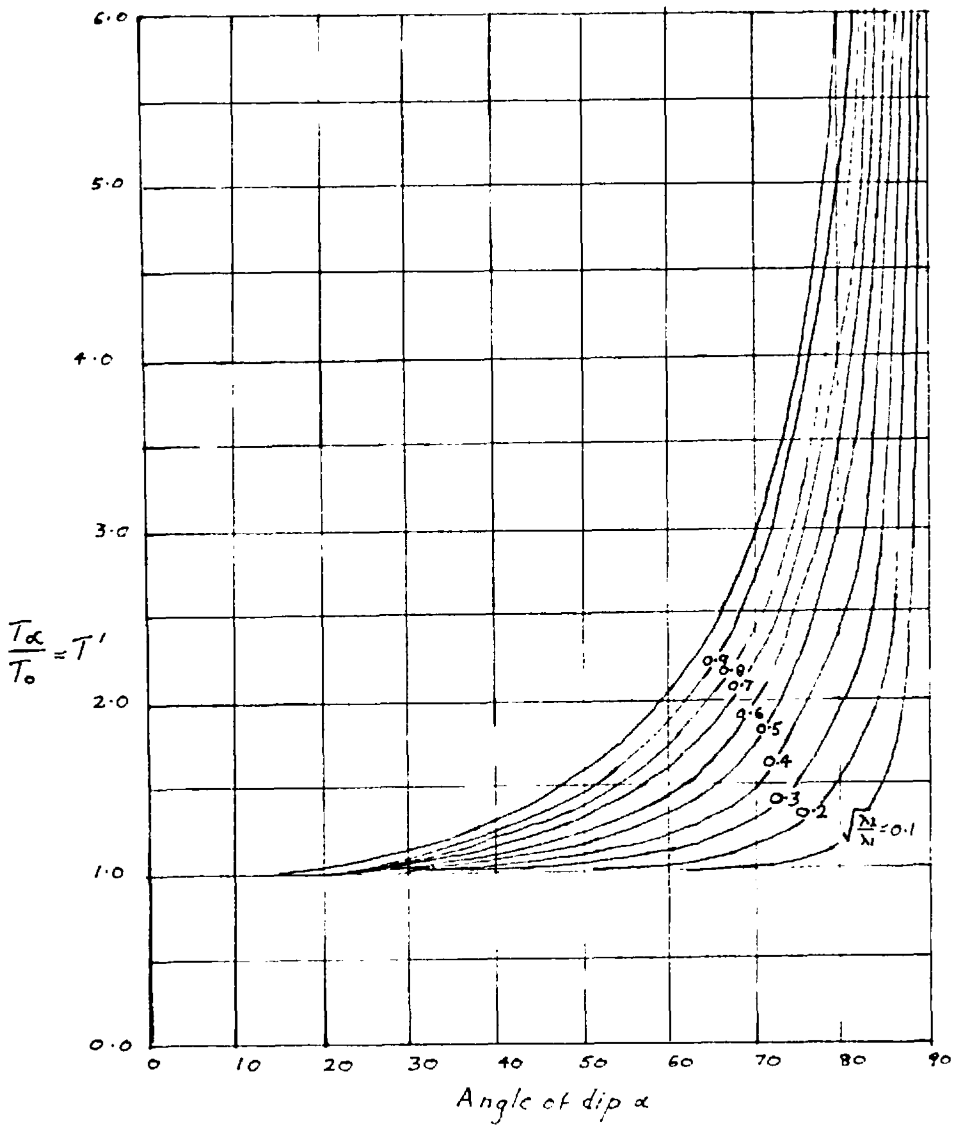
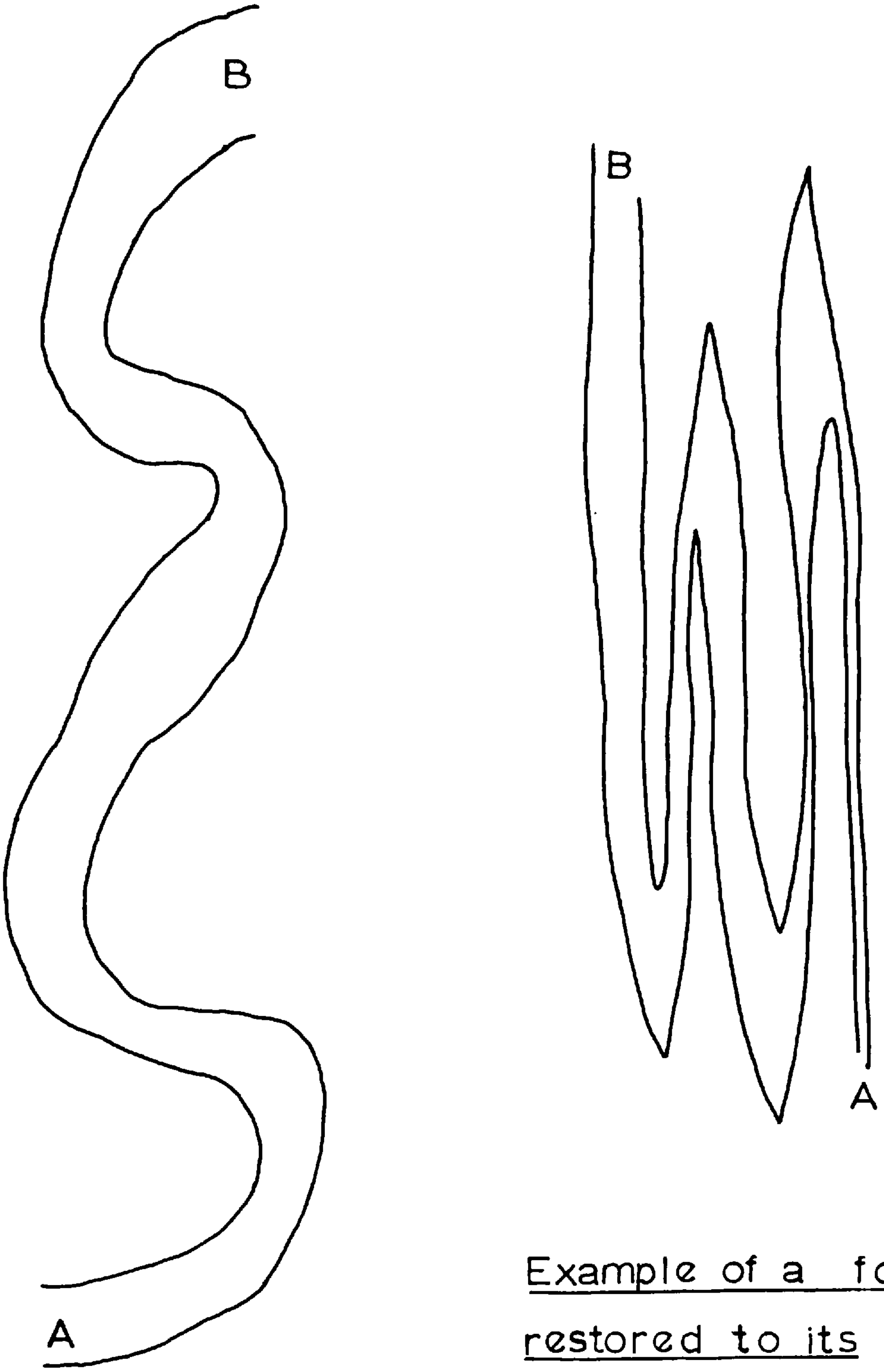
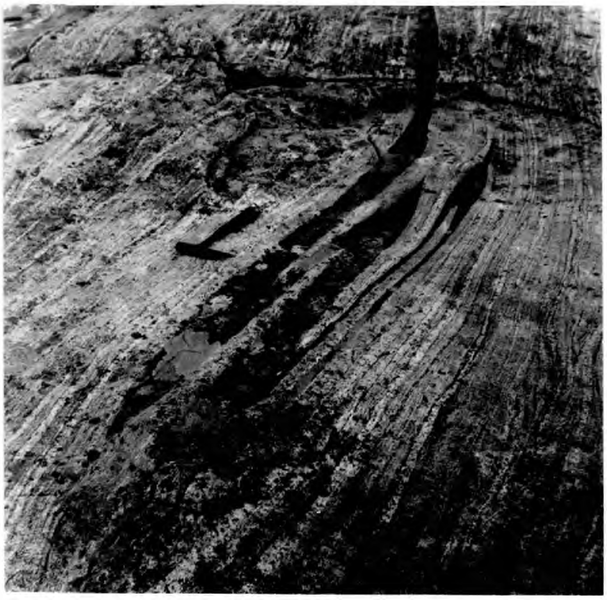


Fig. 8. Graph relating T′ and α for different strain ratios From Ramsay 1967

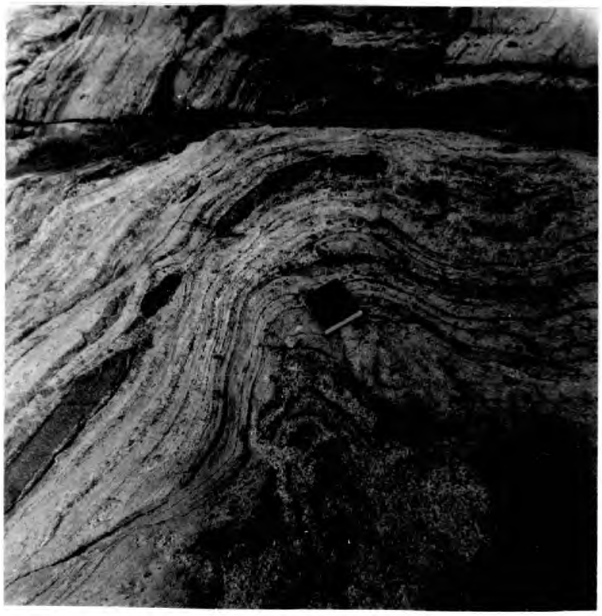


Example of a fold restored to its original parallel style

See also photo 15



15. Highly flattened F_2 folds defined by an amphibolite layer, Scurrival Point. The amphibolite probably represents a Scourie dyke. See also fig. 8. NF 696090



16. F_2 boudins refolded by F_3 minor fold, Scurrival Point. Note the pegmatitic material in the foreground swamping the gneiss layering. NF 696093

assumption is probably not valid in natural rocks, so the data obtained can only give a rough guide to the true strain ratios.

With this proviso, however, two further deductions may be made by restoring flattened folds to their original shape, which are particularly interesting when applied to Scourie dyke amphibolites:-

First, the total compressive strain involved in folding can be derived. This is made up of 3 components; the added compressive strain or "flattening," the original shortening produced during buckling to produce the parallel type fold, and the shortening which occurred <u>before</u> buckling was initiated.

Second, the original viscosity contrast or competance difference may be derived.

Sherwin and Chapple (1968) have produced a graph which summarizes the relationship between the wavelength/thickness ratio of a folded layer and the amplification factor for different values of viscosity contrast and initial compressive strains. It is beyond the scope of this thesis to criticise the validity of this graph, so the results obtained are merely summarized below. Unfortunately, to measure the wavelength/thickness ratio accurately, one requires folded layers showing several crests and troughs, and naturally these are rare. Only four were found that were suitable.

Table 6 again brings out the considerable differences between folds at Scurrival and Ludaig. This is in part due to F_3 modification of F_2 folds on different parts of the F_3 structure, but also in part also reflects variations in the F_2 strain ratios.

TABLE 6

F_2 fold Data. (Folded Scouric Dyke Amphibolites)

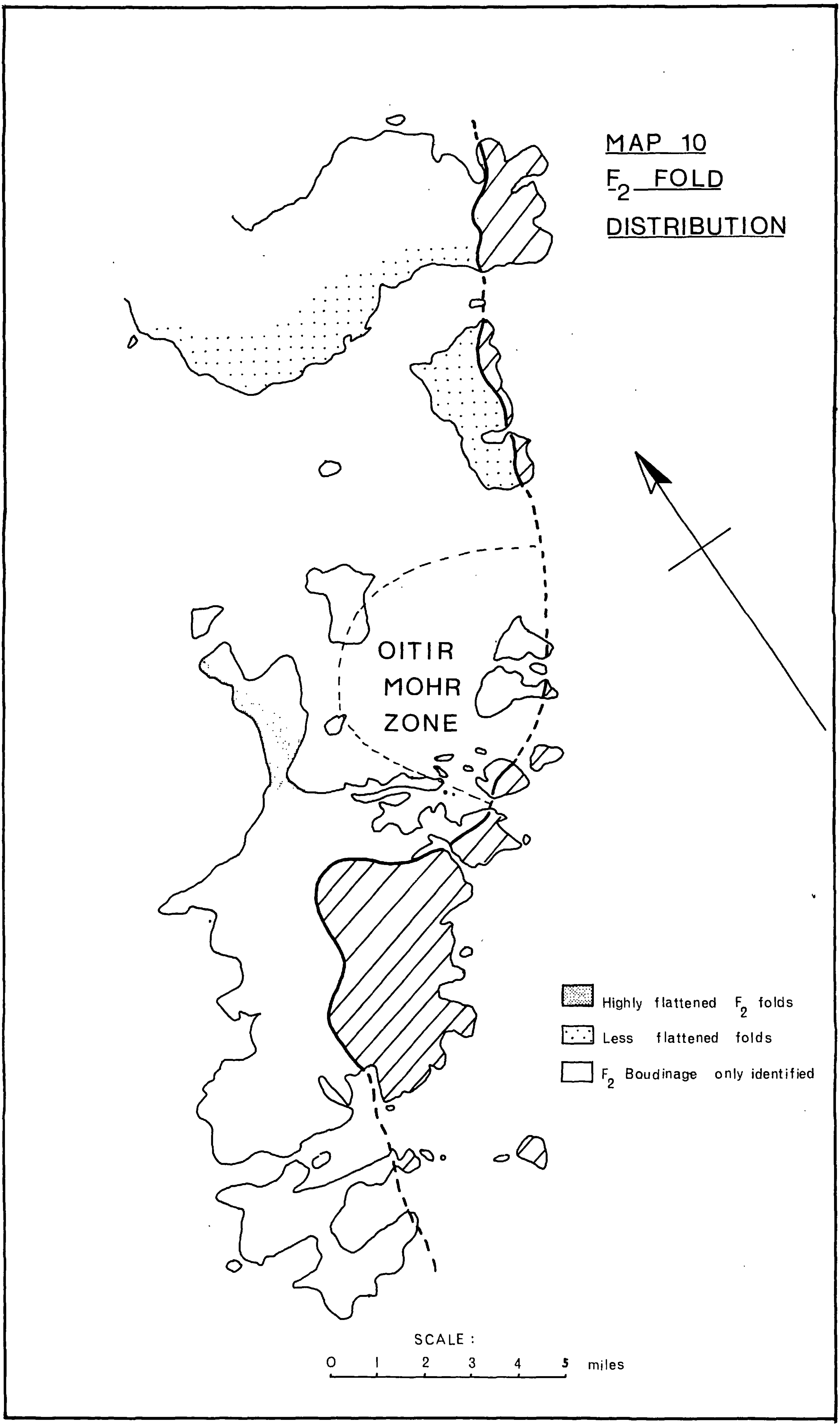
Fold	Wavelength Thickness ratio	Shortening prior to buckling	Shortening during buckling	Shortening by added compressive strains	Total shortening	Viscosity contrast
1. Scurrival	6.8:1	2.2:1	1.3:1	15:1	42.9:1	16
2. Scurrival	4.3:1	3.7:1	1.2:1	9.8:1	32.5:1	11
3. Ludag	7.7:1	2.0:1	1.2:1	7.8:1	18.8:1	20
4. Ludag	8.4:1	1.8:1	1.1:1	5.0:1	10.1	25

Since, however, we never find F_2 folds unaffected by F_3, it is impossible to comment on these original variations in F_2.

There are not sufficient data here on viscosity contrast here to be of much value, but the consistently low results are very interesting, and suggest much lower competence differences between Scourie dyke amphibolites and the acid gneisses than one might intuitively expect.

DISTRIBUTION AND ORIENTATION OF F_2 FOLDS. Apart from folding Scourie Dykes, the F_2 deformation also caused widespread boudinage of them. Boudinage is not an easy phenomenon to date, but in the present area, the most extensive boudinage seems to have occurred during the F_2 fold phase, though some may have been produced as a result of F_1 deformation. F_3 certainly does not seem to have produced extensive boudinage itself, far earlier boudins may often be observed folded by F_3 minor folds (Photo 16). Some extension or shortening of pre-existing boudins may have occurred on the limbs of F_3 folds, but not fresh boudinage. The F_4 deformation produced structures on such a small scale that no major boudinage is likely to have occurred.

Assuming, then, that most of the boudinage that one observes is of F_2 age, then it is interesting to examine the distribution of F_2 folds and boudins. Map 10 illustrates this schematically, and also distinguishes between areas of more and less highly flattened F_2 folds. Two major fields are present; a northern area which has F_2 folds and boudins, and a southern area which has F_2 boudins only. This must indicate an original difference in orientation of the Scourie dykes relative to the F_2 strain elipsoid, the dykes in the north having been



MAP 10
F_2 FOLD
DISTRIBUTION

oriented in the contractional field of the strain ellipsoid, those in the the south in the extensional field.

Such a distribution could have been produced in a very large F_2 fold - shortening in the hinge, extension in the limb - but there is no evidence for any structure of such size. Minor structures for example, mostly have an "M" symmetry in northern Barra, with about equal numbers of S's and Z's while on Eriskay only M's are found and on South Uist there is a slight tendency for S's to predominate over M's. No intelligible pattern emerges from study of these fold-profiles, and consequently there is no evidence for large F_2 folds.

Detailed studies of F_2 minor folds could however produce some interesting results. By measuring the enveloping surfaces to folds in the folded zone and by plotting these directions (of shortening) and of boudinage (extension), it would be possible, theoretically at least, to derive the surface of no finite longitudinal strain, and therefore the strain ratios of the 3-dimensional strain ellipsoid. The practical difficulties, however, coupled with the effects of F_3 modification make this impossible.

Orientation of F_2 fold plunges are difficult to measure, even in the best exposed areas. The few data obtained indicate plunges to the north and north-north west at variable angles, fold axes as a whole appearing to be roughly co-axial with F_3 folds. The axial planes of F_2 folds are always parallel to the regional gneiss foliation, and hence stereographic plots of F_2 axial planes are identical to plots of the gneiss foliation.

(v) The F_3 Fold Phase

The F_3 fold phase produced the largest and most important structure in the area. Folds of all sizes from a few feet to several miles in size are found. Most of the Western gneisses in south South Uist, Eriskay, Barra, Vatersay and all the southern islands as far as Barra Head, dip regularly and uniformly at low angles to the north-east. It is considered that this orientation is that of the long limbs of large F_3 folds, which are asymmetric and consist of a relatively long gentle limb and a short steep to overturned limb. The most important of these folds are the Scurrival antiform and complementary synform, which synform is unfortunately almost unexposed, but is of very great importance.

Before describing the major structure, however, we must examine the smaller folds. These will be described under the same headings as for F_2.

AGE OF F_3 FOLDS. This is fairly unequivocal. F_3 folds often refold earlier F_2 isoclines. F_4 folds frequently form minor structures on the limbs of larger F_3 folds, and have plunges which are controlled by the dip of the limb of the earlier large fold.

FABRICS. F_3 folding was associated with important re-crystallization and migmatization, which will be considered later, but two features are important here.

First, new growth of hornblende laths in coarsely migmatitic gneisses took place to a certain extent during F_3 and in places this produced in the noses of F_3 folds a conspicious mineral lineation.

parallel to the fold plunge. This mineral growth sometimes occurs in small axial planar pegmatites.

Second, a new fabric is developed over a fairly wide area in South Uist, mainly in the hills north of Ludag. The age of this fabric, which we shall call S_3, is extremely uncertain, because the evidence is contradictory. The facts are that in this part of South Uist a fabric is observed which at first sight is very similar to the earlier S_1 fabric, and is closely parallel to it; it does, however, have a fundamentally different relationship to the Scourie dyke amphibolites. In Barra, the amphibolites are everywhere concordant with the S_1 foliation, north of Ludag the amphibolites are not concordant with the foliation, but cross it at angles up to 90°. These features are illustrated in Figures 9,10 and 11

At first sight, this relationship might be considered to be an original feature, but this interpretation is precluded for the following reasons.

First, there is abundant evidence of isoclinally folded Scourie dykes in the same area.

Second, the gneisses are all highly migmatitic, and the Scourie dykes extensively boudinaged and entirely amphibolized - an unlikely environment for the preservation of original discordant relationships.

Third, the S_1 fabric can be seen isoclinally folded by F_2 folds only a short distance away, and relics of it occur in places amongst the S_3 fabric (Fig. 11).

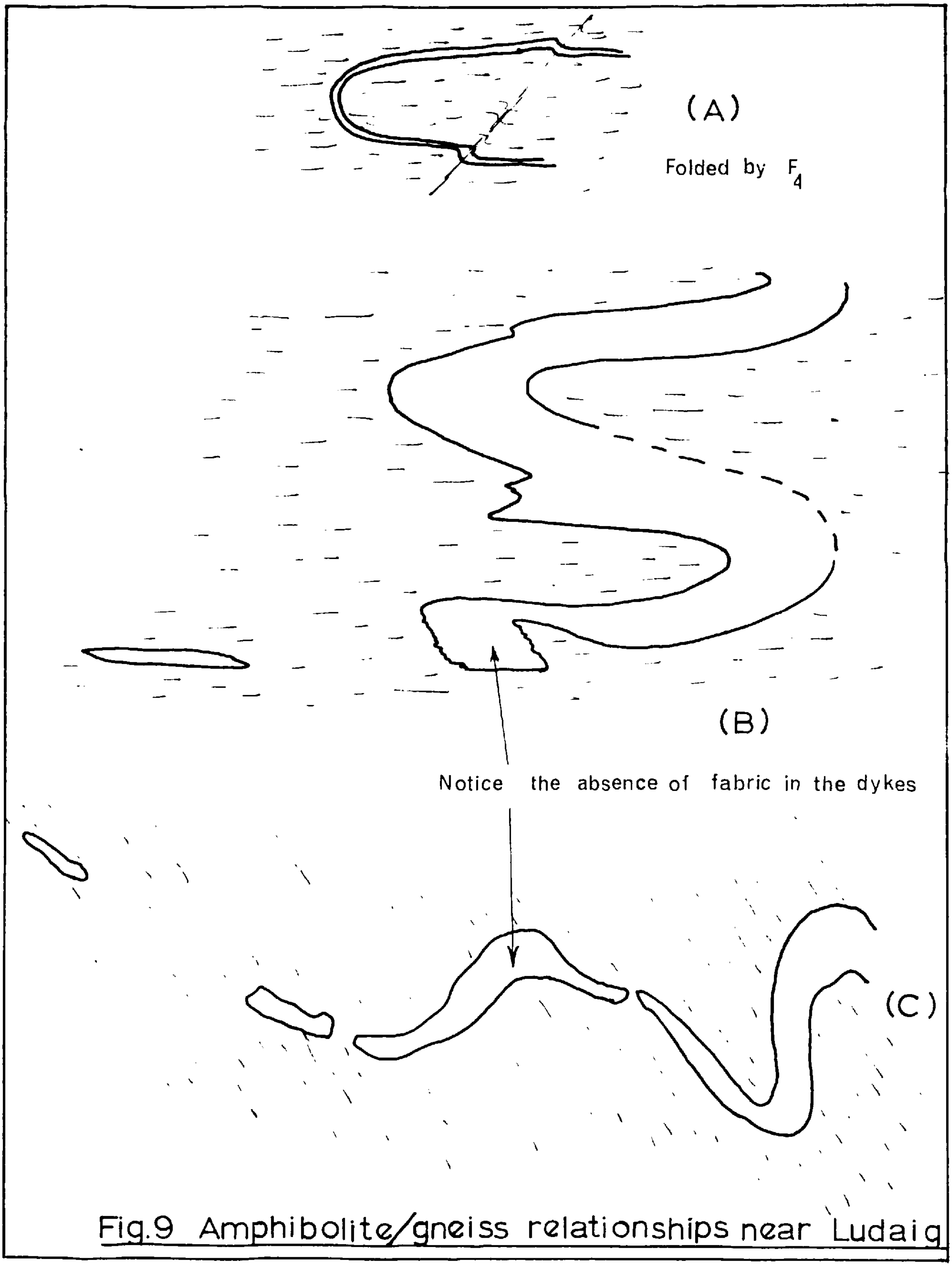


Fig.9 Amphibolite/gneiss relationships near Ludaig

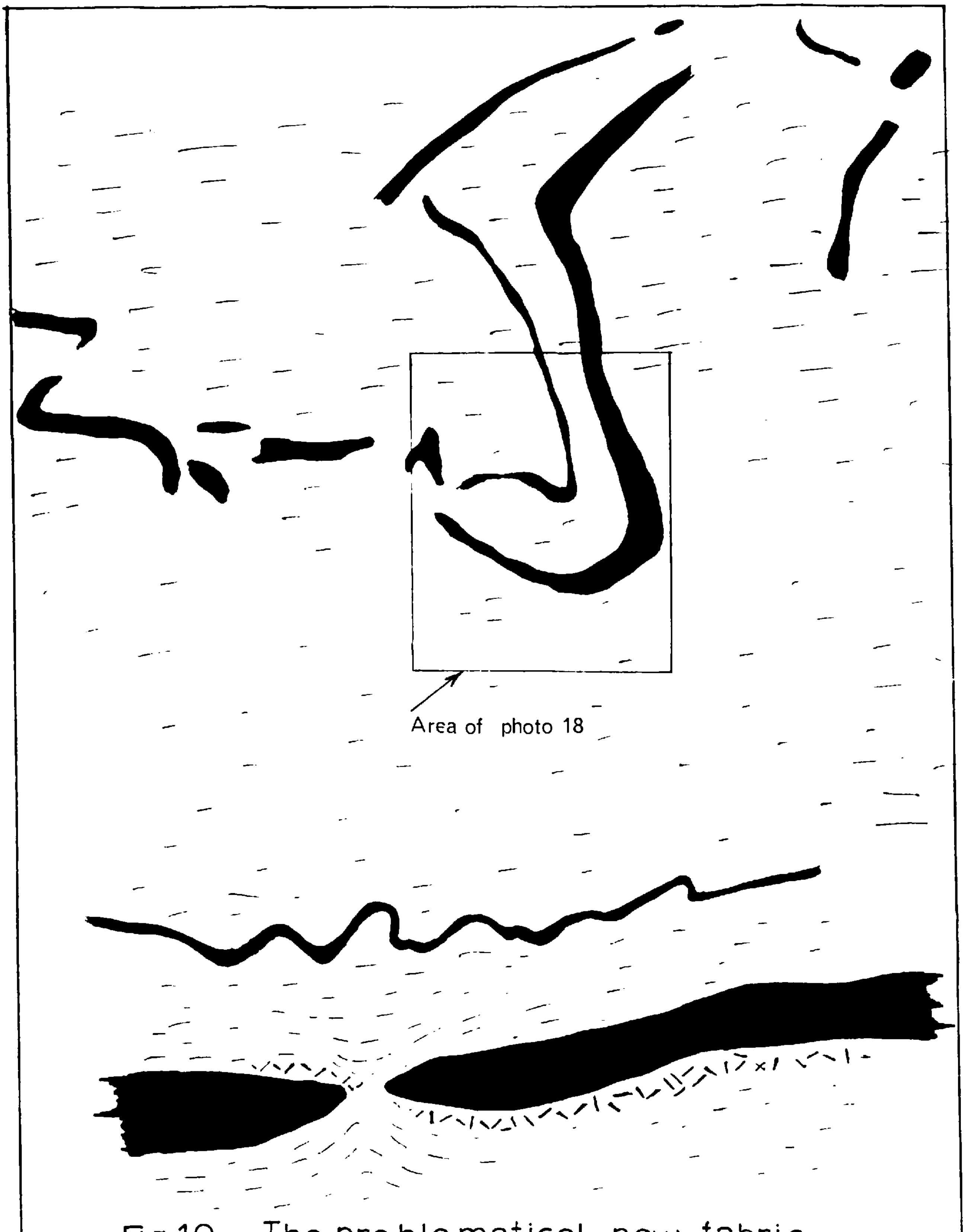


Fig.10. The problematical new fabric

Slabs above Ludaig. See also photo 18.

Fig. 11 Complex dyke pattern above Ludaig

Notice the interference pattern (centre) and the fabric growing across it.

Accepting that this is a new fabric, then we have to decide its age. It is in many places folded by F_4 (Fig 9a), so we can safely assume that it is not a very late feature.

Two possibilities are therefore open:-

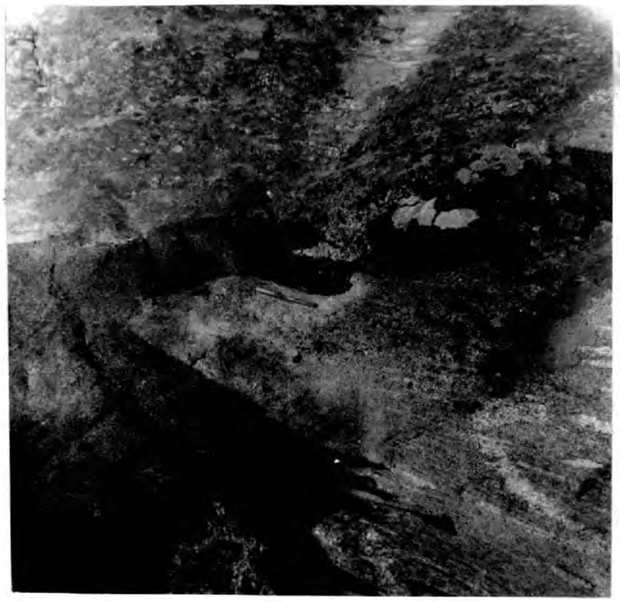
First, it is an F_2 fabric

Seond, it is an F_3 fabric

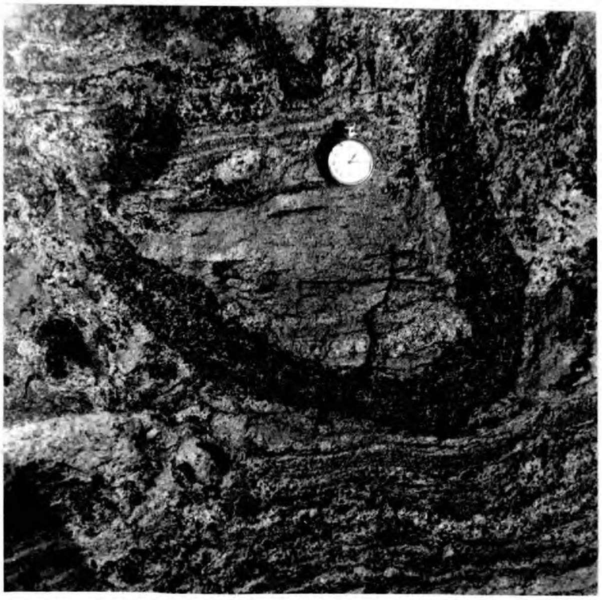
There is some good evidence for the first possibility. Figure 9b and Photo 17, for example, show the S_3 fabric axial planar to F_2 folds of Scourie dykes. When these dykes are traced further, however, they begin to meet the S_3 foliation at all angles up to 90^o . It is unlikely, though not impossible, for an axial plane fabric to develop perpendicular to apparently unfolded layers, and further, the fabric can be observed growing across the axial plane of earlier, F_2 folds (Figure 11 and Photo 18). The structures, here, however are so fiercely complicated that one cannot be sure of the age of any of the early folds.

If we accept, then, that this new fabric is not produced by F_2, it can only be produced by F_3. Unfortunately, there are very few F_3 folds of any sort in this area, so the direct relationship between folds and fabric cannot be observed. The orientation of the fabric is acceptable for it to be axial planar to F_3, dipping as it does gently to the north-north east, but this is about the only positive piece of evidence.

The absence of any fabric within the Scourie dyke amphibolites here is very puzzling. It was remarked earlier that F_2 folds everywhere seemed to lako any tectonite fabric, and this was ascribed to obliteration



17. The problematical new gneiss foliation on the slabs north of Ludaig. Here it is apparently axial planar to a folded amphibolite layer, probably a Scourie dyke, which itself appears to lack any fabric. NF 774148



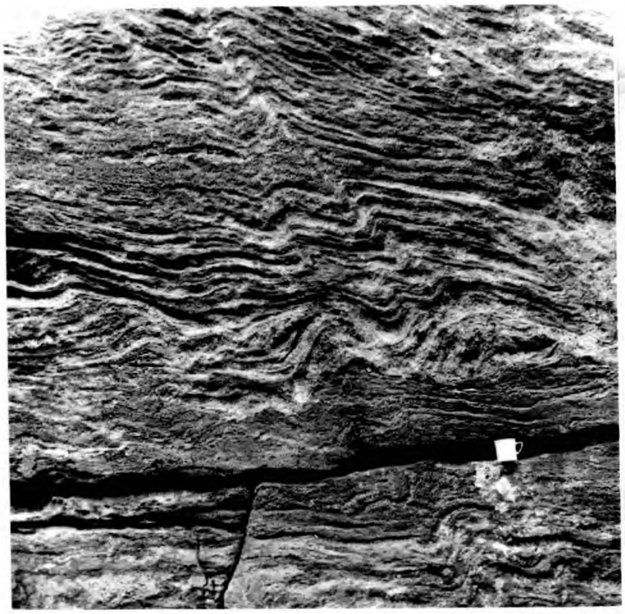
18. The same feature, but here apparently at right angles to an amphibolite. Note the coarsely crystalline appearance of the amphibolite, and its lack of any obvious fabric, NF 777148

by later **recrystallization.** Now there is plenty of evidence for synkinematic F_3 **recrystallization.** producing aligned hornblendes and axial plane pegmatites in folded acid gneisses, and this would effectively destroy any earlier fabrics in amphibolites, but one would of course expect to find F_3 fabric in these amphibolites.

