THE APPLICATION OF METHODS OF STRUCTURAL ANALYSIS TO THE STUDY OF THE BASEMENT COMPLEX OF N.W. LEWIS

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Dedicated to my parents.

"Richard, I hope you will get to know the creator of these rocks as well as you know the rocks themselves."

- Mrs. Macarthur, 35 Carloway, Isle of Lewis.

FRONTISPIECE

GNEISS FABRIC-TYPES IN N.W. LEWIS

Upper Photograph

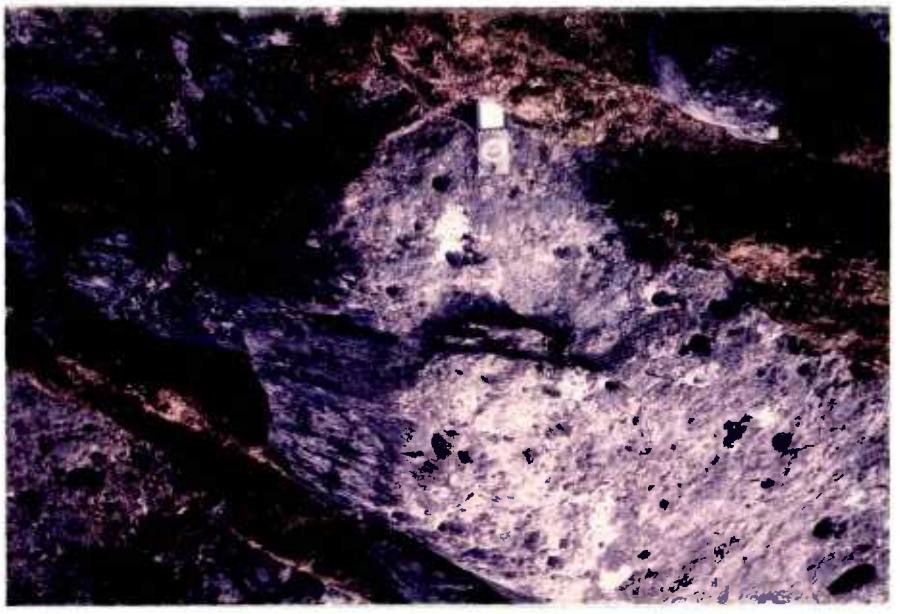
A strong linear gneiss fabric in lensoid gneiss typically occurs in areas of low finite Laxfordian deformation (Dalbeg area).

Middle

Slabby gneiss. Laxfordian deformation has brought about a certain degree of planarity to the gneiss fabric (between Dalbeg and South Shawbost).

Bottom

Flaggy gneiss. An intense fabric in which the planar component dominates. The linear component is still detectable. Found in areas of high finite Laxfordian strains (South Shawbost).







SUMMARY

This thesis describes the structural constitution of an area of Lewisian Gneiss in N.W. Lewis, Outer Hebrides. It then attempts to describe how this structural framework was built up in time by working out a sequence of structure-forming events and then assessing the importance of each event in terms of the strains imparted to the rocks.

In order to achieve this, new methods of structural analysis were applied to express regional variations of structural geometry, to unravel the order of development of superimposed structures and to assess the relative magnitudes of deformation.

The nature of the elements defining the structural pattern (gneissic banding, fabrics, etc.) are examined. New methods of expressing structural geometry include an analysis of the degree of cylindricity shown by the arrangements of banding in the gneisses. New ways of analysing fabrics are investigated.

Studies of the morphology of fabrics, boudinage and folding allow estimates of the different mechanical properties of the rock-types at the time of deformation. Methods of strain calculation were developed using structures such as folds, boudinage, fabrics and dyke discordances to the enclosing gneisses.

A result of this work is a map of the variation of the degree of tectonic modification suffered by the rocks of the area since a set of dykes, the Scourie Dykes, were intruded.

Using this information about the post-dyke (Laxfordian) deformation, attempts are made to estimate the original trends of the

Scourie Dyke swarm and to reconstruct the orientation and form of the structural features within the area at the time immediately preceeding the intrusion of the Scourie Dykes.

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CHAPTER 1 : INTRODUCTION

1. THE FIELDWORK AREA

The thesis concerns itself with the Lewisian rocks of an area in North-West Lewis in the Outer Hebrides (Scotland). The rocks are of Precambrian age and consist mainly of gneisses. The area (approximately 150 square kilometres) includes two regions which have an L-shaped configuration. One region is made up of a coastal strip between Barvas and Dalmore which is a land of low elevation with many lochs. Rock exposure is generally poor with the exception of the Atlantic shore and the low hills in the Dalbeg area to the west. The other region is bounded to the west by Loch Roag and includes the rocks between Carloway and Callanish and extends inland as far east as Ben Choinnich in the Ben Bragar range of hills. On the west of the old Carloway-Stornoway road, hummocky crag-and-tail features, elongated north to south provide exposures of rock on their sides facing south. However, with the exception of the Ben Bragar hills, the rocks to east of the old Carloway-Stornoway road are to a large extent peat-covered. The area covered also extends across East Loch Roag to include the southern half of the island of Great Bernera. The limit of the area studied is shown in Fig. 1.

2. THE AIM OF THE THESIS

Recent advances in the study of Lewisian have involved the recognition of spatial variability in the structural and metamorphic state of the complex. Some of this variation has been accounted for by unevenly-distributed effects of reworking processes on an already-existing gneissic complex. The distinction between reworked and

unmodified areas forms the basis of the subdivision of Lewisian (e.g. Sutton and Watson, 1951).

The primary aims of the thesis were twofold. The first aim was to collect information to build up a picture of the structural constitution in terms of geometry. The other primary aim was to look for ways of subdividing the complex and to find out if the division of the area into reworked and non-reworked areas could be carried out.

The methods used in this work are those of the modern structural geologist. Some of them were existing techniques already applied to other basement areas, some were methods previously used in other structural environments but modified to suit the nature of these basement rocks and some had to be devised with the purpose of fulfilling the aims above.

The analysis of the structural make-up of the rocks of N.W. Lewis revealed spatial variation in the state of the complex. Furthermore, these differences were largely of a transitional nature, i.e. distinct partition into reworked and unreworked areas was not possible. The secondary aim of the thesis then became the assessment in a more quantitative way the extent of reworking effects. New methods to execute this aim were devised and applied to these rocks. The methods permit the representation of these spatially-continuous variations of structural state.

3. THE LAYOUT OF THE THESIS

The thesis is written in three parts. In the first part, the second chapter describes the rock-types exposed within the area and their metamorphic state. The third chapter describes deformation structures with special reference to the order in which they develop.

In this chapter on the structural history, the relationship between tectonic and metamorphic activity is outlined.

Part Two (chapters 4, 5, 6, 7 and 8) deals with individual structural elements and discusses their use in the structural analysis. Descriptions are given of the ways in which these structural elements are used to reconstruct the structural sequence and to assess the extent of the strain modification during each deformation phase.

Part Three (chapter 9) lists the conclusions reached by the application of the techniques (described in the second section) to the complex of North West Lewis. Deductions about the structural evolution of the complex are put in a regional perspective by comparison with neighbouring Lewisian rocks.

4. PREVIOUS RESEARCH

This thesis reports the results of the first-ever systematic mapping on a large scale of this part of North West Lewis. In the past, several geologists have visited the area and some made observations which they relate in more general papers.

Macullough (1819) noted lines of crushing along north-north-west lines on the north side of Loch Carloway.

Murchison and Geikie (1861) pointed out that the prevalent strike of the rocks of Lewis was SE-NW. They discovered a coarse-grained granite at Dalbeg and noted that offshoots from the granite cross-cut the surrounding greisses.

Peach and Horne (1930) carried out traverses across Lewis in 1911 one of which included Carloway and Callanish. Comparing the rocks of northern Lewis with the Lewisian of the mainland, they found the rocks of Lewis more akin to those of the Cape Wrath area than to those of

the Scourie-Lochinver area especially in view of the absence of massive pyroxene gneisses in Lewis. They noted the presence of basics in the complex and recorded the occurrence of mylonites and flinty crush rocks. They give a full petrographic description of the Dalbeg Granite and Sir J.S. Flett, using the collection of Peach and Horne, classified on a mineralogical basis, the gneiss-types of Lewis.

Dougal (1932, read in 1924) refers to the Dalbeg Granite and to grey granitic rocks in the Ben Bragar group of hills. He describes a northwest-trending exposure of gabbro near Breasclete - "a greenish holocrystalline rock of uniform texture". I presume he is here referring to an intrusion at Cleitichean Beag (270365). Dougal relates this type to olivine gabbros elsewhere for example a mass at Maaruig in North Harris.

Jehu and Craig (1932) added greatly to the existing knowledge of the geology of Lewis and provided the first reconnaissance map. They remarked that basic rocks in the complex were unevenly distributed and gave as an example concentrations of basics in the neighbourhood of Carloway. They classified the more basic rocks in Lewis and Harris on mineralogical grounds. A detailed description of the petrological characters of the Cleitichean Beag intrusion was given and the authors added that "this rock has its nearest analogy on the mainland in an olivine norite from Inchnadamff described by Sir J.J. Teall in 1907".

The "granite-gneiss" of Ben Bragar and Ben Choinnich was drawn as a body continuous with the Dalbeg Granite on a sketch map given in their paper (Fig. 5 , Jehu and Craig 1932) and their description of what is called the "Ben Bragar granite" seems to fit that of Dalbeg.

Although some dips and strikes were shown on their sketch-map

(Fig. 5 , Jehu and Craig 1932) they gave little consideration to the structure of the gneiss of Lewis.

Dearnley (1962) divided the Outer Hebrides into three structural zones and said that this configuration is closely analogous to the Scourian and Laxfordian zones of the mainland recognized by Sutton and Watson (1951). (Sutton and Watson 1951 had put forward the idea that the rocks between Scourie and Gruinard Bay belonged to a block which had suffered little structural and metamorphic modification since a swarm of basic dykes, the Scourie Dykes had been intruded. Pre-Scourie Dyke structures or Scourian structures were preserved in this block. To the north and south of this block, post-Scourie Dyke modification had occurred during a Laxfordian cycle of activity. The Lewisian of the mainland could be thought to in terms of three zones, a central Scourian zone bounded to the north and south by two Laxfordian zones.) Dearnley's Scourian zone in the Outer Hebrides included the islands of North Uist and Benbecula as well as the northern half of South Uist. His northern Laxfordian zone embraced Harris and Lewis (Fig. 2a).

Figure 2b summarizes the structural information available about this area of study after Dearnley (1962). Using structural data from the map of Jehu and Craig (1932), he inferred a strike-swing in North West Lewis from an east-north-easterly trend in the ground east of Loch Roag (Fig. 2b). He used the term - the Loch Roag Flat Zone - for a region of gently undulating foliation between Breasclete and Little Loch Roag. He added that within the Loch Roag Flat Zone a south-easterly plunging lineation occurs and noted the occurrence of tight recumbent folds within the flat zone "which generally trend NE-SW".

Dearnley's recognition of Laxfordian and Scourian zones in

Outer Hebrides hinged on his correlation of a suite of basic rocks with the Scourie Dyke Suite on the mainland. His suite of basic rocks included the more basic varieties such as the olivine-bearing sheets at Cleitichean Beag, near Breasclete. The correlation proved to be a useful starting point for the structural chronology and to be an inspiration for work by other geologists.

Watson (1968) examined in more detail the structural characters of this suite of basic rocks in the northern part of Great Bernera (see Fig. 1 for location) and was able to make inferences about the nature of the Laxfordian deformation which the area was shown to have suffered.

Coward et al. (1969) recorded the presence of metasedimentary gneisses in the neighbourhood of Carloway and Coward et al. (1970) emphasized the structural distinctiveness of the Atlantic coastal stretch in North West Lewis and their map (Coward et al, 1970, Fig. 2) shows the dominant strike along this coast.

The Cleitichean Beag intrusion has been dated by Lambert, Myers and Watson (1970) and a date of 2440 m.y. was obtained for this supposed member of the Scourie Dyke suite.

Hopgood and Bowes (1972) undertook a structural survey of the Outer Hebrides and visited several localities in the area of North West Lewis. They make extensive use of fold characters in order to correlate fold sequences throughout the Hebrides and avoid the use of basic intrusions as chronological marks. Some of their findings are discussed in the relevant part of this thesis.

5. MAPPING PROCEDURE

Most of the area was mapped at a scale of 1:6336 but some very well exposed coastal sections warranted mapping on a larger scale.

The techniques of mapping were controlled by three factors:

1) the scarcity of marker horizons traceable over large distances,

2) the scattered nature of the rock exposure,

and 3) the uneven distribution of the rock exposure.

The first and second factors necessitated the collection of abundant structural data throughout the area in order that an attempt could be made to apply Pumpellyan principles for the extrapolation of large-scale structures. The semi-statistical methods applied to the interpreting of the collected data (e.g. stereographic techniques, dividion into subareas, etc.) require that special emphasis be placed on areas of poor exposure. An effort to visit every rock outcrop in such areas was made.

6. TERMINOLOGY, SYMBOLS AND DEFINITIONS

All terms used to describe certain features of structures (e.g. "fold hinge") and the geometry of deformation (e.g. "extension direction") are used in the same sense as the usage of Ramsay (1967). A list of symbols used as abbreviations for parameters relating to deformation are given in Fig. 3.

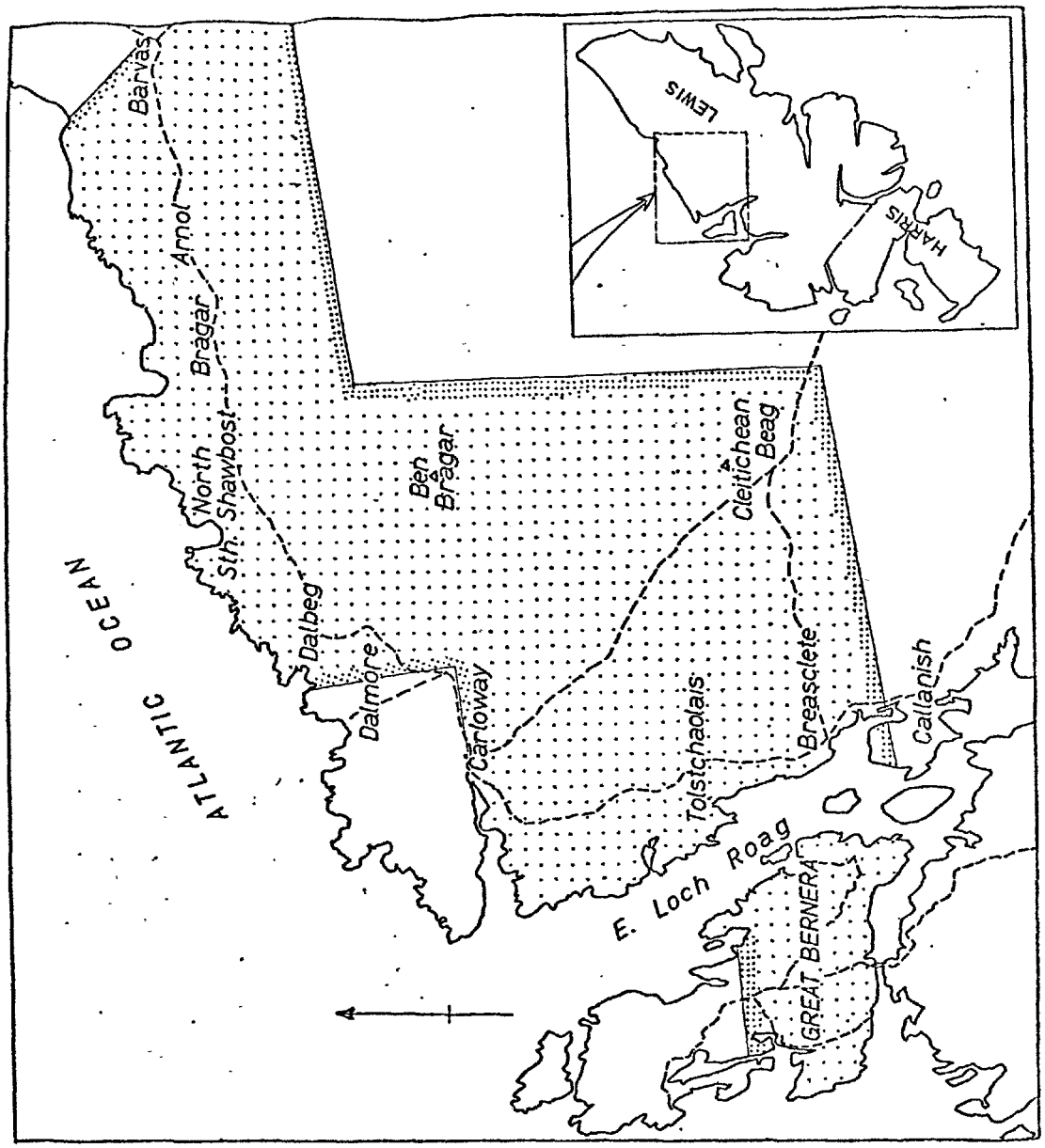
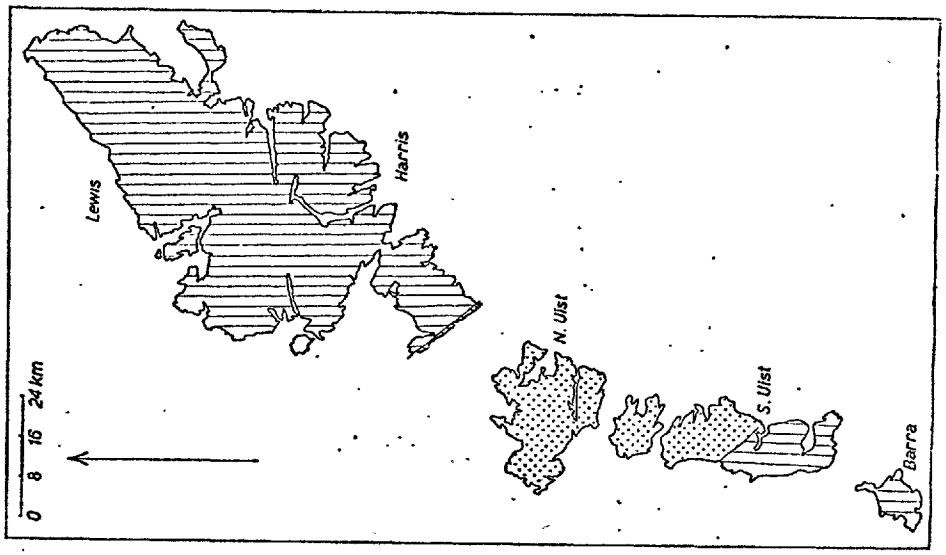
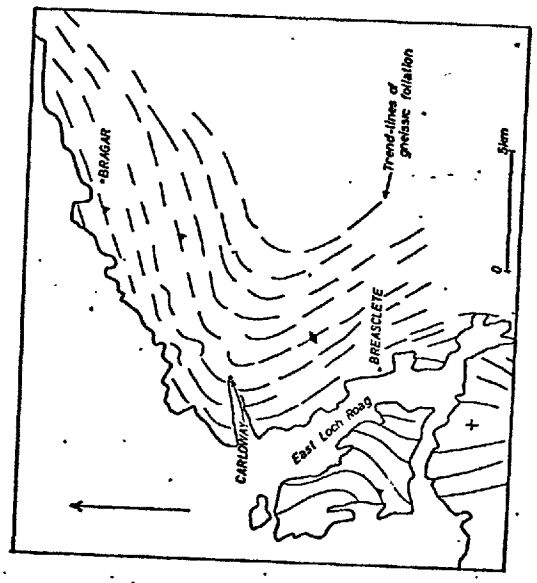


FIGURE 1. THE FIELDWORK AREA (1.5 km = 1 cm).