The solution appears to be that amphibolites as a whole lose their fabrics very much more easily than do acid gneisses by recrystallization. In this instance post-kinematic F_3 **recrystallization** must have been responsible, or alternatively synkinematic or post-kinematic F_4 **recrystallization.** The F_4 fold phase was not particularly important, but it was associated with considerable migmatisation and production of pegmatite material, so that extensive obliteration of earlier fabrics could have occurred.

It is interesting to note here that Watterson (1968) has also commented on the ease with which deformed amphibolites lose tectonic fabrics in the Vesterland area of Greenland, so this is clearly not an unique case. The origins and time relations of the S_3 fabric, however, remain among the most intractable problems in the area.

STYLE OF F_3 MINOR FOLDS. F_3 minor folds are variable, but tend to be rather open structures, with interlimb angles of about 110°. They are asymmetric, with broad gentle limbs and rather narrow vertical to overturned steep limbs. Minor folds parasitic on larger folds are tighter on the steep limbs of these folds than on the gentle limb, and their axial planes show a slight fanning around the nose of the larger structures. Typical minor folds are illustrated in Photo 19.



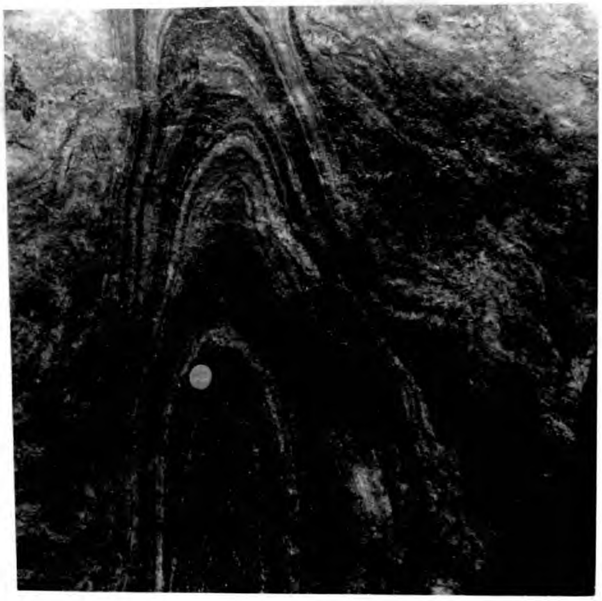
19. F_3 Minor folds in the Ben Tangaval area. Note the incipient axial planar pegmatites and the irregular areas of general recrystalization in the gneisses, NL 636984

20. F_3 Minor folds at Scurrival Point. Note the greater intensity of folding here and the disharmony between the amphibolite layer (left) and the gneiss layers. NF 694089

One of the most striking features of F_3 minor folds is that one relatively rarely finds these folding Scourie dykes, yet in F_2 it was folded Scourie dykes that formed by far the most conspicuous and important folds. Where one does see F_3 folds affecting dykes, there is a marked difference in style - instead of dominating, even identifying the structure, the dykes merely appear to be rather passive and to fold with the gneisses (Photo 16). This has some important relevance to the competence of the Scourie dykes in different fold episodes, and will be discussed further.

The other noteworthy feature of F_3 folds is their tendency towards disharmony - i.e. folds affecting one layer have little or no relationship with folds affecting adjacent layers. This is illustrated in Photos 20 and 21. Photo 21 shows an F_3 minor fold in acid gneisses which has become enormously extended, and we shall see in the next section that such structures may be duplicated on a much larger scale.

Disharmonic folding is characteristic of highly ductile materials, such as calc-silicates and salt deposits, and is due to the development of folds of different characteristic wavelengths in layers of different viscosities. It is common for amphibolite layers to develop wavelenghts much longer than those of the gneisses (Photo 20), but differences within the gneisses themselves can also produce considerable disharmony. The presence of layers in the gneisses of different composition (and viscosities) which are not always visibly obvious is demonstrated by such disharmonic folding, and by the occurrence of boudinage structures within perfectly ordinary looking gneisses.



21. Highly extended F_3 minor fold from the same locality as Photo 20.

22. Scourie dyke showing an early fabric and deformed by F_4, which buckled the dyke as a whole, and also produced a series of pleats or crinkles in the fabric (just visible in the photo). This dyke is also illustrated in Fig. 14. NF 731174

THE F_3 MAJOR STRUCTURES. It is 24 miles in a straight line from the pub at Pollachar to the Barra Head lighthouse. This line is almost at right angles to the strike of the foliation of the Western Gneisses and provides a very informative section through them. 95 percent of the rocks along this section dip at angles of 20° - 30° towards the north-east or north-north east. The presence of such large areas of uniformly dipping gneisses clearly calls for structures of an equally large scale.

Such structures have been recognised in both South and North Uist as well as Barra and it is generally agreed that these form the dominant structures in the Outer Hebrides and produce the dominant north-west south-east structural trend. This subject will be discussed further in a forthcoming joint paper. (Coward et. al. 1969).

The major structures of Barra are two folds, the Scurrival antiform and its complementary synform.

The nose of the antiform is well exposed on Scurrival Point, (Map 11). The gently dipping normal limb of this fold is traceable on Fiaray, northern Fuday across to Eriskay and on the southern part of South Uist. The overturned limb is slightly more complex, with at least one large second order fold on it. (The synform in the lower left hand side of Map 11). The overturned limb passes southward into the major synform, which is almost completely unexposed beneath the Traigh Mohr and Traigh Eais. It is considered that a large, very tight synform is concealed beneath these beaches, and that the southern limb of this synform turns up gradually to form the very uniform low, north-eastward dipping gneisses of northern Barra. This structure is illustrated in sections 1, 2, and 3 (Fig. 12).

Since this tight synform is of considerable significance to this thesis, we must try to justify it a little further. Five lines of evidence suggest its existence.

First, the presence of steeply dipping gneisses striking south-east along the north-east fringe of Barra and recognisable on Ard Mhor, Ard Veenish and Bruernish. This steep zone can be traced gradually and continuously into the regular shallow dipping gneisses a short way to the south west. On the next pieces of exposed ground to the north, at Eoligarry and on Orosay E, steeply dipping foliation is again observed. This indicates at least the strong likelihood of a mile-wide zone of steeply dipping foliation in the right place.

Second, minor F_3 folds have the appropriate symmetry for a large synformal structure. At Orosay E and Eoligarry these folds have Z profiles, while on Ard Mohr and Ard Veenish they have S symmetry. The evidence on Ard Mohr is, however, contradictory in places. This may be due to the presence of second order folds on the limb of the larger structure.

Third, the high degree of flattening of F_2 folds in the Scurrival area would be satisfactorily explained by a large, tight major synform where F_3 flattening deformation would be intense.

Fourth, the style of the postulated structure is comparable with others in the Hebrides. Coward for example has mapped a tight major synform in South Uist.

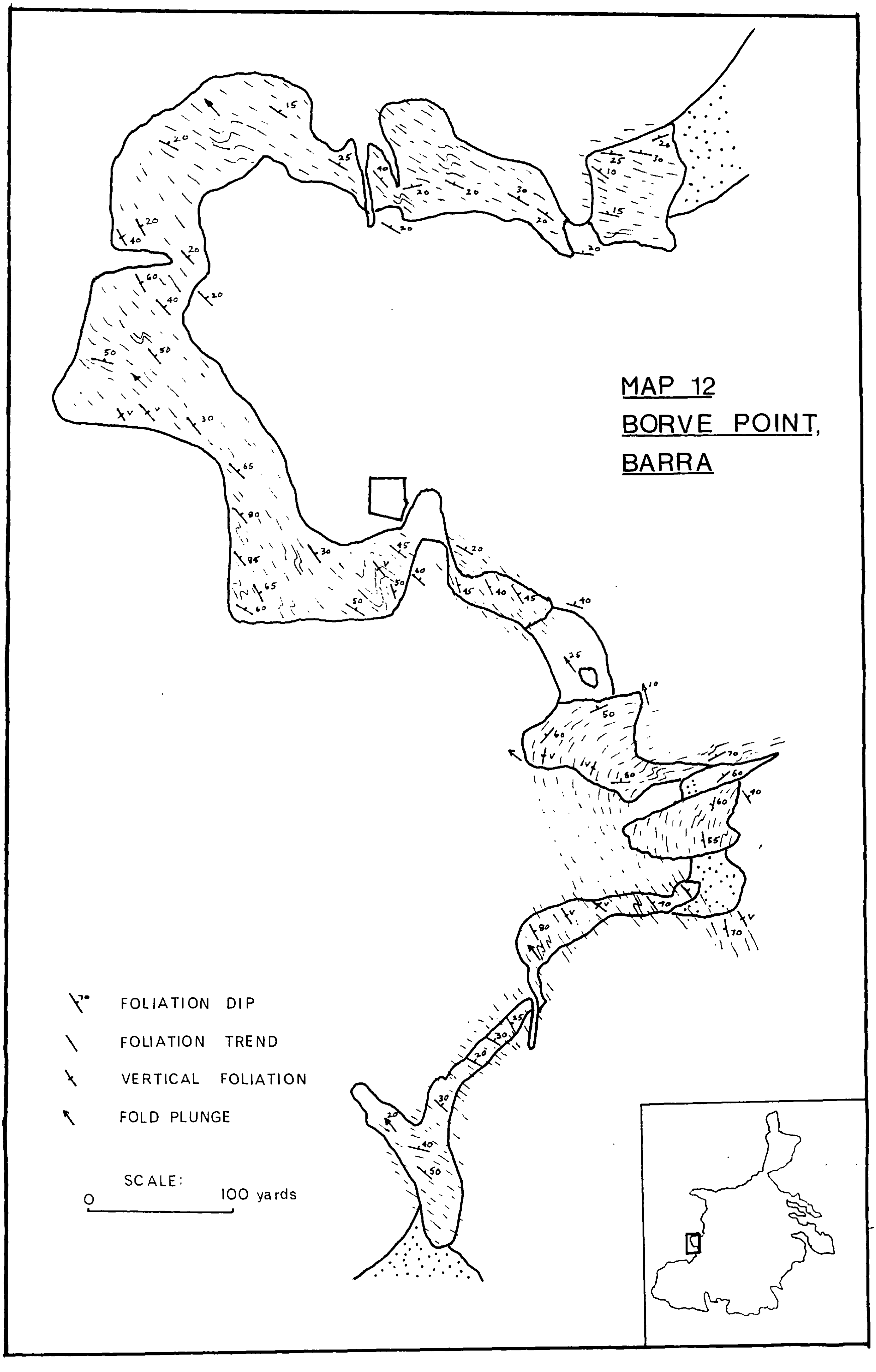
Fifth, it would be difficult to explain the observed relationships in any other way. A very large monoclinal structure is the only alternative possibility.

It is important to note here that the core of the Scurrival antiform is occupied by the rocks of the Oitir Mohr zone. The considerable significance of this arrangement will be discussed in the interpretative part of this thesis.

Although the Scurrival structure is by far the largest F_3 structure in the present area, there are some smaller folds. At Borve Point, for example is a fold which is in many ways similar to that at Scurrival (Map 12). This structure is rather more complex, however, with many F_4 folds confusing the issues, but it does appear that here again there is a simple open antiform with a normal limb dipping gently NE and a zone of very steep, tight foliation in place of a synform.

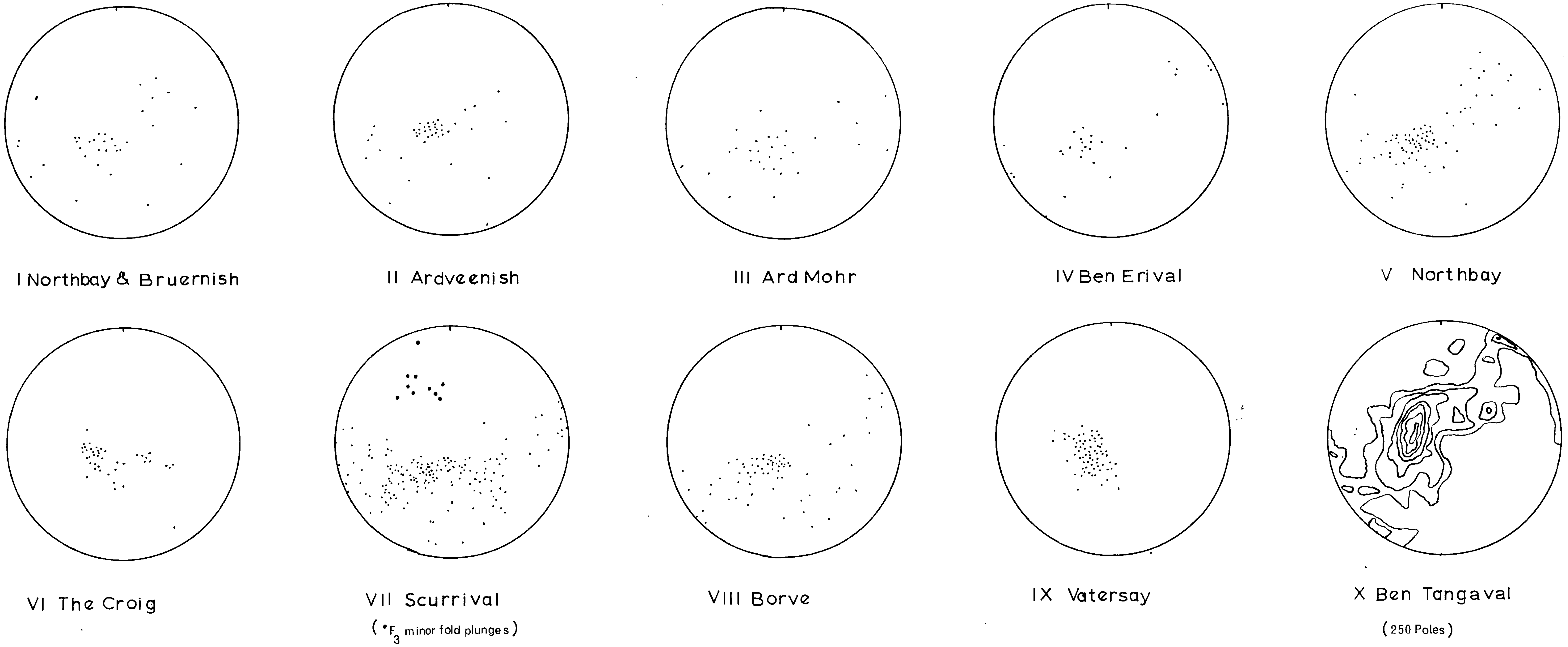
On the whole, however, F_3 folds of this scale are not particularly common, and in some large areas F_3 minor folds are completely absent. Southern South Uist is one such area, and also on Barra there is an extremely large area between Borre and Ben Erival without much sign of F_3 minor structures. Further south, however, such structures become much more abundant.

ORIENTATION. The orientation of the large areas of uniformly low dipping foliation has been summed up on stereograms 1 - 10 which represent various small sub-areas (Fig. 13). It is clear that the orientation varies very little on the whole, and that only in the south is there much significant spreading. This is best seen in the



MAP 12
BORVE POINT,
BARRA

Fig.13 Examples of plots of poles to gneiss foliation



I Northbay & Bruernish

II Ardveenish

III Ard Mohr

IV Ben Erival

V Northbay

VI The Croig

VII Scurrival

(• F_3 minor fold plunges)

VIII Borve

IX Vatersay

X Ben Tangaval

(250 Poles)

Ben Tangaral area, where late warping has produced a complet reversal of F_3 plunges. This is not due to F_4 folding but to later, visible gentle warps of the foliation into undulations with measurable axes of 050°. These warps are responsible for the rather complex foliation trend in Southern Barra and Vatersay.

In areas not affected by later warps, the general plunge of F_3 folds is about 30° to 330°, while axial planes strike about 350° and dip at about 45° to the north-east.

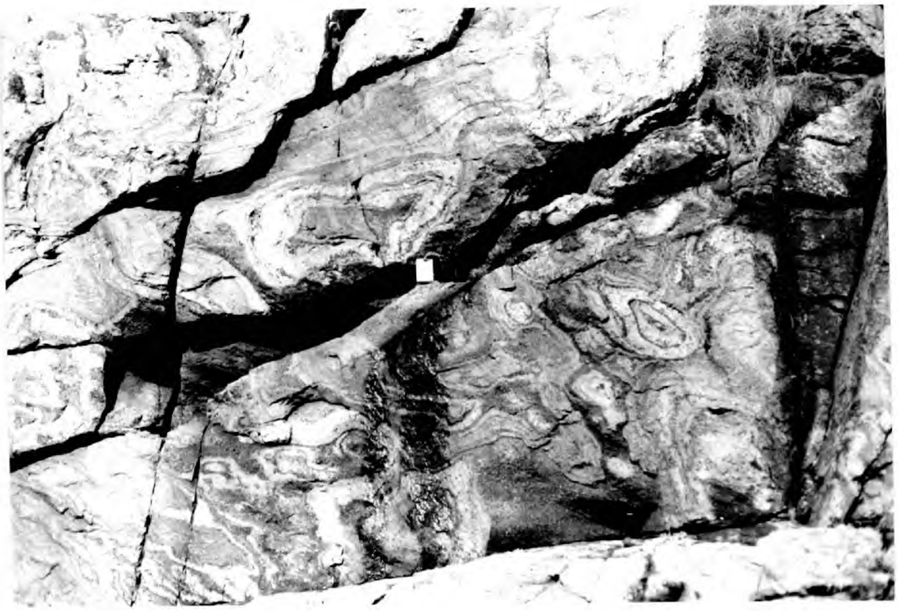
(vi) The F_4 Fold Phase

F_4 folds are extremely abundant throughout the area; they are more common than folds of any other age, but are not very important since they are so small. F_4 folds exceeding a few feet in amplitude are only found in the extreme north west of the area mapped; on the island of Orosay S.U. and in the neighbouring hills.

AGE OF F_4 FOLDS. F_4 folds are clearly later than any of the fold phases previously described, since they frequently refold them. Striking interference patterns produced by refolding of F_3 by F_4 are sometimes found. Photo 23 illustrates a good dome-and-basin pattern from Scurrival Point.

FABRICS. Two fabrics are significant:-

First, a mineral orientation produced by new growth of hornblende prisms in the noses of F_4 folds in coarsely migmatitic gneiss, together with axial planar pegmatites.



23. Dome and basin patterns produced by the interference of F_3 and F_4 folds. Scurrival Point. NF 695096

24. F_4 minor folds on Vatersay. Note the conspicous axial plane pegmatites and the rather low dip of the axial planes here. NL 627936

Second, axial plane fabrics. These occur locally on South Uist, and are particularly well developed on the island of Orosay S.U. where Scourie dykes strongly buckled by F_4 are found. One of these dykes has a good banding or foliation of unknown age (Photo 22 and Fig. 14a). The banding visible in the photograph, which is defined by layers rich in biotite, is puckered into a multitude of small crinkles or pleats, whose axial planes are parallel to the F_4 axial plane.

STYLE OF F_4 FOLDS. This is extremely simple. The folds are rather open, asymmetric buckles as a rule, the symmetry of the fold being controlled by the orientation of the major F_3 structure. Folds tend to be best developed on the steep limbs of these structures, for example at Bor[illegible] Point, where very fine folds are found.

Where boudinaged Scourie Dykes occur in areas of strong F_4 folding, these boudins tend to be pushed together by the F_4 deformation. This is particularly well displayed on Orosay S.U., Fig. 14b, where quite spectacular pinched boudins occur. A few feet from this outcrop is the exposure illustrated in Fig. 14a. Notice that the upper and lower surfaces of the Scourie dyke in Fig. 14a have folded disharmonically - synforms on the lower surface do not match synforms on the upper surface.

Perhaps the most interesting feature of the F_4 folds, is however, the thin stringers of pegmatitic material associated with **them. They are roughly, but not accurately, axial planar to the folds** (Photo 24) and frequently intersect one limb of a fold rather than its hinge. These axial phase pegmatites are most abundant in the

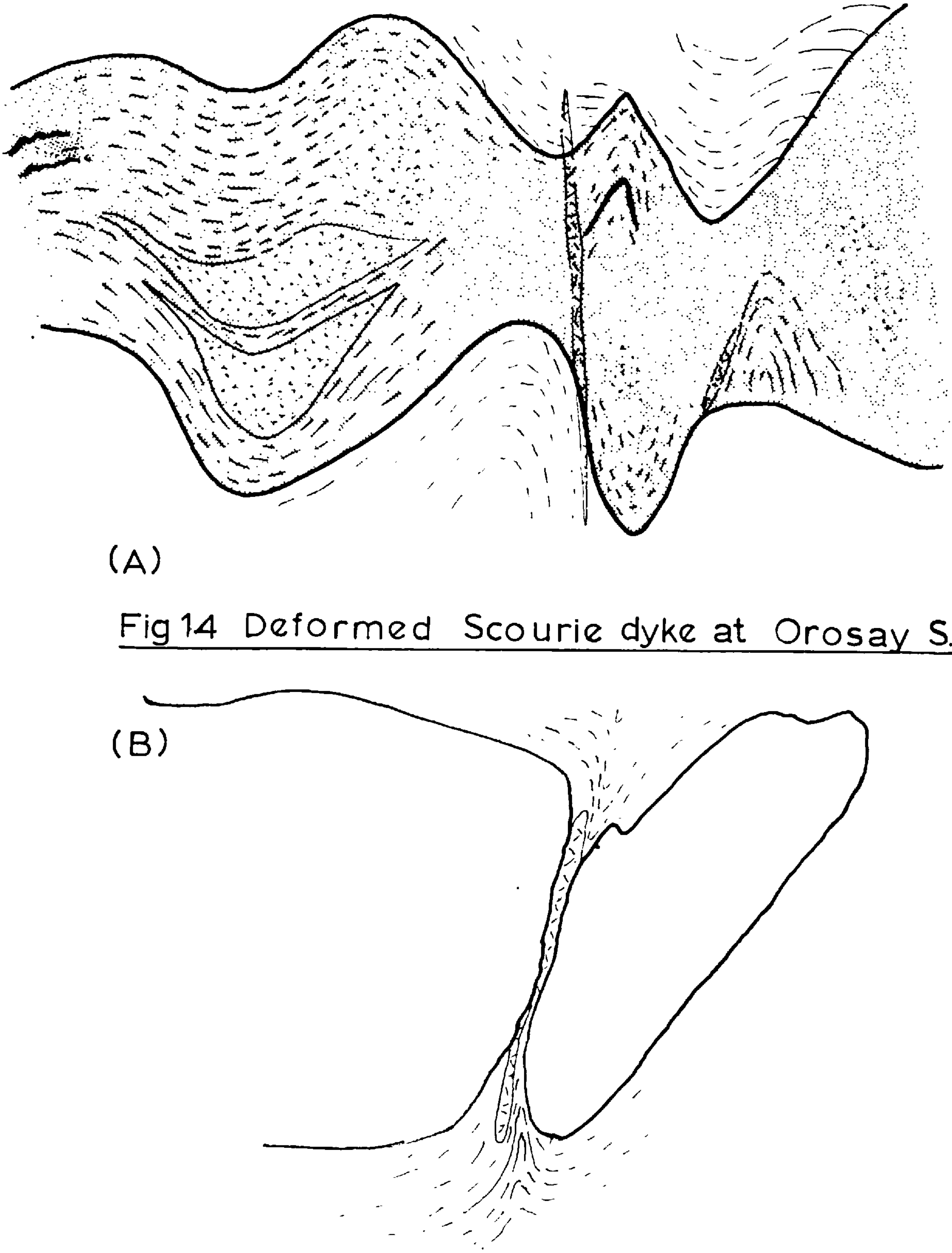


Fig 14 Deformed Scourie dyke at Orosay S.U.

extreme north and south of the area, at Ludaig and Vatersay. When outcropping on a flat surface they form very conspicuous linear features which are quite unmistakable. The structural control of these features is not well understood. It may be linked with the "microlithon" or "gleitbretter" structures found in lower-grade metamorphic rocks.

Apart from the larger folds in the Orosay area, the wavelength of F_4 folds over the rest of the area is remarkably constant, and this probably reflects the dominant wavelength for acid gneisses, since many minor F_3 structures are also of very similar size.

DISTRIBUTION AND ORIENTATION. Minor F_4 folds really are very common throughout the area, although they tend to be scarcer in the areas of very uniform, low dipping foliation.

The orientation of folds is constant over small areas, but does show a regional variation. Over most of Barra, for example, the axial trend is about 100 - 110°. but this gradually swings round to about 070° in the southern part of South Uist. The axial plane dips steeply to the north, averaging about 70°, but this too shows regional variation - on Vatersay and Southern Barra it is only about 50°. The regularity of these regional changes suggests that they may be due to primary tectonic courses, rather than later warping.

The plunge of F_4 folds is of course governed by the shape of the F_3 folds and stereographic plots of fold plunges show the typical great circles.

III THE OITIR MOHR ZONE

General

We come now to examine the third of the principal zones of the field area, the Oitir Mohr Zone. This represents a mass of rocks of Eastern Gneiss affinities structurally below the Western Gneisses and exposed in the core of the Scurrival antiform. The limits of this zone could ideally be defined objectively by the presence of cross-cutting dykes, but unfortunately outcrops are confined to the islands of the Oitir Mohr, and the limits must therefore be largely speculative. Work on the geology of these islands is further hampered by poor inland exposure with only a narrow fringe of well exposed rocks on the coasts. A lack of drinking water also makes prolonged stays impractical, and consequently these islands have not been mapped in anything like the desirable detail. One scarcely has to set foot on the islands, however, to remark how different the rocks are from any others west of the Thrust. Perhaps the most conspicuous differences are the abundance of pyroxene in the gneisses, and the presence of clearly cross-cutting granulite dykes.

In this very brief section, it is proposed to describe the rocks of the Oitir Mohr zone, to compare these with those of the Eastern Gneisses, while comments on the correlations between this zone and other units will be kept until later. Each of the sub-headings used in describing the Eastern Gneisses will be used again here, to point the similarity between the two groups of rocks.

Acid Gneisses

Acid gneisses might be thought to be much the same wherever they are found, but in this zone, there are three features which distinguish these from the Western Gneisses, and identify them with the Eastern:-

First, a large-scale variability - the Western gneisses are conspicuously homogeneous.

Second, and more important, orthopyroxene is abundant, weathering to give "rusty" gneisses in places. The pyroxene is typically in a very much altered condition. Pyroxene, however is not universal in the gneisses, in fact on Hellisay distinct bands of pyroxene-free gneisses occur, which could probably be mapped out as such, given time.

Third, blocks of early basic to intermediate material are common within the gneisses. This is particularly true of the east coast of Gighay, where this blocky habit is closely similar to that described at Bruernish and the gneiss is consequently almost agmatitic.

The gneiss of the Oitir Mohr zone are slightly different from those of the Eastern Gneisses in being somewhat more iron-rich. This is expressed in the presence of grains of magnetite up to half an inch across within the gneisses, particularly on Gighay.

Early Intrusive Bodies

It will be remembered that in the Eastern Gneisses, two rock-types were described under this heading, pyroxene bearing bodies and amphibole bearing bodies. The same division may be made in the

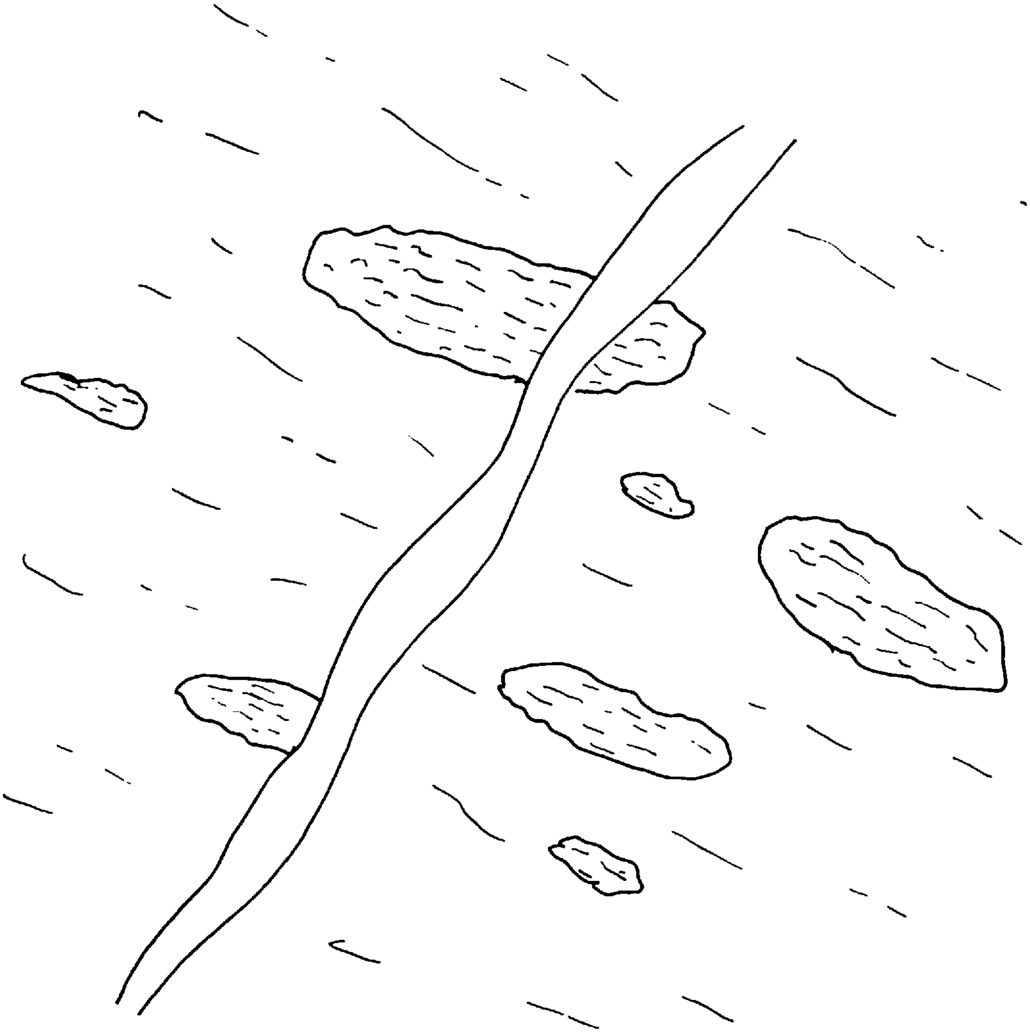


Fig 15 Intermediate dyke cutting earlier blocks, Hellisay

The dyke, blocks and coarse homogeneous matrix all contain orthopyroxene

Oitir Mohr Zone, although amphibole bearing bodies are very scarce.

On Fuday, pyroxene bearing bodies are well displayed in the south-east corner of the island, where rusty, coarse, homogeneous quartz free rocks similar in all respects to the "Balnobadachites" are found, in some places containing exceptionally large crystals of orthopyroxene. The rocks here are cut by at least one Scourie dyke. Towards the north-east corner of the island, there is an exposure of spotted, hornblendic agmatitic material. It is tentatively suggested that this represents the deformed and metamorphosed equivalent of the pyroxene bearing bodies, just on the edge of the Oitir Mohr Zone. It closely resembles a similar rock on Ard Rudhr Mohr, in a somewhat similar structural environment, (Photo 25).

On Gighay and Hellisay the pyroxene bearing bodies present a problem of considerable interest. It was stated that in rocks of this type in the Eastern Gneisses of Barra, a considerable variation in quartz content was present. In rocks of this type in the Oitir Mohr zone, we again find this variation in quartz content, from quartz poor on Fuday to quartz rich on Gighay and Hellisay. The problem is that on these islands there are very large amounts indeed of rather coarse, crumbly, texturally homogeneous rocks consisting essentially of plagioclase, quartz, orthoclase, hornblende, biotite and orthopyroxene.

Under the microscope, one might be justified in describing these as pyroxene-bearing acid gneisses, since mineralogically there is little to distinguish the two. The texture in outcrop is the problem. There is little sign of a gneissose banding although there is a slight foliation, and the general impression is closely similar to that of the Balnobodachites.

Figure 15 gives a clue to the possible origin of these rocks. Here blocks of basic to intermediate composition are found swimming in a matrix of homogeneous coarse orthopyroxene bearing acid gneiss. The whole assemblage is cut by a dyke of the intermediate suite, which is also pyroxene bearing. It seems probable that the coarse homogeneous matrix represents an older, replacive granite which has suffered later matamorphism, with the production of orthopyroxene and a general blurring of the original relationships. If this is the case, then it follows that these rocks, although they look extremely similar to the quartz-free "Balnobodachites," are of completely different origin, and the two cannot be related either in time or composition. It must be confessed, however, that these rocks are not well understood, and that this interpretation may be wrong.