The mapped area is shaded. The main roads are shown as dashed lines. Triangles represent hills. Inset map shows Lewis and Harris and the location of the area.



2a



2b

FIGURE 2a. THE STRUCTURAL ZONES IN THE OUTER HEBRIDES (after Dearnley, 1962).

The Laxfordian areas are shaded and the Scourian areas are dotted.

FIGURE 2b. STRUCTURAL TRENDS IN N.W. LEWIS (after Dearnley, 1962).

FIGURE 3 NOMENCLATURE

D1	=	First Laxfordian phase of deformation
D2	=	Second Laxfordian phase of deformation
F2, etc.	=	Folding produced during D2 deformation
X, Y and Z	=	notation for axes of the strain ellipsoid
XY plane	=	plane containing X and Y axes
l, m, n	=	direction cosines of a line with respect to three co-ordinate axes
N or n	=	number of data
t	=	thickness
$1 + e_1$	=	length of X (long axis) in strain ellipsoid or strain ellipse
$1 + e_2$	=	length of Y axis
λ_1	=	$(1 + e_1)^2$ the quadratic elongation
λ_2	=	$(1 + e_2)^2$
a	=	$(1 + e_1)/(1 + e_2)$
b	=	$(1 + e_2)/(1 + e_3)$
k	=	'shape' of an ellipsoid, $(a - 1)/(b - 1)$
m	=	departure from sphericity of an ellipsoid
	=	$((a - 1)^2 + (b - 1)^2)^{1/2}$

PART ONE

CHAPTER 2 - THE ROCK-TYPES

1. INTRODUCTION

This section is a brief description of the rock-types present in the Lewisian Complex of N.W. Lewis. They will be discussed under nine headings.

A. Grey Gneisses

B. Basic and ultrabasic gneisses

C. Gneisses of supracrustal origin

D. Old Amphibolites

E. The Scourie Dykes

F. Granites

G. Pegmatites

H. Cataclasites and pseudotachylites

I. Late dykes.

Each of these will be described in the following section and a brief descussion of their metamorphic state will be given in the final section.

2. THE MAIN ROCK-TYPES

A. The Grey Gneisses. Dearnley (1962) used the term 'grey gneiss' to describe hornblende - and biotite-gneisses occuring over large areas in the Lewisian of the Outer Hebrides. It is the dominant rock-type in N.W. Lewis.

Grey gneiss is a general term applied to a variety of gneiss-types. It is composed of two components, leucogneiss and dark gneiss, the relative proportions and the spatial distribution of which forms the basis for further subdivision. The leucogneiss is essentially a quartzo-feldspathic rock with small quantities of biotite, hornblende, epidote,

sphene, muscovite and scapolite. Fig. 4 lists modal analyses of such rocks. The dark gneiss is richer in hornblende and biotite so that the name amphibolite gneiss can be used.

Myers (1970) classified gneiss-types in Western Harris on the arrangement of the light and dark components. He used the term amphibolite-lens gneiss or LENSOID GNEISS for a rock in which the darker amphibolite component takes the form of lensoids scattered through the leucogneiss host. This is a very distinctive rock in North West Lewis and the shape of the mafic pods vary greatly. A banding structure is often visible within individual amphibolite lenses which usually is not parallel to the overall banding in the lensoid gneiss. The distribution of the lensoid gneiss is shown in Fig. 49 Fig. 47 is a photograph of the lensoid gneiss.

Where the dark-gneiss and leucogneiss are arranged in alternating parallel layers, Myers (1970) used the term amphibolite-banded gneiss. The term BANDED GNEISS was applied to this rock. It often occurs in different structural regimes from that of the lensoid gneiss. This is a point which will be discussed later in the thesis. Lensoid gneiss and banded gneiss account for only a small proportion of the total grey gneiss.

PEGMATITIC GNEISSES are common and consist of leucogneiss run through by numerous thin layers of pegmatite.

The bulk of the grey gneiss is composed of hornblende- and biotite-gneiss in which a banding is sometimes defined by the variation of mafic mineral content from layer to layer.

The orientation and spatial distribution of individual mineral grains in a rock defines the rock's fabric and texture. Lineated gneiss is produced, for example, by the lining up of hornblende crystals and rods of quartz. Planar gneiss is characterized by plate-shaped aggregates

of minerals or by the tendency for rod-like grains to lie within planes and for platy minerals to adopt parallel arrangements.

Not all the gneisses however show strong fabrics and MOTTLED or SPECKLED HORNBLENDE GNEISS is a leucogneiss in which the hornblendes are isolated, evenly-distributed and randomly oriented. This rock-type seems to be a recrystallized equivalent of hornblende-gneiss with a fabric.

B. Basic and Ultrabasic Gneisses. Thicker units of basic gneiss interlayered with a minor amount of leucogneiss map out as clearly-defined horizons outcropping parallel to the regional strike. Two parallel outcrops of basic gneiss run from Carloway to the south-east. (Refer to general geology map of the area Fig. 5). They are comparatively more homogeneous and more basic in composition than the typical grey gneiss. Nevertheless they are typical gneisses with respect to the textures they show at the outcrop.

Mineralogically they are amphibolite gneisses with hornblende, plagioclase and biotite forming the dominant assemblage. Small amounts of quartz, alkali-feldspar and scapolite can also occur in these rocks.

The ultrabasic gneisses are more scattered in distribution (see Fig. 5) but are areally less significant when they occur. Hornblendite pods occur occasionally throughout the grey gneiss and they are often lensoids elongated in the main lineation direction. A larger ultrabasic pod occurs on the cliffs between South Shawbost and Dalbeg (232466) and consists of phlogopite, clinopyroxene and ores with long laths of tremolite-actinolite. In other places on the northern coast, ultrabasic layers seem to have acted as planes of tectonic movement and now form gullies into the cliffline.

Ultrabasic gneisses occur within the strips of basic gneiss

described above. One body at the bridge near Loch Laxavat (245387) consists of serpentinized olivine and pale-green actinolite.

C. Gneisses of Supracrustal Origin. Within the area there are rocks which could be of supracrustal origin. They show mineralogies unlike those of the grey gneiss with an abundance of alumina, silica- or calcium-rich minerals.

Most of the occurrences of these rocks have not been previously recorded. They occur in three localities:

i) the Laxavat Belt

ii) the northern coastal outcrops

iii) small patches near Loch Neadavat.

The Laxavat Belt consists of a string of exposures running from Carloway towards the south east passing alongside Upper and Lower Loch Laxavat. These outcrops of supracrustals occur near to the contact of the basic gneisses. They are brown-weathering rocks and their assemblages suggest a division into pelitic, semipelitic and psammitic types.

Typical pelitic assemblages are:

Biotite - sillimanite - kyanite - muscovite - plagioclase - quartz - apatite

Biotite - sillimanite - kyanite - muscovite - plagioclase - garnet - graphite

together with biotite-rich rocks:

Biotite - quartz - feldspar

Biotite - garnet - quartz - feldspar

Psammitic types consist of quartz-rich rocks. Very few of them can be called quartzites. For example they have the mineralogies:

Quartz - garnet - amphibole - biotite

Quartz - biotite - feldspar

The minerals grunerite, graphite and carbonate also occur in these supracrustals. A common rock-type of this belt consists of a brown gneiss consisting of feldspar aggregates sitting in a soft weathering matrix of biotite gneiss. The distribution of these possible supracrustal rocks of the Laxavat are shown on the lithology map (see Fig. 5). Several patches of rocks occur along the coast west from South Shawbost towards Dalbeg which are reminiscent of supracrustal rocks. They are flaggy rocks rich in biotite, gneisses containing garnet and biotite and mafic patches rich in diopside.

Inland, east of Loch Neadavat (243438), there are thin strips of quartz-rich gneiss, some containing garnet and showing intense linear fabrics defined by rods of quartz.

D. Old Amphibolites. These are basic rocks, usually quite thin, which form discrete layers and do not belong to the dark gneiss component of the grey gneiss. They show a degree of homogeneity not shown by either the basic gneisses, grey gneisses or supracrustals and this may well have been inherited from an igneous rock. They have a scattered distribution. They are usually simple amphibolites sometimes with large garnets and only very rarely contain pyroxene.

The name old amphibolite is used to differentiate them from the younger Scourie Dyke amphibolites. The old amphibolites have suffered a period of veining not shown by the Scourie Dykes and this forms the basis of their distinction in the field. Fig. 6A shows a photograph of an old amphibolite body from Sliegeag, near Arnol.

E. The Scourie Dykes. The Scourie Dykes are a set of basic to ultrabasic rocks usually having well-defined contacts with surrounding rocks. They make up about 10% of the rock outcrop over much of the area and in the adjacent area of Northern Gt. Bernera they occupy 19.2%

of the rock outcrop. Some are discordant to the banding in the grey gneisses and supracrustals and are obviously dyke-like in form. Others now lie parallel, or nearly so, to the banding in the gneisses. They cross-cut the old amphibolites and are, therefore, demonstrably younger.

Some of their textural characreristics are igneous especially in the larger bodies and ultrabasic types (which tend to occur as sizeable bodies). These characteristics include igneous layering and a sub-ophitic texture which gives the rock a characteristic mottled appearance (cf. Watson 1968). Some of these dykes enclose xenoliths of the gneisses.

The Scourie Dykes can be divided on their degree of metamorphic transformation.

i) less modified-types - these include most of the coarser grained dykes of gabbroic composition together with the ultrabasic types. Texturally they show many igneous features and show the poorest development of metamorphic fabrics although sub-ophitic textures (Fig. 6B) are frequently drawn out to produce a fabric. The more ultrabasic varieties are named Cleitichean-type Scourie Dykes after the largest outcrop of this rock-type which occurs at Cleitichean Beag (270368) near the junction of the Breasclete branch with the Carloway-Stornoway road. The main outcrop was mentioned by Dearnley (1962) and isotopically dated by Lambert, Myers and Watson (1970). Essentially it is composed of orthopyroxene intergrown with clino-pyroxene and olivine with small amounts of labradorite, hornblende, biotite, spinel and magnetite.

It is a coarse-grained rock with a distinctive weathering pattern giving it a dimpled texture. Stumpy-shaped outcrops of Scourie Dykes of Cleitichean type outcrop in a zone stretching westwards from the

main mass at Cleitichean Beag. They occur as isolated blocks within the grey gneiss and form small hillocks.

Figs. 5 and 104 show the distribution of the Cleitichean-type dykes and the shape of their outcrops can be clearly seen. Some are less ultrabasic than the main outcrop with more feldspar and sometimes lacking olivine. Others are very mafic rock, for example at the coast at Tolstachaolais (203368) and near Breaclete, Gt. Bernera (156364, see Fig. 5). Metamorphic fabrics are rarely seen in these dykes of Cleitichean type. This rock-type may have been originally dyke-like in form and may later have been broken in a brittle fashion without appreciable internal modification of the fragments.

ii.) more-altered types. - Other basic bodies, especially the thinner ones show a greater degree of metamorphic modification than the types described above. They are amphibolites and garnet-amphibolites with a hornblende-plagioclase assemblage often with quartz and biotite in small quantities. Sometimes small amounts of pyroxene are retained. The degree of fabric development is variable; sometimes they have fabrics defined by the shape of mineral clusters, other fabricless types show a simple texture due to the isolation of crystals of the same species, especially the mafic minerals.

F. Granites. The grey gneisses and Scourie Dykes are intruded by sheets of pink microgranite which usually trend east-north-east. They are usually foliated and similar foliated granite has been recorded in Gt. Bernera (Watson 1968). As can be seen from the map (Fig. 5) the total area occupied by granite is small. The largest (and coarsest) bodies of granite occur at Dalbeg (235453), Borrowston (185428) and Breasclete. The Dalbeg Granite has previously been described in detail (e.g. Peach and Horne 1930).

G. Pegmatites. Like the granites, discordant pegmatites account for only a small proportion of the area of outcrop. They are widely distributed, frequently zoned and are quartzo-feldspathic with biotite as the most important mafic constituent. Pitchblende was found ~~from~~ *in* one of these cross-cutting pegmatites near the south road into Tolstachaolais.

H. Cataclasites are widespread products of the deformation of the gneisses. The distribution and time of formation of these rocks (together with Pseudotachylites) is discussed in the section on the structural history (Chapter 3).

I. Late Dykes. Apparently undeformed and unmetamorphosed Appinite dykes, trending east-west, occur at Breasclete (Fig. 5) and in the bay north of Fivig (267487) at North Shawbost. Basaltic dykes, probably Tertiary in age, trending north-south occur throughout the area but are more numerous in the west of the area especially in the Carloway and Tolstachaolais areas. They are also common on the east side of Great Bernera.

3. THE METAMORPHIC STATE OF THE ROCKS

Hornblende gneiss and biotite gneiss are the stable rock types of the grey gneisses. Pyroxene is extremely rare even in areas where the gneisses have been little modified structurally since the Scourie Dykes were intruded. The mineral assemblages of the grey gneiss, i.e. hornblende - biotite - plagioclase - K - feldspar - quartz are typical of those of the amphibolite facies.

In the metasediments the occurrence of kyanite and sillimanite alongside micas is quite in accordance with the amphibolite facies assemblages (Turner 1968).

In two groups of rocks, the old amphibolites and the Scourie

Dykes, pyroxene is sometimes a component of the mineral assemblage. In the old amphibolites, pyroxene is rare and judging from the textural state of these rocks the whole mineralogy is unlikely to be metamorphic. In one thin section from an old amphibolite near the Laxavat Bridge (245387) on the Carloway-Stornoway road there is garnet overgrowing and hence post-dating the clinopyroxene. This could represent granulite facies pyroxene preserved in amphibolite facies garnet.

Scourie Dykes which have not been completely amphibolitized show small amounts of clinopyroxene and sometimes orthopyroxene. The pyroxenes almost invariably appear to predate the amphibole which forms at the expense of the pyroxene. This pyroxene may be igneous or metamorphic in origin. It is therefore difficult to deduce the metamorphic facies of the Early Laxfordian metamorphism using the Scourie Dyke mineral assemblages. However it can be said that the more altered types of Scourie Dykes have typical amphibolite facies assemblages and the effectiveness of the amphibolite facies metamorphism (or last metamorphic event) was not thorough because the thicker dykes were incompletely amphibolitized.

Retrograde metamorphism occurs in areas where the last structural movements were most pronounced.

SPECIMEN NUMBER	QUARTZ	FELDSPARS	FERROMAGNESIAN MINERALS	OTHERS
83 RL	9.8	72.7	12.8	4.7
9 RL	34.3	52.8	12.5	0.4
99 RL	57.2	27.82	15.6	0.0
L7 23	4.5	73.1	17.7	4.7
107 RL	32.4	53.6	13.0	1.0
139 RL	26.4	62.3	10.4	0.9
82 RL	32.4	58.5	7.1	2.0
102 RL	30.2	56.0	11.0	2.8
26 RL	29.0	42.3	23.7	5.0
117 RL	26.0	65.4	7.9	0.7
92 RL	42.5	34.2	19.7	3.6
L716	19.0	72.7	8.3	0.0
L717	19.0	73.4	6.6	1.0
L722	17.3	65.6	11.1	6.0
MEAN	27.19	57.84	12.67	2.34

FIGURE 4

MODAL ANALYSIS OF LEUCOGNEISS COMPONENT OF GREY GNEISS

The specimens are mainly from the Carloway - Barvas coast section.





Figure 5

A. Old Amphibolite from Sliegeag near Arnol

B. Typical mottled texture of coarse Scourie Dyke

CHAPTER 3 - STRUCTURAL HISTORY

1. INTRODUCTION

A sequence of structure-forming events has been established in the area using well-established criteria for the determination of the order of development of structures. These criteria include refolding relationships, the formation and modification of fabrics and the use of intrusive bodies in relation to the effects of deformation but were insufficient to solve many of the important problems involved in the sequencing of structural events. This chapter gives a description of the structural history arrived at by the application of these criteria and the unsolved problems come to light during the discussion. It was only by the use of supplementary methods of structural analysis, which are described in Part Two of this thesis, that some of these remaining problems were tackled.

Once the sequence has been determined, a description of the structural products of each deformation episode is given. However, in general, the nature of the structures is very varied and their character is not described as "diagnostic" but instead "typical" of each episode.

Some other aspects of the history, for instance the igneous history, are described alongside the structural history because it was the relationship of the structures to these other features which assisted the erection of a structural sequence.

2. THE PRE-DYKE STRUCTURES

The structural and metamorphic rearrangement of rocks gives rise to modifications of the relationship between rock units and these are relationships upon which the criteria used to determine structural

events are based. It is logical then, that there is a limit beyond which further subdivision of the complex becomes difficult because of the cumulative processes of rearrangement.

On field evidence, the 'earliest' complex contained most of the lithologies embodied in the present complex. The grey gneisses together with basic gneisses and rocks of supracrustal origin were the main components (see Chapter 2). Subsequently it seems possible that the complex was intruded by basic intrusions which now exist as rather distinct bodies of basic material. These are termed old amphibolites (see Chapter 2) and are fairly widespread. Although no discordances have been observed with the adjacent gneisses, their relatively sharp boundaries compared with other bodies of basic material suggests that they were intruded into the earliest complex.

Later these basics became intensely veined with leucocratic material which now has the form of discontinuous blobs (Fig. 6A). It is likely that veining took place at the same time in the host gneisses with formation of some of the migmatic gneisses which can be demonstrated to be of pre-Laxfordian age. The break-up of basic material into separated blocks probably occurred during this phase. This process of agmatization not only led to a separation of basic layers but also to a disruption so that the layering preserved in the fragments became rotated with respect to neighbouring fragments. Some acid gneisses show characters which suggest that they were probably emplaced as pre-Laxfordian granites, perhaps during the phase of migmatisation. It seems likely that this phase of migmatization and agmatization must have led to a general reduction of structural organization on all scales.

Before these agmatitic and migmatitic gneisses were intruded by the Scourie Dykes, a set of structures was impressed upon them.

Nearly all of the visible pre-Laxfordian folds belong to this phase. The migmatitic gneisses laced with disorganized veining were ideally suited for the production of folds. Most of these were small short-limbed folds, often ptygmatic in style with axial surfaces which are steeply inclined and trending NW-SE. (Fig.7, 8 and 9A) Their axes have low plunges to the NW or SE. Fig. 10 shows the distribution of recorded pre-Laxfordian minor folds. Boudinage also formed with axes more or less parallel to the axes of the minor folds. This boudinage led essentially to a two-dimensional separation producing boudins in contrast to the production of three-dimensional blocks by the preceding phase of agmatization. At one locality (N. Shawbost 256484) there is evidence to suggest that some basic bodies had been subjected only to boudinage events and had, for one reason or another, not suffered break up during the agmatization which had affected the surrounding basics.

The axial direction of the pre-Laxfordian folds is more or less parallel to that of early Laxfordian folds. Problems therefore arise when dating certain linear structures - a mineral elongation lineation together with lineations defined by the shape of enclosed bodies. For instance, the lineations inside the modified agmatite, the lensoid gneiss (see Chapter 2) expressed by elongate basic lensoids, is difficult to place in the structural sequence. Furthermore it is difficult to assess how far the structural grain defined by the axes of folds and boudins which developed in pre-Laxfordian times, has been retained by the gneisses in their present state.

These problems will be discussed in more detail in Chapter 4.

3. THE SCOURIE DYKES

A set of basic dykes cuts across the grey gneisses which contain the

agmatites, migmatitic and granitic rocks already described. These intrusions, recognized by Dearnley (1962) as equivalents of the Scourie Dyke suite of the Lewisian on the mainland have been used extensively in this area to separate Laxfordian (post-dyke) and pre-Laxfordian events.

The value of basic intrusions in regional structural analysis in the Lewisian has been repeatedly questioned in recent years (e.g. Bowes and Ghaly 1964). It would be worthwhile here to collect the field evidence for the recognition of a dominant regionally-occurring set of basic intrusions.

In the Carloway area, fine grained basic dykelets cut across the layering in coarser doleritic material and near Dalbeg (231469) one dyke cuts another which is discordant to the banding in the gneisses (Fig. 9B). Although dyke intrusion therefore must have continued for some time, there is no reason to believe that successive intrusions were separated by any major tectono-metamorphic event.

It is not an intention to argue that only one set of basic intrusions occur within the Lewisian. This would be a naïve view contrary to the work in the Carloway area and elsewhere (Francis 1973). But a case is put forward here to adhere to the view that a coherent abundant set of basic intrusions exists whose phase of intrusion was undivided by tectono-metamorphic activity. The existence of dykes intruded at other times will cause problems in constructing a geological history only when the analysis has been based on reconnaissance work. It is only by regional study of a detailed nature that it is possible to recognize the existence of a strongly dominant set of basic intrusions which is useful as a time marker in the structural and metamorphic sequence.

The "one dominant set" concept is attractive for the following

reasons:

i) regional structural changes in the gneisses go consistently hand-in-hand with structural changes (not necessarily of the same type) in the dykes.

ii) structural changes in the host gneisses are associated with regionally-consistent metamorphic effects in the dykes (for example amphibolization of dykes - see chapter 2).

With the absence of evidence to the contrary, the existence of a dominant set was more or less assumed during the course of the field-work. The repeated similarity of deductions based on the dykes to deductions based on criteria independent of the dykes suggests that this assumption was justified.

The Scourie Dykes, even in areas where they seem to be otherwise structurally unmodified, often possess a fabric parallel to the dyke margins. This fabric is best shown in the thinner dykes and is provisionally attributed to D1 (Laxfordian) deformation, because it is modified by D2 (Laxfordian) folding. This fabric has presented special structural interpretation problems; firstly because of the strong control exerted on its orientation by the dyke margins and secondly by the lack of obvious genetically-related structures in the host gneisses. These problems are looked at in Part Two (Chapter 4) where possible explanations are put forward.

4. THE MAIN POST-DYKE DEFORMATION EVENT (D2)

Folds (F2)

The F2 folds usually have flat axial surfaces and axes with low plunges. In the northern part of the area, along the Carloway-Barvas coast, the axes trend east or just north of east (Fig. 11, Subarea 1)

with plunges in either direction. Further south the axial trend swings to the southeast (Fig. 11 subareas 2 and 3). Axial surfaces, when undisturbed by post-D2 deformation are more or less horizontal, although in the central subarea (subarea 2, Fig. 11) in the neighbourhood of the Carloway-Stornoway road they show various amounts of dip to the southwest. It is difficult to judge whether this southwest dip of the axial surfaces in the region is an original feature or has been later imposed by post-D2 tilting. This point will be discussed further in Chapter 5.

The styles of the folds show a high degree of variation. Folded layers rarely have a parallel shape in profile (i.e. class 1B Ramsay 1967) but vary considerably within the intermediate field (class 1C) between parallel and similar fold types (class 2). This variation could be accounted for by differing amounts of homogeneous flattening imposed on the buckled layers (Ramsay 1967). A component of such flattening is always detectable from the geometry of the folded layers.

In tightness the folds range from open to isoclinal. Open folds are occasionally seen and approximately isoclinal folds are often shown by detached layers and care is needed to pick them out. The most often- and easily-recognizable folds are close or tight (Fleuty 1964).

Two orders of folding predominate. The most commonly observed order has a wavelength the size of small outcrops (0.2-3 metres) though sometimes smaller wavelengths are visible. In some areas a lower order can be seen to exist having cliff-sized wavelengths (10-25 metres). A fine example is the F2 folding on the west side of Dalbeg Bay where these two orders are clearly visible. A similar pattern exists on the steep northern slopes of Ben Bragar where the sense of minor F2's reveals that lower order folding on a comparable scale to that at Dalbeg is present.

Elsewhere, however, variation of the sense of F2 folds is rarely observed. The vast majority of outcrop-scale F2 folds have a z sense of asymmetry (observer facing east or southeast). This suggests that the lower order folds are exceptional rather than typical of the scale of F2 folding. It is doubtful whether the differentiation of folding into orders is therefore meaningful on a regional scale. The structural significance of minor folds in relation to the D2 deformation is examined more closely in a later section devoted to folding (Chapter 5 in Part Two).

Boudinage

Frequent examples of boudinaged Scourie Dyke amphibolites on the limbs of F2 folds are believed to be a product of the D2 deformation. The axes of the boudinage are closely parallel to the F2 fold axes (cf. Figs. 11 and 12). The occurrence of boudinage often suggests that it formed in an advanced stage of the folding process in response to a stretching of the limbs of tight folds. The topic of boudinage is discussed further in a later section (Chapter 6).

Fabrics

Parallel or almost parallel to the axes of many of the F2 folds a linear fabric is developed, defined by the shape of mineral aggregates and lithic elements. It commonly plunges at a low angle to the south-east or east-southeast (Fig. 13). The fabric is more planar in areas where intense F2 folding is suspected and planarity has been found to be an indicator of D2 deformation. It is therefore tempting to assign this fabric to the D2 deformation phase.

However there is some evidence suggesting that the fabric is not solely a product of D2. For example, in the northern coastal tract of Shawbost and Bragar, the lineation is oblique to the F2 axial direction.

Evidence of this kind sparks off an important discussion into the nature and origin of fabrics in this region and a part of the second section of this thesis (Part Two, Chapter 4) involves itself with this discussion.

A. The distribution of the products of the D2 deformation

The areas where D2 deformation has been significant can be divided into two main categories: steep zones and flat zones.

The steep zones are so called because, although they show obvious F2 folding on flat axial surfaces, the banding envelope can be seen to be steep. The flat zones show a flat banding though the true run of the envelope is unknown. The flat banding could be the result of D2 deformation on a truly flat envelope so that formation of F2 folds was inhibited. On the other hand, the flat banding may in fact represent the limbs of tight or isoclinal folds, the envelope of which may have a considerable dip.

The area around Breasclete and southern part of Gt. Bernera represents the largest "flat-zone" in the area and forms part of the "Loch Roag Flat zone" of Dearnley (1962). The west side of Dalbeg Bay and North Ben Bragar are examples of steep zones. Flat and steep zones occur also on a smaller scale and the occurrence of occasional F2 hinges in flat zones suggests that at least some of them could be tightly appressed F2 fold packets.

B. The magnitude of D2 strains

i) Fold Profiles

A method of calculating the strain in a folded rock by geometrically extracting the components of distortion which brought about the folding is described by Ramsay (1967, p. 411). In brief, the method assumes that folded layers passed through a stage in which they had the shape

of parallel folds and were subsequently modified to class 1C folds (Ramsay 1967) by a homogeneous strain parallel to the axial surface. The method therefore involves the subtraction of the homogeneous post-buckle component in order to return the layer to a condition of equal orthogonal layer thickness, that is, to a parallel fold shape. An estimate of the strain due to buckling can then be made by simply "straightening-out" the parallel fold. More sophisticated methods attempt to estimate the homogeneous layer shortening which goes on prior to the onset of buckling. Sherwin and Chapple (1968) describe such a method.

No systematic survey of the D2 deformation was undertaken using this method because of the lack of suitable folds. This method can only be applied to single layer folds where the amount of post-buckle flattening modification has been slight to moderate. The method is impracticable for high flattening strains because, after a flattening of 5:1 the change of geometry of the fold becomes insensitive to further flattening.

In spite of these drawbacks, analysis of the profile shape of folded Scourie Dykes give some interesting results. The effect of D2 deformation on thick dykes is to produce F2 folds with a considerable buckling component still detectable. Thin dykes from the same area however show very little buckle component but strong amplification as a result of homogeneous strain.

Fig. 14 shows an F2 fold in a thick Scourie Dyke just north of the farmhouse called Fivig (269494) and the fold is strongly "buckle-shaped". Fig. 15 shows a thin Scourie Dyke which has an almost "similar" profile. The t'_1/α plot reveals that a strong flattening component (10:1 approximately, Fig. 15C) is possessed by the fold. When this flattening is graphically removed (Fig. 15D) we are left with a very

open fold and it seems that the buckling accounted for only a small proportion of the total shortening of this thin dyke. This implies a lower effective competence of thin dykes relative to thick ones. (Thick and thin dykes behave differently in conditions of extension also and this will be further described in Chapter 6.)

Flattened pegmatitic veins within the gneisses can be unflattened graphically to reveal phygmatic buckles (Fig. 16). The fold in Fig. 16 possesses a post-buckle flattening of 2.5:1 and a strain due to buckling of 2.5:1. Therefore an absolute minimum of 6.25:1 can be given for the D2 strain bearing in mind that this figure disregards any pre-buckle contraction that may have taken place. The strong role of buckling in this fold suggests that for thin layers, competence contrasts between pegmatite and gneiss were greater than dyke/gneiss competence contrasts during the D2 deformation.

ii) F2 Folds with boudinage on their limbs

Many F2 folds, especially the larger scale ones, show layers on their limbs which are boudinaged. An accessible example recorded by Dearnley (1962, Fig. 1, Plate 7) occurs opposite the hotel at Duone Carloway (196401). The first effect of buckling is to shorten the layering and actual stretching across the whole thickness of the layer cannot be envisaged until the layer has undergone enough strain to rotate to a position in which extension can proceed, i.e. to the extension field of the strain ellipsoid. It is only then that boudinage can commence on the limbs.

This opens the interesting possibility that the occurrence of folds with boudinaged limbs may indicate a lower limit on the value of the D2 strain. Attempts to derive these limits are made in the discussion of boudinage in Chapter 6.

iii) Discordance

The D2 deformation caused an average reduction in the degree of discordance shown by members of the pre-Laxfordian Scourie Dyke suite and their hosts. Ways in which this modification can be utilized to indicate the type and amount of D2 deformation are explored in the discussion on discordant structures (Chapter 7).

C. Regional occurrence of F2 and the variations of F2 style

It is possible to delineate three regimes based on the occurrence and style of F2 folding:

I - Little or no F2 folding. The folding visible is mostly pre-Laxfordian. The lack of F2 fabrics also suggests that D2 effects were weak.

II - abundant F2 folds visible. They vary from open to tight folds. The north side of Ben Bragar and the stretch of coast between Dalbeg and Dalmore fall in this type of region.

III- F2 folds rarely visible. Strong F2 fabrics and occasional tight and isoclinal F2 hinges showing strong flattening suggest that zone III is a zone of high F2 deformation.

Figs. 17 a and b show folds representative of zones II and III respectively.

The fieldbook records of F2 folds allow the demarcation of zone II (zones I and III being distinguished by fold styles and fabrics). In this way a map of F2 fold regimes has been constructed (Fig. 18). The boundary between zones I and II is well defined and is marked by the sudden appearance of F2 folding. The junction between II and III is more transitional and corresponds to a gradual decrease in the number of visible F2 folds.

It is concluded that the well-defined folding developed in zone II

is an expression of the middle range of D2 deformation. Measurements of strain from folds of this type give minimum estimates for the F2 strain of between 10 and 20:1 for the two dimensional strain in the profile plane. Higher ratios are therefore likely to characterize zone III.

D. The case for a D1 phase of deformation

Besides the early foliation in the Scourie Dykes there are other suggestions that the D2 phase might not have been the first of the Laxfordian deformation phase.

Although no F1 folds have been recognized with any certainty, boudinage is sometimes seen to be modified in what appears to be a "shunting together" of boudins caused by F2 effects. This can be interpreted as D1 boudinage though sometimes we can permit an alternative interpretation of D2 boudinage modified by post-D2 folds on flat axial surfaces.

Furthermore, in certain areas, for example in the Dalbeg cliff sections, F2 folds seem to fold sets of well-developed s-surfaces which are parallel to concordant dykes and had a steep orientation prior to folding.

The possibility exists that an early Laxfordian event occurred producing some boudinage and local planarization of the gneisses prior to the D2 folding. The actual importance of this "phase" in the structural history has not been clearly ascertained.

5. POST-D2 STRUCTURES

This section describes a variety of structures which post-date the relatively well-defined products of the D2 deformation. The relative ages of some of the post-D2 folds are not always clear and it is quite possible that several sets of deformation have produced

the structures described in this section.

It is clear, however, that deformation after D2 was even more heterogeneous than that due to D2 itself. The factors controlling this strain heterogeneity appear to be related to inherited heterogeneities of rock type and structure, a greater component of 'plasticity' in the rheological behaviour of the rocks and the uneven influence of post-D2 metamorphism throughout the area.

A. The Late Laxfordian phase of recrystallization: its products and structures

Localized recrystallization of the gneisses occurred after D2 times. In some areas, planar fabrics inherited from the D2 deformation were partly destroyed by the homogenizing effect of the recrystallization. Sometimes an increase in grain size produced a coarsening of the early lineation which appears to have been an extremely robust structural element. In other cases however the lineation was lost especially where lineated hornblende gneiss was replaced by a fabricless mottled hornblende gneiss. This mottled hornblende rock is a common rock-type in the areas of recrystallization.

Recrystallization of the Scourie Dykes and earlier basic rocks produced even-grained massive rocks and fabrics defined by elongate aggregates of minerals were eradicated and replaced by a more even distribution of single crystals of feldspar and amphibole.

Within the homogenized white-weathering gneisses produced by the recrystallization, the growth of certain individual crystals was favoured. Some of these megacrysts, especially those of feldspar, have diameters of up to ten centimetres. In some places, the whole rock is reconstructed by these megacrysts leading to the formation in situ of pegmatites.