Amphibolite bearing bodies were found only on Hellisay, where a splendid net-veined coarse amphibolite exactly like those of the east coast of Barra is well exposed, and is convincingly cut by a Scourie dyke.

Early Intrusive Dykes

These are by no means as common as in the Eastern gneisses, although they are still clearly identifiable. Only examples of the intermediate suite were found, and these were in every way comparable with those of the Eastern gneisses, except that orthopyroxene is sometimes found within them. On Fuiay, on the southern fringe of the

Oitir Mohr Zone, large outcrops of homogeneous, well foliated meta-diorite were found, and these were identical with those in the more deformed zone of the Eastern Gneisses.

Early Granites and Pegmatites

No early granites were observed anywhere within the Oitir Mohr Zone, although on Fuday some particularly granitic looking augen-gneisses closely approaching granites in composition were found.

The pegmatitic material net-veining the coarse amphibolite already mentioned is almost certainly pre-Scourie dyke in age.

Scourie Dykes

Cross-cutting granulite dykes are abundant within the Oitir Mohr Zone, although it should not be thought that every dyke is discordant - many are not. Those in the eastern part of Hellisay, (below the Thrust), for example are both concordant and somewhat amphibolized. The mineralogy of these dykes is identical with those of the Eastern Gneisses.

Perhaps the most interesting aspect of the dykes in this area is the amazing rapid transition from recognisable cross-cutting dykes to concordant amphibolite bands. In the southern part of Fuday, for example, dykes such as that in Fig. 16 occur, and similar dykes may be found as far north as Rudha-Carraig-Chrom. Beyond this point, however, dykes are all concordant amphibolites, as they are throughout the Western Gneisses.

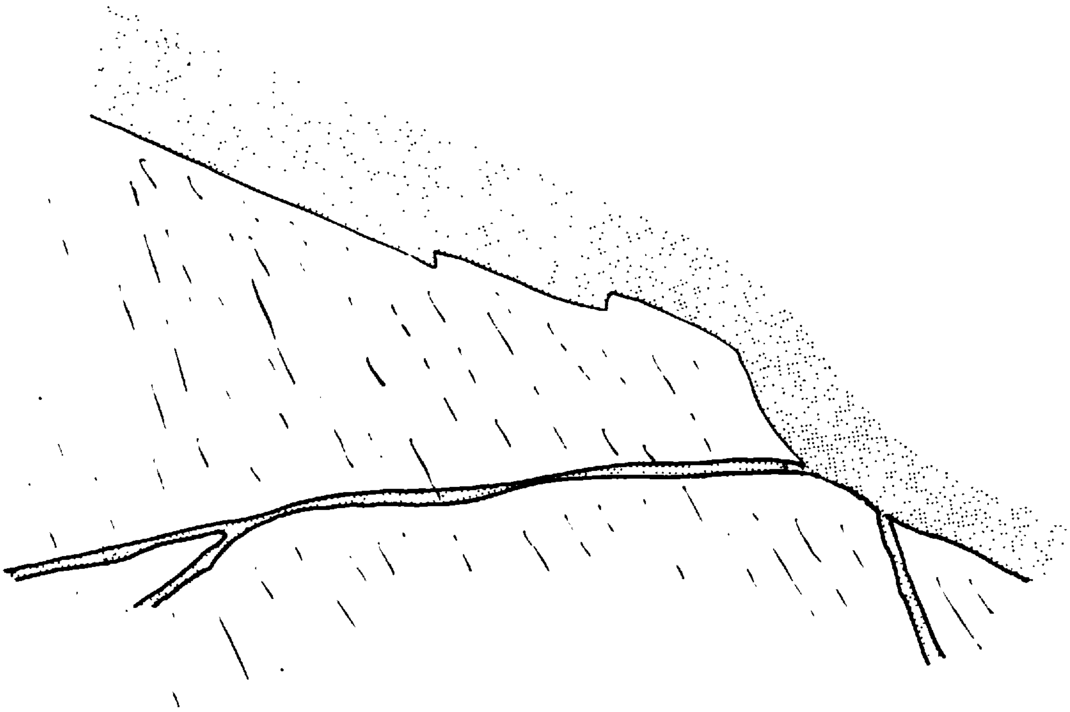


Fig. 16. Discordant Scourie dyke Southern Fuday

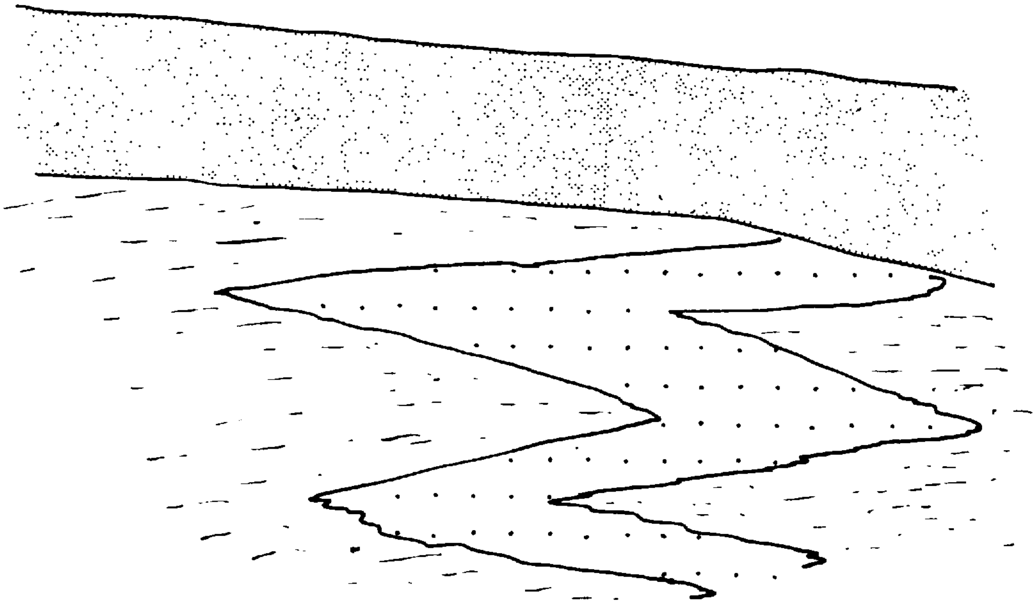


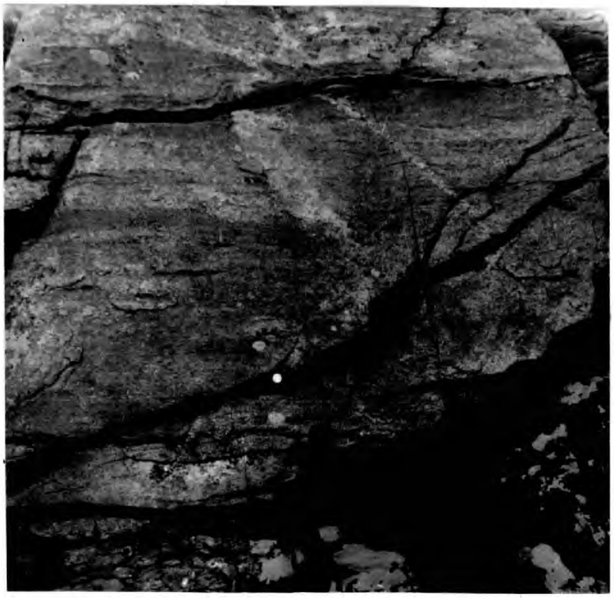
Fig.17. Deformed intermediate dyke Northern Fuday

On Fuiay, just on the edge of the zone, there is a series of very large concordant granulite bodies. The largest of these, about 200 yards across, is by far the largest such body within the present area, and appears to be exposed again on the islands Sgeirislam and Lingayfhada, extending over a distance of at least a mile. It is not known whether the presence of several large masses is due to repetition by folding of a single sheet-like body. The mineralogy of these very large bodies is identical with that of the smaller bodies in the Eastern gneisses, and the texture is uniformly maculose. Small shear zones are common (Photo 26). In a few places, features which might possibly be interpreted as original igneous graded bedding were observed, where coarse, maculose granulite gave way abruptly to very much finer grained granulite which then in turn passed gradually up into the normal coarse variety. This layering is not widespread, however, and horizons can never be traced for more than a few feet, so that it is considered to be more likely the result of a metamorphic segregation process.

Structural History of the Oitir Mohr Zone

Remarkably few folds of any age occur within this zone, hence it is difficult to write about its structural history at any length. Structurally, the transition between the Western Gneisses and the Oitir Mohr zone is very rapid. On Orosay E, one of the two islands where the transition is exposed, the southern part of the island is made of gneisses forming part of the major tight F_3 synform in the western gneisses, and many folds are found, including F_3 folds of Scourie dykes. On the northern part of the island, however, folds are absent

26. Parallel shear zones in a large, maculose body of the Scourie dyke suite. Note the sigmoidal pattern of the foliation in the shear zones. This example is from Fuiay, NF 739026



27. Highly discordant apophysis near a much larger, granulitic sykw, Loenish Point. NL 700986

and dykes are merely boudinaged, with local cross-cutting relationships preserved.

On Fuday, cross-cutting dykes are found on the Southern part of the island. As one moves northward, they become more concordant, and in the northern part of the island they are completely concordant and boudinaged. The northern part of the island, however, forms part of the large, normal limb of the F_3 Scurrival antiform, so minor F_3 folds are absent.

Within the Oitir Mohr zone, two episodes of post-dyke deformation seem to be recorded:-

First, an early phase which was responsible for a general re-orientation, tending to align all planar elements. This process has gone to completion in those places where dykes are now concordant, as in eastern Hellisay, where Scourie dykes are also foliated and somewhat amphibolitized. In some localities, where dykes and country rock were suitably oriented initially, folds were produced in the gneisses with axial planes parallel to the dykes, exactly like those described in the Eastern Gneisses. Figure 17 illustrates such a structure. This is particularly interesting since it shows a folded intermediate dyke apparently cut by a Scourie dyke. The Scourie dyke is well foliated, however, and it is clear that this is not evidence for a phase of folding between intrusion of intermediate and Scourie dykes.

This early phase was followed by a later event on a regional scale, which produced the present roughly E-W foliation trend, dipping gently north, and also produced some large minor folds and warps.

Such folds are best developed on Hellisay, but may also occur on Gighay, where, however, exposure is very poor.

IV INTERPRETATIONS

GENERAL

The first part of this thesis has been,or was intended to be, a reasonably factual description of the geology of the area mapped. It is now time to deal with some much less factual but perhaps more interesting aspects, to draw some general inferences from the observations, to relate the three sub-areas to one another, to build up a general picture of the areas as a whole and to relate this to other areas. The topics that will actually be considered are the following:-

First, the metamorphic history of each of the three sub-areas.

Second, correlations between the sub-areas of metamorphic and structural events.

Third, some problems of structural interpretations and their significance.

Fourth, the regional setting, and correlations with the rest of the Outer Hebrides and with the mainland of Scotland.

REGIONAL METAMORPHISM

Introduction

Metamorphism is perhaps the most difficult topic for a field geologist to deal with, since he can only observe the end results of processes governed by conditions of which he can have no direct knowledge. His task is to assess these conditions, and to examine their variation through time; yet he can measure none of the important variables - temperature pressure or primary chemical composition which define the conditions.

His only tools are the empirical classic criteria based on mineral assemblages, and modern experimental work which has only recently started to explore the immense problems of metamorphism, and which still has a long way to go before anything like precision is obtained - consider for example, the numerous and different results obtained for the comparatively simple determination of the kyanite-sillimanite-andalusite triple point. Such variations imspire little confidence, both in leading exponents of experimental methods, such as Fife, and in those already somewhat cynical of the value of laboratory gadgetry, such as myself.

The geologist can usually make only two observations; the present mineral assemblage and texture, and possibly the present chemical composition. He knows nothing of the conditions which produced the assemblage - temperature, pressure, partial pressure of water, of oxygen, of other gases, or of the primary chemical composition, although he may be able to make a reasonable assessment of the latter. Because of this inadequacy, a cautious approach towards metamorphism has been adopted in this thesis, and it is proposed to consider only the large scale aspects, and to ignore the complex minutiae. The large scale aspects, however, are of considerable interest, and pose some important problems which will be discussed in the next few pages.

Three principal sub-headings will again be used: Eastern Gneisses, Oitir Mohr Zone and Western Gneisses.

Metamorphism in the Eastern Gneisses

It should be noted that in the following discussion, it is considered that the orthopyroxene in the Scourie Dyke rocks is a primary feature, and was not produced by a regional pyroxene granulite grade metamorphism; orthopyroxene in some of the gneisses, on the other hand, seems to date from an earlier episode of metamorphism, so the two should not be confused.

(i) The Formation of the Earliest Complex

The gneisses which are cut by the various intrusive bodies are by no means homogeneous. As we have seen, in many places they contain numerous fragments of early basic material, and it seems reasonable to suggest that this material originally formed discrete bands within the gneisses which were then disrupted and agmatised in a general mobilization of the whole assemblage of acid and basic rocks. This mobilization, which could have affected an earlier polycycli- complex is the earliest event for which we have any direct evidence,. It is likely that it occurred in conditions of amphibolite facies since this is the facies in which regional mobilization generally seems to take place. However, since we have relatively little knowledge of the earliest complex, it would perhaps be best not to persue this too far.

TABLE 7.

SUMMARY OF METAMORPHIC HISTORY IN EASTERN GNEISSES

Metamorphic Condition	Time-phase or event	Evidence
Amphibolite facies	Post-Scourie dyke fold phases, F_1 F_2 and F_3	Complete or partial amphibolitization of Scourie dykes, especially in deformed zone.
Dykes believed to have primary granulite assemblages	Intrusion of Scourie Dykes	Complex. Dykes have fresh orthopyroxene cut gneisses with regressed pyroxene, etc.
Amphibolite facies	Early pegmatites and granites	Regional regression of orthopyroxene
Pyroxene granulite facies	Regional pyroxene granulite facies metamorphism	Orthopyroxene crystallizes in rocks of all composition
Possibly amphibolite facies	Early intrusive Dykes intruded Early intrusive bodies	Most dykes have amphibolite facies assemblages, in which orthopyroxene is later.
Regional mobilisation, presumably amphibolite facies	Formation of earliest complex	Production of extensive agmatitic bodies

(ii) Metamorphic Conditions at the Time of Intrusion of the Early Dykes and Early Intrusive Bodies

It is again difficult to comment on this, in view of the long history of events that these rocks have undergone.

These rocks are almost all of amphibolite mineralogy, except for those that contain orthopyroxene. Accepting for the moment that this orthopyroxene was produced by a regional metamorphic event, we then have to decide whether the amphibolite assemblages were earlier than this metamorphism, or later than it. The orthopyroxenes, wherever they are found, are extensively retrogressed, and it is considered that this was the effect of amphibolite facies metamorphism synchronous with the intrusion of the early granites. Now if we consider the important case of the early intermediate dykes, what do we find? At only one locality in the Eastern gneisses do these rocks contain orthopyroxene (in the deformed zone), elsewhere they are uniformly of amphibolite facies. It is therefore suggested that complete retrogression of orthopyroxene has occurred, and that the mineralogy of these dykes is entirely the result of the amphibolite facies metamorphism at the time of intrusion of the early granite.

In the case of rocks which have retained some pyroxene, such as the granodiorite~~s~~ set of early dykes, and the orthopyroxene bearing bodies, the large equant habit of the orthopyroxene crystals suggest that they grew post-kinematically in the rock with an earlier mineral assemblage. Since there is no evidence for an early episode of pyroxene crystallization, it is concluded that the original assemblages in these rocks was of amphibolite facies.

(iii) The Pyroxene-granulite Metamorphism

Orthopyroxene is found widely in the rocks of the Eastern gneisses, particularly in the gneisses of the north-east of Barra. It is much less common in the deformed zone than in the less deformed, and is found at only two localities, both in meta-diorites. It is completely absent within the sub-zone of acid gneisses, and this raises the important question of whether these rocks originally contained orthopyroxene and have since lost it by migmatisation and metamorphism, or whether they were originally amphibolites. This point will be of importance in discussing the general structure of the area.

The lower age limit of this metamorphism is difficult to fix; its upper age limit is relatively easier to fix since the youngest rocks in which orthopyroxene is found are those of the granodiorites suite of early dykes. Orthopyroxene is found in all earlier rocks, of almost all compositions. This in itself is interesting, as in the most acid rocks orthopyroxene is found without clinopyroxene, while in more basic rocks the two are found together. It would be instructive to examine the changes in pyroxene composition in these different rock types, but this is really in the realms of the geochemist.

(iv) The Early Amphibolite Facies Metamorphism

This metamorphism is considered to be synchronous with the formation of early granites and pegmatites, and to have produced widespread retrogression of the earlier orthopyroxene bearing assemblages. The granite bodies themselves have already been described, and it is clear from the wide distribution of early granites that this must have been a fairly important event. The retrogression of the pyroxenes is less easy to describe, and it is of great importance to be able to date the retrogression. The facts here are not in dispute:- almost every thin section containing orthopyroxene shows evidence of its breakdown to a mass of finer-grained material, probably biotite, with a fair amount of rather peculiar, serpentinous minerals. Can we demonstrate at what point in time this retrogression occurred?

We know beyond doubt that an episode of granitization occurred before intrusion of the Scourie Dykes, and also that extensive migmatization took place afterwards, mainly in the deformed zone. There are thus two possible occasions on which the regional retrogression could have occurred.

Three factors suggest that this was an early event:-

First, rocks containing extensively retrogressed pyroxenes ar cut by Scourie Dykes containing perfectly fresh orthopyroxene-clinopyroxene assemblages. This raises several problems which will be discussed shortly.

Second, it would be reasonable to expect the early phase of granitization to be accompanied by some sort of retrogression, and therefore by a process of induction rather than deduction, the retrogression that we actually observe can be related to the early granitization.

Third, within the less deformed zone there is little evidence for extensive post-dyke migmatization. This is observed only locally, and its effects are not profound. Within the deformed zone, massive post-dyke migmatization and amphibolitization has occurred, completely obliterating any pre-existing pyroxene in the gneisses.

Some of the absolute age dates obtained by Moorbath can also help us in dating this retrogression. The large hornblendes in the early amphibole bearing bodies gave K/Ar dates of 2,528 m.y., which are very close indeed to those of the early pegmatites, 2,600 m.y., and although the actual figures are not important these results could offer two interesting interpretations:-

First, that the crystallization of the large hornblendes was roughly contemporaneous with the episode of granitization and pegmatite production.

Second, the hornblende in these rocks is likely to have grown at the expense of pyroxene, although the petrographic evidence for this is not conclusive. It is further interesting to note that the pyroxene of the same rock gave anomolously old ages (c.6,000 m.y.) which, problems of excess argon apart, indicate an old age for the pyroxenes themselves.

(v) Metamorphism in the Scourie Dykes

The mineral assemblages of the Scourie Dykes are of uniformly high metamorphic grade throughout the less deformed zone, and involve us in one of the most difficult problems in the field area. There are two possible origins for these assemblages:- the Scourie dykes either crystallized initially with their high grade metamorphic mineralogy, or they suffered a later regional pyroxene granulite grade metamorphism which obliterated their original igneous assemblages.

The evidences for and against these two possibilities will be discussed in this section, but first of all some facts. Thin sections of about 40 Scourie dykes were examined, and a variety of assemblages was found. The following 9 assemblages all occurred at least once:-

1. Plag. - hbl. - opaque
2. Plag. - hbl. - cl. pyx. - opaque.
3. Plag. - hbl. - cl. pyx.
4. Plag. - hbl. - cl. pyx. - garnet - opaque
5. Plag. - hbl. - cl. pyx. - or. pyx. - garnet - opaque
6. Plag. - hbl. - cl. pyx. - or. pyx. - opaque
7. Plag. - hbl. - cl. pyx. - or. pyx.
8. Plag. - cl. pyx. - or. pyx. - opaque
9. Plag. - cl. pyx. - or. pyx. - garnet - opaque

Of these, type 6 was by far the most abundant, and was the assemblage found at the centre of nearly all dykes. 1, 2 and 3 are all found in a narrow zone at the edge of larger bodies. Assemblages containing garnet seem to be distributed erratically. Usually, garnet is found sprinkled uniformly throughout a dyke, or even part of a dyke, but occasionally shears or joints infilled with quartzo-feldspathic material show a marked increase in size and abundance of garnets at their edge.

These assemblages are closely comparable with those described by Dearnley (1962) from the Hebrides as a whole, and may be confidently ascribed to either the hornblende-granulite or the pyroxene-granulite subfacies of the granulite facies. Dearnley considered these assemblages to be due to a regional metamorphism, which he suggests can also be recognised on the mainland of Scotland. Discussion of this latter point, would however, be somewhat premature, so let us instead first consider the evidence for these assemblages being non-metamorphic, and then examine the evidence for a regional metamorphism.

O'Hara first suggested (1961) that a dolerite dyke intruded into hot country rocks might produce metamorphic rather than igneous assemblages. O'Hara was dealing with dykes having igneous assemblages at their centre, and granulite facies, or almandine-amphibolite (cpy.-gar.-hbl.-andesine) facies assemblages in places in a narrow marginal zone. The dykes we are concerned with have granulite facies assemblage at the centre, and amphibolite facies edges. Can we explain them on O'Hara's model?

Dearnley has shown that the chemistry of Hebridean granulites is consistent with that of dolerite, and it is obvious that the assemblage cpy.-opy.-hbl.-plag.-opaque is not vastly different from that of a dolerite. The only significant differences appear to be the presence of hornblende, in small quantities at the centre, but in large amounts at the edges, and in the general tendency for plagioclases to be less calcic than in a conventional dolerite.

Assume, then, that liquid of approximately doleritic composition was intruded into rocks at great depths, into rocks a good deal hotter than similar rocks under surface conditions. The higher ambient temperature would mean that this rate of cooling of the body would be greatly reduced. This follows directly from Newton's Law of Cooling, and would have two important effects.

First, the shape of the intrusion might be different from the sheet-like classic dyke shape that is usually produced in a brittle environment, since here we have a very slowly hardening crystal mush intruded into hot, rather plastic acid gneisses. Irregular intrusion shapes are common, particularly in the deformed zone. If final consolidation was delayed until deformation had begun, the dyke material would show a lower competence relative to the acid gneisses than completely solidified dykes. Competence differences between dykes and acid gneisses are in fact usually surprisingly low.

Second, the exceptionally slow rate of cooling is likely to produce different mineral textures from those in rapidly cooled rocks. It is clear that the larger the body, the more likely it is to have normal textures - as the size of the body increases a limit is eventually reached at which the initial rate of cooling at a point in the centre is effectively independent of the outside temperature, since the centre is effectively insulated from the outside. It is suggested that normal igneous assemblages crystallized out during the first stages of cooling of such large bodies, producing the ophitic textures now preserved as relics, and that as cooling continued very slowly, static recrystallization took place producing the simple granulite relict textures now observed. In smaller bodies, the ophitic texture would not develop, and the final texture produced would be a homogeneous, even-grained granulite texture.

It is a sine qua non that the final assemblage should be controlled by the temperature of the country-rock gneisses. If, for example, the country-rock was at roughly amphibolite facies temperatures, then the edges of the dykes at least should show some evidence of this. This is exactly what is observed. The edge zones of all dykes show assemblages 1, 2 or 3 which grade very rapidly into normal assemblages such as 6, and, very important, there are no textures at all to indicate that this is primarily the result of <u>later</u> amphibolitization, though this of course may be the case locally. Now one might raise here the question of partial pressures of water - the dyke edges could be "wet" while the centres are "dry". It seems possible that rocks crystallizing in the immediate vicinity of acid gneisses might themselves become somewhat dampened, so that the effects of water partial pressure may be as important as those of temperature, but further discussion of this aspect is really within the scope of the experimental petrologist.

Let us now examine the evidence for the alternative possibility, that the assemblages were produced by a regional metamorphism subsequent to dyke intrusion.

There would appear to be a prima facie case for this suggestion, since there is abundant evidence for a granulite facies metamorphism throughout the country-rock gneisses. An attempt has already been made, however, to show that extensive retrogression of the abundant orthopyroxene in the gneisses occurred prior to Scourie Dyke intrusion, and that therefore this pyroxene granulite metamorphism must itself be earlier than the Scourie dykes. Let us sum up briefly the evidence for this:-

First, the early, pre-Scourie dyke granites in the less-deformed zone contain no pyroxene, yet earlier rocks of closely similar composition do - for example the granodioritic suite of early intrusive dykes.

Second, pyroxene rich gneisses are found in areas where Scourie dykes have not been significantly affected by post-dyke amphibolitization.

Third, and rather circumstantial, K/Ar dates on orthopyroxene are anomalously old. Such extremely old dates would not be expected if the pyroxenes were post-Scourie dyke in age.

None of these points is particularly convincing by itself, so let us consider the evidence for a post-Scourie dyke metamorphism.

First, the possibility arises that we may be looking at the results of two metamorphisms, one early, producing the pyroxene in the gneisses, and one later, producing the pyroxene in the dykes, and that this later metamorphism may itself have caused retrogression of the earlier pyroxene. This sounds at first unlikely, but it is possible that a metamorphic event affecting relatively "dry" igneous rocks and relatively "wet" gneisses might produce "granulite" facies assemblages in the former, and "amphibolite" facies assemblages in the latter.

Second, it is possible that a single regional granulite facies metamorphism occurred, and was followed by retrogression under lower grade conditions It is further possible that this retrogression may have produced much more drastic results in the acid gneisses than in the rather massive homogeneous dyke rocks, of which only the edges would be affected. Dearnley has stressed (1962) the likely differences in results produced by hydrous retrograde metamorphism, and it is clearly a viable possibility. In the next section, however, a full-blooded amphibolitization and retrogression of pyroxenes in dykes will be described. There seems to be little sign of any resistance to amphibolitization here, particularly since this very rapid retrogression can be observed locally within the deformed zone itself.

Third, the orthopyroxene in the gneisses is very different from that in the dykes, for what this is worth. The pyroxenes are almost always very small in the dykes; in the gneisses they are huge. In the dykes, the pyroxenes are almost violently pleochroic from pink to green, in the gneisses, they are only slightly pleochroic. At only one locality, Ruleos, were orthopyroxenes found that looked at first sight at all similar to those in the gneisses, but in thin section these were again very different.

It is the writer's opinion that the balance of the field evidence, although it is not conclusive, suggests that the Scourie dykes acquired their present mineralogy at the time of intrusion, and not in a post-intrusion regional metamorphism. If we turn away from the present area, we do find similar situations elsewhere. Bridgwater, Sutton, and Watterson (1966), describing the rocks of the Kap Farvel area of Greenland, found dykes and sills cutting the migmatite complex and state that "The basic sills and dykes have typical metamorphic textures in thin section and are hypersthene bearing, and are of a higher metamorphic grade than the surrounding gneisses. The dykes occasionally show intrusion features suggesting emplacement in plastic country rocks.........the present textures and mineral assemblages of the dykes are original features and are the products of crystallization in a plutonic environment when the country rocks were at an elevated temperature and possibly undergoing regional metamorphism". Here, in a nutshell, is clearly a very close parallel to the situation in the present area.

Dawes, however (1968), working on the Tassiuarsaq area of Greenland observed dykes containing high-grade metamorphic assemblages and textures cutting gneisses which had experienced an earlier pyroxene-granulite facies metamorphism, and he explained this situation as the result of the "dipsenic" metamorphism of the dykes. In other words, the early regional pyroxene granulite grade metamorphism left the rocks in a very "dry" condition, so that later intruded, original doleritic dykes were able to acquire a high grade assemblage through recrystallization at lower temperature-pressure conditions than those normal in the granulite facies. Dawes compared his rocks with other examples of water-deficient metamorphism of dolerites described by Poldervaart and Wilcox, which are very similar.

Clearly, Dawe's dipsenic hypothesis could be applied to Barra, since we have already seen evidence for a pre-dyke pyroxene granulite metamorphism. The situation is complicated, however, by the likelihood of a mild amphibolite facies metamorphism, contemporaneous with the early granites. To conclude, then, it seems that the high-grade assemblages in the Scourie Dykes of Barra were produced by the conditions of the rocks into which they were intruded, and that these conditions may have been unusually hot, or unusually dry, or some combination of the two.

(vi) Post-Scourie Dyke Migmatization and Amphibolitization

The evidence for this episode of amphibolite facies metamorphism within the deformed zone is so obvious that it is not proposed to deal with it at length. The most complete and extensive migmatization occurs in the zone of acid gneisses, and Photo 6 shows the extent to which Scourie dykes are affected Outside the acid gneiss zone, the amphibolitization tends to be less complete, particularly in larger dykes.

It is not possible to define precisely the age relationships of this metamorphism, since recrystallization has obscured most of the relevant fabrics. However, we can observe that many of the dykes of the deformed zone were folded while still granulites and that some hornblende developed in tectonite fabrics in these folds, so it is suggested that the amphibolitization commenced during F_1 times, and continued in F_2 times and beyond, with a great deal of entirely post-kinematic recrystallization. It does not appear as though there were successive metamorphic episodes of different facies. Late pegmatites dated by Moorbath at 1,620 m.y. give a guide to the absolute age of the end of this episode.

Metamorphism in the Oitir Mohr Zone

This zone is characterised by substantially the same sequence of events as the Eastern Gneisses, with the same questions about the age of the pyroxene granulite metamorphism which produced the orthopyroxene in the acid gneisses. It is interesting to compare the effects of the alternative hypotheses on the situation in the Oitir Mohr zone.

Possibility 1 Pre-Dyke Metamorphism	Possibility 2 Post-Dyke Metamorphism	Eastern Gneiss history for comparison
	Regression of pyroxene	
	Pyroxene granulite metamorphism	
Scourie Dykes	Scourie Dykes	Scourie Dykes
Retrogression of pyroxene, some pegmatites	Granitization + pegmatite formation	Granitization, and retrogression of pyroxene
Pyroxene granulite metamorphism		Pyroxene granulite metamorphism
Early dykes	Early dykes	Early dykes
Early granitization		
Early intrusives	Early intrusives	Early intrusives
Original complex	Original complex	Original complex

The significance of this is that if the second possibility is correct, then the granitization event which produced the large areas of homogeneous (now pyroxene bearing) gneisses could be the equivalent of the pre-dyke early granitization in the Eastern Gneisses.

The strongest evidence against this, however, is that the early granites in the Eastern Gneisses do not contain pyroxene, nor is there any evidence that they ever did, while rocks older than them in the same area do contain orthopyroxene.

Metamorphism in the Western Gneisses

(i) General

It is difficult to deal with metamorphism, which is concerned with minerals and mineralogical changes, when one has only a few minerals to deal with. The problem is particularly acute in the Western gneisses where we are faced with a monotonous series of acid gneisses containing only quartz, feldspars, hornblende and biotite.

Only two criteria can be used to determine the metamorphic history of these rocks; the mineralogy of dykes within the gneisses and the textures in these and in the acid gneisses. Using these criteria, a tentative sequence of events has been deduced and is summarised in Table 8.

(ii) The Early, Pre-Scourie Dyke Pyroxene Granulite Metamorphism

This is perhaps the most important but least known event. It is essential, as we shall see later, to know what was the original condition of the Western gneisses if we are to understand their

TABLE 8

METAMORPHISM IN THE WESTERN GNEISSES

Time or event	Evidence	Metamorphic Conditions
Very late	Epidotisation in joints. "Ribs" produced.	Very low grade
Late, post-tectonic	Pegmatite formation and general recrystallization.	Amphibolite facies
F_4	Axial plane pegmatites, growth of hornblende.	Amphibolite facies
F_3	"	"
F_2	Granulite facies Scourie dykes develop fabrics	Amphibolitization commences?
F_1	No evidence	Debatable
Dyke - intrusion		Dykes believed to have primary granulite facies minerals
Pre-dyke	Orthopyroxene in gneisses	Possibly an early pre-dyke granulite facies metamorphism

relationships with the Eastern gneisses.

On the south coast of Eriskay there occur in the Western Gneisses a series of irregular masses of granulitic Scourie dyke material, some of them isoclinally folded by F_2 folds. In just one locality an originally branching dyke has been folded, so that in the nose of the fold a multilayered sequence of dyke/gneiss/dyke/gneiss is present. The gneisses between dyke layers are the distinctive rusty kind familiar from the Eastern gneisses of Barra, and contain splendid orthopyroxene crystals.

This is the single piece of evidence for an early granulite facies we have in the present area, but it is significant to note at this point that Dearnley reported the presence of pyroxene in the gneisses at Ardivachor point, and this suggests at least the possibility of a widespread early metamorphism.

(iii) The Scourie Dykes and their Original Assemblages

This is a suitable place to remind the reader that the boundary to the Oitir Mohr zone has been drawn where Scourie dykes cease to be cross-cutting. In the Western gneisses, Scourie dykes with orthopyroxene-clinopyroxene assemblages may still be found over a large but definite area (Map 9), and it is only large bodies that retain these assemblages. To avoid re-stating arguments already used, let us assume that the dykes acquired their high-grade assemblages as a result of intrusion into either hot or dry rocks at depth, with the same reservations as before.