Intrusive granites occur in localized zones. The bodies at Dalbeg (235454), Borrowston (185428) and Breasclete appear to be flat sheet-like bodies. The thicker ones at Breasclete are more or less concordant with the adjacent gneisses but at Dalbeg the gneisses below the sheet dip more steeply than the sheet contact. Besides the coarse granite at Borrowston and Dalbeg, thinner sheets of microgranite occur in zones which trend ENE (Fig. 5). They are usually discordant and some are only a few centimetres thick. These granite sheets commonly have a strike of approximately 060° with a steep dip to the SSE. The zones of granite are composed of patchy lenses and sheets sometimes arranged en echelon. A good example of such a granite zone passes through the north part of the village of Tolstachaolais (Fig. 19).

The localities marked on Fig. 20 indicate outcrops of rocks which have undergone considerable recrystallization. The distribution of areas of recrystallization is patchy but two trends can be detected. The main trend has an ENE direction and is parallel to the granite zones already described. A possible second trend seems to be parallel to the main strike of the gneisses which in turn is the structural and lithological trend. This could suggest that inherited structural and/or lithological characters affect the distribution of the recrystallization. The main zones of recrystallization occur in the south of the area and one set of particularly strong recrystallization runs ENE from the village of Breasclete.

Within some of these areas there is evidence that movement of the rocks accompanied recrystallization. The Scourie Dykes, which seem to have behaved in a brittle manner in these circumstances, broke up into blocks which were subsequently rotated. This was accompanied by the development of complex and more ductile structures in the gneisses.

Outside the main areas of recrystallization the ductile yielding

of rocks was more localized producing shears which are often filled with pegmatite. Fig. 21 shows examples of such structures. In large basic bodies too, it seems that bulk changes of shape were accomplished by interlocking sets of heterogeneous shear zones similar to those described by Graham (1970) and Ramsay and Graham (1970). In some places shears in the gneisses contained tension gashes representing a more brittle response to this deformation. Epidote veining took place during this time.

B. The F3 structures

A particularly distinctive set of post-D2 folds possessing diagnostic fold characters and with axes oblique to the trends of earlier fold phases has been distinguished from other post-D2 structures. Their discreteness as a set of folds warrants the use of term F3 for the members of this set, although there is no evidence that they immediately succeeded the D2 phase or that designated F3 folds are the only folds produced by this phase of deformation (D3).

These folds are most abundant in areas of strong D2 deformation and where recrystallization had not destroyed the planar fabrics developed during D2. F3 folds sometimes fold Laxfordian granite veins.

The axes of these folds show shallow plunges to the northeast or southwest. Axial surfaces usually dip to the east or southeast (Fig. 23 and 112). An axial plane fabric is sometimes developed in the neighbourhood of F3 folds especially where granite has been involved in the folding (Fig. 24B).

Usually the folds are asymmetrical with a short limb which often shows considerable thinning so that the axial surfaces (Ramsay 1967) dip more steeply than do the axial planes (Fleuty 1964). This thinning is most prevalent with folds with an upright short limb but is not always

a feature of F3 folds. Symmetrical parasitic folds are often developed on the steep short limb. A rounded hinge is typical and contrasts with the generally angular hinges of F2 folds. Fig. 24 shows the profile shape of some typical F3 folds.

The strain concentration in one limb of some of these structures sometimes suggests that they are more akin to shear zones than folds. The lack of any obvious periodicity and their meaningless sense of asymmetry in terms of any observed major structure further favours the shear zone idea. However these structures are not zones of heterogeneous simple shear. Dip isogons (Fig. 25) do not show the parallel arrangement expected from zones of heterogenous simple shear. It is concluded that the term "shear zone" can only be applied in a general sense to the attenuated limbs of some F3 folds.

There is a systematic correlation between the interlimb angle and the dip of the axial surface of these structures (Fig. 26). This can be seen in single folds where the tighter sections of the fold have flatter axial surfaces. From this evidence it is tempting to speculate about the orientation of the maximum principal stress at the time of the formation of the F3 folds. Assuming that the graph in Fig. 26 describes the change in axial surface orientation during the development of a single fold, we can infer that the folds initiates (ILA = 180) with an almost vertical axial surface (dip = 32°). This seems reasonable because the horizontal pre-F3 banding is likely to have exercised a strong control on the orientation of the folds in their early development. Experimental studies on fold initiation have shown that the first formed folds have axial surfaces perpendicular to the layering (Beach 1969) but as the fold tightens the regional stress becomes more effective in controlling the fold orientation. As the F3 folds developed, the axial surfaces tilted to the east. There is a

limiting value on this tilting and this is achieved when the fold has completely closed up (ILA = 0°). A logical interpretation of this limit would be that the fold axial surface at this stage has become perpendicular to the maximum principal stress. Fig. 26 shows that the predicted inclination of the axial surface of the isoclinal fold is 31° and it follows that the maximum principal stress direction dipped at 60° towards the west during the development of these folds.

This dependence of the axial surface orientation on the stage of development of the folds suggests further that buckling played an important part in their development. Folds produced by simple shear would retain a constant axial surface orientation parallel to the shear (ab) plane during progressive deformation.

Although F3 folds are widely distributed (Fig. 12) they are important structural features in three areas. On the south side of Ben Bragar and on Ben Rahacleit (263424) F3 folds often with symmetrical folds developed on their short west-facing limbs, deform F2 structures and the early lineation. They often show axial-plane pegmatites. Fig. 28 is a map of Ben Rahacleit showing the effect of F3 folding on the outcrop pattern. In Southern Gt. Bernera tighter F3 folds are visible (Fig. 27). Lineations are folded by F3 folds especially near the village of Hacklete (150344). F3 folds occur at an accessible exposure at Bernera Bridge (165342). Fig. 27 gives the interpretation of the Bernera Bridge locality and compares it with that of Hopgood and Bowes (1972, Fig. 7d). Around Breasclete, as in part of Southern Gt. Bernera, F3 folding becomes an important element controlling the present arrangement of the banding, the limbs of F3 giving a northeast trend to some of the banding. This trend is oblique to the earlier trends. This intersection of two trends gives rise to structural geometry with a strong element of non-cylindricity and the effects

of F3 on the amount of non-cylindricity is evaluated in a later discussion devoted to folding topics (Chapter 5).

C. The post-D2 folds of the Carloway-Barvas coast

Post-D2 folding is common along this coast but the wide variety of folds coupled with the restricted distribution of some types make these structures difficult to analyse. They are difficult to date with respect to each other and with respect to the F3 folds. A large scale post-D2 structure will be described first.

The Bragar Monocline. A monoclinal structure accounts for a zone of gneisses which dip moderately or steeply to the south-southeast. The outcrop of the steep limb runs more or less parallel to the coast and extends from north of Carloway to North Bragar (Fig. 29A). This structure is responsible for the east-northeast strike of the gneisses of North Bragar and Dalbeg together with east-northeast trend of the thick Scourie dyke at North Shawbost.

The monocline has a shallow plunge to the west-southwest and a northerly-dipping axial surface. In the steep limb, F2 axial surfaces are tilted sowthwards (Fig. 29B and Fig. 30). Probable small-scale equivalents of the Bragar monocline occur in coastal rocks north of the graveyard at North Bragar (289490) and on the high cliffs of the Dalbeg area (Fig. 30C).

Smaller scale folds. On both the steep and flat limbs of the Bragar monocline, smaller scale folds occur with east-west axes or ENE-WSW axes. The axes show gentle plunges and the axial surfaces are usually perpendicular to the banding envelope. Asymmetrical folds often have flat-lying axial surfaces. The deformation producing these folds sometimes shunted together D2 boudinage (Fig. 31A). Some of these folds may be contemporaneous with the Bragar monocline.

This type of folding is well displayed on the North Bragar peninsula (Fig. 31) where Type 3 interference patterns (Ramsay 1967) are produced by the refolding of F2 folds. D2 boudinage is also folded (Fig. 31B). Fig. 32 is a stereographic plot of the post-F2 fold axes in this area. If the best great circle through these axes is taken to represent the orientation of the mean surface on which these folds developed, we can infer that an east-west strike was present in this area prior to this folding. This is important evidence for the discussion on the origin of the strike-swing in the northern part of this area and the whole problem of the evolution of structural trends is enlarged upon later (Chapter 8).

D. The Late Pegmatites

Pegmatites with planar margins post-date the main phase of recrystallization. Frequently zoned, these pegmatites seem to show a preference for positions of high local strain, for example the steep attenuated limbs of F3 folds and the contacts of thick Scourie Dyke bodies. As a result, many of the pegmatites inland show trends parallel to steep F3 fold limbs (i.e. north or northeast trending).

On the northern coast many trend ENE. Although some are sill-like in form, they seem to favour an upright attitude. This invites the vague suggestion that they post-date the Bragar monocline where they are relatively abundant and usually steeply dipping.

E. Post-pegmatites structures

There are indications of a deformation which took place after the late pegmatites were intruded. Some of the granite sheets are cut across by pegmatites which, in turn, have been folded. Axial planar to these folds a foliation is developed in the granite host. This foliation in the granites is a widespread feature and is usually inclined to the

contacts of the wall of the vein. Fig. 34C shows the orientation of this foliation which evidently formed after the late pegmatites were intruded. It is, however, difficult to further specify the timing of this deformation.

F. The cataclastic deformation

The exposures along the coast from South Shawbost to Barvas show the effects of a phase of cataclastic deformation which considerably hinder the analysis of earlier structures. The grey gneisses were converted to flaser gneisses and those containing most quartz show the dramatic textural changes. On the late pegmatites was locally imposed a coarse augen structure and thin layers of mylonite or flinty crush rock were formed which now smear many of the flat outcrop surfaces along this coast.

The effect of the cataclasis was to emphasize the horizontal flattening previously acquired during the D2 deformation and the cataclasis is strongly developed in the flat zones outside the Bragar monocline. Late pegmatites were folded on flat axial surfaces and a cataclastic foliation was formed in the host gneisses axial planar to these folds.

As well as flattening on horizontal planes there is evidence of horizontal movements with the puckering of gneiss layers to form syn-cataclastic folds. Decollement or slip surfaces play an important role in the development of these structures. Mylonite development and folding seems to have gone on simultaneously. Folded mylonite horizons are sometimes cut across by later planar mylonite seams in a period of repeated buckling, brittle failure and slippage. Fig. 33 shows some of the minor structural types produced by this cataclastic phase of deformation.

Within the area affected by the cataclastic deformation a flaser lineation is developed. It is localized to closely-spaced planes of slip and seems to consist of a streaking out of quartz grains and a grooving structure on quartz veins which were intruded before this cataclastic deformation had ceased. This lineation plunges at low angles to the SE or NW and is remarkably constant in orientation for widely-separated outcrops (Fig. 34). The development of flinty-crush rock and the flaser lineation rarely takes place on steeply dipping surfaces (Fig. 34). The foliation in the Dalbeg Granite has a cataclastic appearance and slip surfaces within the granite show a lineation similar in direction to the flaser lineation in the gneisses on the coast (Fig. 34). A low-angled shear-cleavage, restricted in its distribution, could date from this time.

Many of the surfaces pasted with flinty-crush rock are warped by open folds sometimes in two directions, giving open basins and domes.

Pseudotachylite occurs mainly in the east part of the area between Arnol and Barvas. The map in Fig. 35 shows the occurrences of pseudotachylite together with products of the cataclastic phase.

6. METAMORPHISM IN RELATION TO THE STRUCTURAL HISTORY

From the foregoing description of the structural events it should now be obvious that the earliest recognizable structures and the subsequent structures except for those of the late Laxfordian have common linear directions. This lineation is well developed in rocks showing pre-Scourie Dyke structures.

These fabrics associated with the earlier part of the structural sequence are defined by minerals which fit into assemblages of amphibolite facies type, e.g. sillimanite, biotite and hornblende. There is no

evidence to suggest that this linear fabric was originally defined by granulite facies minerals and then endowed to the rock in its amphibolite facies state. It is suggested then that the earliest structures formed under conditions of the amphibolite facies.

The Scourie Dykes exhibit a variation in their metamorphic condition and it would be interesting to look at this variation with respect to the intensity of the Laxfordian structural modification. In practice there are difficulties in correlating the regional metamorphic state of the dykes with Laxfordian structural modification, because there are many local factors. For example the metamorphic condition expressed by the degree of amphibolization shown by the dykes seems to depend on the thickness of the dyke, the position of the rock with respect to the dyke margin and on the presence of local strain concentrations in, for instance, shear zones which cross-cut the dykes.

We have seen in this chapter how the late Laxfordian recrystallization is associated with its own particular style of structure. There is a tendency for structures of the shear-zone type to develop (e.g. Fig. 21, and 22) with recrystallization being more pronounced within the high strain domain of the structure. There are two explanations which could account for this relationship between structure and metamorphism. It is possible that the structure developed preferentially in a zone in which recrystallization had initiated because this was a zone which was more capable of accommodating displacements, that is it was relatively incompetent. Alternatively recrystallization may have been more complete in this zone because of the higher strain energy possessed by the crystals as a result of deformation. Later in the thesis we will meet other situations where it is difficult to distinguish cause from effect in the relationship between metamorphic

and tectonic modifications.

Associated with the late cataclastic phase there is a retrogressive phase of metamorphism where the hornblende in the gneisses seems to become unstable and minerals such as tremolite-actinolite, chlorite and epidote develop. Retrogressed rocks associated with late movements are well displayed on the north-facing coastal rocks at Aird Mhor Bragair (273496). There is evidence from microscopic examination of the rocks that at least some of the cataclastic movements outlived the phase of retrogression.

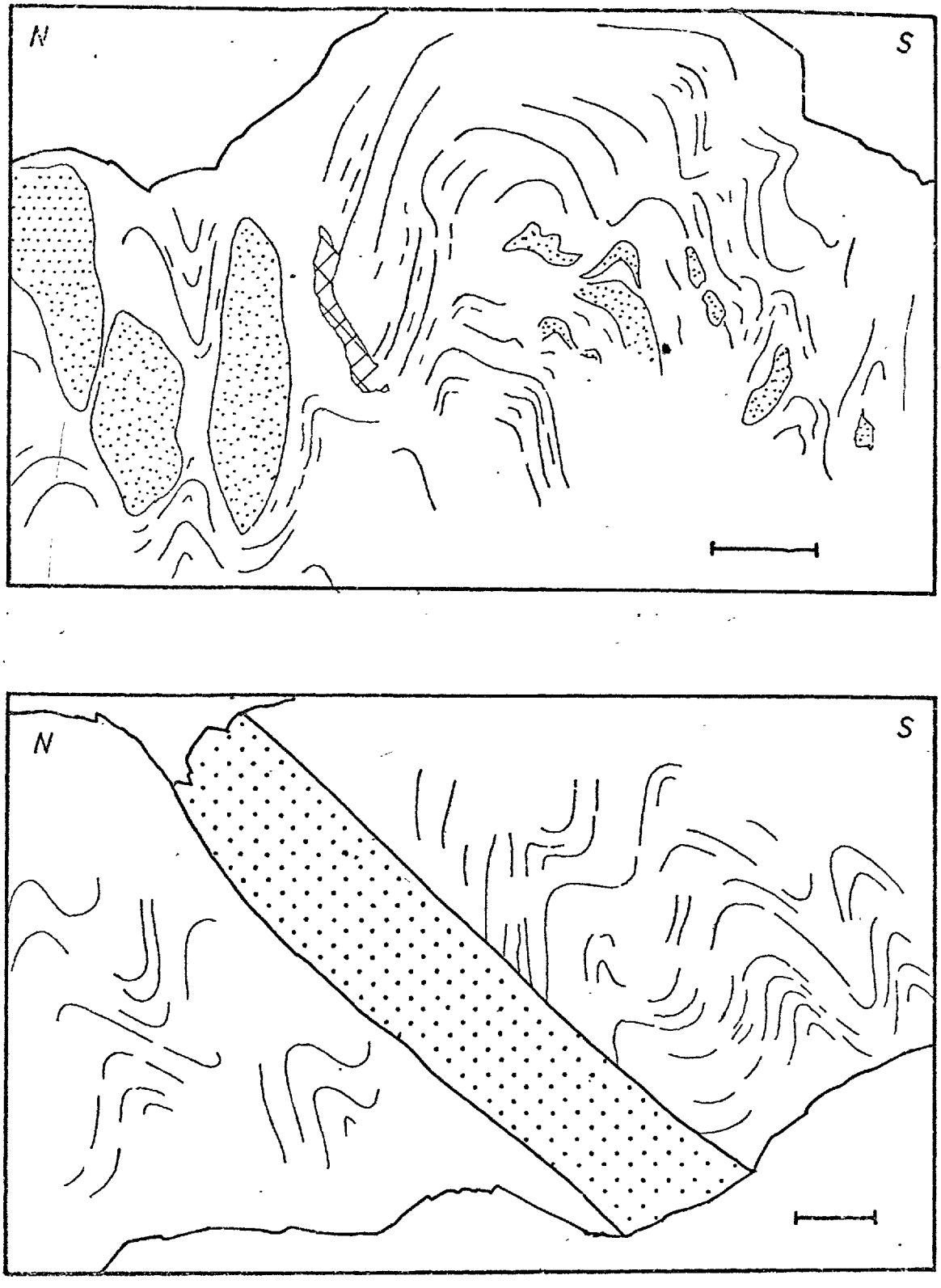


FIGURE 7

SCOURIAN STRUCTURES

Scale = 10 cms. Key to rock types : Fine stipple = Scourian basic gneiss, Coarse stipple = Scourie Dyke, Cross-hatched = pegmatite.

A. The Dalbeg Low deformation area (467232)

B. East of Loch Neadavat (238436)

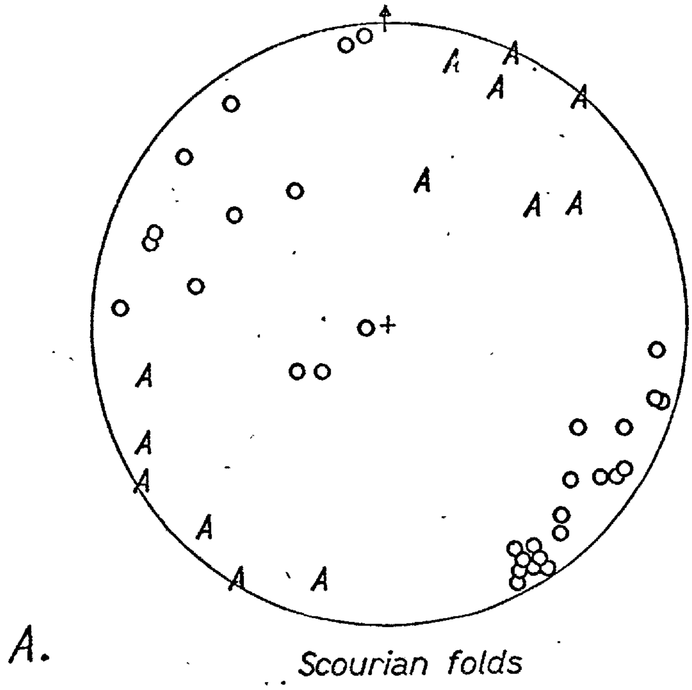




FIGURE 8

A. Scourian folds truncated by a Scourie Dyke, Dalbeg

B. The early lineation, Dalbeg



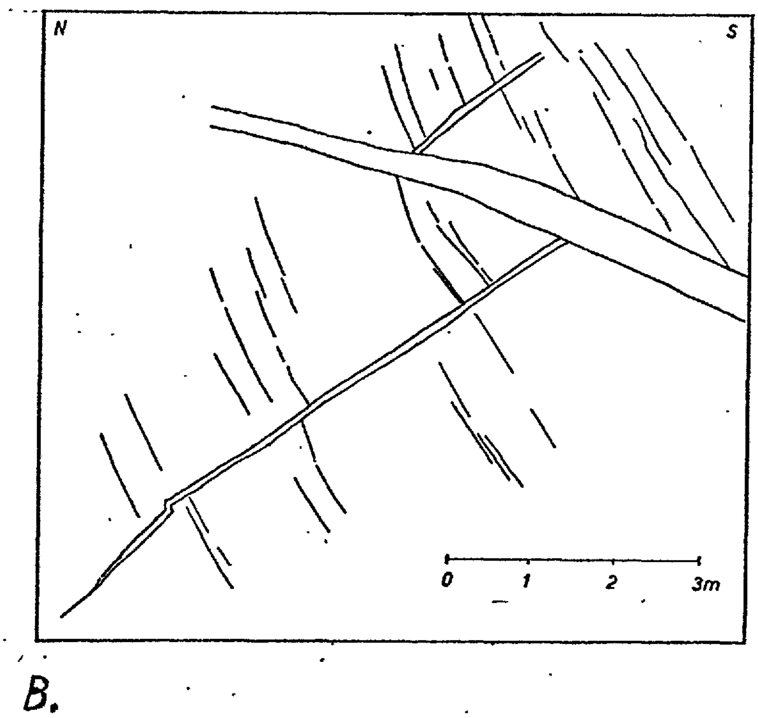


FIGURE 9

A. Axes (circles) and Axial Surfaces (As) of Scourian folds. Whole area.

B. Basic dykes cutting one another and the gneissic banding.
Cliffs East of Dalbeg (231469)

FIGURE 10

THE DISTRIBUTION OF THE DOMINANT FOLD PHASE

Dotted areas - the dominant folding is pre-Scourie Dyke in age.
Vertical lines - " " " " F2 in age.
Diagonal lines - " " " " post-F2 in age.

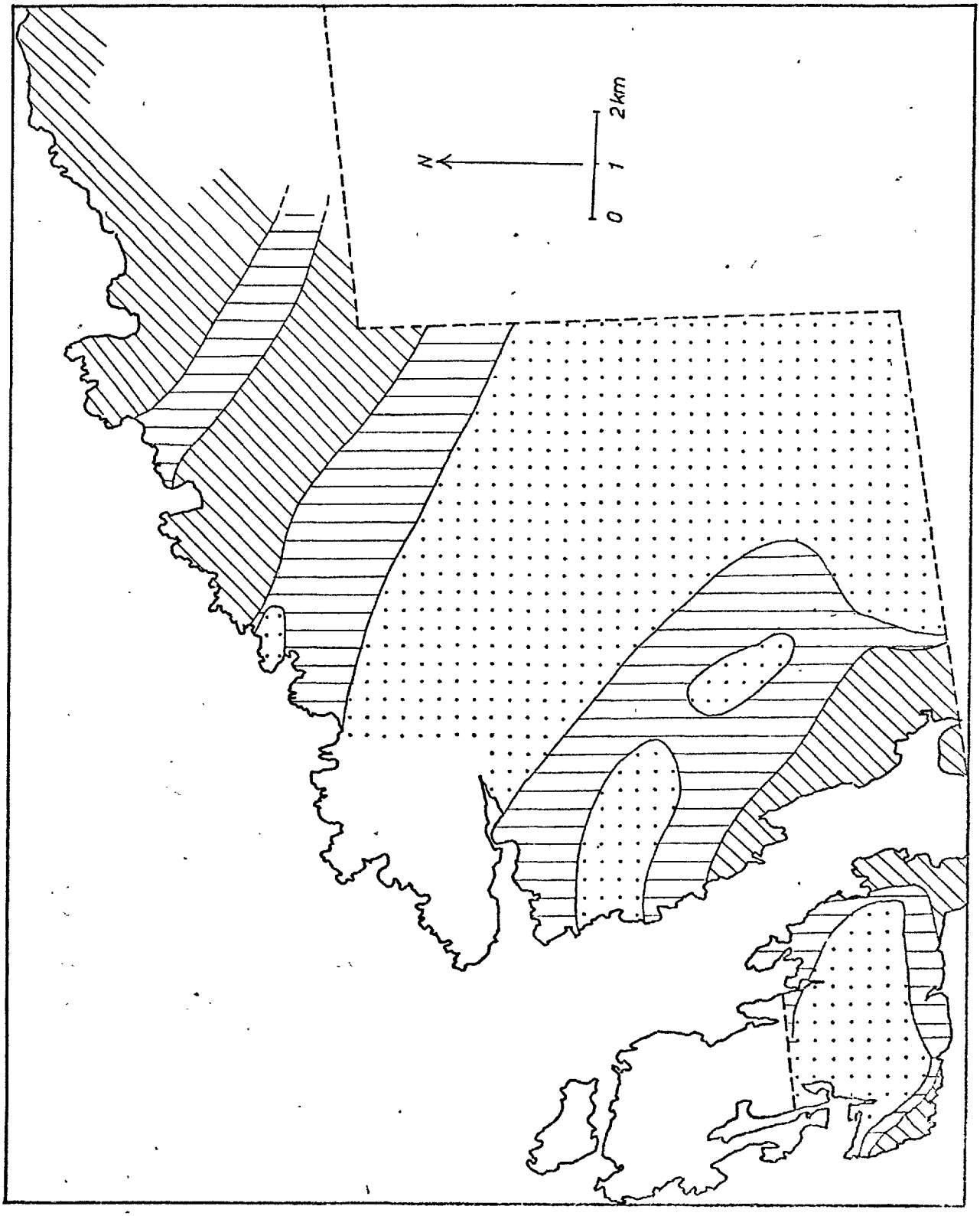


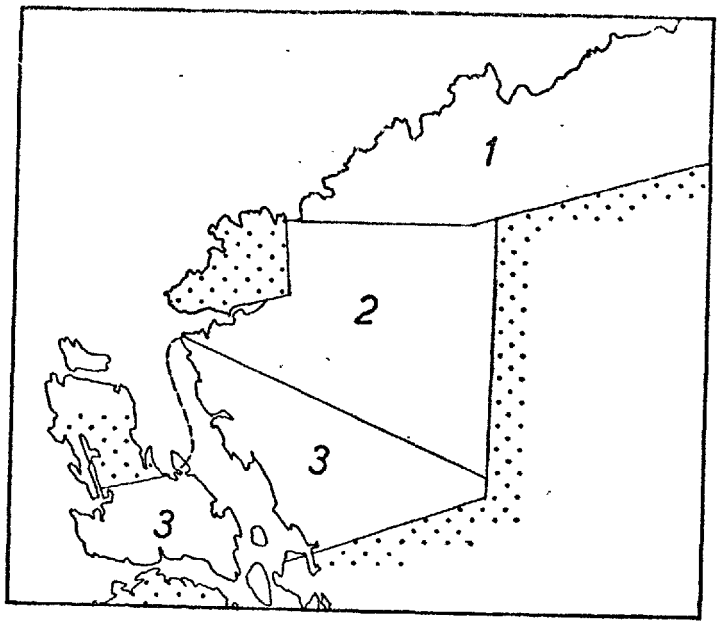
FIGURE **11**

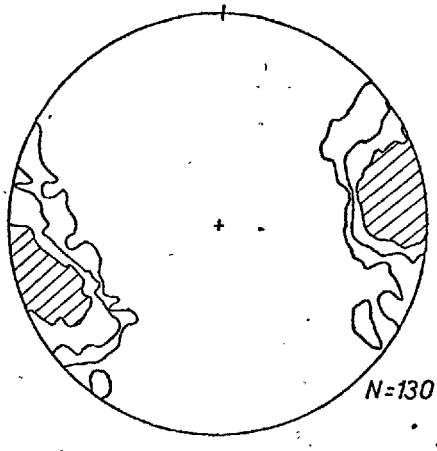
F2 FOLD ORIENTATIONS

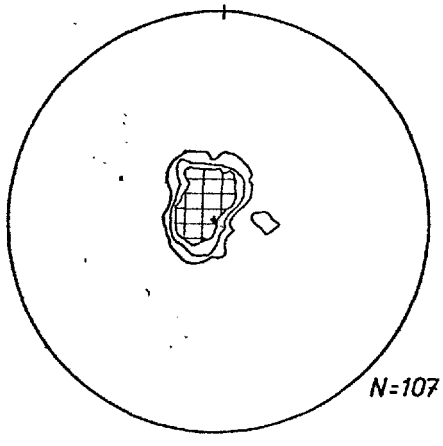
Map shows locations of subareas 1,2 and 3.

Left hand stereograms - fold axes. Contours at 2.5, 5 and 10% / 1% area.

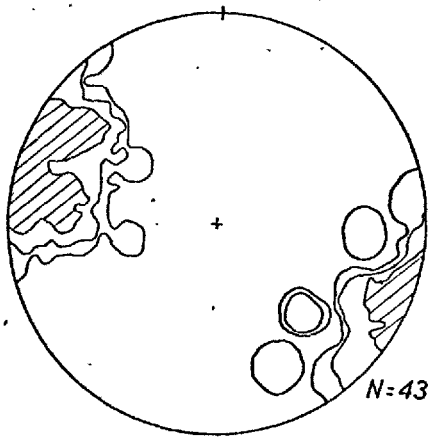
Right hand stereograms - fold axial surfaces. Contours at 2, 4 and 8% / 1% area.

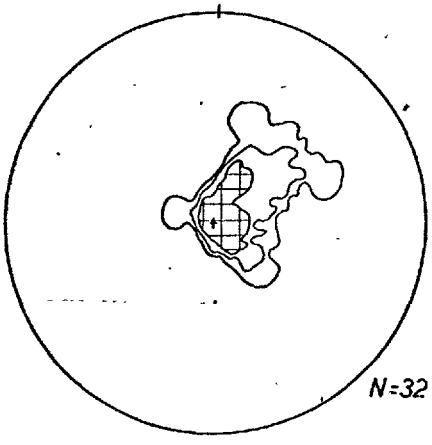




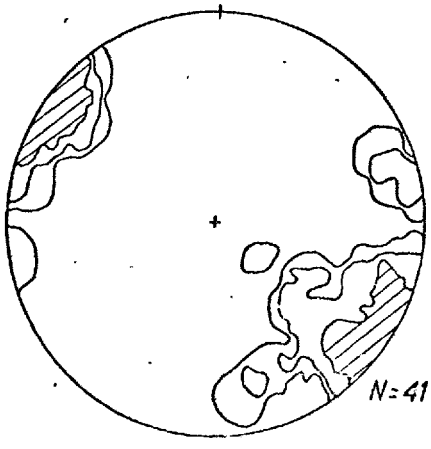


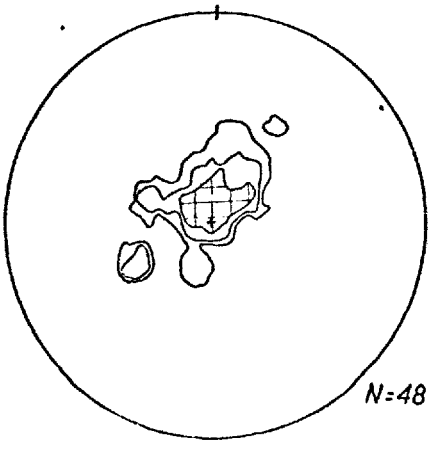
SUBAREA 1





SUBAREA 2





SUBAREA 3

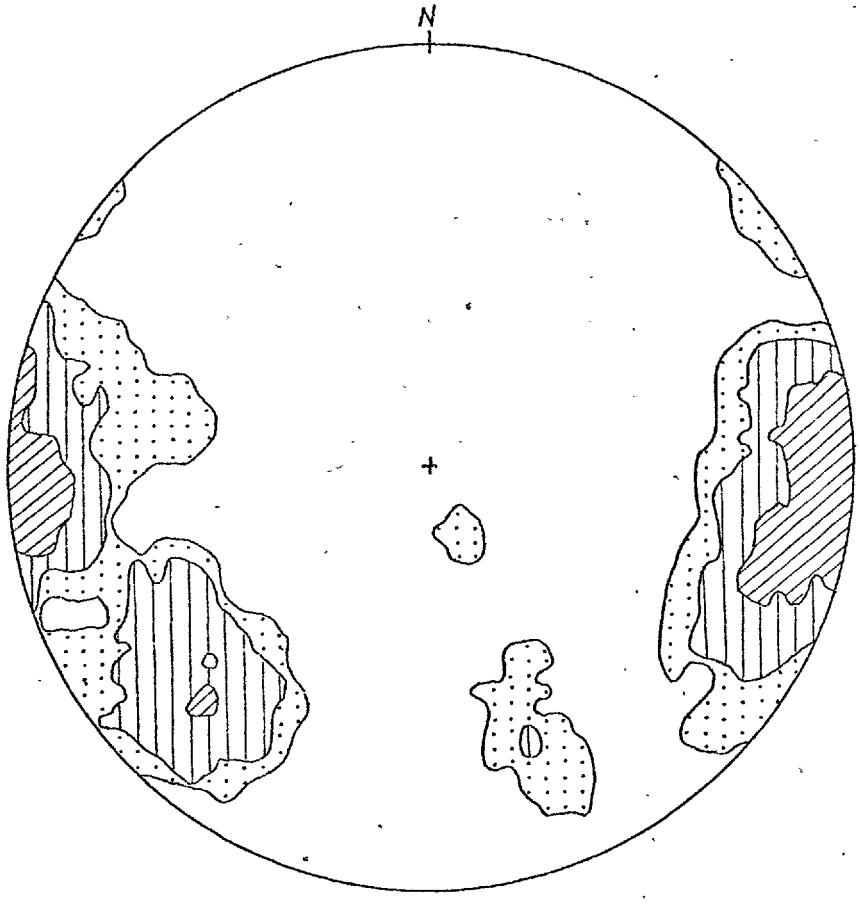


FIGURE 12

BOUDIN AXES

Whole area. Number of data = 90.

Contours at 2, 4 and 10% / 1% area.

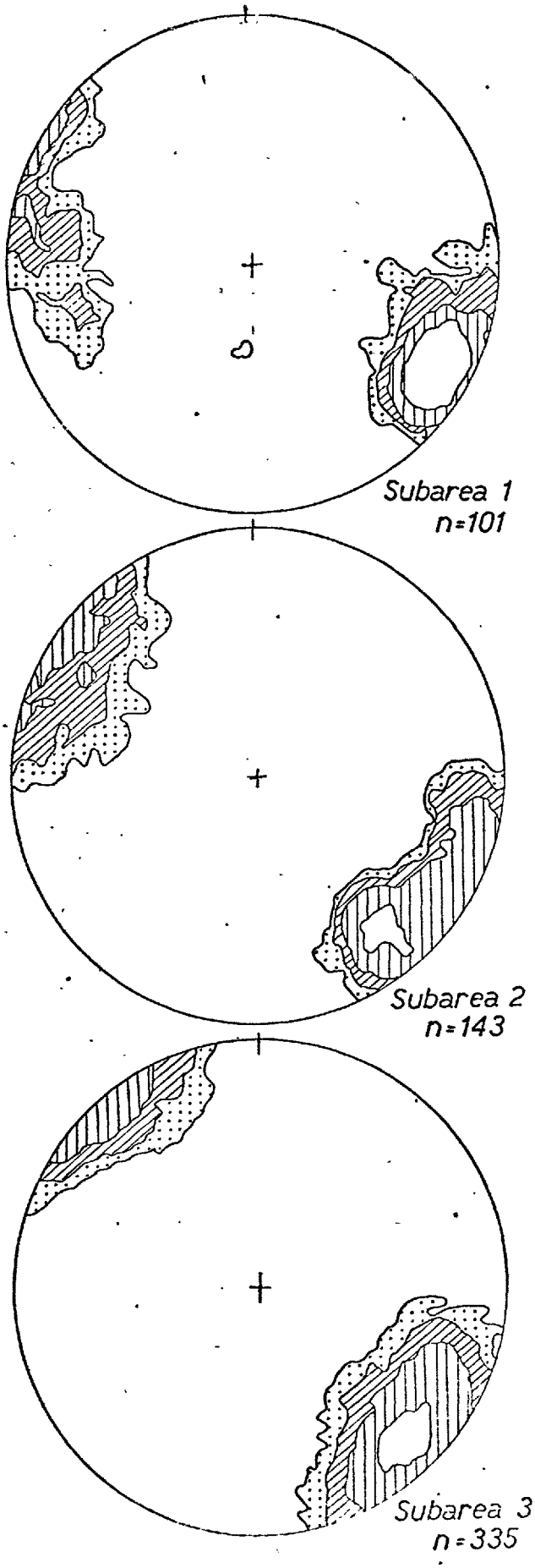


FIGURE **13**

EARLY LINEATION - orientation.