The metamorphic history of the Western gneisses then resolves itself very largely into the history of progressive amphibolitization and recrystallization of the Scourie dykes through the various fold phases. The preservation of granulite mineralogy is however partly controlled by the size of the body, and this introduces complications. Consider, for example, a very large amphibolite sheet on Vatersay, about 30-40 feet thick. The problem arises, was it ever a granulite?, or has it merely been particularly thoroughly amphibolitized? The latter appears to be the case, since this sheet is found in an area of exceptionally intense late migmatization, so it is assumed that dykes throughout the area were originally of granulite facies mineralogy.

(iv) Conditions during the F_1 Fold Phase

There is too little evidence for much comment to be made, but it is suggested that during F_1 Scourie dykes were deformed while still retaining their granulite assemblages, possibly with local growth of hornblende in tectonic fabrics. It was suggested earlier that the present, S_1, foliation of the acid gneisses was developed during F_1 but that there was a possibility that the S_1 foliation might be partly pre-Scourie dyke in age, due to the difficulty in correlating very early folds. Because of this complication, it is difficult to be dogmatic about the condition of the gneisses, but the likelihood is that they were at or near amphibolite facies. This is a point which will be discussed later.

(v) Conditions during the F_2 Fold Phase

Although most of the evidence of the early condition of Scourie dykes has largely been destroyed by later-recrystallization, there is one area, on Eriskay, where dykes isoclinally folded by F_2 still have their granulite mineralogy, and a slight linear fabric defined by aligned hornblende crystals. It is suggested that this is typical of Scourie dykes during F_2 - in other words the most important fold phase to affect the dykes was initiated while they still retained their original assemblages. This is a very important point, which will be examined further when considering the initial competence differences between dykes and gneisses, which decide in fact whether folding will occur at all.

In the acid gneisses, there is no evidence for production of a new fabric or foliation, and F_2 folds definitely do not have the axial plane pegmatites so characteristic of F_3 and F_4. There are, however, numerous quartzo-feldspathic stringers parallel to the S_1 foliation and the F_2 axial plane which are probably of F_2 age, and these suggest that some recrystallization had started in the gneisses, presumably in amphibolite facies conditions.

(vi) Conditions during the F_3 Fold Phase

We have already noted that F_3 minor folds do not particularly commonly involve Scourie Dykes, in marked contrast to F_2. This may reflect a change in competence in the dyke material - during F_2 the dykes behaved competently to produce folds of characteristic wavelength/thickness ratio, whereas in F_3, dykes acted with little or no competence relative to the gneisses, and merely behaved as passive layers in the gneisses. This is a considerable over-simplification, however, and the point will be pursued later. However, a very good reason for a change in competence is clear - a change from granulite mineralogy to amphibolite, so that we can suggest that during F_3, dykes were, or became, completely amphibolitized. None of the critical mineral fabrics are preserved, however, so this is rather a speculative point.

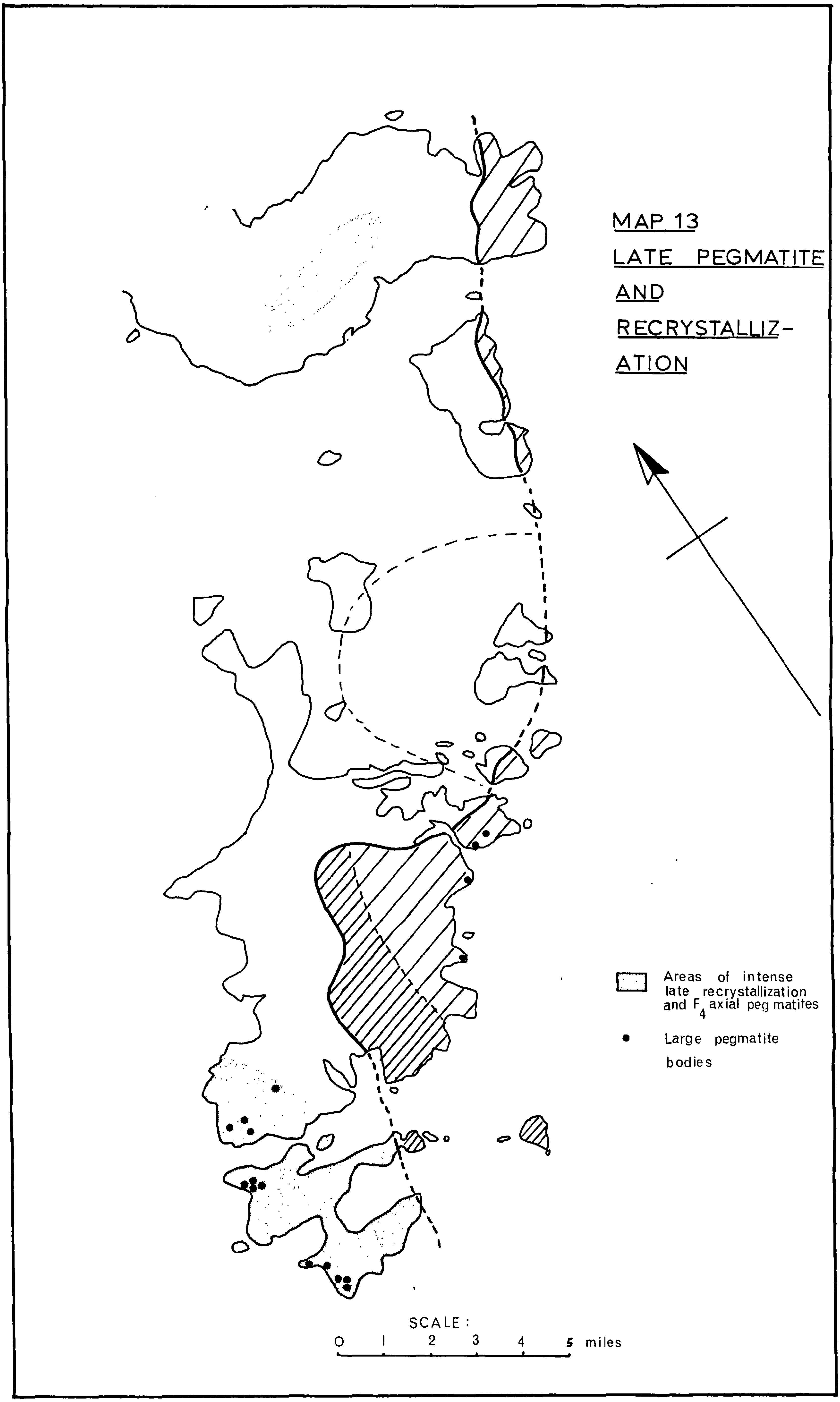
In the gneisses, however, there is plenty of evidence for extensive recrystallization in amphibolite facies - axial plane pegmatites in F_3 folds, growth of oriented hornblende laths in F_3 fold noses, and of course the extensive if somewhat debatable new F_3 foliation in the gneisses of southern South Uist.

On the whole, then, there seems little reason to doubt that during F_3 there was a general change to, or great increase in amphibolite facies recrystallization in both gneisses and dykes.

(vii) Conditions during the F_4 Fold Phase

F_4 fabrics are particularly well developed in dykes in South Uist, where one finds a linear fabric defined by hornblende and biotite, and this indicates fairly conclusively that the dykes were folded in amphibolite facies conditions. Such fabrics, however, are not observed in the southern part of the area, due to the effects of later recrystallization.

In gneisses folded by F_4, axial planar pegmatites are particularly common. Map 13 shows a very schematic summary of their


MAP 13 LATE PEGMATITE AND RECRYSTALLIZATION

distribution, and reveals two areas of particular abundance, one in southern South Uist, and one in south western Barra and Vatersay. It seems clear that the conditions prevailing during F_4 were a continuation of those in F_3, with a general recrystallization in amphibolite facies.

(viii) Late Pegmatites and Post-Tectonic Recrystallization

The late pegmatites are easily dealt with. They occur either as dyke like sheets or as irregular masses swamping and permeating the gneisses. The largest dyke like sheets are up to 20 feet wide and are traceable for 50 yards. Mineralogically, they consist almost entirely of pink potash feldspar with some quartz and a little biotite, and occasionally small amounts of magnetite and some more exotic minerals such as allanite. Allanite is also found occasionally within the gneisses as small dark red masses surrounded by a network of radiating cracks.

In some of the more diffuse pegmatite masses, traces can often be found of the gneiss foliation, revealed by parallel streaks of hornblende and biotite, and this clearly indicates the replacive nature of the pegmatites.

The late recrystallization is rather less tangible, and more difficult to describe. The principal evidence for it is the remarkable homogeneity of the gneisses and particularly the amphibolites, which rarely ever show any sign of earlier tectonic fabric. Map 13 shows a subjective impression of the most affected areas, which are south west Barra and Vatersay. On Vatersay, the recrystallization seems to have been so intense as to lead to the local production of granite. At ML 644958, for example, F_4 folds appear to be swamped in homogeneous granite. This granitization, however, was extremely local, and nowhere produced significant quantities of granite.

(ix) Summary

With some reservations about the very early metamorphic history, it appears that amphibolite facies metamorphism began during the F_2 fold phase, and continued throughout F_3 and F_4, becoming more extensive with the passage of time, and reached a climax after all tectonic activity had ceased with complete recrystallization in amphibolite facies over almost the entire Western Gneisses. This process appears to have been most intensive in the southern part of the area, with very local production of granite.

For the sake of completion, two other topics should be mentioned, although they are not really relevant.

First, there are "ribs". These are narrow, upstanding ribs or ridges of discoloured rock which may be found with a variety of orientations, mostly about E-W. They may represent some sort of mild alteration along joints, although no actual joint plane can be observed. Their age is unknown.

Second, there are locally joint planes whose surfaces are covered with fine epidote crystals. Again, their age is unknown, since the jointing could be any age from Caledonian to Tertiary.

CORRELATIONS BETWEEN THE SUB-AREAS

The boundary between the Western Gneisses and the Oitir Mohr zone is artificial, in that it is based on the presence or absence of cross-cutting dykes, but these two sub-areas are separated from the third by a major natural feature, the Outer Hebrides Thrust. The relations between the two sub-areas west of the Thrust will be described first, and then it will be shown that a correlation can be carried over the Thrust.

(1) The Western Gneisses and the Oitir Mohr Zone

The general structural trend of the rocks on the islands in the Oitir Mohr zone is roughly East-West, dipping to the north at about 40° (Map 6). Some minor, rather open folds and warps also occur, making the trend somewhat irregular. It has been shown that the large F_3 antiform in the Western gneisses, the Scurrival antiform has a gently dipping, East-West trending normal limb, which is exposed on Scurrival Point, northern Fuday, Eriskay and South Uist. It is reasonable to suppose that this large structure is continued into the Oitir Mohr zone, and that the rocks in that zone lie on the East-West trending limb of the same F_3 structure.

In the Western Gneisses, the F_2 fold phase produced important folds, particularly of Scourie Dykes; in the Oitir Mohr zone there are no folded dykes, but there is, as we have seen, evidence for an early phase of flattening, which occasionally produced minor folds in the gneisses with axial planes parallel to the dykes (Fig. 17). It is suggested that this early flattening corresponds to the F_2 fold phase in the Western Gneisses; it is also possible that it represents the combined effects of F_2 and F_1 - there is not way at all of distinguishing.

The suggested correlations thus are:-

Western Gneisses	Oitir Mohr Zone
F_4 (Abundant minor folds)	Not identified
F_3 (Regional structure minor folds)	Later phase of deformation (Regional structure, broad open warps)
F_2 (Abundant minor folds)	) Early phase of deformation) Flattening of dykes, occasional) minor folds in gneisses.
F_1 (Some few minor folds)	

Scourie Dyke Intrusion

A further point of correlation is the possibility that both sub-areas shared the early pyroxene granulite grade metamorphism which is so well preserved in the Oitir Mohr Zone, but recognisable at just one locality in the Western Gneisses.

Conclusions

These two sub-areas are very different in two respects:- the Western gneisses are highly deformed; the Oitir Mohr zone is relatively undeformed. The Western gneisses have undergone extensive migmatisation and metamorphism in amphibolite facies, the Oitir

Mohr zone has not. Despite these differences, the two areas appear to have had broadly the same post-dyke structural history, the difference being primarily that the dykes and gneisses of the Western gneisses were extensively folded during F_2, while in the Oitir Mohr zone only a flattening is observed. The reasons for this contrast are discussed shortly.

(2) Correlations across the Outer Hebrides Thrust

The largest structure that was described in the Eastern Gneisses was a large antiform, whose north-south limb was formed by the steeply dipping gneisses which form most of the coast section, and whose gentle limb is formed by the low-dipping, warped gneisses in the Bruernish area. It is suggested that this large antiform structure represents the extension above the Thrust of the major Scurrival antiform in the Western Gneisses. The axis of this large structure above the thrust is more or less north-south; below it N.N.W-S.S.E. It is suggested that this relationship was produced by rotational movement on the Thrust plane of about 20°.

If we accept, then, that the large antiform in the Eastern Gneisses corresponds to the F_3 structure in the Western gneisses, what of the complementary synform? There is no direct structural evidence for a major tight pinched synform such as that in the Western gneisses, but it is interesting to speculate on the significance of the broad band of ordinary acid gneisses in the deformed zone. This band contains the most highly deformed and migmatised Scourie Dykes, and is bounded on both east and west by rocks containing less deformed and less migmatized dykes It is suggested as faintly possible that this zone of acid gneisses represents a pinched synform between more massive blocks, and further, that it may represent a tightly interfolded wedge of Western Gneisses folded into the Eastern gneisses, (Fig. 12) This point will be considered again later.

In the Eastern Gneisses, we have an area containing folded dykes and an area of unfolded but flattened dykes. These early episodes of folding and flattening are correlated with the F_2 phase in the Western gneisses, although, as in the Oitir Mohr zone, they may represent the combined effects of F_1 and F_2.

The structural correlations therefore are believed to be thus:-

<u>WEST OF THE THRUST</u>	<u>EAST OF THE THRUST</u>
F_4 100 trending minor folds (Not found in O.M.Z)	F_{3E} A few minor 100 trending folds in less deformed zone.
F_3 Regional structures in W. gneisses and O.M.Z	F_{2E} Regional structures
F_2 Folding in W. gneisses, flattening O.M.Z	
	F_{1E} folds in Deformed zone flattening in less deformed zone
F_1 A few minor folds	

3. Scourie Dyke Intrusion

Apart from these structural correlations, there are, of course very close similarities between the pre-Scourie dyke histories of the Eastern Gneisses and the Oitir Mohr zone. These are summarized below:-

Oitir Mohr Zone	Eastern Gneisses
Post dyke deformation	Post dyke deformation
Scourie Dyke intrusion	Scourie Dyke intrusion
Some net veining pegmatites	Early pegmatites
Retrogression of orthopyroxene	Early granites and retrogression of orthopyroxene in gneisses
Pyroxene granulite facies metamorphism	Pyroxene granulite facies metamorphism
Early intrusive dykes	Early intrusive dykes) Youngest 3 sets) Intermediate) Oldest
Early intrusive bodies, pyroxene and amphibole bearing. Possibily early granitisation	Early intrusive bodies, pyroxene and amphibole bearing.
Formation of early complex	Formation of early complex

(3) Conclusions

It seems inescapable that the rocks of the Oitir Mohr Zone and the Eastern Gneisses are parts of the same original assemblage. The structural evidence shows that the Oitir Mohr Zone lies in the core of the north-westerly plunging Scurrival antiform, and therefore it follows that rocks of Western Gneiss type are on a regional scale structurally above rocks of Eastern Gneiss type. If we may introduce a term originally used by Wegmann in Greenland, we have a supra-structure of Western Gneisses overlying an infra-structure of Eastern Gneisses. Wegmann, however, was describing a situation where more migmatitic rocks were overlain by less migmatitic rocks (Wegmann 1935), the complete inverse of the present arrangement.

Although the infrastructure is exposed only in a small area west of the Thrust, it appears that the Thrust has carried a large mass of infrastructure rocks up and over the Western Gneiss supra-structure. The position of the zone of acid gneisses in the Eastern Gneisses can also be better understood if one considers it as a tight infold of the gneisses of the supra-structure into the infra-structure. Some more convincing structural data, however, are needed for this to be more than a speculative idea.

Some very convincing independant confirmation of this general picture is provided by geophysical data. A recent gravity survey conducted by the I.G.S. shows an exceptionally high gravity anomaly precisely over the Oitir Mohr Zone. This anomaly, which incidentally is one of the highest rocorded from Great Britain, clearly reflects the presence of a large mass of rock considerably denser than ordinary acid gneisses. Some Heath-Robinson determinations of the densities of various rocks confirms this:- ordinary Western gneisses gave values of about 2.6, while pyroxene gneisses and "Balnabodachites" from the Oitir Mohr zone gave values between 2.7 and 2.9. Granulite facies Scourie Dykes consistently gave values of 3.0 and slightly over.

The gravity map of the rocks east of the Thrust is not so straightforward, but this is understandable, since in most areas dense Eastern Gneisses are present as only a thin wedge over less dense Western Gneisses. There is however, a general trend towards increasing density to the east, as one would expect.

The aeromagnetic survey is also interesting. The Oitir Mohr zone is not particularly well picked out, but the Eastern Gneisses pr produce a very strong anomoly. This anomoly continues under the sea southwards, east of all the islands in the chain, and finally dissapears roughly level with Berneray. It is suggested that rocks of the infra-structure occur above the Thrust overall that distance, about 25 miles, although they are nowhere exposed.

Both infra-structure and supra-structure have shared the same post-Scourie dyke history of deformation. The fundamental difference between them is that the supra-structure was extensively deformed and mobilised after dyke intrusion, the infra-structure very much less so. In the next section, some aspects of this problem will be exposed, to see if the reasons for this important difference in behaviour can be determined, and to consider its implications.

SOME GENERAL ASPECTS OF DYKE DEFORMATION

Intrusive dykes are one of the most reliable time markers in basement rocks, and therefore it is of great interest to examine how dykes respond to deformation in different environments. The problem which principally concerns us is the presence of a supra-structure containing highly deformed, folded dykes overlying an apparently less deformed infra-structure containing unfolded dykes. If we could establish the reasons for this contrast, we would know a great deal about the fundamental relationships of these very large units.

Since we cannot measure directly the amounts of deformation in different areas, let us concentrate on what is directly observable - folding. Three conditions must be fulfilled in order for dykes to fold.

First, a sufficient stress should be applied.

Second, the dykes must have different mechanical properties from the surrounding gneisses, or else the whole mass would deform homogeneously.

Third, the dykes must be correctly oriented relative to the applied stress.

Before considering each of these points, it is worth remarking that all three must prevail simultaneously - any two will not bv themselves produce folding.

(1) Stress

It is perhaps worth making the obvious point that the same applied stress will produce different strains in different media. The relationship between stress and strain is summed up in the bulk modulus of the medium in question.

When, therefore one finds adjacent masses of more and less deformed rocks, we have to inquire whether these difference arose from a difference in applied stress, or whether different strains were produced by the same applied stress, due to the different bulk moduli of the two masses.

It is perfectly possible for variations in applied stress to a arise in geological environments, and these can be represented by stress trajectories (Ramsay 1967 p. 46). Stress analysis is an extremely difficult mathematical process, but it is possible to examine stress variations experimentally, and it can be shown that areas of low stress can develop in particular positions in fold structures. We have seen that the Oitir Mohr zone lies in the core of a large F_3 fold, and that this antiform may be traced into the Eastern Gneisses. Is it possible, therefore that the less deformed areas represent areas of low F_3 stress during folding?

The answer appears to be, not, for the differences in deformation existed prior to F_3, which merely re-oriented the earlier structures, and we are primarily concerned with variations in response to F_2 (and possibly F_1), and not F_3. No large F_2 structure is known, nor is there any obvious reason why F_2 stresses should have varied so considerably. It is therefore concluded that a fundamental difference in bulk modulus existed between the infra-structure and supra-structure to account for the different responses to presumably the same applied stress, and that this difference had been established at an early stage in the deformational history.

(2) Mechanical Properties of Dykes

Given a suitable applied stress, it is essential that for buckling of layers to occur in the strained medium these layers should have a difference in competence from the surrounding medium or in other words, a viscosity contrast. A good deal of rather technical mathematical work has been devoted to this topic so let us concern ourselves only with the field relations of intrusive dykes in the gneisses of Barra. Here are some empirical observations:-

First, dykes with granulite facies mineralogy cutting pyroxene bearing gneisses are not folded nor significantly boudinaged. (The Oitir Mohr zone, the less deformed zone of the Eastern Gneisses).

Second, dykes with granulite facies mineralogy in amphibolitic gneisses are folded and boudinaged. (Parts of the more deformed zone, of the Eastern gneisses, also southern Eriskay).

Third, Dykes which are now completely amphibolitized are folded and boudinaged in amphibolite gneisses. (Most of the Western Gneisses).

Fourth, thin amphibolitic bodies in gneisses often show features indicating competence similar to or less than that of the gneisses. (Locally in the Eastern Gneisses).

These observations have far-reaching implications, so let us examine the evidence for each in turn.

First, this is merely a statement of fact. Not only are granulite dykes in pyroxene gneiss not folded, they are also cross-cutting and branching.

Second, on Ru-fear-Vatersay and on the island of Vatersay itself folded granulite dykes are found within the deformed zone. The matrix to the dykes is made up of amphibolitic gneiss (R.f.V.) and early granite (Vatersay). The granulites are partially amphibolitised while the gneisses and granite are completely pyroxene free. Some of the structures observed are also extremely complex, and indicate rather odd original intrusion shapes. (The significance of original dyke shape was touched on earlier, in considering their metamorphic condition).

Third, this is at once the most important and most difficult observation to interpret, though the facts are clear - there are numerous folded amphibolite dykes in the amphibolitic gneisses of the Western gneisses. The problem is to decide whether these dykes were folded when they were still granulitic, and amphibolitized after folding, or whether they were already amphibolites before folding.

To answer this question, one has to study the shapes of folded layers. Competent layers on folding produce folds with convergent isogons, and therefore isogon plots of the folds in question can tell us something about the original nature of the folded layer. The situation is comlicated, however, by original thickness variations in the layers, and by the effects of later modification of the original fold shape. (F_2 folds, for example, are extensively flattened by F_3). The results of such isogon studies reveal that most layers which are now completely amphibolitic acted competently when folded by F_2, making allowances for the effects of F_3 modifications.

Now, as we shall see in the next section, amphibolitic material in Barra generally apears to be less competent than acid gneisses, and therefore where the shape of amphibolite layers indicates competent behaviour, then this must be due to a change in the nature of the layer, in other words a change from granulite mineralogy to amphibolite mineralogy.

The isogon data, here, however are not really conclusive, and the above must be considered as more of an opinion than an observation. It is interesting to repeat the observation, however, that while it is Scourie dykes that define F_2 folds, the same dykes appear to have act more or less passively during F_3 folding, strongly indicating a change in the nature of the dyke material from relatively competent to incompetent. It is also worth reminding the reader that such evidence as is available suggests that the original viscosity constrasts (compet- ence differneces) were extremely low, (Table 6), and therefore relatively small changes in the properties of the dyke would bring about a change from more competent to less competent.

Fourth, minor amphibolites. When looking at discordant dykes in deformed areas, one soon notices that the narrower a dyke is, the more discordant it is likely to be. It has already been noted that the majority of dykes in the less Deformed zone of the Eastern Gneisses lie at small angles to the regional gneiss foliation. Minor apophyses from the same dykes, however are often highly discordant (Photo 27), and, significantly the apophyses are amphibolitic while the parent dyke is granulitic and the matrix is ordinary hornblende-biotite gneiss

There are, of course, a great many possible explanations for individual occurrences of this sort, but when one finds the same situation consistently, a general explanation is called for. It is suggested that this situation arises when relatively competent granulites and relatively incompetent amphibolites are deformed together. The competent granulite bodies will either buckle or rotate, according to their original orientation before deformation, while the incompetent minor amphibolite apophyses will deform more or less homogeneously with the matrix.

The result of this should be that the angle of discordance of competent granulites falling in the extension field of the strain ellipsoid will tend to decrease, while in those falling into the shortening field the angle will vary around the folds produced, and may be locally increased or decreased. The relatively incompetent apophyses, on the other hand, will not buckle, even if their original orientation were in the shortening field. Their angular relationships with the gneiss foliation, will of course be altered, but the degree to which this occurs will be controlled by the competence relationships between gneiss and amphibolite; if the amphibolite has much the same competence as the gneiss, then the whole mass will deform homogeneously;

if the amphibolite is much less competent, then it is possible that the gneisses will buckle while the amphibolite is passively folded with them. The problem is thus very complex, and really requires a great deal more information on the mechanisms of deformation. It is clear, though that this explanation must be at least partly true, since one does find folded granulite dykes with apparently undeformed apophyses. This is illustrated in Fig. 18 and Photo 28 which show the situation at an outcrop on Vatersay. The problem is further complicted here, however, by the very peculiar original shapes of the intrusive bodies, which may themselves be significant, as we have seen.

Three other less common features are also worthy of mention. First, cuspate structures are sometimes observed at the interface between dykes and gneisses. Two examples are shown in Fig. 19. The important point to note is that in these examples, the dyke material is "pinched" into the gneiss. This pinching, which is seen here on a scale of inches, occurs on all scales in geology, the classic example being the pinched synforms of the Alps, and is always developed where there is an interface between more and less competent rocks. In the examples shown, it is the amphibolitized marginal zones of dykes which are behaving as the incompetent material, while the main, granulitic body of the dykes are behaving competently.

Second, quartzo-feldspathic pegmatites often cut granulite dykes. In no instance has such a pegmatite been observed to be folded within the granulitic body. However, it has been occasionally [illegible] that where a narrow amphibolitic dyke is cut be a pegmatite. the pegmatite is folded within the dyke. Fig. 20 illustrates a good

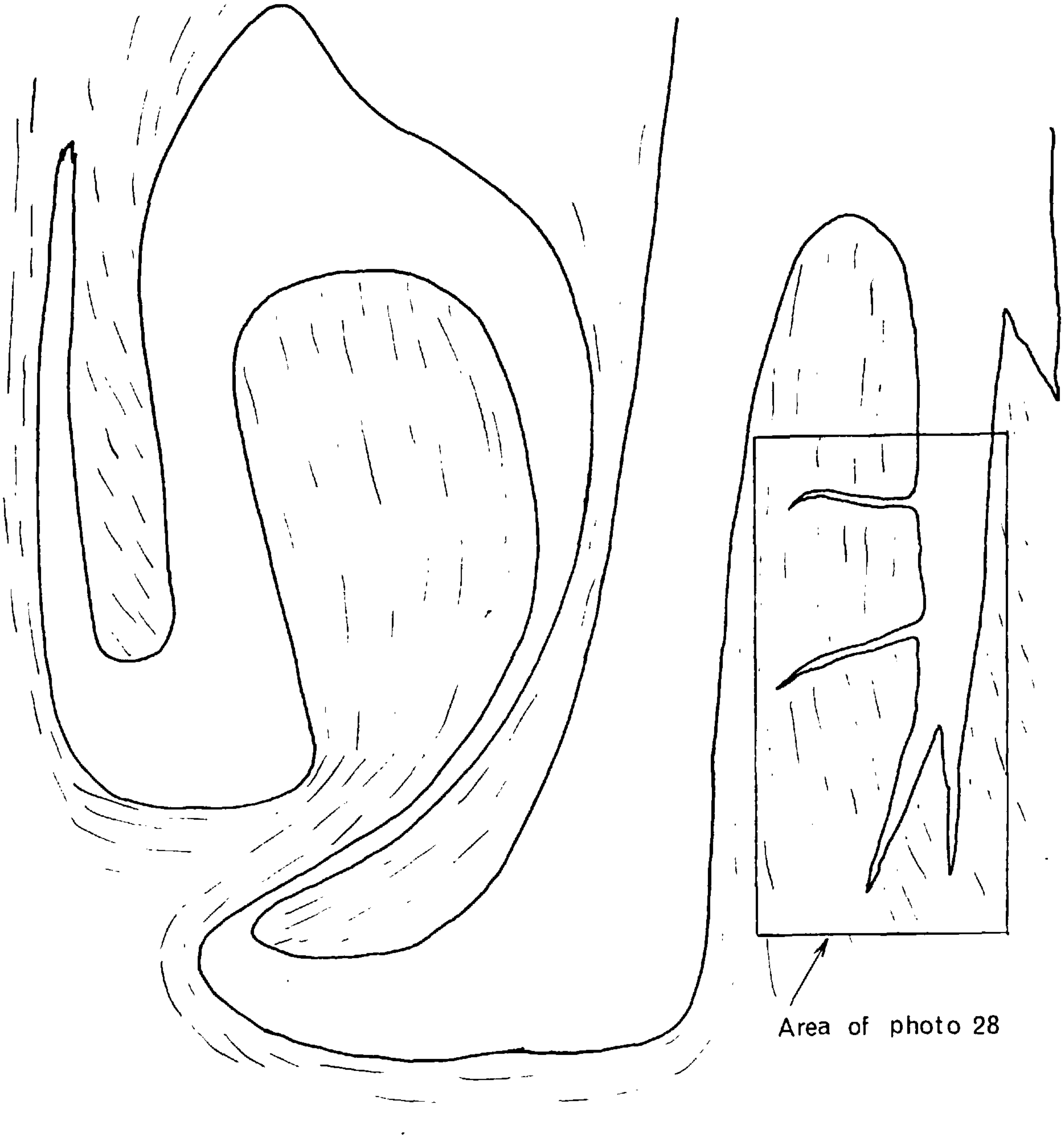
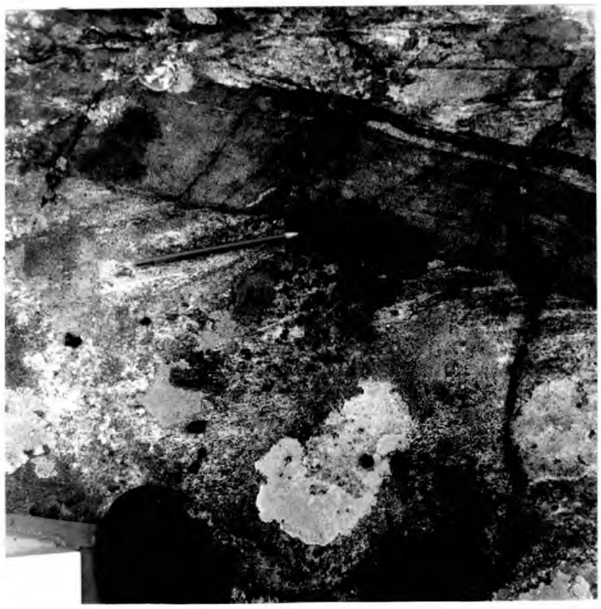


Fig. 18 Deformed Scourie dyke, Vatersay

Notice the discordances and irregular shape

28. Highly irregular Scourie dyke throwing off small apophyses, Vatersay. The matrix is a foliated early granite. See also Fig. 18. NL 663956



29. A small, amphibolitic Scourie dyke at Bruernish Point. Notice that although the dyke is discordant, it does have a foliation parallel to its margins.

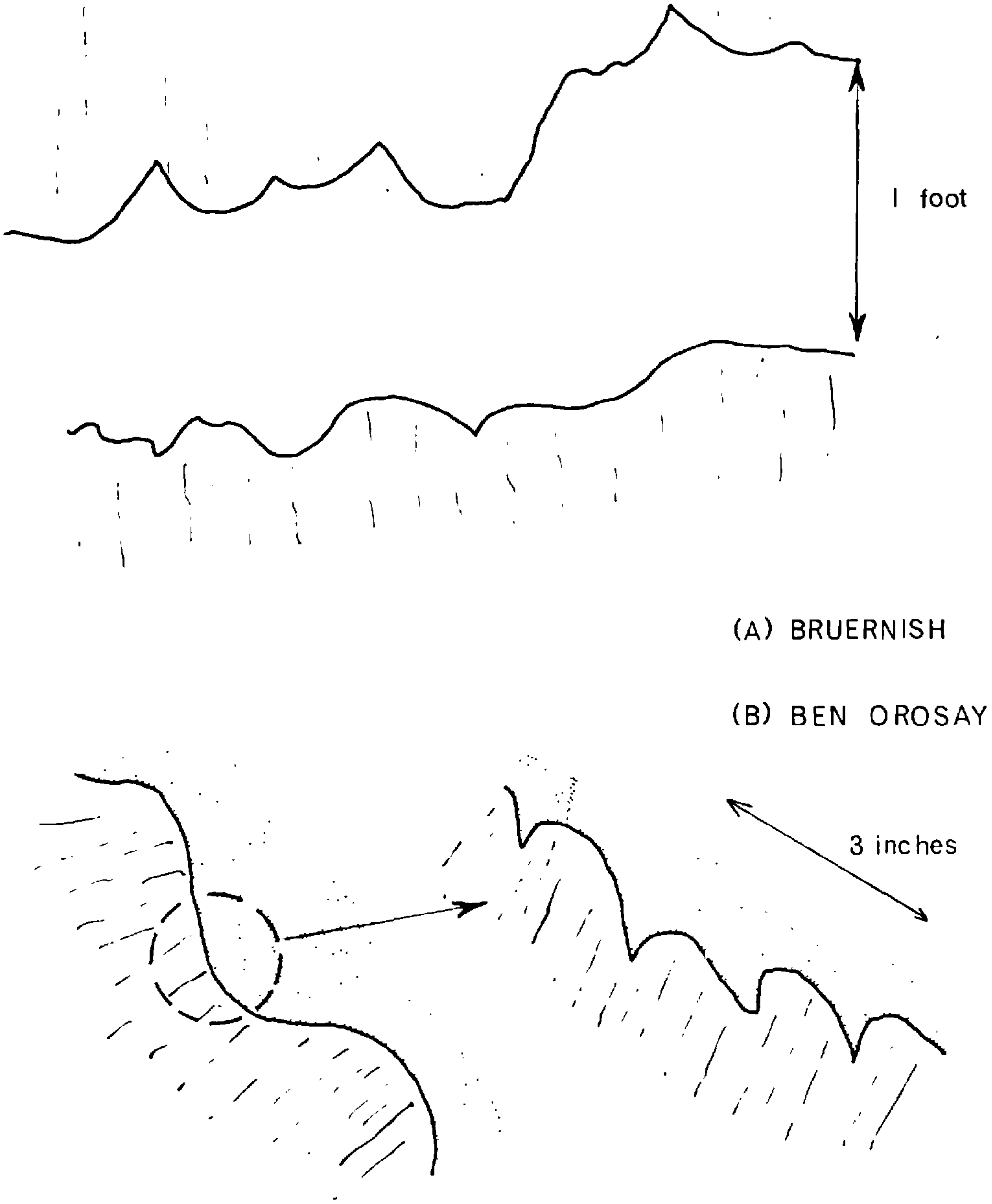


Fig 19 Examples of small scale cusp structures

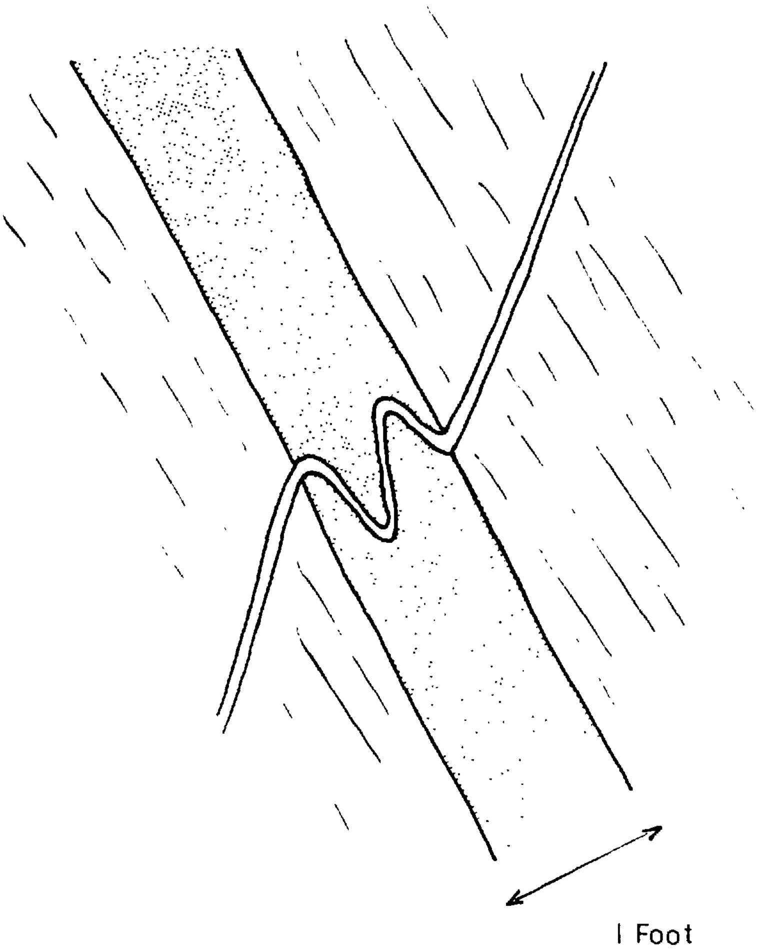


Fig. 20 Pegmatite vein folded within an amphibolitic Scourie dyke, Leenish

example from Leenish. The pegmatite runs regularly through acid gneisses, is folded within the dyke, and continues regularly beyond it. In this case, the pegmatite has deformed homogeneously within the acid gneisses, but has buckled as a competent layer within the amphibolitic material.

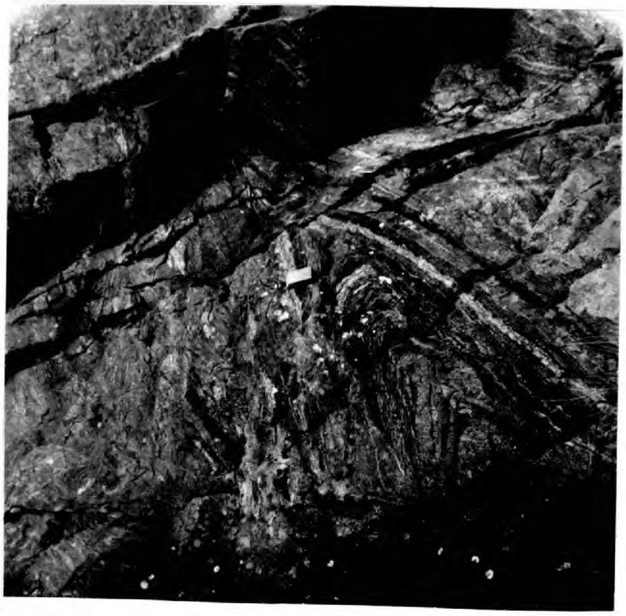
Third, dykes are occasionally observed with a foliation parallel to their margins, and independant of any fabric in the gneisses. Photo 29 illustrates this in a small, amphibolitic Scourie dyke and Photo 30 in a rather fine intermediate dyke of the early suite. This is the sort of result one might expect in incompetent bodies on flattening, when shearing parallel to their margins would develop.

(3) Orientation

Assuming a suitable applied stress and appropriate mechanical properties, a dyke still has to be correctly oriented relative to the applied stress before folding will occur. It could reasonably be argued therefore, other factors aside, that in areas where dykes are not now folded, the initial orientation of the dykes was not favourable to folding. If however, the dykes did not lie initially in the shortening field of the finite strain ellipsoid, then they must have suffered extension. There is little or no evidence of boudinage within either the Oitir Mohr Zone or the less-deformed zone of the Eastern Gneisses and it therefore appears that within these areas dykes must have deformed homogeneously; otherwise one would expect to find evidence of either boudinage or folding, or both.

The problem, however, is not as simple as this, for to predict fully the effects of deformation on dyke orientation we need to know three parameters:-

30. A discordant Intermediate dyke with a strongly developed fabric parallel to its margins. (A close-up view of the dyke in Photo 4, from Brevig) NL 706994



31. A tight, almost isoclinal fold developed in crushed rocks in the Greian Head area. Notice the generally highly fractured appearance. NF 660047

First, the initial dyke orientation, and also whether the dykes formed originally a parallel swarm, or were randomly arranged.

Second, the shape of the finite strain ellipsoid.

Third, the nature of the mechanism of deformation.

We know very little of the initial orientation of dykes, since we nowhere find dykes which are completely undeformed. There seems to be no tendency for dykes to cross-cut the banding of the gneisses in any consistent sense - locally, dextral discordances may predominate over sinistral and vice versa, but there is no regional consistency, and some dykes show different relationships at different points along their length. None of the major dykes, however, is more than 10 to 20 degrees discordant, and this strongly suggests that whatever the nature of the deformation, the dykes must originally have formed a roughly parallel swarm, since if they were randomly arranged, one would expect to find after deformation, a few dykes which lie at high angles.

The present dyke trend, is of course, controlled by the post-dykes fold structures. The enveloping surface to the F_3 folds trends roughly north-east south-west, and this in turn is the trend of the axial planes of F_2 folds. F_2 deformation caused most of the dyke re-orientation within the present area, so if one "removes" the effect of F_2 folding and flattening, we should have a rough idea of the original trend of the dyke swarm This appears to be roughly north-west south-east, which is very much the same as the trend of major Scourie dykes in the Scourian zone of the mainland The fact, however, that in the northern part of the area dykes were folded by F_2 whereas in the south they were not suggests that there may have been regional variations in the trend of the dyke swarm.

We can only make a guess at the shape of the finiate strain ellipsoid. We know that the final arrangement of lines and planar surfaces within a strain ellipsoid is different from that in the undeformed condition, and that the arrangement is controlled by the shape of the ellipsoid. Using the notation of Flinn (1962) ellipsoids of type $K = \infty$ tend to produce an arrangement of planes which plots out as a girdle on a stereographic net, while those of type $K = 0$ tend to produce a cluster, with all intermediate degrees. In Barra, there is no tendency at all towards the former, while there is a definite tendency for all planar elements to be parallel, so it seems likely that the ellipsoid was more "pancake" than "cigar" shaped.

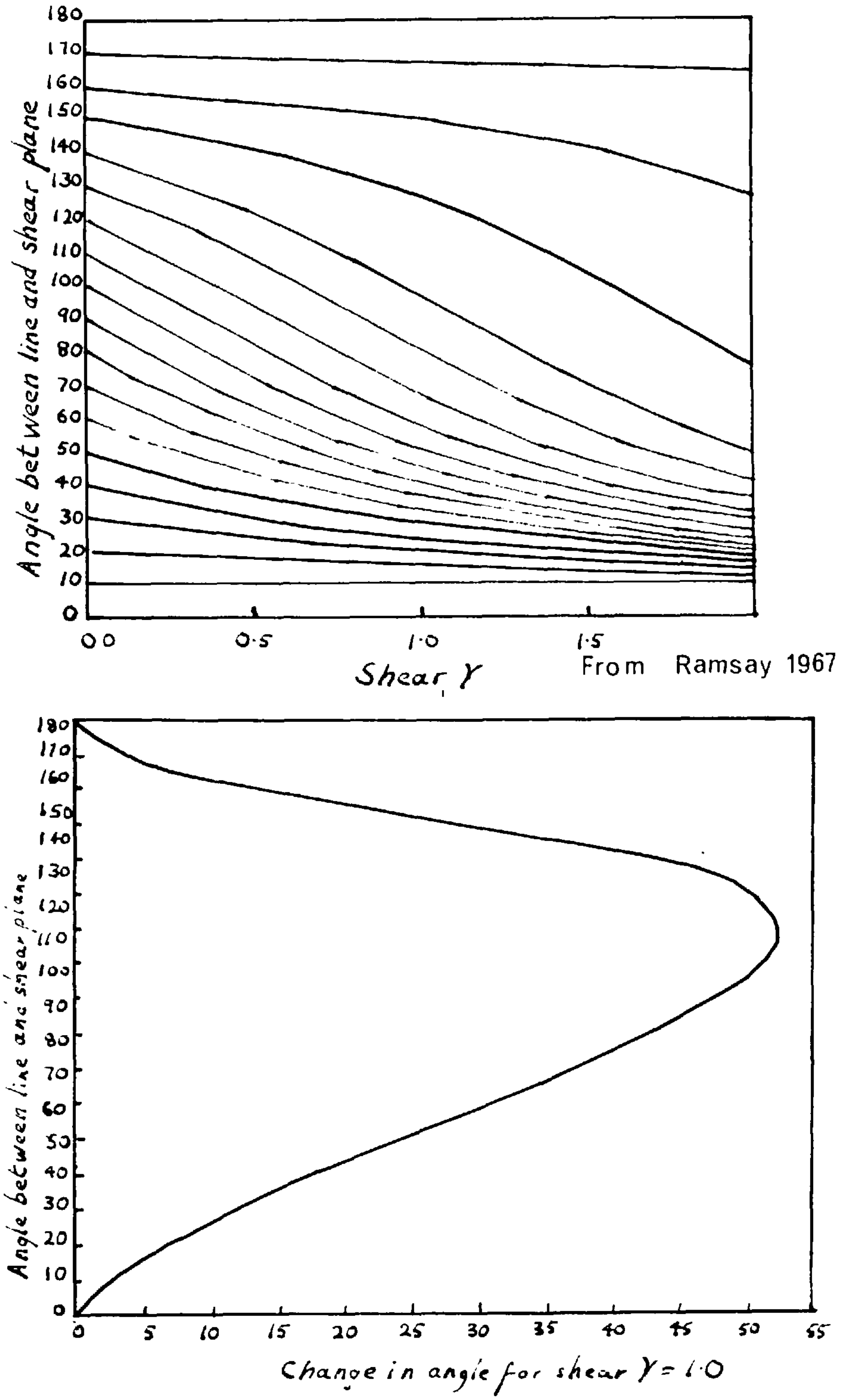
In more favourable terrain this estimate could be quantified by measuring the orientation of folded and non-folded layers (Talbot), a method which Watterson (1968) has attempted to apply to a rather similar gneissose terrain in Greenland. In this area, however, there is a distinct lack of suitable folded material, so the method is inapplicable.

The nature of the mechanism of deformation is extremely difficult to deduce from field evidence, particularly when one comes to consider problems of the rotation during deformation which will occur when rigid or semi-rigid bodies are deformed in a more ductile matrix. This as Ramsay (1967) states, is an important field for future investigation.

Hopgood touched on the problem of mechanism of deformation both in his thesis and in a published paper (Hopgood 1965), in which he investigated the re-orientation of dykes by shear. In his paper, Hopgood presented an incredibly tortuous account of the effects of simple shear on dykes, illustrated by cardboard cut-out models, and also concludes that dykes of several (of his) generations at Leenish Point have not been re-oriented by shear, partly because the older dykes are the more discordant. Without deviating here into a detailed criticism of Hopgood's paper, it seems to me that Hopgood has completely overlooked the possibility of mechanisms other than simple shear affecting dykes, and also that his principal conclusion, that no shear re-orientation has occurred is wrong.

This conclusion is based on his observation that the older dykes in the Leenish area are the more discordant, and is illustrated by a rather mis-leading schematic diagram. There is, however, a grain of truth to his observation - a few early dykes, such as that in Photo 3, are remarkably discordant, but this is very easily explained by a simple shear mechanism. Fig. 21 shows the changes in angles of lines of different initial orientations during shear strain. It is clear that many lines actually greatly increase their angle to the plane of shear, while others are less affected. Thus almost any arrangement of dykes of any age could be produced, given only the correct initial orientations.

The problem of the nature of the deformation is complicated by the scale factor. On a microscopic scale, the deformation is likely to have been homogeneous, and one could no doubt fint evidence for either pure



From Ramsay 1967

Fig 21 Changes in angle in simple shear

shear or simple shear in different environments. On an intermediate scale, however, considerable heterogeneity is likely, due to the differences and thus considerable complications will be introduced, with different styles of deformation, for example, in different parts of the same folded dyke. On a larger scale, the small differences between dykes and gneisses would be negligible, and the deformation would be effectively homogeneous pure shear.

(4) Conclusions

Four interesting and far reaching conclusions may be drawn from an examination of the state of deformation of dykes within the present area:-

First, that the Oitir Mohr Zone and the less deformed zone of the Eastern Gneisses represent masses of rock which have been on the whole more resistant to deformation than the Western Gneisses.

Second, that within these masses Scourie dykes with granulite facies mineralogy have deformed homogeneously with the pyroxene bearing gneisses.

Third, that Scourie dykes with different mineralogies had diff competences relative to the gneisses, and that folding of Scourie dykes occurred where competent granulite dykes were deformed in less competent amphibolitic gneisses.

Fourth, that therefore all the gneisses of the Western gneisses were in an amphibolitic condition before the onset of folding, while the dykes were only partially amphibolitized.

It is worthwhile noting here in connexion with the first conclusion, that the Scourie dykes in the Eastern gneisses are on the whole much thicker than those in the Western gneisses - many dykes in the Eastern are sufficiently large to map out; no such dyke was found in the Western gneisses. This observation is clearly of highly debatable significance, but it might indicate an important difference in bulk modulus between Western and Eastern Gneisses, expressed by the considerable [illegible] of dykes in the Western Gneisses.

SOME GENERAL CONCLUSIONS AND CORRELATIONS

We have seen that two principal units exist within the area mapped - a supra-structure and an infra-structure, which are distinguishable both geologically and geophysically; that these two units have shared a major phase of dyke intrusion and that they have responded very differently to the same sequence of post-dyke deformation. It now remains for us to try and explain the origin of these two very important units.

Two contrasted hypotheses must be considered:-

First, that the uniform acid gneisses of the supra-structure represent an original cover series overlying an older infra-structure.

Second, that there was no such original contrast, and that the two units developed as a result of metamorphic and migmatitic processes in an originally homogeneous mass.

The merits of each of these will now be considered.

COVER BASEMENT RELATIONSHIP. This is at first sight a most attractive hypothesis, but one which has as much evidence against it as in favour of it. The advantages are these:-

First, the remarkably sharp contrasts between units, particularly between the Oitir Mohr Zone and the Western Gneisses. (Note that it is assumed, for the sake of argument, that the broad zone of the acid gneisses in the Eastern Gneisses represents a synformal wedge of Western Gneisses, that is the supra-structure, although there is no positive structural evidence for this).

Second, the early intrusive rocks so characteristic of the infra-structure do not appear to be recognisable in the supra-structure, even where it is locally undeformed, for example at Orosay S.U. It would be reasonable to suggest that large, homogeneous meta-diorite bodies would still be recognisable, even when much deformed and mobilized, yet within the area mapped, only one body was found within the Western gneisses that could possibly be attributed to this suite. (At NF767138). Coward, however, has suggested that there may be early igneous rocks of this suite in north east South Uist, while Watson has also demonstrated the presence of good meta-diorites in north-west Lewis.

Third, it could account for the observed differences in metamorphic state of the two units. One might argue that the cover series was deposited on an already pyroxene-bearing infrastructure, or, perhaps more convincingly, that since the cover consisted of wet, first generation sediments overlying relatively "dry" gneisses, then on metamorphism the cover would produce hydrous, amphibolitic assemblages and the basement anhydrous, pyroxene-bearing assemblages.

Fourth, and perhaps most interesting, recognisable metasedimentary relics are found in the supra-structure, but not in the infra-structure. The distribution and significance of metasediments in the Outer Hebrides as a whole will be further discussed in a forthcoming joint paper. (Coward et al. 1969).

The arguments against a simple cover/basement relationship are rather grave:-

First it can be shown that the supra-structure was gneissose prior to Scourie Dyke intrusion. This can be demonstrated at Orosay S.U. within the present field area, and at other localities further afield, for example Ardivachar Point.

Second, the gneisses of the supra-structure had a history of deformation prior to Scourie dyke intrusion, yet the early dykes of the infrastructure are unfolded, whereas if the cover series was later than the early dykes, one would expect these dykes also to be deformed. It is remotely possible, however, that the infrastructure may have been a mass resistant to deformation throughout its history, in that it contains little evidence of deformational events taking place in the supra-structure above it.

Third, there is some slight evidence that the suprastructure itself was pyroxene bearing prior to Scourie Dyke intrusion.

Fourth, it could be argued that the early intrusive rocks are rather specialized types, which one would not expect to find so widely distributed as a dolerite dyke swarm.

DIFFERENTIATION IN AN ORIGINALLY HOMOGENEOUS MASS

The alternative hypothesis that a major post-Scourie dyke period of regeneration acting on an originally homogeneous mass produced a large scale segregation and diffusion which resulted in the separation of two zones of contrasting properties would require some rather intricate mechanisms to operate, but there is some evidence in its favour:-

First, as we have already seen, there is some evidence that both infra-structure and supra-structure were originally pyroxene bearing.

Second, although there is little evidence in the Western Gneisses of the area mapped of any deformed equivalents of the early intrusive rocks of the Eastern Gneisses, Coward, Graham and Myers have all shown the presence of early, Scourian granites in their respective areas, so it is possible that at least this early episode was common to both infra- and supra-structure.

Third, boundaries between granulite and amphibolite horizons are well known in geology on various scales, and have been described by Buddington (1963) who suggested that the differences arose due to contrasting fugacity of H_2O

Two features stand out against this hypothesis however:-

First, the extreme sharpness of the boundary between units, which seems inherently unlikely on this scale.

Second, the evidence for the early pyroxene granulite metamorphism in the supra-structure and therefore of the original similarity between the two units, is not convincing. Only at one locality in the area mapped was any evidence found, and this at the extreme edge of the Oitir Mohr zone. No pyroxene was found at Orosay S.U., and Coward has contested Dearnley's finding of pyroxene in the gneisses of Ardivachar Point.

Before coming to any conclusion on either of these hypotheses, let us see to what extent the supra-structure/infra-structure situation on Barra relates to other areas.

The closest parallel is clearly with the classic ground in the Scourie-Laxford area. (Sutton and Watson 1951). In both, there are areas of pyroxene bearing rocks which are cut by a suite of little deformed dykes, and in both areas these pyroxene gneisses give way relatively rapidly to migmatitic acid gneisses in which the same set of dykes is migmatized and deformed.

Dearnley first suggested that the suite of dykes in the Outer Hebrides might be correlated with the dykes of the Scourie area, and suggested that clouding of feldspars in the Scourie dykes might indicat a post-dyke metamorphism on the mainland which correlated with his postulated post-dyke granulite facies metamorphism in the Outer Hebrides. While the evidence for this metamorphism is arguable, the actual correlation between dyke suites seems to be perfectly logical. Absolute age dates also confirm the general similarity between the two areas: results from material from Leenish Point give several mutually accordant values of approximately 2,600 m.y., while later post-dyke pegmatites give ages of approximately 1600 m.y., as do the Western Gneisses as a whole. It is thus reasonably established that we can now consider Barra in terms of a Scourian infra- structure and a Laxfordian supra-structure. There seems to be no evidence whatever for the Inverian of Evans (1965) and other authors.

There are however, some noteworthy differences between the present area and the Scourie Laxford area. First, the early intrusive suites so characteristic of the infra-structure of the Barra area appear to be absent in the Scourie area, with the exception of early, pre-dyke pegmatites.

Second, the important Laxfordian granite sheets which mark the boundary between Scourian and Laxfordian zones appear to have no parallels in the present area.

Third, the Scourie dykes of the Scourie area have predominantly original igneous assemblages while those of the present area appear to have metamorphic assemblages.

None of these differences is particularly significant in itself, however, and when the geophysical data for the two areas are compared, the overall similarity is much strengthened.

In the Lewisian of the Outer Hebrides there is no such close parallel of the situation in Barra. Perhaps the nearest approach is in the South Harris complex (Davidson 1943) where a large mass of anorthosite and meta-tonalite is surrounded by meta-sediments and gneisses. Within the anorthosite discordant dykes are relatively abundant, in the surrounding metasediments and gneisses, discordant dykes are very scarce or entirely absent.

In the Uists, Coward and Graham have inferred the presence of large F_3 **fold** structures with a distinctive style:- tight, pinched synforms and broad, open antiforms. In the antiforms are regions of relatively low deformation, but the boundaries to these regions are hard to define since

Point. This poor exposure makes it difficult to comment on the detailed relationships of these areas of low deformation, but within them there are some interesting analogies with the less deformed area of the Barra Islands. The gneisses are often agmatitic rather than homogeneous, and there is at least one early pegmatitic body which has been dated at 2,300 m.y. (Dearnley and Dunning 1968). This pegmatite has been the source of some controversy between Dearnley and Coward, Dearnley having suggested that it had been deformed in the Scourian, and that therefore it must itself be of Katarchean age, while Coward inclines to the view that the deformation may be later and hence that the pegmatite is only Scourian in age.

Without trespassing further into this contested ground, two interesting features emerge from the work on these areas of low deformation. First, the larger dykes have cores of hornblende-granulite facies assemblages (plagioclase, clinopyroxene, garnet, hornblende, quartz) and have margins of amphibolite facies assemblages. These large dykes are frequently buckled and folded, whereas narrower apophyses are often remarkably discordant and apparently undeformed. Second, there is a very strong linear fabric in both dykes and gneisses, which is conspicuously absent in the Barra area.

There is no evidence of any discordant dykes of the early suite in these areas of low deformation, but Myers has shown on Scarp the presence of early granite dykes and pegmatite sheets cross-cutting the early gneiss complex, very similar to those of eastern Barra.

It is not proposed to enter here into a discussion of the structure of the Outer Hebrides as a whole. This will be the subject of a forthcoming joint paper. It is interesting, however, to note that one of the principal objects of that paper will be to show the existence in the Lewisian generally of units which could be considered as "infra-structure" and "supra-structure." Thus the regional importance of this division makes it even more important to try and explain the nature of these two units within the present area.

The problem we are faced with can be simplified into this:- how does the situation arise where a deformed, migmatitic supra-structure characterised by amphibole bearing assemblages overlies a less deformed non-migmatitic infra-structure characterised by pyroxene bearing assemblages and early intrusive igneous bodies? Two contrasting hypotheses have already been put forward to account for the situation . How valid are they?

Perhaps the chief obstacle to answering these questions is the problem of deciding at what point in time the two units achieved their separate identities. We have seen that whatever differences existed, they were effective before the main phases of Laxfordian deformation occurred, since Scourie dykes in the supra-structure have been extensively deformed and folded, while those in the infra-structure have not. There is also some slight evidence that differences may have existed prior to dyke intrusion, since where granulite Scourie dykes were intruded into definitely amphibolitic rocks (such as granites) these most complex intrusion shapes resulted, whereas where dykes were intruded into pyroxene bearing rocks, much more regular intrusion shapes were produced. (See also discussion of metamorphic state of Scourie dykes).

It is therefore suggested that prior to Scourie dyke intrusion, the supra-structure and infra-structure were already defined; the supra-structure amphibolitic and relatively incompetent, the infra-structure pyroxene bearing and relatively competent. Neither of the two hypotheses suggested earlier can by themselves account for all the observed characterics of these two units, so the following compromise is suggested as a basis for argument:-

Consider first that a thick sedimentary sequence is deposited on top of a basement complex of ordinary acid gneisses, and that the whole is mobilised in a major crustal event, the Scourian at about 3,000 m.y. It is suggested that the original interface would be preserved throughout the mobilisation, although much deformed and modified, and that a contrast in water fugacity could be developed between the two units. The original sedimentary sequence would become gneissose, while the underlying basement complex would merely be re-worked. It is possible that the contrast in water fugacity between the newly formed gneisses and the re-worked gneisses might be heightened by a general migration of water upwards from the basement or infra-structure into the cover. This is partly suggested by the lack of very early pegmatitic material in the infra-structure.

Some time after the main deformational phases had ceased, it is suggested that a series of minor intrusions were emplaced, the most widespread of which were of intermediate, dioritic composition, and that these intrusions tended to concentrate at the interface between supra-structure and infra-structure. This tendency for intrusive bodies to congregate at the interface between major units has been frequently described by authors working in Greenland, so it is by no means unusual. The final stages of this major crustal event were marked, it is suggested, by the crystallization of orthopyroxene in the gneisses of the infra-structure and of amphibole in those of the supra-structure, each being in equilibrium with the prevailing conditions of water fugacity.

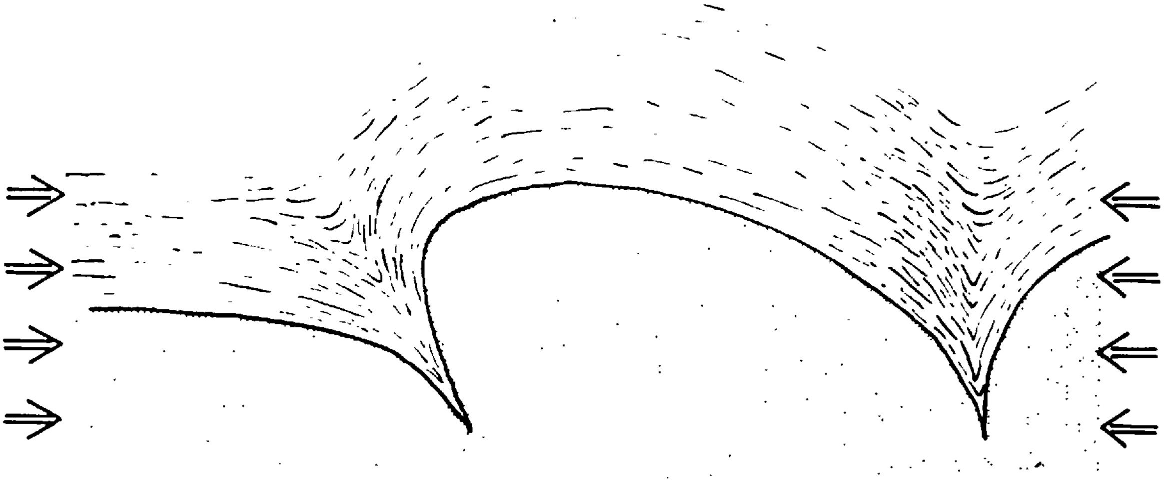
A minor, but widespread episode of granitisation then occurred, affecting both infra-structure and supra-structure, which tended to produce retrogression of the pyroxene bearing assemblages of the infra-structure, and so to tring about a convergence between the two units. This event can be fairly confidently dated at 2,600 m.y. and can be considered as late Scourian.

At a later date, probably about 2,000 m.y., Scourie dykes were intruded. It has been suggested that the dykes in the infra-structure crystallized with primary pyroxene-granulite facies assemblages. It is possible, even probable, that dykes intruded into the different conditions of the supra-structure crystallized with different assemblages, possibly of hornblende-granulite or almandine amphibolite facies, or even igneous assemblages. This would account for the observation that none of the dykes in even the most undeformed parts of South Uist and elsewhere are of higher grade than hornblende-granulite facies.

It is suggested that following dyke intrusion, a long period of steadily but slowly rising temperatures ensued, during which the dykes and gneisses of the supra-structure began to deform under their own weight, and eventually to flow, with the development of folds. In the infra-structure, dykes merely rotated bodily, with a general tendency towards parallelism of all planar bodies. This gravity controlled mechanism is suggested since it would account for the production of vast areas of horizontally or low dipping foliation in the supra-structure, and for the general tendency for F_1 and F_2 folds to be co-axial, a fact which can be observed locally in the present area, but much better elsewhere in the Hebrides. Such deformation would be accomplished by a slow creep mechanism, which would naturally be facilitated by relatively high temperatures, and we have already seen that amphibolite facies conditions prevailed throughout all of the Laxfordian history of the supra-structure.

The tendency toward flow which produced the F_1 and F_2 folds may have been iniated by small vertical movements in the infra-structure. It is important to note here that Bellousov has stressed the significance of vertical movements in geotectonics, since these involve only gravitational forces, and eliminate the necessity for the enormous horizontal compressive forces required to produce structures of a regional scale. In considering the origins of the major F_3 structures in the Hebrides, then, one is faced by a choice between two contrasted mechanisms:-

Either the regional F_3 folds were produced by very large horizontal compressive stresses acting on the interface between supra-structure and infra-structure, to produce cusp-like structures.



(A) LATERAL COMPRESSION OF INTERFACE

(B) VERTICAL MOVEMENTS IN THE INFRA-STRUCTURE

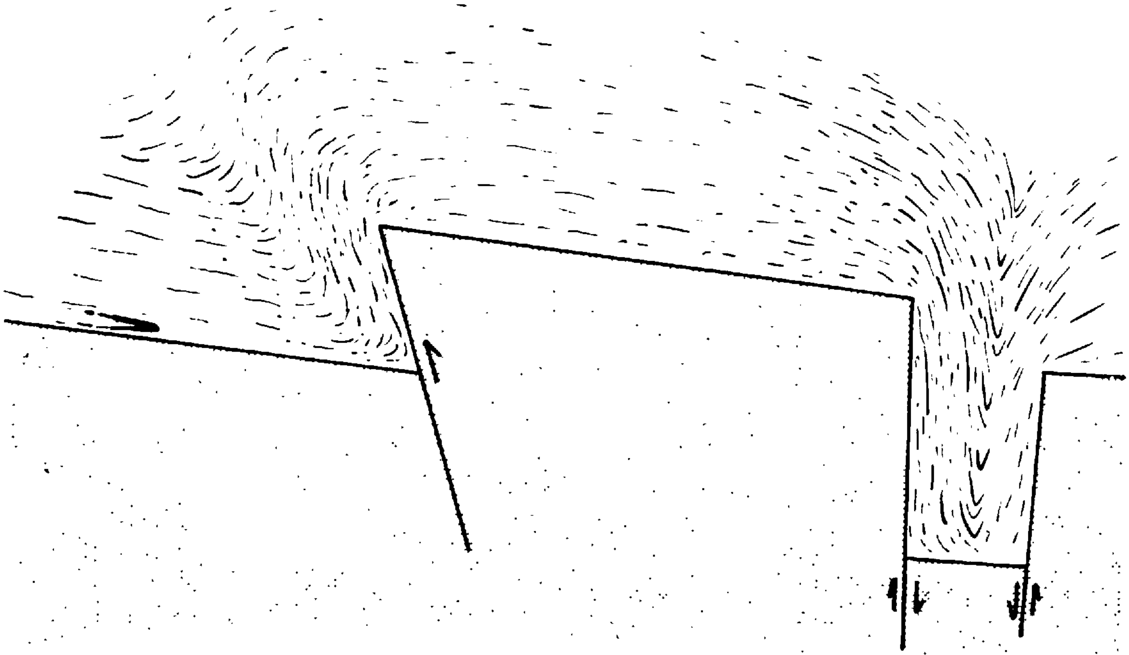


Fig. 22. Contrasted models for formation of regional structures.