Same subareas as F2 fold data.

Contours 2,4,8,16% / 1% area.

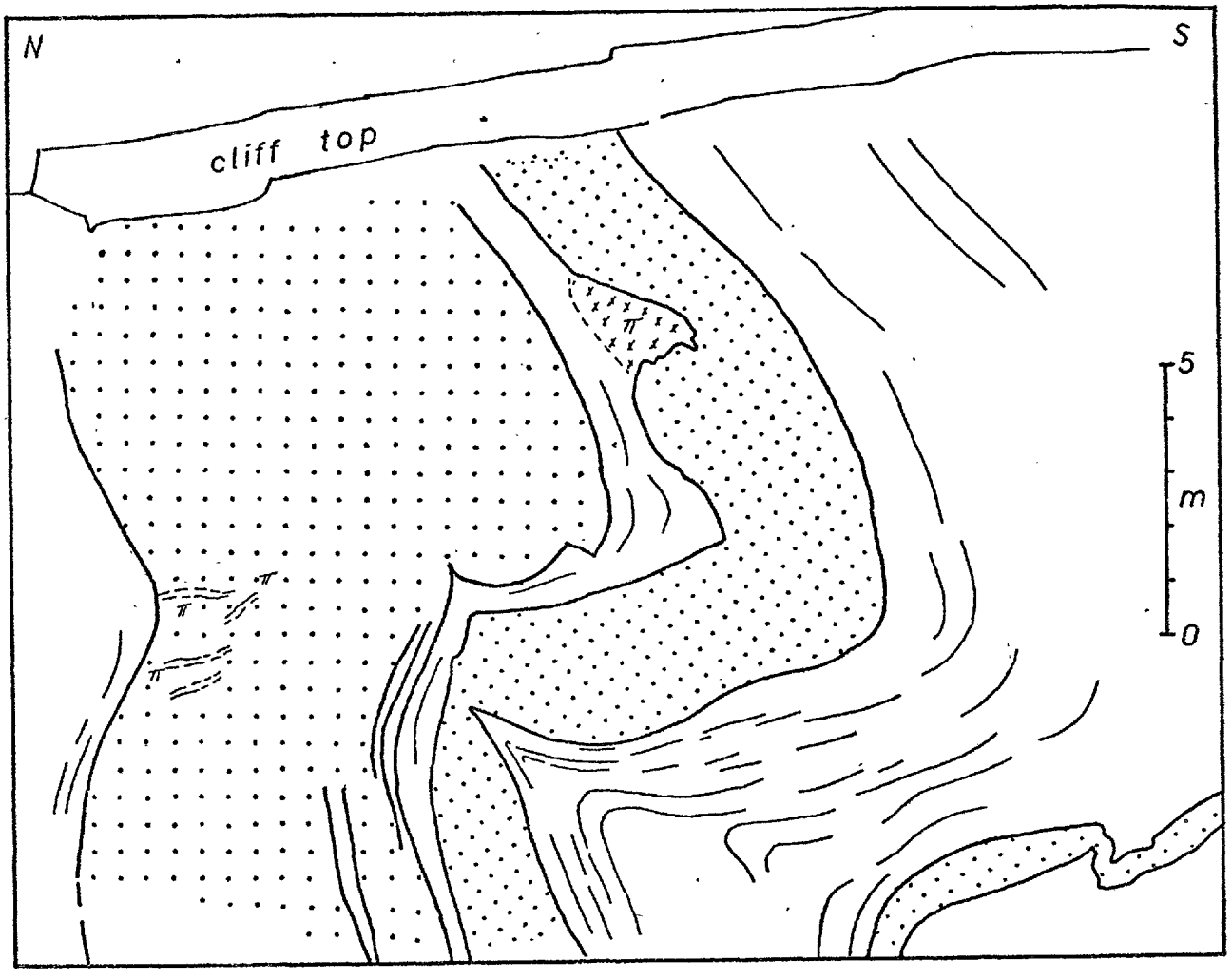


FIGURE **14**

LARGE SCALE F2 FOLDING. Cliff section - Aird Mhor Bragair.

Coarse stipple - pre-Scourie Dyke garnet amphibolite.

Finer stipple - Scourie Dyke amphibolite.

Crosses - pegmatite.

FIGURE 15

STRAIN DETERMINATION FROM A FOLDED SCOURIE DYKE

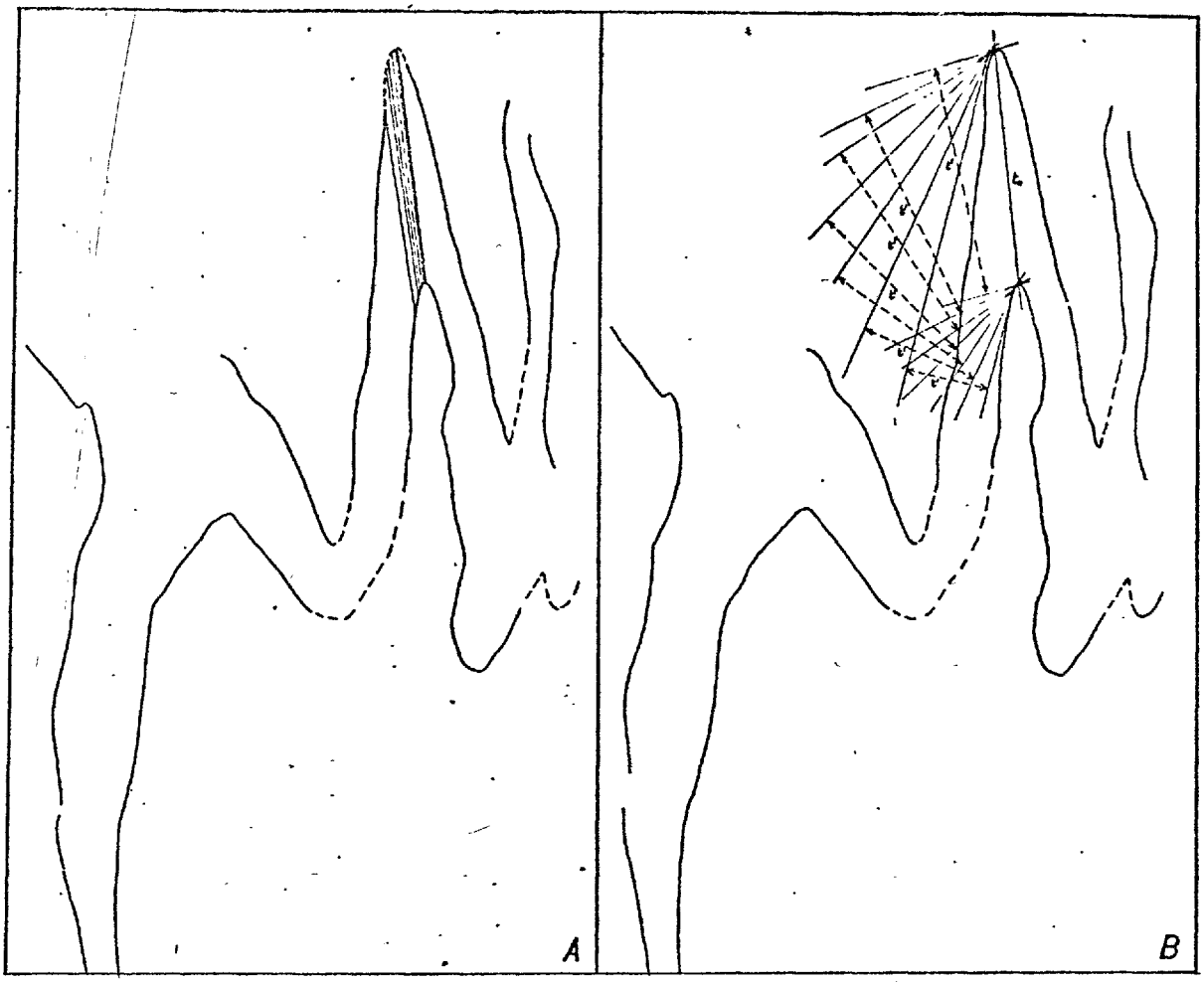
A. Folded dyke with dip isogons.

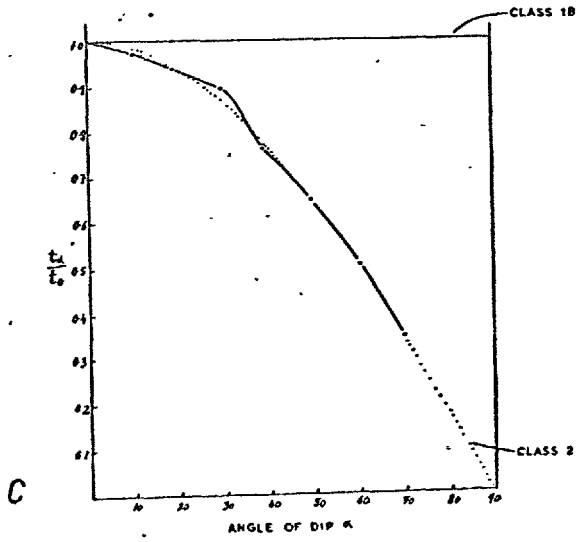
B. The orthogonal thickness, t, and the thickness at the hinge to.

C. Graph of $\frac{t\alpha}{to}$ against α , the angle of dip.

The curve indicates that the flattening over most of the limb has been strong producing a fold approximating to Class 2. A minimum flattening strain of 10:1 is indicated.

D. Fold after homogeneous flattening has been graphically removed.





C

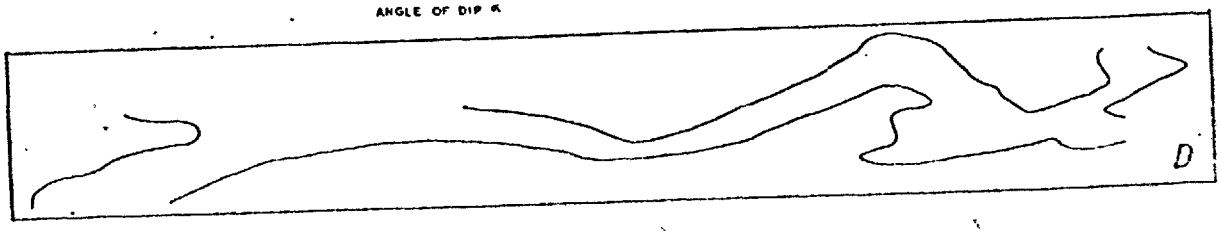


FIGURE 16

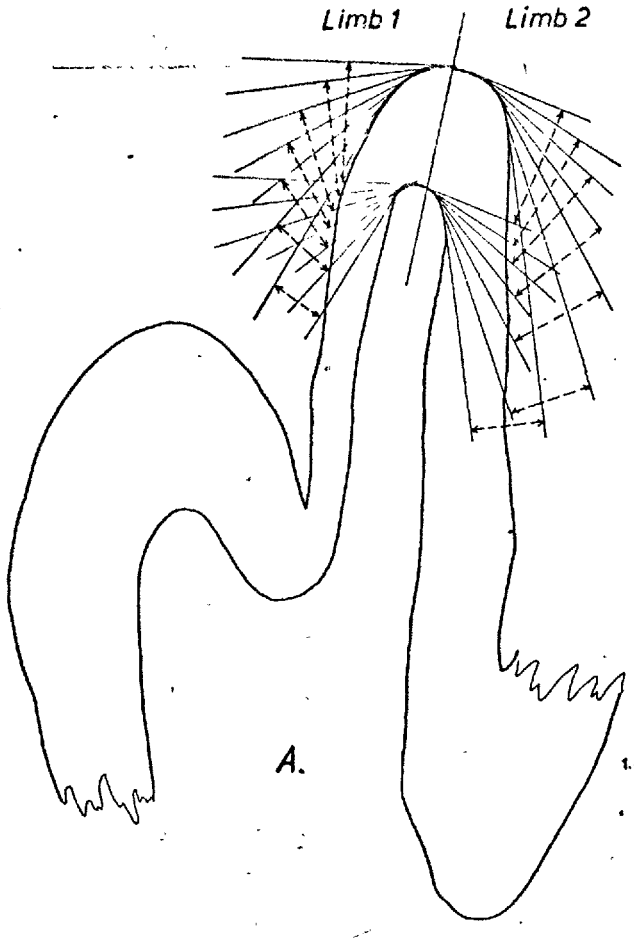
THE t'/α METHOD APPLIED TO A FOLDED (F2) PEGMATITE VEIN

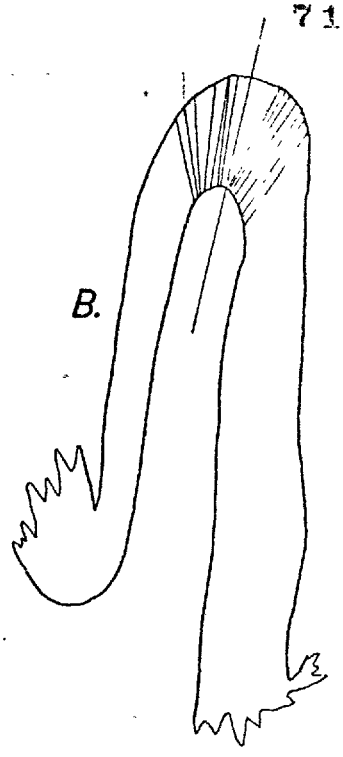
A. Orthogonal thickness (t) variations for both limbs.

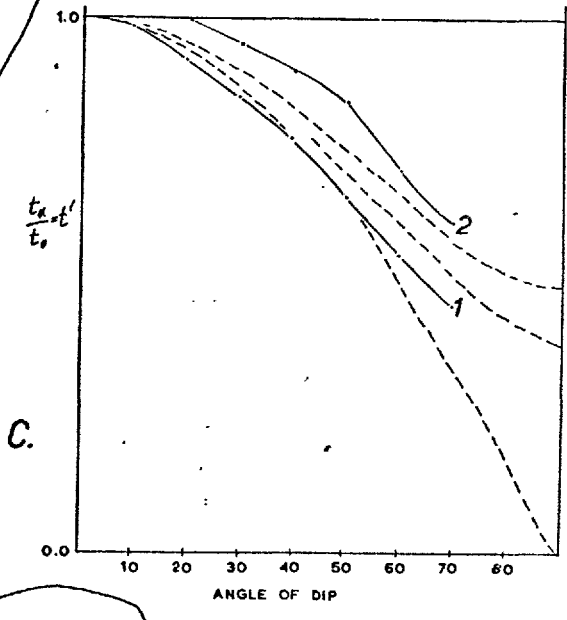
B. Dip isogons.

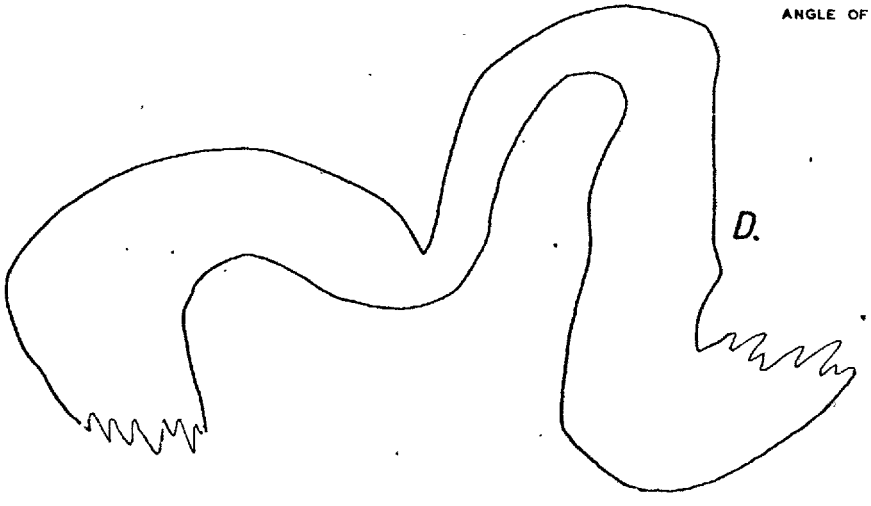
C. t'/α graph. Limbs show different flattening amounts but a mean of 2.5:1 is estimated.

D. Vein after homogeneous flattening has been removed. This buckle can be "straightened out" to calculate the strain due to buckling.


Limb 1
Limb 2
A.


B.


1.0
0.0
$\frac{t_a - t'}{t_a}$
2
1
C.
10
20
30
40
50
60
70
80
ANGLE OF DIP


D.