Or these structures were produced by large vertical movements of blocks of infra-structure, which caused the overlying supra-structure gneisses to flow, and to drape themselves around the blocks of infra-structure.

Both of these mechanisms could be applied to the Barra area, and are illustrated in Fig. 22. In trying to decide which is the more probable mechanism, one has to look further afield, to the Lewisian as a whole. In the Outer Hebrides, the geometry of the postulated structures may tend to support the first of these hypotheses, but on the mainland, Sutton and Watson (1969) have suggested that the major structures, particularly the Scourie/Laxford boundaries, are monoclinal, and this strongly supports the second hypothesis. On the whole, it is the writer's personal opinion that this second hypothesis has the advantage of being mechanistically more feasible, and therefore it is concluded that the major Laxfordian structures in the Lewisian are the result of vertical movements of large blocks in the infra-structure. One can only speculate on the reason for large vertical movements at these deep levels, but at least it would not be necessary to involve a large measure of crustal shortening.

The production of these large F_3 structures was the last major event in the present area, though amphibolite facies conditions persisted until after F_4 folding had occurred. As we have seen, widespread re-crystallization occurred in the gneisses during and after the F_3 and F_4 fold phases, and seems to have reached a maximum in the southern part of the area after F_4 folding had ceased.

It seems likely that metamorphic conditions waned fairly rapidly after this in the present area, but probably declined much more slowly further north, since Coward has shown the presence of extensive low grade late or post-Laxfordian alteration and metamorphism in South Uist, particularly in the north-east of the island.

In proposing this hypothetical summary of the history of area, the importance of four factors is stressed:-

First, that the major episode of deformation and mobilisation which might be termed the "Scourian Orogeny" was a good deal older than the 2,600 m.y. ages obtained from pegmatites. It is suggested that these pegmatites have the same relation to the Scourian as the well-known Laxfordian pegmatites have to the Laxfordian deformation cycle - in other works, they are a very late event. This implies that the actual Scourian "orogeny" could well be as old as 3,000 m.y. and thus might be considered as Katarchean, or pre-ketilidian in the chronology of Greenland. The general similarity between the chronologies of the Lewisian and Greenland is illustrated below:-

Greenland	Lewisian
Pre-Ketilidian 2,700 - 2,300 m.y.	Scourian 2,600 m.y. plus
Kuanitic Dykes (c.2,000 m.y.)	Scourie Dykes
Ketilidian 1,800 m.y. (?)	Laxfordian 1,600 m.y. plus
Sanerutian 1,600 m.y.	

There does not appear to be any equivalent in the Lewisian of the rocks of the Gardar cycle of Greenland, at about 1,200 m.y but it is worthwhile noting that the Ketilidian rocks are considered by workers on Greenland to represent a cover series of metasediments and meta-volcanics overlying the pre-Ketilidian basement.

The second important factor is the ability of original cover/basement relationships to be preserved through later episodes of deformation and metamorphism. This is a fairly well known geological phenomenon, and may be illustrated by the preservation of Moine/Lewisian relationships through the Caledonian orogeny.

Thirdly, there is the importance of gravity as a prime mover in geology. One is accustomed to talk in terms of "orogenic belts" in the pre-Cambrian, yet there is little tangible evidence that they ever had anything to do with mountain building, and they generally tend to be much broader and more diffuse than the true orogenic belts of later eras. When considering the enormous extent of some of the older belts, it seems reasonable that only gravitational forces could have been of sufficient magnitude to act over the whole of these areas.

Fourth, there is the general similarity between the Scourian blocks of the Barra area and the Scourie area. Perhpas the most obvious difference between them is in the metamorphic state of the Scourie dykes in them. It is suggested that this may reflect different conditions at the time of dyke intrusion, rather than later events. These could have arisen, if, for example, the dykes of the Scourie area were intruded at higher levels, and therefore under lower pressures, than the corresponding dykes in the Barra area.

V THE OUTER HEBRIDES THRUST

INTRODUCTION

The Outer Hebrides Thrust is undoubtedly one of the largest tectonic features of the British Isles, rivalling in length of outcrop the classic Moine Thrust. For all its size, however, it has never received the attention that it deserves, and has only once previously been discussed in the course of a regional study. In this thesis, it is proposed only to describe the general features of the Thrust as it is exposed within the present area, and to make some observations on the nature of thrusting mechanisms.

PREVIOUS WORK

Very little has been written on the Thrust itself, but there is an extensive literature on thrusting mechanisms and the origin of psuedotachylyte, which will be reviewed separately. Dougal was the first author to describe the existence of a large zone of crushed rocks in the Hebrides, but it was Jehu and Craig who provided the first description of the Thrust. In their work on Barra, Jehu and Craig never in fact mentioned the existence of a major thrust, and talked only in terms of "crush zones" and "flinty-crush" rocks, and it was not until they published their descriptions of the geology of South Uist and Eriskay that they introduced the term "thrust," with the implication that the "crush zones" of Barra were also thrust phenomena. This may have been because on South Uist there is a relatively obvious contrast in lithologies across the Thrust, whereas on Barra the contrast is less obvious.

Their mapping of Thrust-related features is also considerably over-simplified and somewhat haphazard.

On the whole, however, their work is extremely good, and their petrographic studies are of such high standard that their work is quoted in nearly every later work on psuedotachylyte, and must be considered as a classic account of this material. Hopgood, in fact considered that Jehu and Craig's work could not be improved on, and confined his work on the Thrust to some rather dubious observations on its direction of movement. Kursten gave a good description of the Thrust just to the north of the present area (near Lochboisdale).

In this section, it is not proposed to duplicate Jehu and Craig's descriptive work on petrography, but, rather to concentrate on larger-scale phenomena which they rather overlooked, and also to examine some theoretical aspects of thrusting. Before this, however, the use of three rather confusing terms will be established:-

First, "The Thrust." This term is applied to the Outer Hebrides Thrust as a whole, and is conveniently vague.

Second, Thrust zone. This is rather more specific, and is applied to the zone or belt of crushed rocks within which thrust movements have actually been located.

Third, Thrust plane. This is used to describe a definite, discrete plane along which some movement has occurred. Where observed, this element usually represents the plane of last movement within a thrust zone, and it should not be considered that this plane uniquely represents the plane on which all movement has occurred.

Notice that the Outer Hebrides Thrust itself consists of several separate thrusts, particularly on South Uist, each of which may have its own thrust zone and thrust plane(s). A single distinct thrust-plane is present in most of the field area, except for South Uist where these are many.

DESCRIPTION OF THE THRUST

The Thrust will be described in this section from its most southerly exposure in the Outer Hebrides, on the island of Sandray, to the southern part of South Uist, where it is a much more complex structure. The description will be covered on an island-by-island basis, since small islands often offer as much information as poorly exposed larger ones.

Sandray

THRUST PLANE. No thrust plane is exposed anywhere on Sandray, but a distinct N.N.E-S.S.W. linear feature about 75 yards wide is present, filled with blown sand and forming beaches at both its northern and southern ends. It is considered that this feature represents an important thrust plane. Air photographs show that this feature is very straight and steep, and in fact the Thrust appears to be much more nearly vertical here than at any other point in the area.

THRUST ZONE. A belt of crushed rock containing much psuedotachylyte constitutes the Thrust Zone on Sandray. This belt is at least 800 ft. thick, and forms a visible topographic feature east of the Gleann Mohr. The gneisses in the extreme west of Sandray are very low dipping; as one approaches the Thrust, the dip increases and within the thrust zone, the general "grain" is very steep. Nothing is known of the rocks east of the Thrust here.

Vatersay

The Thrust outcrops on both of the arms of the H-shaped island of Vatersay, at Am Meall in the south and Craig Mohr in the north.

Am Meall

THRUST PLANE. No thrust plane is exposed on this headland, and the main part of the Thrust must lie slightly further east, under the sea. No measurement of the dip of the Thrust can be made, though the grain of the crushed rocks suggests that it is steep.

THRUST ZONE. The whole of the hill Am Meall is made up of crushed material, indicating a minimum thickness of the thrust zone of about 1,100 ft. Within the crushed zone, the rocks are very strongly jointed and are massed with psuedotachylyte. The "grain" seems to be roughly N.N.E. and very steep. This "grain" is defined partly by strong joint sets and partly be large masses of psuedotachylyte, one of which is almost dyke-like and can be traced for many yards. This mass may be partly recognisable in the little line of skerries running S.S.W. of Am Meall.

Creag Mohr

THRUST PLANE. Again, no thrust plane actually outcrops, but a 200 yard wide stretch of beach on both sides of the narrow peninsula strongly suggests the presence of an important thrust plane. This concealment of thrust planes is due to the presence along the plane of extensively altered, highly friable material which will be easily eroded. This material can be observed in a few localities further north. It is not possible to obtain a measurement of the dip of the concealed plane, but the grain of the crushed rocks suggests that it may be less steep than in the localities further south.

THRUST ZONE. The amount of crushed rock here seems to be much less than at Am Meal, but this may only be because less is exposed. For the first time, however, we find fresh, uncrushed rocks above the Thrust, and these are very distinctive rocks of Eastern Gneiss type. Many minor, possibly second order thrust planes occur in these rocks, especially nearest the Thrust, and one such at NL 658956 is a gently, regularly dipping plane coated with a thin layer of psuedotachylytic material. This is the psuedotachylyte "pavement" of Jehu and Craig, who reported similar pavements from Mingulay, Pabbay and some other localities.

Barra

The Outer Hebrides Thrust runs right across the middle of Barra, making a rather sharp turn as it does so, (Map 6). Apart from the belt of crushing in the Thrust zone, there are also two other areas of crushed rock, both recognised by Jehu and Craig. One of these, at Ard na Gregaig, is of little importance, but the other, in the Greian Head-Cliad area, is much more extensive and interesting, and will be described in this section because it contains well exposed examples of many features typical of crush zones in general.

THRUST PLANE. The Outer Hebrides Thrust on Barra appears to consist of an important thrust plane situated towards the top of a thick thrust zone. The thrust plane forms a very prominent valley feature immediately behind Castlebay Church, and this feature can be traced inland over the saddle known as Cadha Mohr (NL 665998), into the top of the Borve valley, becoming progressively less distinct. Exposure is generally very poor over the next part of the outcrop, and it is mainly on the basis of change of slope that the Thrust is mapped in near Dun Barpha and along the western flanks of Cora Bheinn. The Thrust appears to execute a sharp turn at the north of Cora Bheinn, but the situation is complicated by the presence in the crushed rocks of the Thrust zone of a double topographic feature, which might be the result of minor faulting rather than thrusting. Exposure is very poor indeed between Cora Bheinn and the next outcrop of the thrust plane, in the stream section near Northbay school.

The southern slopes of Ben Obe contain a great deal of highly crushed material, and a very strong valley feature runs up the hill from the school. This feature is interpreted as produced by a minor thrust-plane, perhaps a splay off the major structure. The E-W spur of Loch Obe indicates the continuation of the Thrust, which is next exposed on Bruernish peninsula, where a very conspicuous, rectilinear E-W feature is present, along which a great deal of psuedotachylyte is occasionally exposed.

Two possibilities are suggested for the very sharp change in direction of the Thrust on Barra:-

First, that the original geometry of the Thrust was not planar, but shovel shaped, and that this original shape has been exaggerated by the effects of topography.

Second, that later faulting or flexuring has modified the original shape of the Thrust.

At Castlebay, the thrust-plane unambiguously dips east at about 25 degrees, and this easterly dip continues as far as Cora-Bhein, so far as can be judged. On Bruernish, the dip definitely is towards the south, but the outcrop here is so rectilinear that one is inclined to suspect the presence of a fault. However, there is no evidence for the continuation of any such fault on Fuiay, where the Thrust is very well exposed, and dips to the S.S.E. It is suggested that the change in strike is a reflection of the original shape of the Thrust, and that it is not the result of later flexuring since there is no other evidence of late major flexuring of any sort in the area.

THE THRUST ZONE. Perhaps the most interesting feature of the Thrust zone on Barra is that it is almost entirely developed in the Western Gneisses below the Thrust - fresh, uncrushed Eastern Gneisses run straight up to the thrust-plane outcrop, beyond which the zone of crush extends. This feature is seen everywhere on Barra, at Bruernish, on Cora Bhein, and at Castlebay, and also on Vatersay, but in the more northerly islands the situation is reversed. This suggests that plane of last movement, which presumably produced the present thrust plane, was situated at varying levels in the zone of crushing and imbrication of the Thrust as a whole.

The maximum thickness of crushed rocks appears to be in the area known as the Croig, where it is at least 600 feet. Within this area, many fairly large, highly irregular folds and structures occur, and in one locality NF664002, a N-S trending vertical belt is present which appears to have been mapped by Hopgood as an early fold belonging to one of his numerous fold phases. The thickness of the crushed zone appears to reach a minimum in the Bruernish area but there is a slight possibility that part of this zone has been faulted out in this area.

The Grian Head - Cliad Crush Zone

This zone was originally mapped by Jehu and Craig as a broad diffuse "area affected by flinty crush", contiguous with a rather narrow band running E-W towards Bruernish. This is a considerable over-simplification of the situation. The pattern appears to be one involving a great many minor crush horizons, trending S.S.E., separated by varying thicknesses of unaffected gneisses, so that in walking across the zone one is continuously crossing from crushed to uncrushed material.

Jehu and Craig implied that this crush zone was contemporary with the main (Thrust) zone of crushing, but a second possibility exists, that the two structures are independent of one another, and that the Grian Head crush zone is older than the Thrust. In this region, the unaffected gneisses dip uniformly to the N.E. at about 25°. Now it is a striking fact that most of the crush structures occur in broadly planar sheets parallel to the regional foliation. This suggests immediately that the foliation planes in the gneisses have acted as planes of weakness along which failure has preferentially occurred. It is possible that some complex second or third order stress system associated with the Thrust could have produced such failure, but it is equally possible that failure has occurred under an earlier stress system.

This is supported by the observation that the crush horizons in the Grian Head zone can be traced towards the Thrust, which they meet at a high angle, and there is no sign of a complementary crush zone in the Eastern Gneisses above the Thrust. An early episode of brittle deformation would also fit the regional chronology and this point will be discussed further in considering the age of the Thrust itself.

Some minor structures which are particularly well exposed in the Grian Head-Cliad zone will now be described.

MYLONITIC STREAKS. Close examination of almost any outcrop of crushed rocks reveals a multitude of very fine greenish-grey streaks, usually parallel to the gneiss foliation but sometimes discordant to it. In this section, these streaks appear as narrow zones of mylonization, which are often fairly sharply defined. Near them, biotite and hornblende grains show signs of strain and imminent disruption - biotite becomes crinkled and crystals lose their optical continuity, while hornblende often shows a distinctive brown discolouration. Quartz grains throughout the slide show marked undulose extinction. The material within the streak itself consists largely of comminuted grains, with some epidote and chlorite, and other low grade minerals including, rarely, calcite.

Nowhere do these mylonitic streaks attain a thickness greater than 1/20th of an inch, and they are thus vastly subordinate in volume to pseudotachylyte within these zones. This applies equally to the rest of the area, and will be of great interest and importance when we come to discuss the difference in origin of the two materials.

MINOR FOLDS. On many of the exposures on Grian Head, interesting fold structures are displayed. There is little or no sense of regularity about them, nor do they relate to any other fold episodes. Close examination shows that the folds are always somewhat disrupted irregular structures which vary from almost isoclinal folds (Photo 31) to rather open warps (Photo 32). All of these folds are in heavily crushed areas of otherwise almost unfolded gneisses, and there is every reason to think that they are the product of the crushing deformation and are not earlier. This view is reinforced by the observation that early mylonitic stringers are often folded round the noses of these folds, showing that the folds post-date the mylonization.

Hopgood considered that there was evidence for a very early phase of thrusting and pseudotachylyte formation, which pre-dated one of his major fold episodes, and stated that in places pseudotachylyte veins were folded by this episode. It seems probable that Hopgood was confusing these late fold structures with his earlier folds, and that he may have mistaken fine mylonitic streaks for pseudotachylyte veins. No instance was found by the present writer of a folded

34. Pseudotachylyte from Greian Head. Notice the two different modes of occurence, as very distinct veins and in a conglomeratic mass which itself has a distinct margin. NF 662047.

35. A pseudotachylyte conglomerate in the Greian Head area. Notice that the pebble under the three-penny bit is cut by a small vein of pseudotachylyte, which is itself cut by a series of small micro-faults. NF 662046.

pseudotachylyte vein, although some curved pseudotachylyte veinlets were found, the veinlet following the curved gneiss foliation.

PSEUDOTACHYLYTE OCCURRENCES. The first impression received when entering an "area affected by flinty crush" is one of complete chaos, but usually some order may be discerned. Three distinct types of pseudotachylyte occurrences may be recognised in the field:-

First, as thin veins or dykes up to an inch or two thick along regular planar surfaces (Photo 33)

Secondly, as very irregular dykelets up to 6 inches thick, which may show dark "chilled" edges (Photo 34).

Third, as the matrix to the very distinctive conglomerates (Photo 33).

The "conglomerates" usually form sheet-like bodies as a whole, often parallel to the gneiss foliation but sometimes cutting across it at high angles. Sometimes, these sheets are sharply defined at top and bottom, but almost always there is one sharp margin which is itself the site of a thin regular pseudotachylyte stringer and almost certainly represents a movement plane (Photo 33).

The pebbles within these conglomerates show every gradation between extreme angularity and extreme roundness (although rounded forms are the most common), and a similar variation in the nature of their edges. Some edges are perfectly knife-sharp against pseudotachylyte, others are diffuse. Different types of edges may be seen

32. Rather open folds in the Grein Head crush zone, which fold earlier mylonitic stringers. NF 663045

33. A good example of a pseudotachylyte conglomerate. Notice the regular, planar pseudotachylyte veins on the left of the conglomerate mass. Gighay. NF 772043

on the same pebble. Evidence for the long and complex history of these conglomerates is often observed. Photo 35 for example shows a pebble with three sharp edges and one diffuse edge. This pebble is cut by a later veinlet of pseudotachylyte, and this veinlet is itself broken up by a series of step-like microfaults.

The irregular dykelets seem to be definitely distinguishable from the other two types, occurring independehtly as branching and splitting bodies at high angles to the gneiss foliation, and rarely containing any significant amounts of included fragmentary material. They also have different time-relations from the conglomerate sheets. Photo 34, for example, shows a typical dykelet cut by and displaced by a later conglomerate sheet.

Within the Grian Head-Cliad area, a simple chronology may be worked out:-

(3) Formation of pseudotachylyte (In sheets
 (As veins
(2) Crushing and folding
(1) Early mynlonitization

This is the sequence which is observed throughout the present area, the pseudotachylyte always representing the last events. Kursten has also made the same observation in South Uist.

JOINTING. One of the most conspicuous features of all the areas affected by crushing is the strong jointing that is developed on all scales. Joints are developed both in crushed gneisses and in

TABLE 9

Strikes of Joint Pairs		Angle between Pairs
080	180	100
040	140	100
045	155	110
010	115	105
345	095	110
360	090	90
080	355	85
345	080	95
090	-	-
095	-	-
085	340	105
335	080	110
340	080	100
345	055	70
075	350	85
360	115	115
355	090	100
360	100	100
060	345	75
350	090	95
	Average	97.0 degrees

pseudotachylyte, but it is in the latter that by far the greatest number of joint-sets are present. Since this was one of the few aspects of pseudotachylyte that had not been explored previously, it was decided to measure joints in a selected area on Grian Head to see if any pattern emerged. Two features were noted:-

First, and predictably, that the main joint sets in both gneisses and pseudotachylyte were parallel to major regional joint directions. For example, Tertiary dykes on Barra are very often aligned with a major joint direction, trending about 100-110°, and this direction can be consistently identified in areas of crush.

Second, within pseudotachylyte masses, joints tend to occur in sets, and several such sets may be present in any small outcrop. This explains the tendency for pseudotachylyte to fracture into roughly rhomb shaped fragments. It was found that by measuring the two strongest steep joints on a horizontal surface that some consistency emerged. Table 9 lists the strike of joint pairs at 20 localities within 50 yards of one another.

Measurements were made only to the nearest 5° because of the difficulty of measuring some of the very short joint plane strikes, and because of the strong possibility that the magnetic properties of the pseudotachylyte might offset the compass. Locally, complete reversal of the compass occurred, and no readings were taken in areas of such high magnetic interference.

The rose-diagram (Fig. 23) shows that there is rather a wide scatter in the orientation of the joint pairs, but the angle between

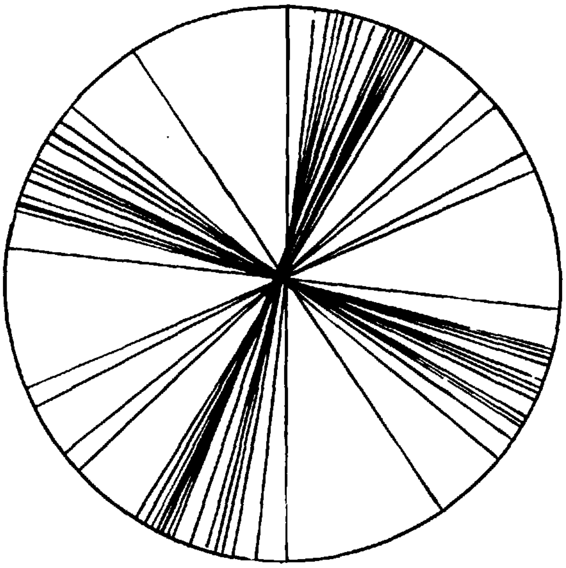


Fig. 23 Joint directions in psuedotachylyte from Grian Head

them is much more consistent, at about 97°. This was also observed when measurements from near-by areas were introduced the tendency to form any sort of pattern on the rose-diagram dissappeared, but the angle between joint pairs remained at about 100°.

If these joints represent pairs of shear-joints, then this angle is diagnostic of the properties of the rock at time of fracture, and gives a measure of the co-effecient of internal friction. The angle between shear planes and the principal axis of compressive stress is 45° when the co-efficient of internal friction is zero, and it would appear that in the present case, where the angle is about 40°, the co-efficient must be very low indeed.

Much more detailed and rigorous analysis of the jointing, however, is required and would form an interesting field for research in itself.

Fuiay

THRUST PLANE. A very good thrust plane is exposed on the west coast of Fuiay, and forms a strong topographic feature which can be traced right across the island. The measured dip is towards the south-south east at low angles, between 20° and 30° degrees. The actual exposure of the thrust-plane is not particularly informative, since extensive alteration has rendered the rocks almost unrecognisable.

THRUST ZONE. Several large basic masses may be traced up to about 100° yards from the base of the thrust-plane, extensive crushing is developed, to a total thickness of some 600 feet, the thrust-plane being somewhat nearer the base of the thrust zone than the top. It is interesting to note here that large pegmatitic bodies appear to be relatively unaffected in the crush-zone, perhaps because of their coarse, homogeneous nature.

Hellisay

THRUST PLANE. Beneath the magnificent, towering crags of Meall Mohr, the thrust plane itself is exposed, and is here a sharply defined plane eroded out into a deep notch. Erosion has excavated a 'dirt' horizon on the thrust plane, which has been formed by the extreme alteration and break-down of rocks. For some distance above and below this dirt layer, the crushed rocks are made of unrecognisable rotten greenish material, but in the unaltered material below this altered zone, a series of rather small, minor planes are developed, together with some rather small crush folds a foot or two in amplitude.

The distinctive dirt layer and its topographic feature may be traced continuously around the west end of Meall Mohr, and down on to the island of Carrish, where it is exposed in the low western cliffs. The measured dips of the thrust plane were again between 20 and 30 degrees, but here the strike is now N.E. rather than E.N.E. as the Thrust swings around northward.

THRUST ZONE. The thrust plane here seems to be near the base of the thrust zone, since very little crushing is developed beneath it. A small feature and some crushing near the hill Meall Mchadonach suggests that a minor ancilliary thrust is present beneath the main Thrust. The thickness of crushed rock above the thrust plane must be many hundreds of feet, but the top is not exposed. The entire height of the crags of Meall Mohr, however, exposes highly crushed rocks and gives a very good impression of the nature of the thrust zone.

Gighay

Unfortunately, no thrust-plane can be identified on Gighay, although much crushed rock with pseudotachylyte is found in the extreme south-east corner. It is suggested that the continuation of the thrust-plane of neighbouring Carrish lies somewhere in the sea, just off the coast of Gighay. A very large Tertiary dyke runs through the narrow straits between Gighay and Hellisay, and some displacement may have occurred along it.

Eriskay

Crushed rocks with pseudotachylyte are found along all the eastern part of Eriskay, but no uncrushed rocks above the Thrust are found. It is suggested that on Eriskay no single thrust plane is present, and that the thrust-zone as a whole just skims the tops of the hills on the east of Eriskay, so that the eastern slopes are mantled with crushed rocks. The dip of the thrust zone appears to be lower here, about 15°, and this may also account for the very wide outcrop of crushed rocks.

South Uist

The south-east corner of South Uist is an extremely complex area of thrust, crushed and faulted rocks, and is very poorly exposed.

The following short account is based on a brief reconnaissance and on air photograph interpretation.

It is tentatively suggested that the area as a whole may be divided into four distinct tectonic units in a structural succession whose lowest member is in the region of Bagh Hartavagh. These units, which are shown on Map 14, may be distinguished by a variety of characters such as topographic features, lithology, degree of crushing, joint trends etc.

Unit 1

This is the lowest unit, and is characterised by very distinctive rocks, "Eastern Gneisses" of South Uist type. These rocks form an important unit, which is exposed East of the Thrust in the main part of South Uist, and also in North Uist, though it is generally very much affected by crushing and shearing. The term "Eastern Gneisses" was first introduced by Dearnley to describe the "relatively uniform foliated and locally banded pyroxene granulites" which characterise this unit, and it is emphasized that these rocks should not be confused with with the Eastern Gneisses of Barra. Jehu and Craig first referred to these quartz-poor pyroxene bearing gneisses containing garnet-pyroxene basic bodies, and also described an unusual scapolite bearing pyroxene gneiss. These easily recognisable rocks definitely occur in the area of Meal and Iasgaich, but it is not known how far to the west they extend. There is a multitude of small topographic features in this area which suggest the presence of a series of thrust slices, and some of the thrust slices may consist of ordinary, though crushed, gneisses.

This unit is also characterised by the presence, at its base, of a fairly thick zone of mylonite. Mylonite are most unusual within the area mapped, and this is the only locality where they have been found in any quantity. They are best exposed on the shores of Bagh Hartavagh, especially at NF 828153.

Unit 2

This consists of ordinary acid gneisses, not much crushed, but with a very well developed and conspicuous jointing trending E.N.E. The base of this unit appears to be a strong topographic feature, running W-E from near the top of Hartabreck.

Unit 3

This also comprises ordinary acid gneisses, but these are extensively crushed and pseudotachylyte is massively developed. A strong feature running north east from Roneval to the crags west of Maol na h-Ordaig defines the base of this unit.

The pseudotachylyte is found in ridges consisting almost entirely of pseudotachylyte, such as that near Loch an Geohidach, but the largest development is in the E-W ridge of Maol na h-Ordaig. Jehu and Craig in a splendid understatement said that in this locality "there is a remarkable development of the flinty crush rock." Remarkable indeed, for it is easily the largest mass of flinty crush within the present area, and probably within the Hebrides as a whole, though it is by no means as completely homogeneous pseudotachylyte as in some other localities. Very strong E-W jointing is again present, these joints show a considerable tendency to curve.

Unit 4.

The rocks of this unit are distinguished by a complete absence of crushing and jointing, and are perfectly ordinary acid gneisses trending roughly 100° and containing concordant amphibolite bands. A strong, steep E-W feature defines the base of this unit. The situation is complicated at the west end of the unit, where it is terminated against a NE trending fault, and also at the east end where it is faulted against a large mass of crushed and pseudotachylytic rock forming the hill Ru Melvick. This probably represents an up-faulted portion of Unit 3.

Jehu and Craig described a quartz-andesine-hornblende-clinopyroxene -garnet granulite, typical of a Scourie dyke, from this area, but their locality "west of Ru Melvick" was rather vague and it was not found. In view of the structural position of the gneisses of this unit, it is proposed to consider them as Eastern Gneisses rather than Western (in Barra terminology), though on purely lithological grounds they could be either.

Fig. 24 represents an interpretative section across this part of South Uist, in which each of the units is represented as a thrust-sheet. It will be noticed that the "Eastern Gneisses" of Unit 1 are shown as thrust-wedges which have been over-ridden by other sheets from the South east. The extreme crushing and pseudotachylyte development in Unit 3 may be a result of its position sandwiched between sliding masses, with the production of E-W trending imbrication structures.

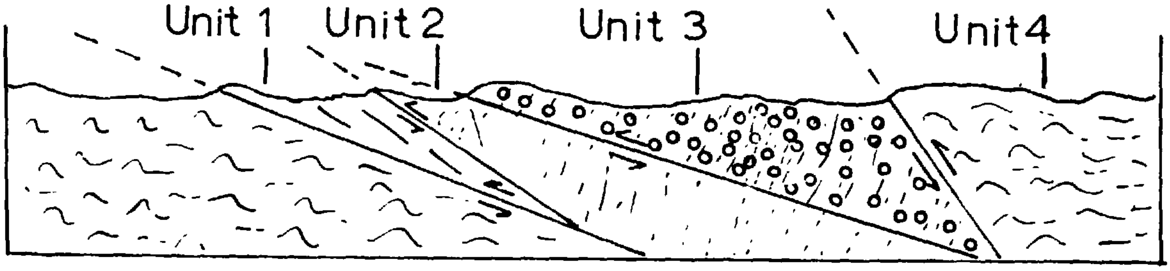
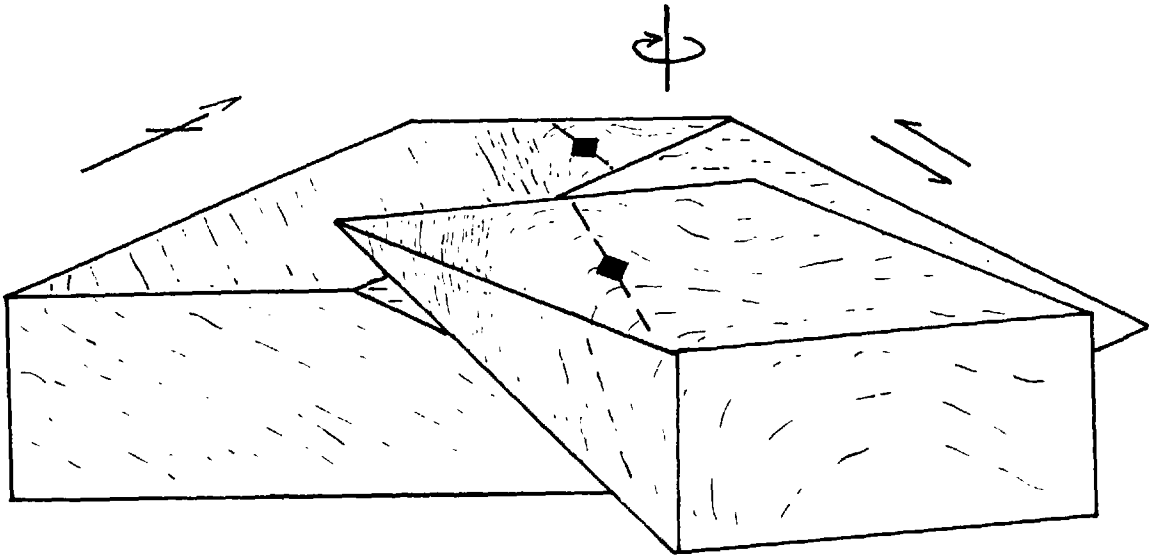


Fig 24 Schematic section across S. Uist Thrust Zone



BLOCK DIAGRAM ILLUSTRATING ROTATIONAL AND TRANSLATIONAL DISPLACEMENT ON THRUST IN BARRA

This situation is very closely akin to that further north, where Coward has shown the Eastern Gneisses of South Uist to be situated between major thrusts to the west and the thrusts associated with the Usinish mylonites in the east. In this light, the Eastern Gneisses of Barra could be seen as an over-thrust sheet of gneisses which has completely over-ridden the South Uist Eastern gneisses in the South, with the degree of over-riding decreasing northward.

The Age of Thrust

The Outer Hebrides Thrust is a major tectonic feature, and it is clearly important to know its age. Two lines of evidence may be used to determine the age, direct and indirect.

Direct evidence is unfortunately not very precise. The upper and lower limits cannot be separated by less than 1500 m.y; the upper limit is the age of Tertiary dyke (c. 60 m.y.) intrusion, and the lower limit is post-Laxfordian (c. 1600 m.y.), since these are the youngest and oldest rocks respectively in the present area which may be used to date the Thrust.

Further afield, the Stornoway Beds of Lewis contain pebbles of gneiss affected by crushing,. and therefore it has been suggested that the Thrust pre-dates this formation. Unfortunately, however, the Stornoway Beds themselves cannot be positively dated; Jehu and Craig correlated them with the Torridonian of the mainland, while Kursten considered them to be of Old Red Sandstone age. Others opinions: have ranged as high as the Triassic.

On the mainland, however, indisputably Torrodonian conglomerates overlay north westerly trending crush belts containing pseudotachylyte, first described by Clough (1907). These belts are clearly Pre-Cambrian in age, and it is suggested that the Grian Head-Cliad crush zone of Barra, which has the same trend, may be of the same age, and is therefore also Pre-Cambrian.

Two possible methods remain of obtaining direct evidence of the ago of the Thrust itself. First, pseudotachylyte could be dated by the K/Ar method. Even if this gave a mixed age, it would help in defining a lower limit. Second, although most of the dykes cutting the Thrust are Tertiary in age, closer study may reveal dykes of other generations, and these would provide a better upper limit.

Indirect evidence is based on the comparison of the Thrust with major faults on the mainland of Scotland. There are four of these the Southern Uplands Boundary Fault, the Highland Boundary Fault, the Great Glen Fault and the Moine Thrust, and they are all of broadly the same age, late Caledonian or early Hercynian. The Moine Thrust affects rocks as young as the Cambrian, and is cut by intrusive rocks of pre-Middle Old Red Sandstone age (c. 400 m.y.) while Kennedy (1946) placed the main displacement on the Great Glen between the Middle O.R.S. and the Upper Carboniferous, and suggested that the fault may be related to early Hercynian movements.

It seems reasonable that the Outer Hebrides Thrust is of the same family of faults, and is therefore of broadly the same age, namely late Caledonian. Naturally, there are particularly close similarities between this Thrust and the Moine Thrust, a similarity which Kursten first drew attention to when also suggesting a Caledonian age for this Thrust.

Magnitude and Direction of Displacement of the Thrust

It is extremely difficult to form reliable estimates of the displacements of most of the major fractures in the world. The Great Glen immediately comes to mind of course, but other equally important faults such as the San Andreas are the subject of controversy. In general also there is a tendency to consider faults in watertight compartments, such as "wrench" or "thrust" and to underplay the possibility of more complex diagonal or even rotational movements on fault planes.

Direction of Displacement

On the Moine Thrust, "candle flamed" worm tubes in Cambrian sediments have been used to determine directly the direction of movement. No comparable structure is present here. Hopgood attempted to use sigmoidal tension gashes in the thrust zone to derive the sense of movement. On examining his photograph, however, one is not convinced that the features he is using are either sigmoidal or tension gashes. He did, however, suggest that these may have been a rotational movement on the Thrust, and in this he is partly correct.

Magnitude of Displacement

Kennedy, referring to the Great Glen, stated that "proof of lateral displacement depends however on the positive identification and corrèlation of homologous structures which have been intersected and displaced by the fault" (Kennedy 1946 p 57). Is there any such structure in the present area? There is one possibility.

It was shown that the Oitir Mohr zone lies in the core of a large F_3 antiform and that a similar large antiform may exist in the Eastern Gneisses. The boundary to the Oitir Mohr zone is a line drawn to separate areas with concordant dykes from areas with discordant dykes, and marks the south-west limb of the large F_3 antiform. A similar line is present in the Eastern Gneisses, and these two lines are off-set across the Thrust, the off-set being about 3 miles.

It is at this point that we need to know the direction of movement of the Thrust. If the movement was lateral, then the total displacement would be about 3 miles. If the movement was up the thrust plane, then the displacement could be considerably more. The F_3 Scurrival Antiform plunges N.W. at about 30°. It is therefore a simple problem in geometry to find the movement up the Thrust required to produce the observed off-set of the fold limbs. A figure of about 5 miles is obtained, and though these figures are far from precise, they do give a good guide to the order of magnitude of the displacements involved.

The large F_3 fold also gives us a very rapid means of establishing the rotational component of the displacement. The steep limb of the structure in the Western Gneiss strikes about 150° in the Eastern Gneiss it strikes 180°. Thus a roatation of about 30° clockwise is indicated. Notice that if this estimate is valid, it will tend to minimise the apparent translational movements on the Thrust, so that the actual off-set of the two lines across the thrust will be nearly 4 miles rather than 3.

The Pseudotachylyte Problem

(i) General

The origin of the Outer Hebrides Thrust and its associated pseudotachylyte present effectively the same problem. If we can deduce the conditions that produced pseudotachylyte, then we will also have a guide to the mechanism producing the Thrust as a whole.

Pseudotachylyte was first described by Clough in 1888 as "flinty crush," by Holland in 1900 as "trap shotten" bands and by Shand in 1916 as "pseudotachylyte." It has thus been known for a very long time, yet it is commonly considered to be a rather odd and exceptional material, and on the whole it is probably commoner than one might have expected, for the following reasons:-

First, it is the sort of material that might easily be overlooked by a geologist who was not familiar with it, especially if present in only small amounts.

Second, it may be disguised in the literature under a variety of names, for example "gang mylonite" or "ultramylonite."

Third, study of the literature does in fact reveal many little-known reports of pseudotachylyte. In the course of preparation of this thesis, references were found to pseudotachylyte in nearly every part of the world with the notable exception of Australia. There is a striking similarity between all these descriptions, so that any conclusions drawn on the nature of pseudotachylyte are likely to be of general application.

(ii) Previous Work

A whole host of fringe subjects is relevant to pseudotachylyte, so the topic will be reviewed under three headings; descriptive work, theoretical work on thrusting and work on the origin of pseudotachylyte.

DESCRIPTIVE WORK. Macculloch in 1800 was the first person to describe an occurrence of pseudotachylyte although he was not aware of its true nature. Clough in 1888 first described "flinty crush" in the Cheviot granite, in 1907 in several localities in the North Western Highlands, and again in 1909 from Glen Coe. Holland described the "trap-shotten" bands in charnockitic rocks of southern India in 1900, and was the first to suggest that melting of rock might occur through mechanically generated heat:- "the black tongues and veins which superficially resemble'trap' have the microscopic chacters of mylonite which has been hardened - fritted and rarely half-fused - by the heat generated through the dislocation being confined to narrow bands." Clough and Holland both had a very clear idea of the nature of the material, better, in fact than many more recent workers on the same topic.

Shand in 1916 described perhaps the best known pseudotachylyte locality in the world, in the Vredefort Granite, and also coined the word. The only significant difference between his locality and the Hebrides is that in Vredefort, there is no evidence for any major thrust or fault plane, and Shand considered that melting had occurred "caused not by shearing, but by shock or alternatively by gas fluxing." In the absence of any obvious evidence of shearing, Shand may be excused for discounting it, but he can scarcely be pardoned for introducing the term "gas fluxing" without definition or explanation. This vague term has been used by many later workers, and has caused nothing but confusion

Jehu and Craig's work (1935 etc.) was mainly descriptive, and requires no comment apart from pointing out that they were aware "that these peculiar rocks are the product of mechanical stresses which have at places raised the temperature to an extent sufficient to bring about melting in the crushed gneisses."

Waters and Campbell (1935) attempted to clarify the nomenclature of mylonitic and related rocks, and also described mylonites from the San Andreas Fault, and particularly "ultra mylonites" which they defined as "homogeneous aphanitic rock of cherty, felsitic or quartzitic appearance. Differs from flinty crush and pseudotachylyte in the absence of evidence of fusion."

Some of their ultramylonites contain isotropic bands or layers which grade into layers with a sub-microscopic granular appearance, but Waters and Campbell concluded that "the apparently isotropic base of these rocks is certainly not now glass, and there is very little evidence that they were ever molten," and they attempted to extend similar arguments against the melting origin of pseudotachylytes generally, suggesting that they are the result of extreme milling down of rock to an ultra microscopic paste. They do admit at least the possibility of melting, however, and came to no definite conclusion. Although they introduced the word "paste" Waters and Campbell do not on the whole seem to have considered the possibility of anything intermediate between a powder and a liquid yet it seem natural to expect to find evidence for a continuous range of materials, from mostly milled rock powder to mostly melted.

Willemse re-examined some of the Vredefort material in 1937. His most interesting conclusion was that X-ray studies of pseudotachylyte gave results more typical of a crystalline powder of extremely fine grain rather than of a glass.

Three more recent works are worth noting. Philpotts and Miller (1963) obtained an absolute age date of 900 m.y. on a glassy pseudotachylyte from Quebec. This is probably a mixed age, since it is very close to the age of the adjacent gneisses. Park (1961) re-examined in detail one of the flinty crush belts in the Lewisian of the Loch Marree area described by Clough. He observed small quantities of glassy material, with some spherulitic textures, and concluded that the pseudotachylyte had been formed by melting. Jensen (1969 and personal communications) has examined a locality in Greenland where pseudotachylyte occurs both as concordant stringers in a mass of banded ultramylonite, and also as discordant veinlets. Good glassy material is abundant.

THEORETICAL WORK ON THRUSTING. The literature on this topic is so extensive that is proposed only to mention the principal categories:-

First, there are the papers concerned with geological aspects of thrusting. Anderson's (1951) of course was an important early contribution but perhaps the most important of all was Hubbert and Rubey's (1959) introduction of the concept of effective pressure and the influence of pore-water pressure in sediments. This concept was extended by Carlisle (1964) in a paper to which further reference will be made.

The second principal category consists of those works dealing with sliding friction. Geologically, this is usually conceived from a rock mechanics point of view, but there has also been a great deal of pure research into friction as a whole. Theoretical and experimental work has shown that very high temperatures can be achieved locally in sliding friction. Stated very briefly, two important variables control the temperature rise in a given material; the rate of sliding, and the ratio of the real area of contact to the apparent area of contact of the sliding surfaces.

Thirdly, there is the vast field of seismology, which is primarily concerned with earthquakes, but is intimately involved with the study of how faults move.

WORK ON THE ORIGIN OF PSEUDOTACHYLYTE. It was Clough who was once again the first to realise the significance of rapid rates of movement in pseudotachylyte formation in his work on Glen Coe:- "movement of subsidence was of a somewhat unusual, probably very rapid type, as is indicated by the manufacture of a flinty crush rock at some points." (Clough 1909).

Jefferies (1942) was the first and so far the only author to quantify the problem. He showed that at a depth of 1 km. the rate of generation of heat in sliding friction would produce melting when the rate of sliding was about 5 cm. per sec, and that pseudotachylyte should be expected normally on fault-planes since earthquake data show that rates of movements producing shocks are very high. Since it is not commonly found, he suggested that the displacement must take place in very small stages indeed, and that a fault of 100 metres displacement would have to be the result of at least 2,000 separate movements if pseudotachylyte was not to be produced.

This agrees well with earthquake data, which shows that single displacements of as much as 6 metres are very rare, and that most movements are of stochiastic or stick-slip type.

Perhaps because it was couched in rather terse, mathematical terms, Jefferies paper has been almost completely ignored (it is never referred to by later authors) and other hypotheses have been proposed, notably the concept of fluidization by Reynolds (1954). Since this paper has received widespread acclaim, it is proposed to consider its relevance at some length later in this section.

The most recent contribution to the study of the origin of pseudotachylyte is by Philpotts, based on work in Quebec. (Philpotts 1964). He reached five important conclusions:-

First that pseudotachylyte formed by frictional fusion can be distinguished from rocks of similar appearance by the presence of features such as glass, and recognizes two categories of rock that might be termed pseudotachylyte; injected mylonites consisting of fragmentary material, and melted rocks produced by frictional heating.

Philpotts seems here to be following Waters and Campbell's rather strange separation into wholly fused and non-fused types, when it is much more natural to think in terms of a range of partly fused types: those at one extreme being mostly fused and those at the other mostly fragmentary - in other words a paste of fused and unfused material.

Second, the chemical analyses that he undertook showed that total melting rather than partial melting occurred in the formation of pseudotachylyte. He also suggested that regionally elevated temperatures of the rocks were essential before melting could occur, and produced some very unconvincing evidence to demonstrate this had been the case in his field area.

Third, he suggested that pseudotachylyte is not the end result of extreme mylonization, and that mylonization reduces the probability of fusion occurring. Philpotts also suggested that quartz must be present in the rock, since it hinders the production of mylonite, but this can scarcely be true generally, since there are numerous accounts of mylonites in quartz-rich rocks.

Fourth, he suggested that abundant gas was involved in the formation of pseudotachylyte, as evidenced by the amygdules and vesicles found in the occurrences in the Himalayas and the Antarctic. He further suggested that hot gases escaping from sliding surfaces might cause melting along fractures some distance away, in undisturbed rock. This is inherently improbable if one considers the likely temperature of such gases, their thermal capacity, the specific heat and latent heat of fusion of rocks, and the Joule-Thomson cooling that the gases would undergo as they escaped from the sliding surface.

Fifth, and perhaps most interesting, that selective melting of included material in the molten pseudotachylyte tends to alter the composition of the liquid, and that rapid decomposition of biotite tends to produce aluminium rich liquids. As Philpotts points out, mafic fragments are very unusual in pseudotachylyte and seem to break down before quartz and feldspar. The significance of this point is that though total melts appear to be formed first, in their subsequent history their composition can be changed, by digestion of fragmentary material.

This extended survey of the literature has been included to emphasize that this is an extremely well described and much debated topic, and it is therefore hard to introduce new facts into discussion and even harder to offer new explanations.

(iii) The Nature of the Material

Numerous authors (for example, Waters and Campbell, Willemse and Philpott) have cast doubts on the origin of pseudotachylyte as a melt, and have suggested that many pseudotachylytes may be merely intruded unfused mylonitic material. This seems unlikely for the following reasons:-

First, all transitions exist between indisputably melted, glassy material and material composed of crystalline phases. This may be the case in Waters and Campbell's "ultramylonites with isotropic matrix," and certainly seems to be the case in the example described by Jensen

Second, it is difficult to envisage a process of sliding which leads to melting through the generation of frictional heat that would not also produce a great deal of fragmentary material. A pastey mixture of melted and non-melted material would be the expected product.

Third, it is very difficult to understand how any sort of unfused mylonitic material could be intruded as veins and dykes, without being mobilized by some sort of fluid.

It is thus concluded that wherever glassy or intrusive pseudotachylytes occur, melting has taken place, at least to a limited extent.

(iv) Factors Controlling Pseudotachylyte Production

GAS. Shand, Reynolds and Philpotts have all stressed the importance of gas in pseudotachylyte formation, and their suggestions have been widely accepted. The only direct evidence for gas activity, however, is the vesicles which are found in some localities of pseudotachylyte. Such vesicles are often filled with minerals usually associated with hydrous alteration (quartz calcite and chlorite in the Antarctic locality) which may suggest the presence of low temperature gases. Vesciles on the whole, however are not common, and it is suggested that where they are found, gas played a secondary rather than a primary part in the formation of pseudotachylyte.

The industrial process of fluidization was introduced to geology by Reynolds in 1954. She described many examples of geological phenomena which could be explained by this previously neglected mechanism. Many of these examples are first class, but unfortunately she also attempted to explain the occurrence of pseudotachylyte in the Vredfort area on the same basis, inspired perhaps by Shand's concept of "gas fluxing." There are four principal objections to interpreting pseudotachylyte as a fluidization phenomenon:-

First, as Reynolds herself states in her paper, a fluidized system requires the free passage of very large volumes of gases. Most of the geological examples she cited were in potentially gas abundant environments, such as near volcanoes or granite intrusions. In the case of pseudotachylyte, however, it is impossible to suggest a source for such large volumes of gas, nor is there any passage for its flow. A fluidized system must inevitably be an open system; all pseudotachylyte occurrences suggest that they formed in closed systems.

Second, in the industrial applications of fluidization, one of the chief purposes is to accelerate reactions in the gas/particle system, and in many of the geological examples quoted by Reynolds, the material concerned is visibly altered. The intrusive appinites, for example, (of the type first described by Pitcher and Read) show excellent onion skin alteration of the pebbles involved, which is what one might expect if they had been in contact with hot, high pressure gases. The walls of the intrusion pipes are similarly altered. In no case, however, has an occurrence of pseudotachylyte been described in which the fragmentary material or the wall rocks are at all altered.

Third, Reynolds considered that veins and dykes produced by this mechanism should be non-dilational, and showed in the case of the famous enstatite granophyre of Vredefort that this might be the case . In the case of pseudotachylyte, it is often possible to show that the veins are dilational, by matching up features across them. There is some room for argument, however, in the case of the pseudotachylyte conglomerates.

Fourth, she suggested that a gas/particle fluidized system would act as a sand blast and would account for the observed rounding of the included fragments. Such rounding is well seen in the present area (Photo 33) and does require explanation. That it need not have been produced by sand-blasting is suggested by the results of laboratory experiments by Kuenen and others, who have shown that the bulk of rounding occurs relatively rapidly in the first part of the experiment, that large fragments are much more easily rounded than small ones (by a factor of 300 times) and of course that such rounding can occur in liquid/particle systems.

The problem of rounding will be returned to later, but on the basis of the evidence so far, it is suggested that gases may be discounted in considering the primary origin of pseudotachylyte.

ROCK TYPE. Almost all the known occurences of pseudotachylyte in the world are in granites or gneisses. If one was to say merely crystalline rocks, this would sum up the distribution neatly, and take account of the few occurrences in hornfelses and quartzites. Rocks of granite gneiss composition are by far the most common, though Philpotts has described occurrences in jotunites and norites. In the present area, pseudotachylytes may be found in both amphibolites and gneisses, but it is always impossible to say whether it has been introduced. amphibolites, or whether it was actually formed from amphibolite. Philpotts has shown that slight differences in composition are found in pseudotachylytes from different rock types, and this aspect would be well worth further investigation.

Chemical considerations apart, the rock type is significant for two reasons; first, because variations in pore-water content of rocks can materially affect their behaviour in thrusting as we shall see later, and second because variations in mechanical properties can produce variations in the heat generated in sliding. The important variables are the rate of sliding, the coefficient of friction and the ratio of the true to apparent area of contact.

Sliding surfaces are considered in terms of asperities (no surface is perfectly smooth) which interlock and fuse on sliding, and it is the shearing of these fused asperities which produces resistance to sliding, or friction. As Bowden and Taylor (1956) show:-

$$\text{Coefficient of friction} = \frac{F}{N} = \frac{As}{Ap} = \frac{s}{p} = \frac{\text{shear strength}}{\text{yield pressure}}$$

where: F = frictional force, N = normal load, A = area

Now in an unloaded state, the asperities form the only true contact between the two surfaces, and the area of contact may be as low as 1 millionth of the apparent area of contact. On loading, the asperities deform, elastically initially and ultimately plastically, and the true area of contact increases. Archard has shown that the coefficient of friction decreases with load in the elastic stage, but remains constant with increasing load in the plastic stage. This is where the effect of rock type is important. Strong rocks, such as granites and quartzites will not show a very great increase in area of real contact, while weaker rocks will, under the same conditions. This is illustrated by a table of Carlisle's:-

Rock type	Pm (Yield pressure) 10^3 Kg/cm^2
Quartzite	18 - 55
Granite	42 - 48
Basalt	29 - 57
Limestone and marble	4 - 15
Siltstone	1 - 4

Thus, under the same loading conditions, a marble, for example, would show a much higher area of real contact than a granite, and this in turn means+that the temperature rise at the asperities would be higher in granite than in marble. Under given conditions, then, crystalline rocks are inherently more likely to produce the high temperatures required to produce pseudotachylyte than weaker materials.

DEPTH OF BURIAL. Several authors, most recently Park and Philpotts have stressed the necessity of great depths of burial in order to obtain the high temperatures required to produce pseudotachylyte. Philpotts suggested a background temperature of at least 400°C. The reverse may in fact be the case, in other words that pseudotachylyte formation is less rather than more likely with increasing depth and temperatures. This is indicated for the following reasons:-

First, in considering melting taking place at tiny asperities on sliding surfaces, the total amount of energy involved at each asperity is relatively small whereas the total amount of energy available in sliding is relatively large, and could easily provide sufficient heat to increase the temperature at the asperity by, say, 200°C.

Secondly, the mechanical properties of rocks are drastically changed by increasing temperatures. Any text on rock mechanics will show time-strain graphs for rocks at different temperatures:- at ordinary temperatures the initial, instantaneous elastic strain is followed by primary or elastic creep, secondary steady state or pseudoviscous creep and tertiary or accelerating creep. At higher temperatures, the creep mode of deformation sets in earlier, and becomes much more extensive. This has two consequences:-

In hot rocks, the asperities on sliding surfaces will be much more liable to deform plastically, thus increasing the true area of contact and reducing the possible temperature in sliding.

Also, and more important, with increasing depth, there will be much less tendency for rocks to fail at all - the rocks will no longer show brittle behaviour but will respond to shear stresses on the fault plane by a slow creep. Clearly, in the absence of brittle failure, sliding of course will not occur, and thus pseudotachylyte will not be formed.

RATE OF SLIDING. This will be considered from two points of view:- the rate of sliding required to generate sufficient heat to cause melting, and the rate of sliding that can actually be expected to occur in geological environments.

The work of Bowden and Taylor (1956) etc. can be used to obtain directly a value for the temperature rise in sliding. Their method is briefly summarized in an appendix, but it should be emphasized that it applies to an asperity of an ideal granitic rock sliding over similar material. It deviates from natural situations for the following reasons.

First, the rubbing surfaces would not be simple planes, but complex zones of rupture and deformation. The concept of asperities however will apply on the microscopic scale of individual surfaces in the zone.

Second, it assumes mechanical properties for the rock material which have been determined in the laboratory on small specimens, which may not be directly applicable to natural rocks.

These factors must be borne in mind when considering the results, which show that at a normal pressure equivalent to a depth of 1 k.m. a temperature rise of 180°C will occur in steady sliding at 1 cm. per sec., and that the temperature increases approximately logorithmically with rate of sliding, so that at 10 cm/sec a temperature rise of 1400°C would theoretically be expected.

Jefferies considering the problem in terms of bulk heat energy generated and the rate of dissippation of heat, concluded that, for the same depth of burial, a rate of sliding of about 5 cm per sec would be necessary to produce fusion. There is clearly a fairly good agreement between these two independant methods, and they provide a guide to the order of magnitude of the rate of sliding necessary to produce melting.

In considering the rates of sliding that may be expected in geological situations, we have to resort to seismological methods. It can be shown that when displacement along a fault results in an earthquake the two sides of the fault will move past one another with a relative velocity V, where

$$V = \frac{TS}{2G}$$

and where T = average strength of the surface
S = shear wave velocity in solid
G = bulk modulus of material

Now depending on the figures used, this gives values for rate of sliding between 500 cm/sec (Jefferies) and 1,000 cm/sec (Ambraseys). This is clearly greater than the velocity required to produce sliding by a factor of about 10, and as Jefferies observed, one would expect to find pseudotachylyte on most faults. Ambraseys has indicated two possible reasons why this is not in fact the case.

First, he has shown that in modern earthquakes, partiaularly in Anatolia, a fault-scarp is almost always produced, which may be many feet high, but that the severity of damage produced by the earthquake is much less than one would predict from an instantaneous movement of several feet, and he has shown that in fact the total displacement at the time of the earthquake is very small, and that the large displacements are produced after the main shock by creep, which may continue for several hours.

Secondly, he suggests a modification of the above equation which takes account of the residual strength on the surface by a factor p, which is the ratio of the strength at failure to the residual strength:-

$$V = \frac{TS(1 - p)}{2G}$$

p is a function of the depth of burial and the nature of the material. At shallow levels and in brittle materials, p approaches zero, while at high confining pressures and depths, materials are more ductile and p approaches 1.0, reaching 0.9 at about 15-20 k.m. At low values of p, maximum relative velocities are obtained, and as p increases, the velocity decreases. At p = 0.75, a value which corresponds to the depth at which shallow earthquakes occur, the velocity would be above 100 cm/sec.

A complicating factor is introduced by strain rate. The sort of movement we are considering on faults is caused by a sudden failure in response to gradually and continually increasing stresses- after failure, these stresses begin to build up again, so that the movement on the whole follows a "stick slip" cycle. For very slow strain rates, each of these stick-slip cycles may be considered as an individual fracture, independant of others before or after it, but in which the peak, strength of the surface is much below what it would be in an undisturbed mass, and the strength drop on failure is very small, so that p approaches 1.0. As Ambraseys states "if p = 1 there will be no energy release and no shock, and if p = 0, there will be a maximum velocity with which the fault will move, but the work done on the fault will be zero."

The significance of this for our purposes is that where p = 1 particularly at great depths there will be no release of strain energy on the fault, which will move in a slow continuous creep, whereas where p = 0 the fault will move in a sudden, fast jerk, but no work will be done in sliding, and thus no heat will be generated. For melting to occur in sliding, work must be done, and this is done where p is greater than zero, in overcoming the residual strength of the surface.

For vertical faults, which are the cases where the factor p is principally concerned, one would expect melting to occur at relatively deep levels, but in the case of low angle thrusts not only does one have to consider the residual strength of the surface, but also the work done against gravity, and thus one would expect melting at much shallower levels. This might explain why psuedotachylyte is more commonly found on large thrusts than on vertical faults.

FLUID PRESSURE. We have already noted that pseudotachylytes are confined to crystalline rocks. Thus our problems are very different from those that have arisen in most studies of thrust mechanisms, such as that of Rubey and Hubbert who were dealing with sediments saturated with water. Carlisle even went so far as to suggest that the nose of his thrust, the Roberts Mountain Thrust, ended up in the sea. Their ideas, however are important. Rubey and Hubbert suggested that pore water in sediments might reduce the effective pressure, and thus reduce the coefficient of friction to very low values, as low in fact as 0.078 which is close to that for materials sliding on ice.

Carlisle developed their concept, and suggested that all that would be required would be a thin saturated clay layer at the interface, which would have a very low shear strength, and therefore a very low coefficient of friction, low enough in his case to allow the upper plate to glide some 50 miles down a slope of only a few degrees.

Highly interesting though these ideas are, it is difficult to apply them to the present situation. Data on pore water pressure in crystalline rocks are very scarce, and it seems unlikely that pore water could significantly affect the load pressure in fresh rocks. (Notice that we are only concerned with liquid water, since water vapour, being compressible, will not affect the issue). However, the crush zones of faults and thrusts in crystalline rocks could well be permeated by water, so that the effective pressure concept could be applied to the later stages of thrusting. If this were the case, then one would expect the coefficient of friction to be reduced in the later stages, and therefore one would expect pseudotachylyte to be formed only in the initial stages of thrusting.

It is interesting to speculate here on the part pseudotachylyte itself might play. Could a melt of rocks on a fault-plane provide its own thin film of liquid which would act as a lubricant? This is of course a possibility, because the liquid will have a low shear strength, and therefore a low coefficient of friction, and would also reduce the effective pressure. Such a situation, however, would be self-terminating since as soon as the effective pressure on the surface is reduced, the rate of generation of heat will decrease, and the pseudotachylyte will solidify again, so the whole process would grind to a halt, unless some sort of equilibrium were attained.

(v) The Problem of Pseudotachylyte Intrusion

In trying to define the condition and environment in which pseudotachylyte is formed, it is important to consider its very distinctive mode of intrustion, which appears to be much the same the world over. Three general types of intrusion were described earlier, and are probably of general application:-

First, along distinct, regular planar surfaces as thin veins or stringers, and often associated with minor mylonites.

Second, as irregular, non-planar veins or dykes, up to six inches thick, which may show darker "chilled" edges.

Third, as the matrix to conglomerates.

No example was found of a conglomerate that was not intimately associated with a member of the first type, which forms a floor or ceiling to the conglomerate. (Photo 33). The first and second types, however, may be found entirely independently. It is suggested that it is only in examples of the first type, that pseudotachylyte can have been generated by sliding friction, since these clearly can be interpreted as shear planes along which movement must represent intrusion of pseudotachylyte away from the source of generation.

How do we account for the formation of these highly irregular veins and conglomerates? It is not possible to introduce any hypothesis which involves compressive stresses, since these are well known to produced shear planes or regular geometry. It is suggested that they can only be produced by tensile failure in brittle conditions. Tersile failure in rocks has been little investigated in general, due to the; practical difficulties involved in performing anything more than simple uniaxial tensile strength tests.

Apart from boudinage, examples of tensile conditions are unusual in geology, except, possibly on a continental scale. How do they arise in the present circumstances? It is suggested that they arise as a result of the reflection of shock waves at a surface, which produces the phenomenon known in mining and civil engineering as spalling. Ambraseys has explained the mechanism as follows:-

> "Consider a plane wave from an explosion or earthquake advancing in a semi-infinite elastic solid, with a given shape, amplitude and speed, impinging on a free surface. At this moment, a similar wave, but with opposite sign, will arise and will interfere with the arriving wave in order to satisfy the stress free condition at the surface. As these two waves sweep past one another in opposite directions, these will be a moment and also a distance from the free surface when the resulting stress will become tensile, and equal to the tensile strength of the solid. Splitting of the mass will occur, and a 'slab' of the solid will be detached, carrying away part of the momentum of the wave and becoming an independant vibrating system."

Putting this in geological terms, if one had a free surface, in this case a shear plane in a rock mass, then in the event of an earthquake arrival of the stress wave from the earthquake at the free surface would momentarily produce tensile conditions. This would cause fracturing of the rock adjacent to the free surface, which would ideally produce a slab of rock, but is more likely in practice to produce broken fragments.

Such fragments would naturally be angular. How then do they become rounded, as we observe them in pseudotachylyte assemblages. Two possible mechanisms are suggested:-

First, during later movements on the free surface (shear plane), pseudotachylyte would be generated and would be intruded into the spaces around the fragmented material, producing in the first instance a pseudotachylyte breccia. The liquid pseudotachylyte however, would have a finite quantity of heat energy which might produce local melting of the fragments before the whole became cooled by conduction. Such melting might cause a certain degree of rounding, but is more likely to produce textures suggesting digestion. Such textures are in fact commonly observed.

Secondly, in circumstances where angular fragments of gneiss were contained in a matrix of solid pseudotachylyte, there would be marked contrasts in properties across the interfaces between fragments and pseudotachylyte. Such margins would provide ideal planes of weakness, and in the event of later shocks or stresses, small movements would tend to concentrate along these surfaces. This would produce a smoothing off of the surface of the fragment, but it would not necessarily produce rounding. Strongly curved fractures or joints may, however, be developed and by the intersection of several such joints, a roundedpebble might be produced. This naturally sounds suspect, but such curved joints are in fact quite common. Photo 36 illustrates a very good example. Here the rounded edge of a pebble may be traced directly into a curved joint or micro-fault, which very convincingly truncates another pebble.

36. A pseudotachylyte conglomerate on Gighay. Notice the rounded pebble shapes and the curved joints. NF 772043.

Conclusions

In the preceding pages, the environment and conditions favourable to the formation of pseudotachylyte have been reviewed, and it is clear that these conditions are not particularly exotic. It is proposed to conclude, therefore, by attempting to answer two questions·- Why is pseudotachylyte relatively rare in nature? and what is the relationship between pseudotachylyte and mylonite?

The Scarcity of Pseudotachylyte

It is suggested that the rareness of pseudotachylyte is more apparent than real. The "intrusive" mylonites of some earlier authors are almost certainly pseudotachylytes, and we have already seen that there are good grounds for thinking that some "ultra mylonites" consist at least partially of fused material. Ultramylonites are relatively common in the literature, and it is suggested that further close examination of some of these would conclusively reveal the presence of pseudotachylyte.

Furthermore, it is remarkable that in that part of the world which has been known longest and mapped in greatest detail (Northern Scotland) the largest number of pseudotachylyte localities have been described. It is suggested that if, for example, parts of the Canadian shield were mapped in similar detail, more examples would be forthcoming.

The Relation Between Pseudotachylyte and Mylonites

Mylonites are well known throughout the world, and are very well developed in the Highlands along the Moine Thrust. Also, as one traces the Outer Hebrides Thrust (zone) northwards, mylonites appear to become progressively more common. On a brief reconnaissance of the Thrust in the Park district of Lewis, it was noted there that pseudotachylyte was subordinate in volume to mylonitic material, and that it tended to occur as ill-defined streaks interbanded with the mylonites. Similar relationships have been described by Park, Jensen and many other authors, and there is clearly, as one might expect, an intimate relationship between the two. What factors dictate whether mylonite will be produced instead of pseudotachylyte in the same rocks? In the writer's opinion, only three variables can affect the issue.

First, the mechanical condition of the rocks. Ambraseys pointed out that most faulting occurs along the line of pre-existing fault zones or shear zones. This may seem obvious, but it is most important because the strength of sheared, damaged rocks is much less than that of fresh rocks, and consequently much less work is done in the course of movements in an old fault-zone than in a completely new fault. It is possible that pseudotachylyte may be formed during the first movements of a new fault, but not in its subsequent history. Later movements in the fault-zone, of course, may obliterate any evidence of earlier pseudotachylyte, and the whole will constitute a zone of crushed or milled rocks, in other mylonite.

Second, pore water pressure. In a thrust zone, the crushed rocks will naturally be more permeable to liquids than fresh rocks, so a pore water pressure could act in the later history of the thrust, reducing the effective pressure and thus the work done in thrusting, and therefore reducing the probability of pseudotachylyte formation.