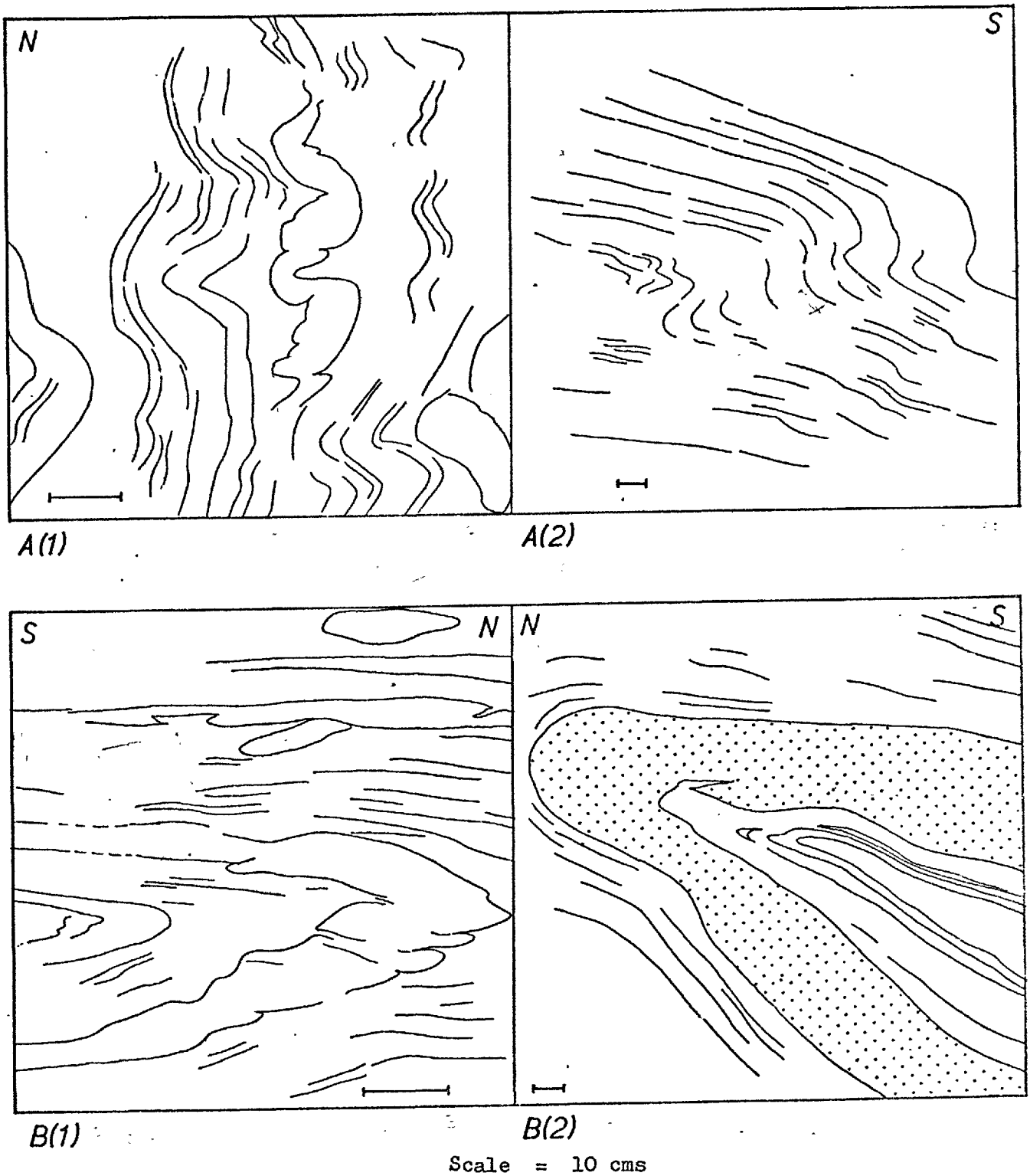


Figure 17 F2 Fold styles

A. Folds of zone II

A1. Dalbeg (231466) A2. Dalbeg (240459)

B. Folds of zone III

B1. S. Shawbost (245481) B2. Labost (280499)

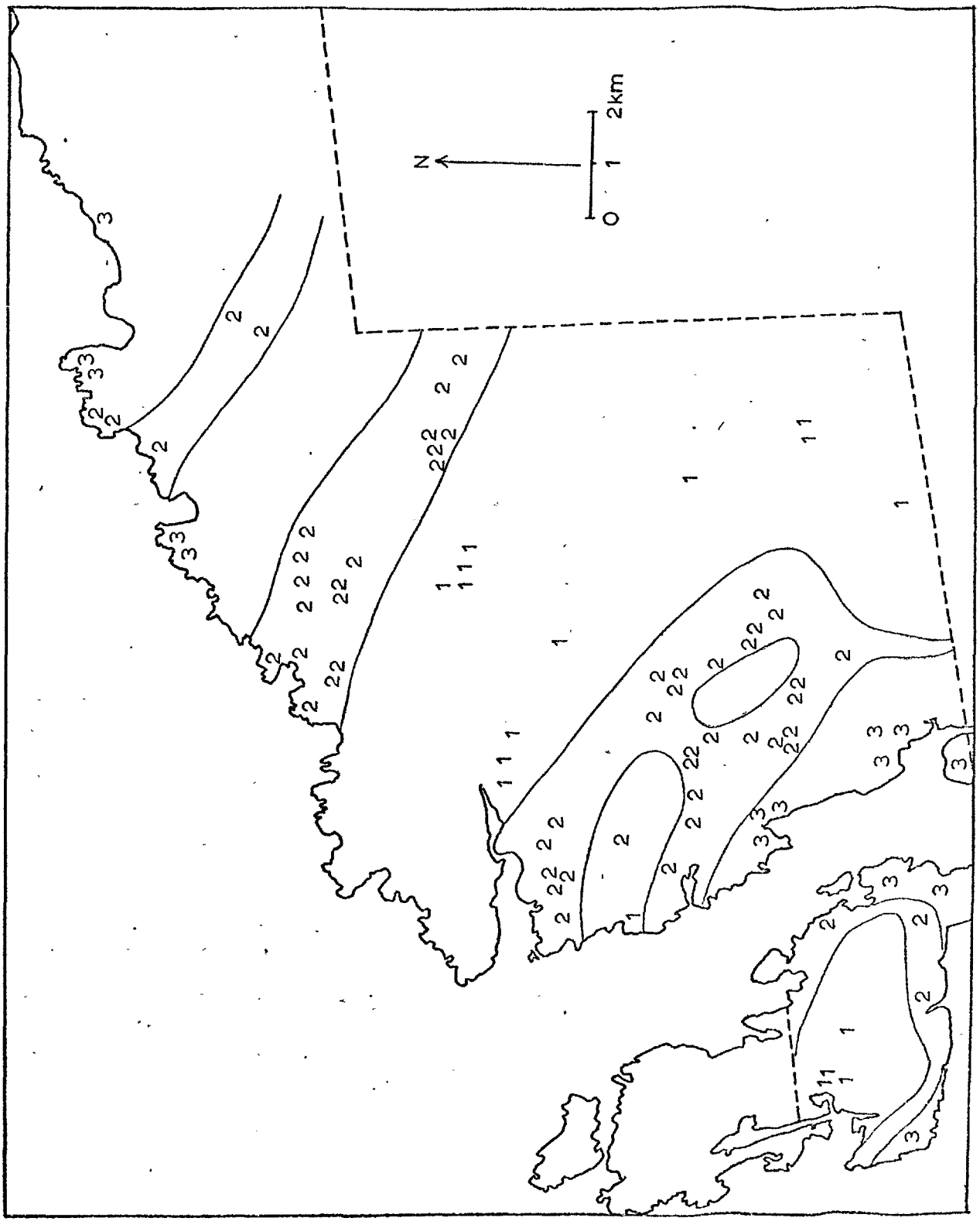


FIGURE 18

MAP OF F2 FOLD REGIMES

1 = zone I, 2 = zone II, 3 = zone III. See text for explanation.

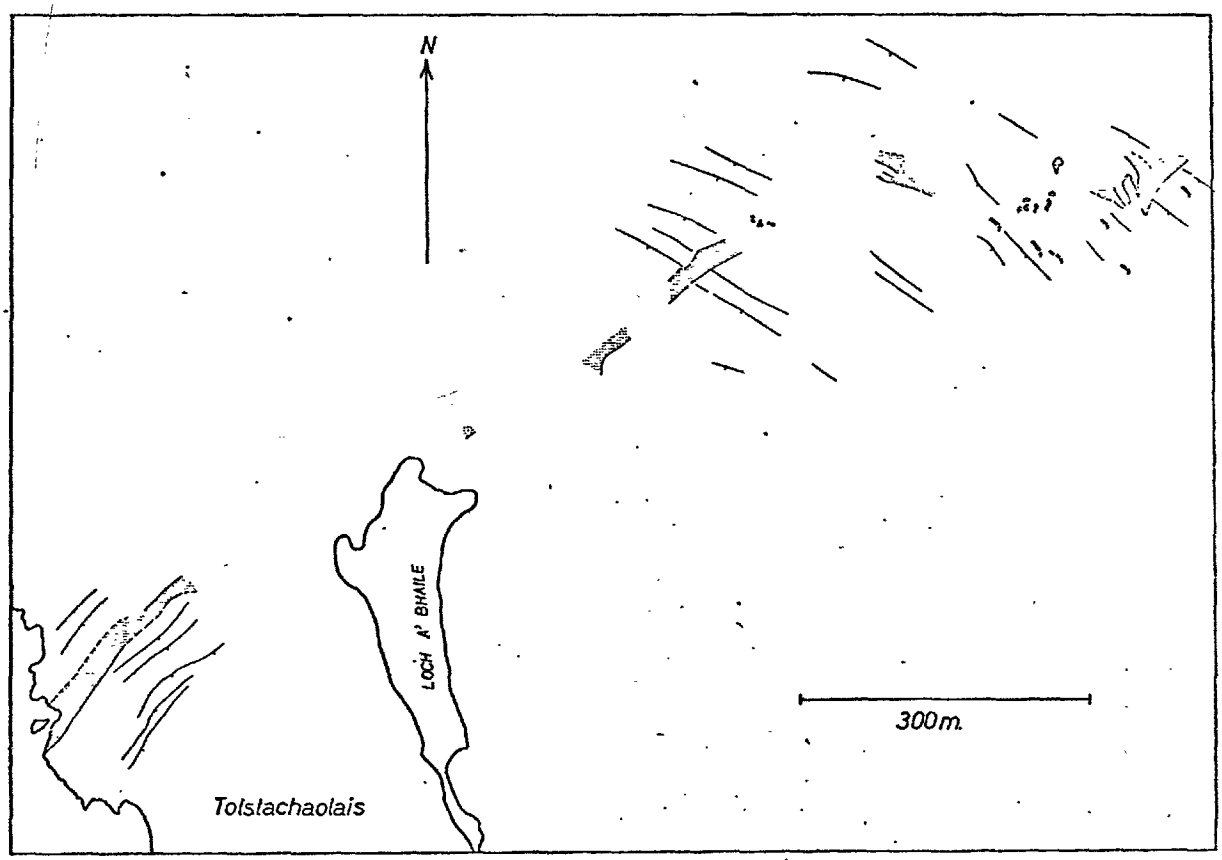


FIGURE 19

THE TOLSTACHAOLAIS GRANITE ZONE

Shaded areas are granite. Banding in the gneisses is shown.

FIGURE 20

THE DISTRIBUTION OF RECRYSTALLIZATION TEXTURES.

Outcrops showing recrystallization textures are marked with a dot.

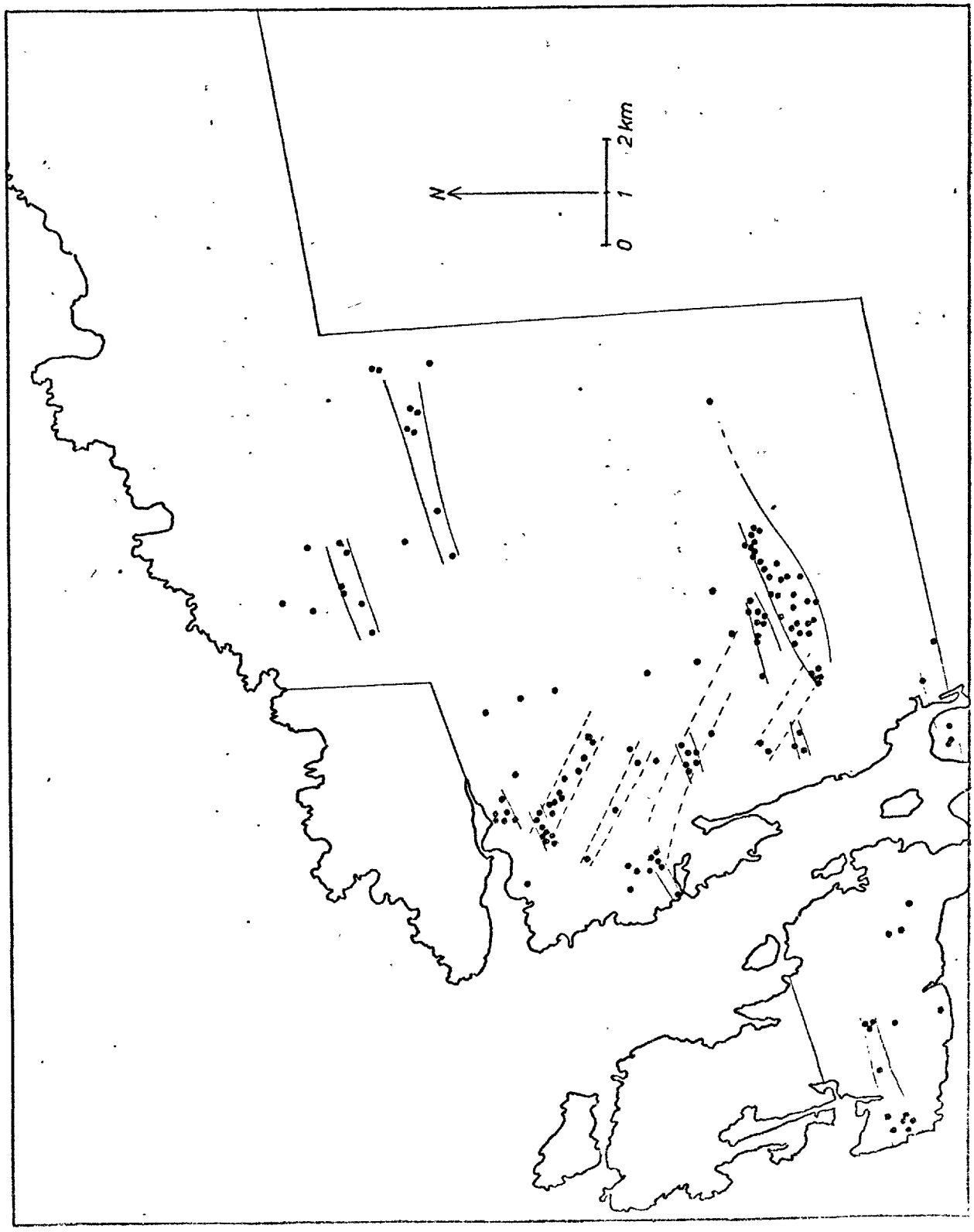


FIGURE 21

SYN - RECRYSTALLIZATION STRUCTURES

A. Horizontal surface. Fine pegmatite along shears in the gneisses. These syn - recrystallization shears distort earlier fold closures. Duone Carloway (210398)

B. Vertical section. Fine dots - recrystallized gneiss, Coarse dots - amphibolite.
Coastal rocks at North Shawbost.

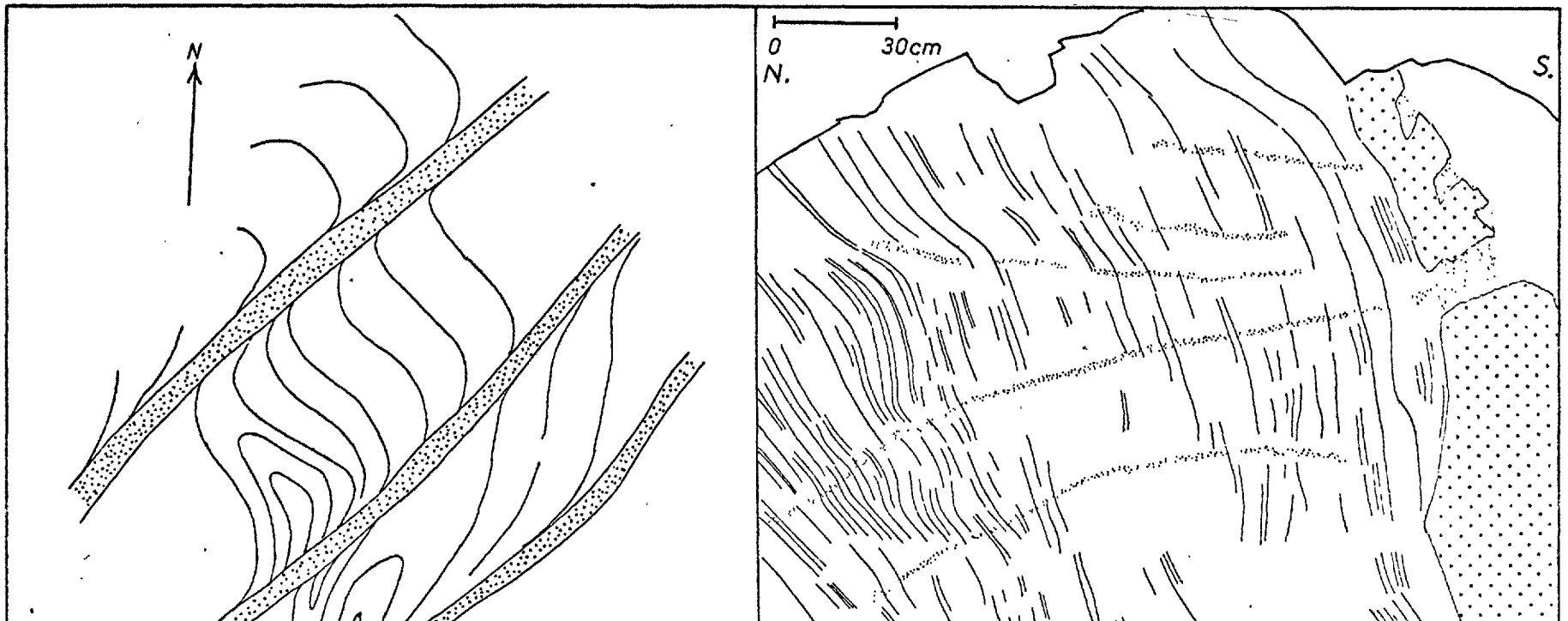

N
A.
0
30cm
N.
S.
B.