Therefore in rocks with an appreciable pore-water content one would expect to find mylonites rather than pseudotachylytes.

Third, and by far the most important, there is the effect of strain rate. As we have seen, pseudotachylyte requires high strain rates, whereas most geological processes are customarily considered to be exceedingly slow. Slow strain rates in rocks at ordinary temperatures will cause crushing, fracturing and mechanical granulation of polycrystalline aggregates. The "cataclastic flow" will lead to this production of a very fine grained homogeneous rock powder, which might well be described as an "ultra mylonite." At higher temperatures, the material will behave in a more plastic fashion, and recrystallization or annealing may occur, and this may account for the very marked banding that is frequently observed in mylonites, as some sort of segregation may occur during re-crystallization.

Differences in strain rates can thus very simply and easily be used to explain the contrast between the Moine Thrust, characterised by mylonites, and the Outer Hebrides Thrust, characterised by pseudotachylytes. The factors controlling strain rates must be left to discussion by geotectonic philosophers.

APPENDIX

Temperature Rise in Sliding Friction

In the text of this section some figures were quoted for the temperatures which might be expected on faults. The background work was not really relevant to the text, but it may be of interest to summarize it briefly here.

As we saw earlier, the two chief variables controlling the temperature rise are the rate of sliding and the ratio between the true and apparent areas of contact of the sliding surfaces. The first of these is rather obvious, the second perhaps less so. No surface, however highly polished, is perfectly smooth, and under the microscope any surface will be seen to consist of asperities and depressions. The resistance to sliding is produced by asperities interlocking, and it is the strength of these asperities which govern the coefficient of friction. Naturally, as the load on the surface is increased, each asperity deforms and increases its area of contact. Bowden and Taylor (1956) show that under conditions of sliding contact, the area of contact at each point is a circle of diameter d, and that

$$d = 1.75 \quad Wr\left(\frac{1}{E_1} + \frac{1}{E_2}\right)^{\frac{1}{3}}$$

where W = load
r = radius of original hemispherical asperity
E_1, E_2 = Young's moduli for surfaces in contact

and that the mean pressure, p, at each point is therefore:-

$$p = 0.42W^{\frac{1}{3}} \quad r \left(\frac{1}{E_1} + \frac{1}{E_2}\right)^{\frac{-2}{3}}$$

Under quite small loads, the asperities crush down plastically until they can support the load when:-

$$p_m 4l^2 = W$$

where p_m = yield pressure

$2l$ = length of side of square of area equivalent to area of contract.

As the area of contact increases with increasing loads, the force per unit area, or yield pressure thus tends to remain the same, and this is in accordance with laboratory observations.

Now Blok and Jaeger (1942 etc.) show that the temperature rise in sliding, T, is given by the expression:-

$$T = \frac{UWgv}{4.24lJ} \quad \frac{1}{K_1 + K_2}$$

Where U = Coefficient of friction
W = load
v = velocity of sliding
$2l$ = length of side of square equivalent to area of actual contact region.
K_1, K_2 = Coefficients of thermal conducting of the two surfaces.

This equation assumes that a steady thermal state is reached, so it is valid for low rates of sliding only. At higher speeds, the upper surface is cooled by the oncoming positions of cooler surface, and thus the temperature rise will be less. At higher rates of sliding, then, the rise will be thus:-

$$T = \frac{x^{\frac{1}{2}}UWgv}{3.71J} \; 1.125K_1x_1^{\frac{1}{2}} + K_2(lv)^{\frac{1}{2}}$$

where x_1 is the thermal diffusivity

These are several important assumptions involved in using this expression principally:-

(1) That all the frictional energy is dissipated by thermal conduction and none is lost by surface emissivity.

(2) The heat is liberated at the contact area only, and not from within a small region of contact.

(3) That there is only one area of contact - i.e. heat produced at other adjacent points is neglected.

(4) That (for our purposes) the average size of irregularity or asperity on the sliding surface is about 0.2 cm, and that they may be considered to be roughly hemispherical.

Armed with these equations and the appropriate physical constants for rock materials, it is only a matter of rather tortuous arithmetic to obtain the temperature rise in any given conditions.

VI SUMMARY

At the beginning of this thesis, it was stated that its aim was "to produce a regional study of the area, to determine its structural and metamorphic history, and to relate this as far as possible with that of the rest of the Outer Hebrides and with the mainland of Scotland." It is proposed now to summarize very briefly the results of this work.

It has been demonstrated that the Lewisian rocks of the Barra area may be divided into a supra-structure of amphibolite facies gneisses and an infra-structure of predominantly pyroxene bearing gneisses. Both units contain representatives of the Scourie Dyke suite; in the supra-structure they are highly deformed and folded, whereas in the infra-structure they are unfolded and relatively undeformed. The infra-structure in addition contains representatives of several suites of intrusive rocks earlier than the Scourie Dyke suite, many of which retain their original discordant relationships with the gneisses. By far the most widespread of these is a suite of intrusive dykes and larger bodies of intermediate or dioritic composition, but early granites, pegmatites and other dyke sets are also recognised.

In both units the same sequence of Laxfordian phases of deformation can be recognised. An important early phase produced very tight folding of dykes and gneisses in the supra-structure, and a general "flattening" in the infra-structure, and was followed by a phase which produced the very large north-westerly plunging structures which are the principal tectonic features in the Hebrides. Folding in the supra-structure took place in amphibolite facies conditions which became progressively more widespread and caused amphibolitization of almost all Scourie Dykes and obliteration of all evidence of pre-dyke history. In the infra-structure, on the other hand, evidence for a pre-dyke pyroxene granulite facies metamorphism is preserved, and the Scourie Dykes almost all retain pyroxene-granulite facies assemblages which show little sign of later amphibolitization. It was suggested that the assemblages in the dykes, however, do not indicate a major post-dyke granulite facies metamorphism, but that the dykes may have acquired these assemblages initially, on intrusion into hot or dry county rock gneisses.

It has also been shown that in most of the area mapped, the supra- and infra-structures are separated by the Outer Hebrides Thrust, but that in one area, the Oitir Mohr, an undisturbed relationship between the two units exists, and in that area rocks of the infra-structure are structurally below those of the supra-structure, in the case of a major fold, the Scurrival antiform. This fold was also identified in the rocks above the Thrust, and was used to obtain an estimate of the displacement of the Thrust. The Thrust itself was traced from its most southerly exposure in the Hebrides, on the island of Sandray, to the southern part of South Uist, where it becomes very much more complex, and where four different tectonic units may be recognised. A fairly extensive discussion of the origin of pseudotachylyte was undertaken, and it was suggested that perhaps the most important feature controlling its production was the strain rate.

The existance of a supra-structure/infra-structure relationship was shown to be supported by independant geophysical evidence, and that in general terms the structure of the Barra area could be considered as a Scourian infra-structure overlain by a Laxfordian supra-structure. The overall similarity between the Scourian block of the mainland and that of Barra was pointed out, which is underlined by the absolute age dates obtained by Moorbath, and some comparisons were also made with other areas of low deformation in the Hebrides.

Some Suggestions for Future Work

Of the many topics that came to light in any work and which deserve following up only a few of the more interesting will be mentioned here. Perhaps the most interesting of all that arose in the present work is the way that the metamorphic state of a dyke and its country rock may control its behaviour in deformation. Almost certainly, the same problems will be met with in other areas, where dykes and gneisses may have had different metamorphic histories. It would also be interesting to see to what extent the shapes of intrusions may be controlled by the metamorphic state of the county rock at the time of intrusion.

Secondly, it is clear that areas of low deformation, such as the Scourie block of the mainland, have been areas of low deformation for very long periods. What is it that decides whether or not a particular block will remain undeformed? Is it its metamorphic state, or its regional structural position? Does the presence of pyroxene bearing assemblages produce areas of low deformation or vice versa? Answers to some of these questions would be of great value in interpreting basement structures as a whole, and in investigating the supra-structure/infra-structure relationships in general terms. In the present area, the supra-structure is characterised by amphibolite facies assemblages, the infra-structure by pyroxene granulite facies assemblages. Is this pattern a general one, in other words, are pyroxene granulite facies assemblages always at low structural levels, or is it a purely local arrangement? The general pattern of the Lewisian suggests that it may be of fairly large-scale significance, so it would be interesting to see if the same pattern can be discerned in other areas of basement rocks.

Thirdly, of course there is the question of the extent to which the conditions prevailing in the country rocks at the time of intrusion will govern the assemblage of minerals just produced in a dyke on crystallization. There does appear to be a growing body of opinion that the primary assemblage will be directly governed by the outside conditions, but there is room for argument.

There is clearly a great deal of scope for work on the large scale metamorphic conditions in basement rocks and it is suggested that future research directed at the metamorphic controls of deformation styles may throw some light on the fundamental patterns of basement structures.

Turning now to the Outer Hebrides Thrust, much still remains to be done, since even the basic mapping has not been completed, especially of the northern continuation of the Thrust in Lewis. In the present area, too, more work is required, especially in the complex area of South South Uist described in the text. Little is known of cataclastic rocks associated with the Thrust in Lewis, except that mylonites and pseudotachylytes occur together. It would be most interesting to investigate the relations between these rock types, to see if any conclusions may be reached on the factors which have produced mylonites here, but not further south.

In general terms, it would be valuable to make a study of cataclastic rocks as a whole, a group which has been largely neglected in recent years. Not only would this probably reveal closer relationships between the various types of cataclastic rocks than is generally considered (for example the pseudotachylyte - ultramylonite - mylonite group), but it would also give a much better idea of the general conditions which control the movement of major fractures.

On a smaller scale, it would be interesting to examine in detail some of the minor structures associated with the Thrust. The jointing, for example, which is so well developed in the crush-zones, might well repay analysis, and so might some of the questions posed by pseudotachylyte.- Just how rounded are the pebbles in the conglomerates, and is there any significance in the distribution of more and less rounded forms? What is the ratio of volumes of pebbles to matrix? Has there been a net increase in volume, or has digestion occurred? What is the relation between these bodies and so called "explosion breccias?" And so one might go on . . . .

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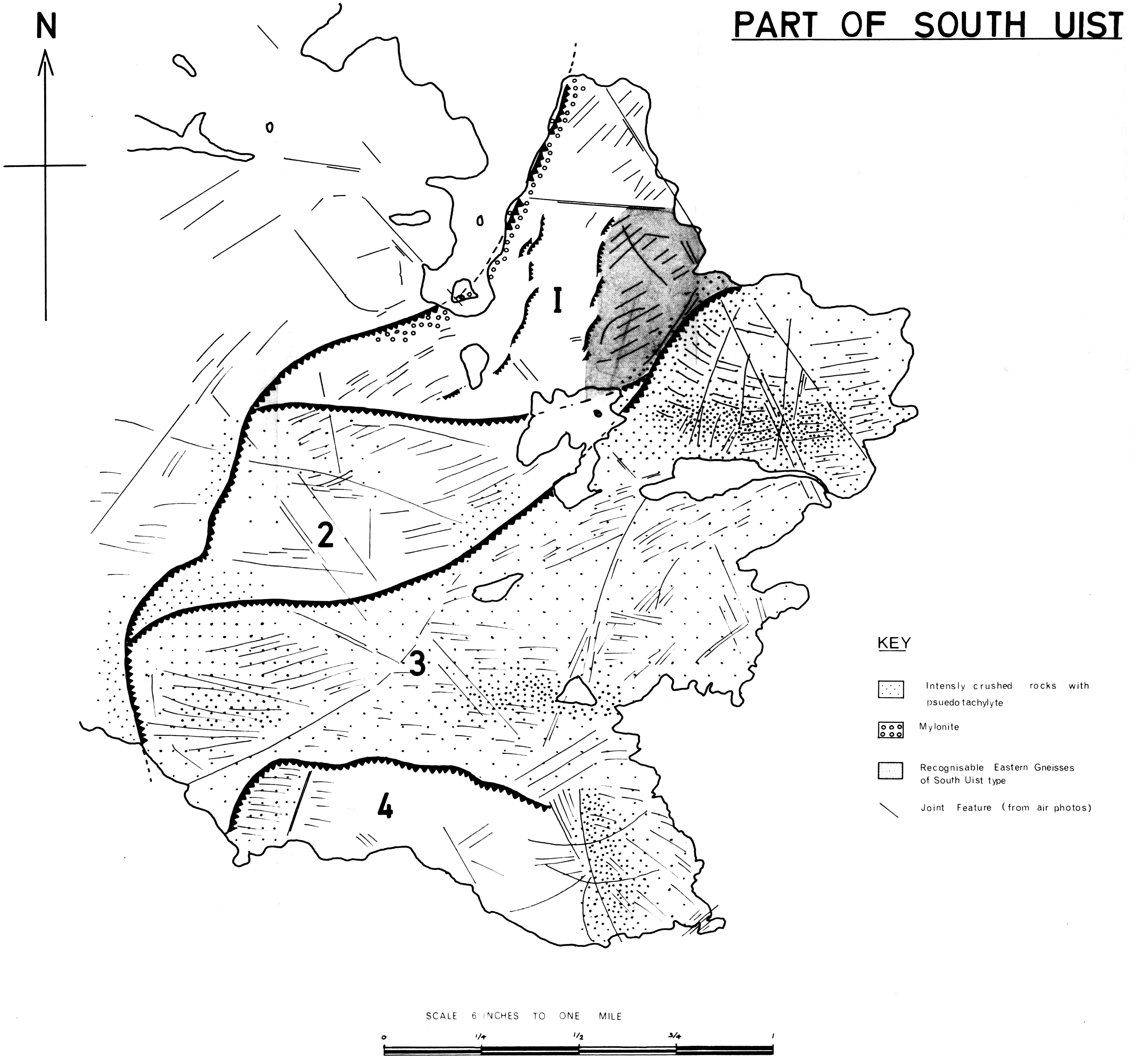
MAP 14 THE SOUTH EAST PART OF SOUTH UIST



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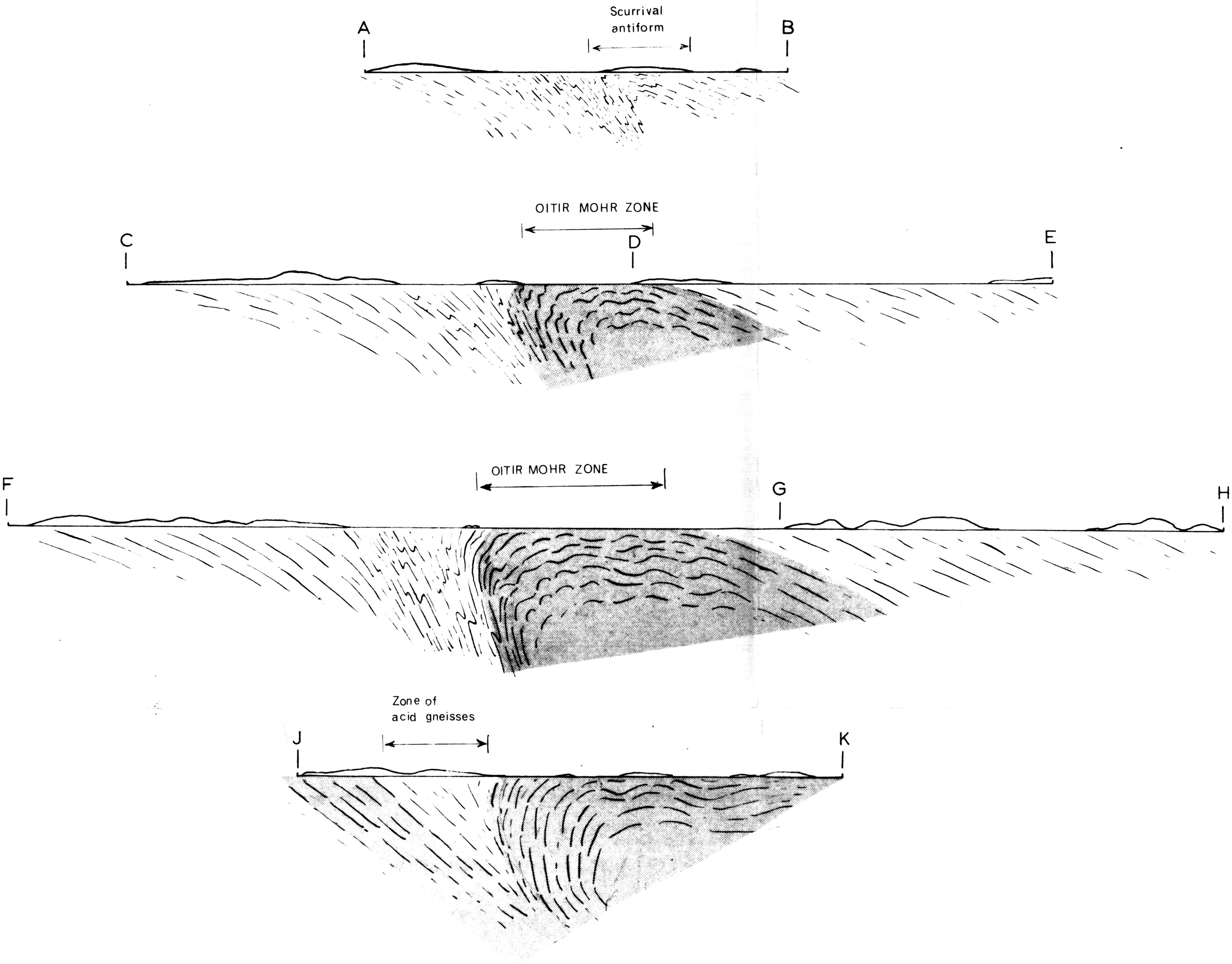

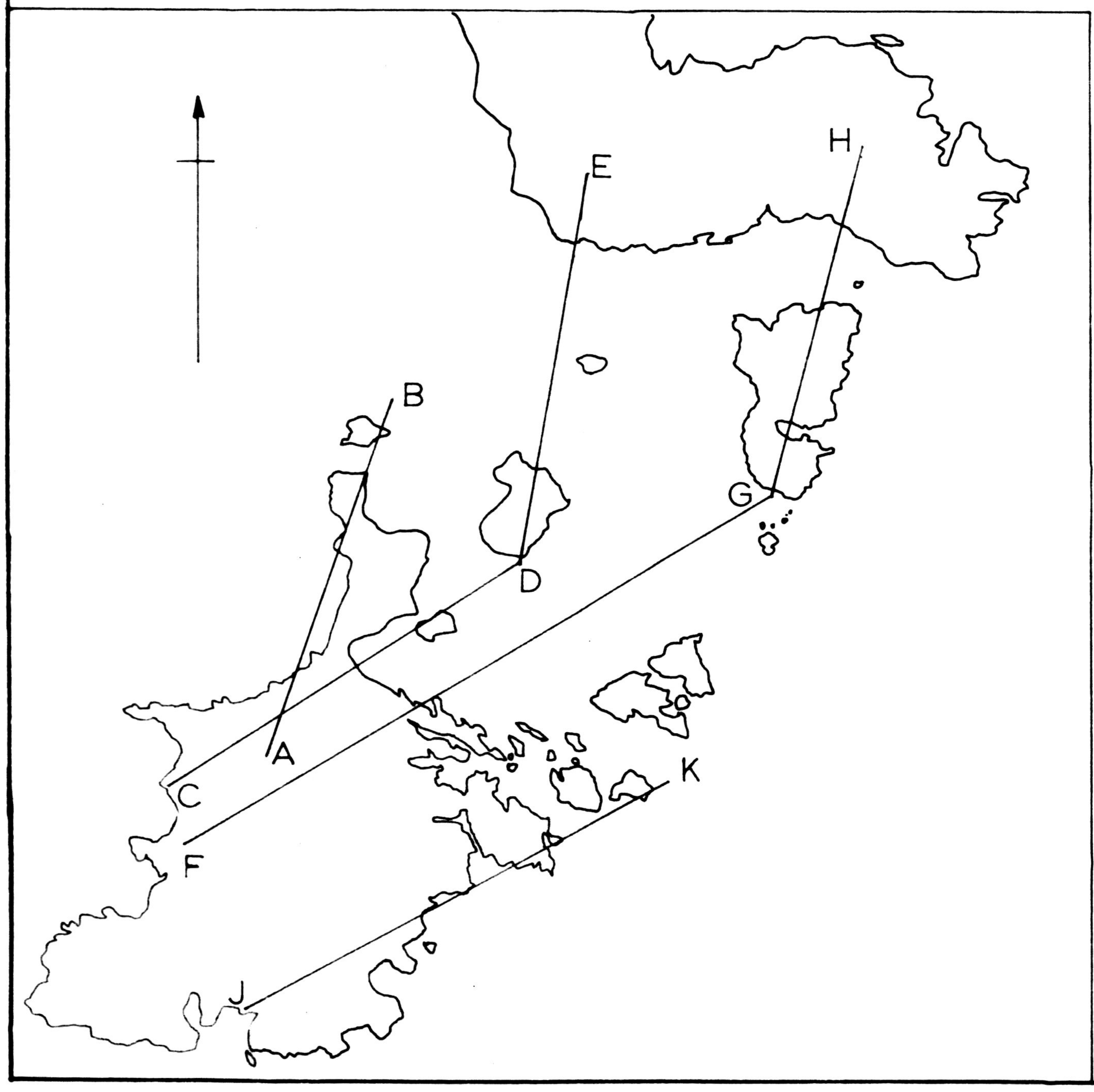

FIG. 12. SKETCH SECTIONS ILLUSTRATING THE SUGGESTED STRUCTURE OF THE AREA

☐ Western Gneisses (Supra structure)

▨ Eastern Gneisses (Infra structure)

Horizontal Scale 1 inch to 1 mile

Vertical Scale roughly twice horizontal

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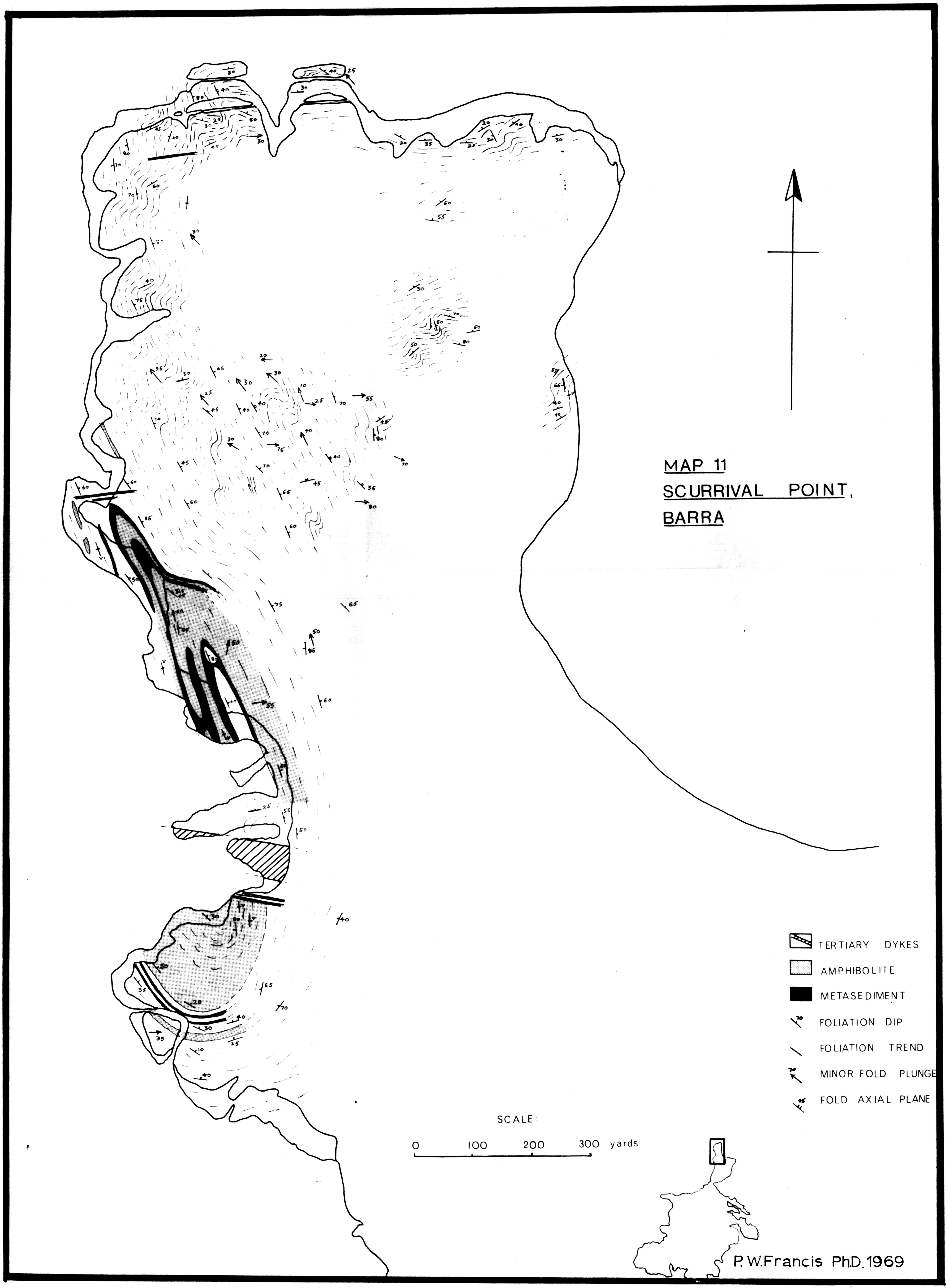

MAP 11 SCURRIVAL POINT, BARRA

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MAP 6 GENERAL MAP OF THE FIELD AREA

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MAP 5 THE EAST COAST OF BARRA

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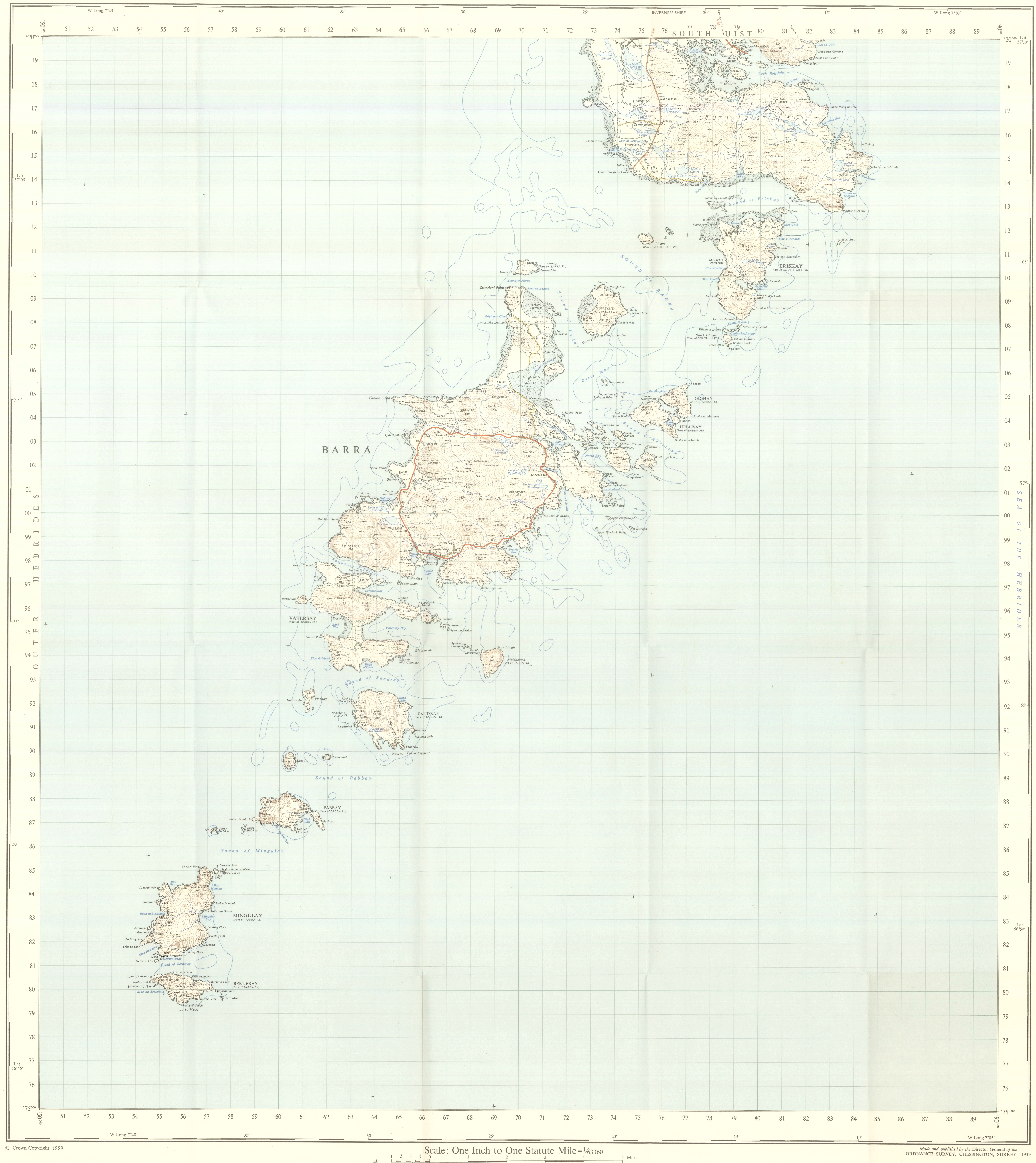
ORDNANCE SURVEY of GREAT BRITAIN
One Inch to One Mile Map (Seventh Series)

MAP 4 BARRA

SHEET 32



REVISION DIAGRAM

- Fully Revised 1956
- Road revision with later corrections
- Revised from Air Photos

Index to adjoining Sheets. Hatching denotes overlaps

Difference from Grid North

(1) True North	
4° 52′ E	N W Corner
4° 19′ E	N E ,,
4° 48′ E	S W ,,
4° 15′ E	S E ,,

(2) Mag North
about 8½° W in 1959
decreasing by about ½° in four years

Magnetic North / Grid North / True North

The Submarine Contours are given in Fathoms and are taken from the Soundings of Admiralty Surveys.

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SHEET 32

Scale: One Inch to One Statute Mile = 1/63360

1 ¾ ½ ¼ 0 1 2 3 4 5 Miles
1,000 0 1,000 2,000 3,000 4,000 5,000 6,000 7,000 8,000 9,000 Yards
1 0 1 2 3 4 5 6 7 8 Kilometres

TO GIVE A GRID REFERENCE CORRECT TO 100 METRES

The incidence of grid letters and numbers on this sheet

NF (08)
00
NL (07)

EXAMPLE		Clettu	
See diagram on left for Grid Letters. They are NL			
East Take west edge of kilometre square in which point lies and read the large figures printed opposite this line on north or south margins. Estimate tenths Eastwards	64 7 647	North Take south edge of kilometre square in which point lies and read the large figures printed opposite this line on east or west margins. Estimate tenths Northwards	89 9 899
Full 100 Metre Reference NL 647899			

The above Full Reference is unique. For many purposes the first grid letter can be omitted, giving a reference L 647899 which recurs at intervals of 500 Kilometres. If both grid letters are omitted, the resulting reference 647899 recurs at intervals of 100 Kilometres. When the area concerned is sufficiently restricted, as will usually be the case with maps on scales of one inch to the mile and larger, both the grid letters are normally omitted.

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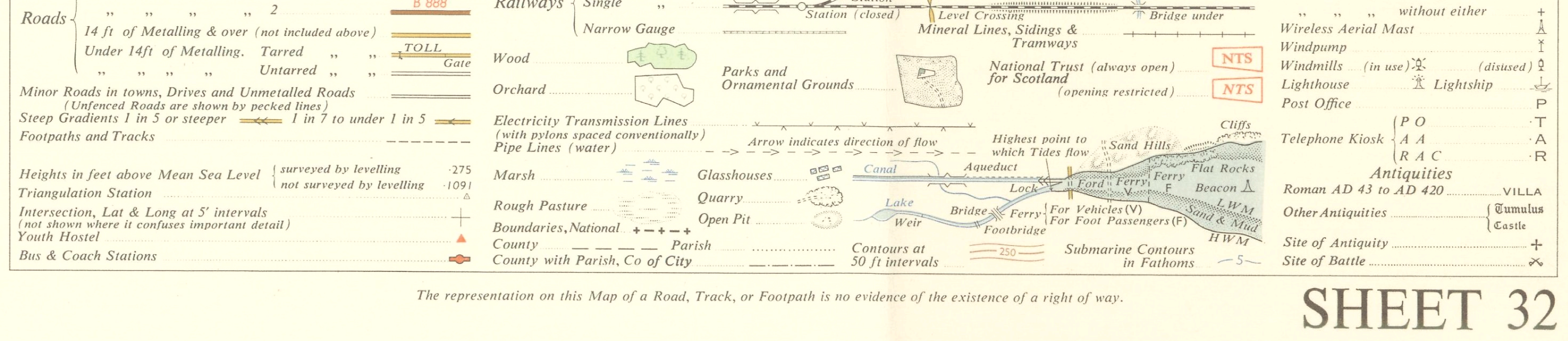

The representation on this Map of a Road, Track, or Footpath is no evidence of the existence of a right of way.

SHEET 32

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