Figure 22

Shear zone associated with pegmatite

South Shawbost

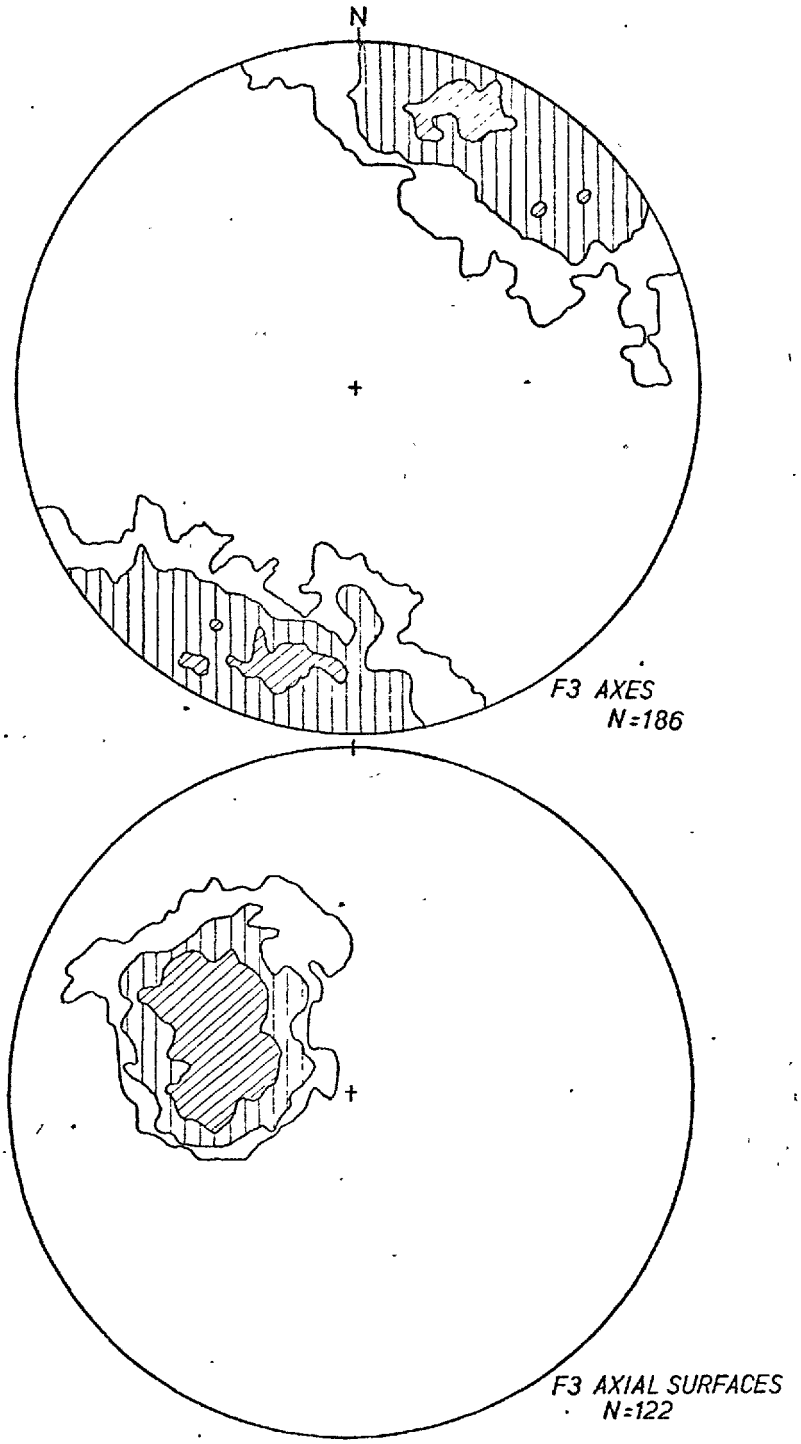


FIGURE 23

F3 FOLDS - Orientation.

Contours at 2,4 and 8% / 1% area.





FIGURE 24
F3 FOLDS

A. Coastal rocks between S.Shawbost and Dalbeg

B. Folding late Laxfordian granite vein Hacklete, Great Bernera

FIGURE 25

F3 folds with dip isogons

Coast west of Hacklete, W. side of Great Bernera.

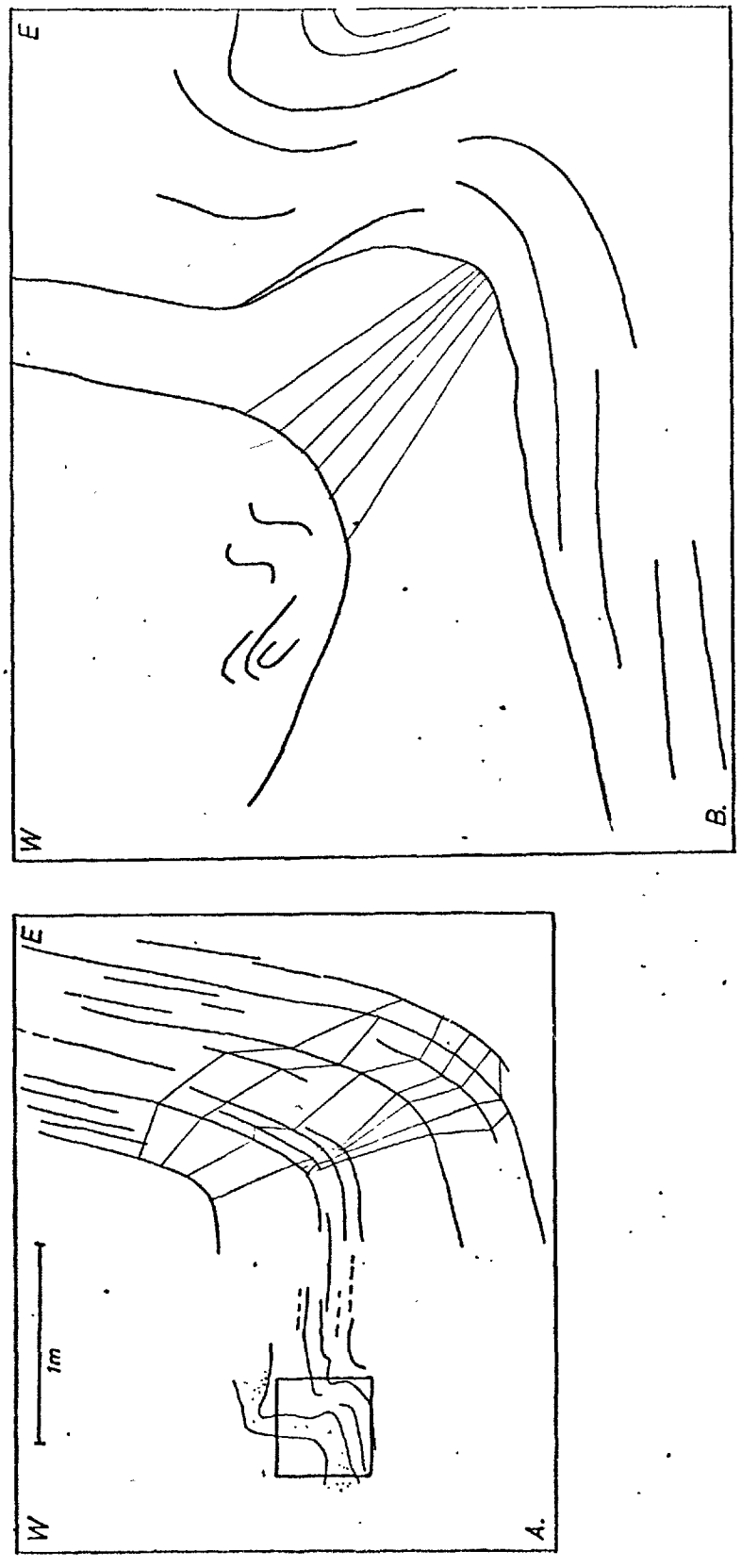


FIGURE 26

F3 FOLDS

The relationship between the dip of the axial surface and fold interlimb angle.

By least-squares method, eqn. of best-fit line :

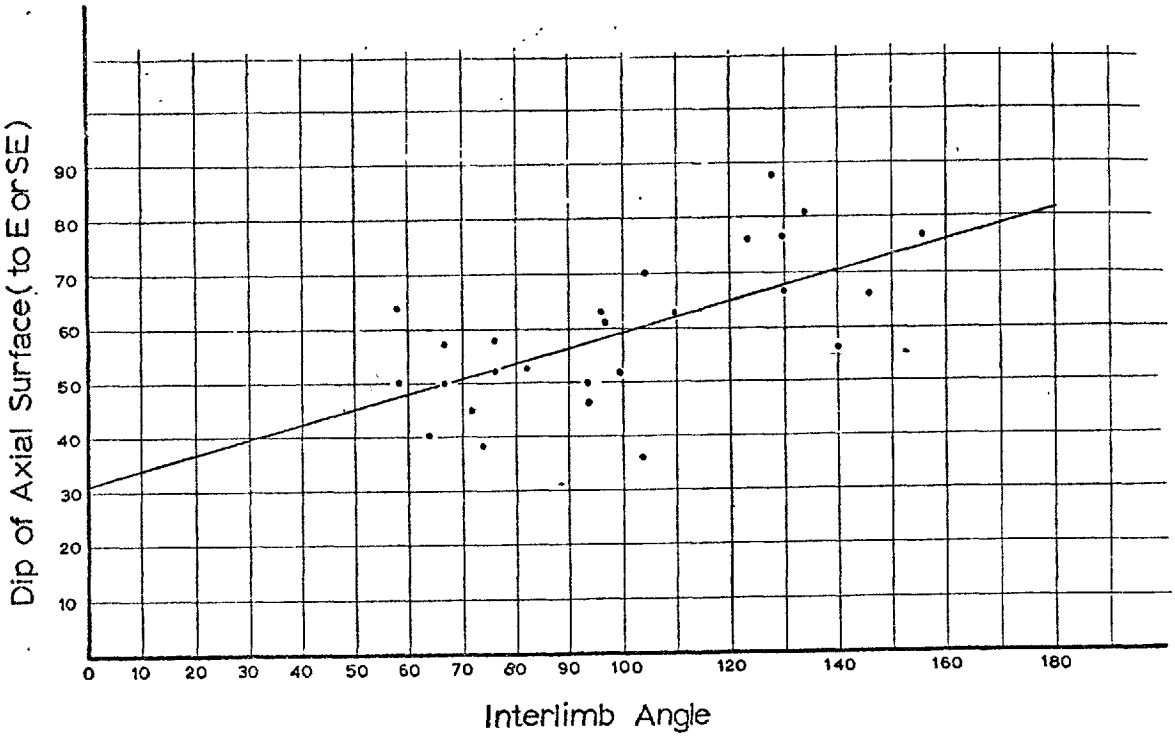
$$DIP = 31.3 + 0.28\ ILA$$

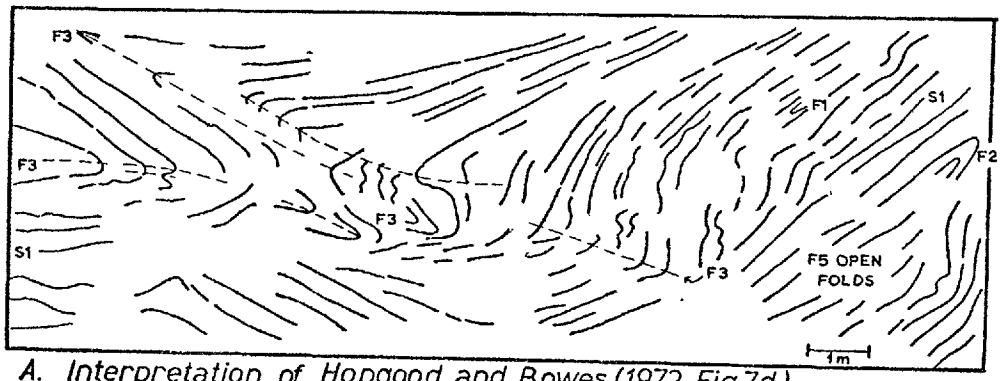
FIGURE 27

A ROADSIDE EXPOSURE ON THE NORTHERN SIDE OF BERNERA BRIDGE

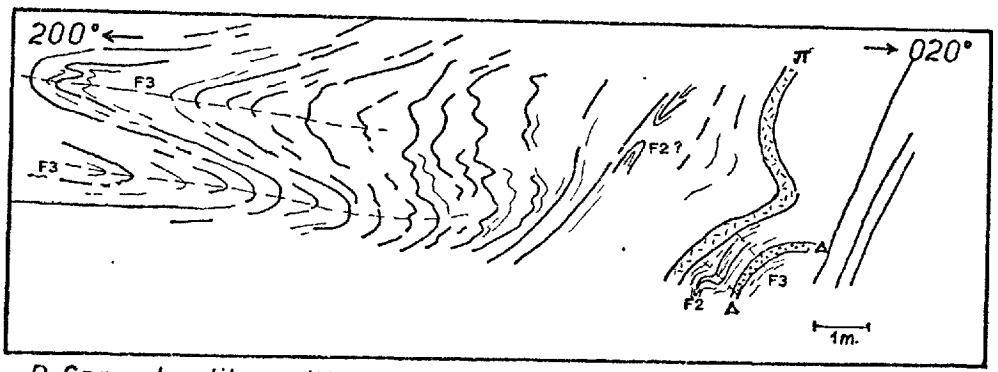
π = pegmatite

Δ = Scourie Dyke





A. Interpretation of Hopgood and Bowes (1972, Fig 7d)



B. Same locality - with fold terminology used here

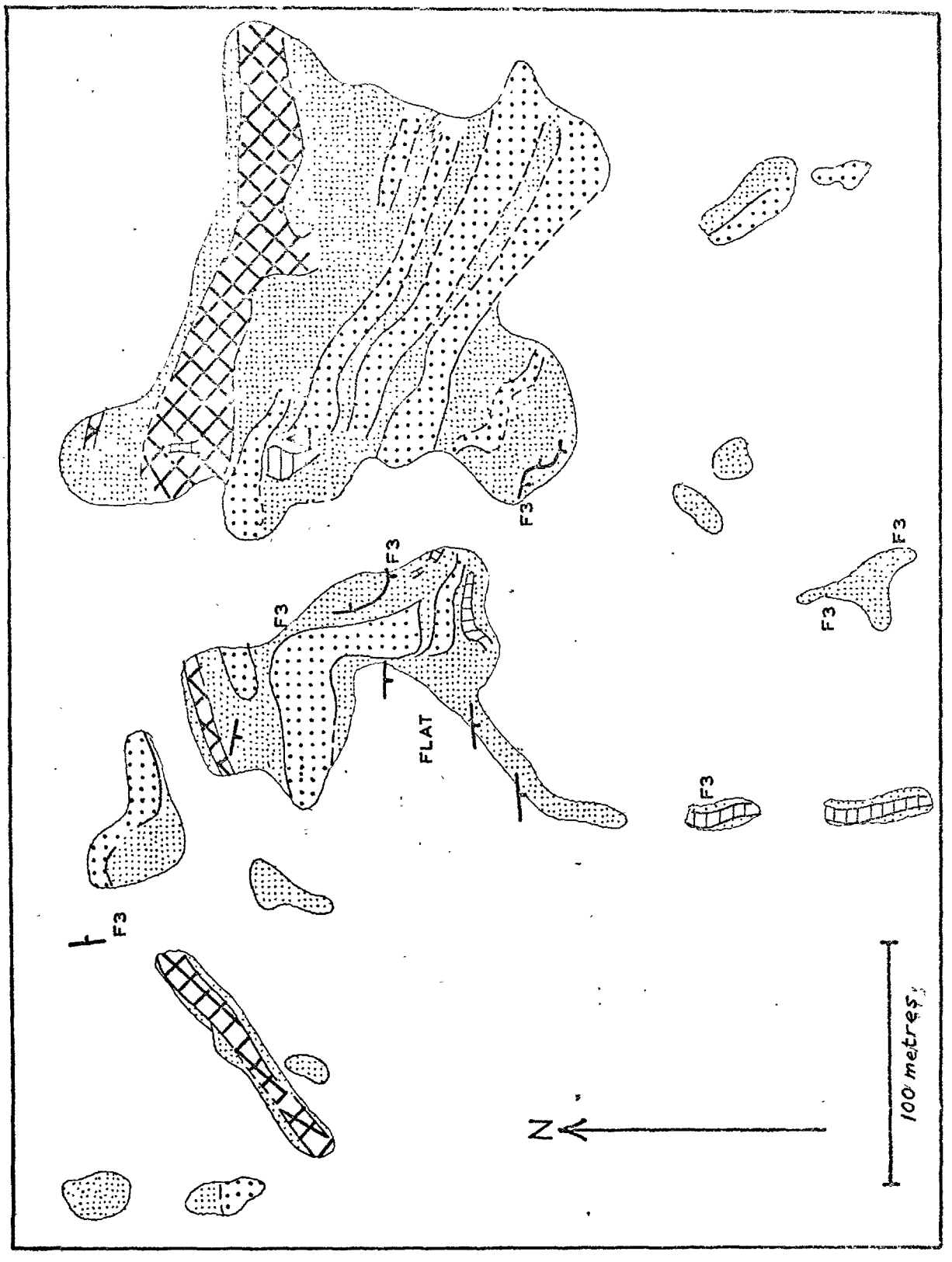
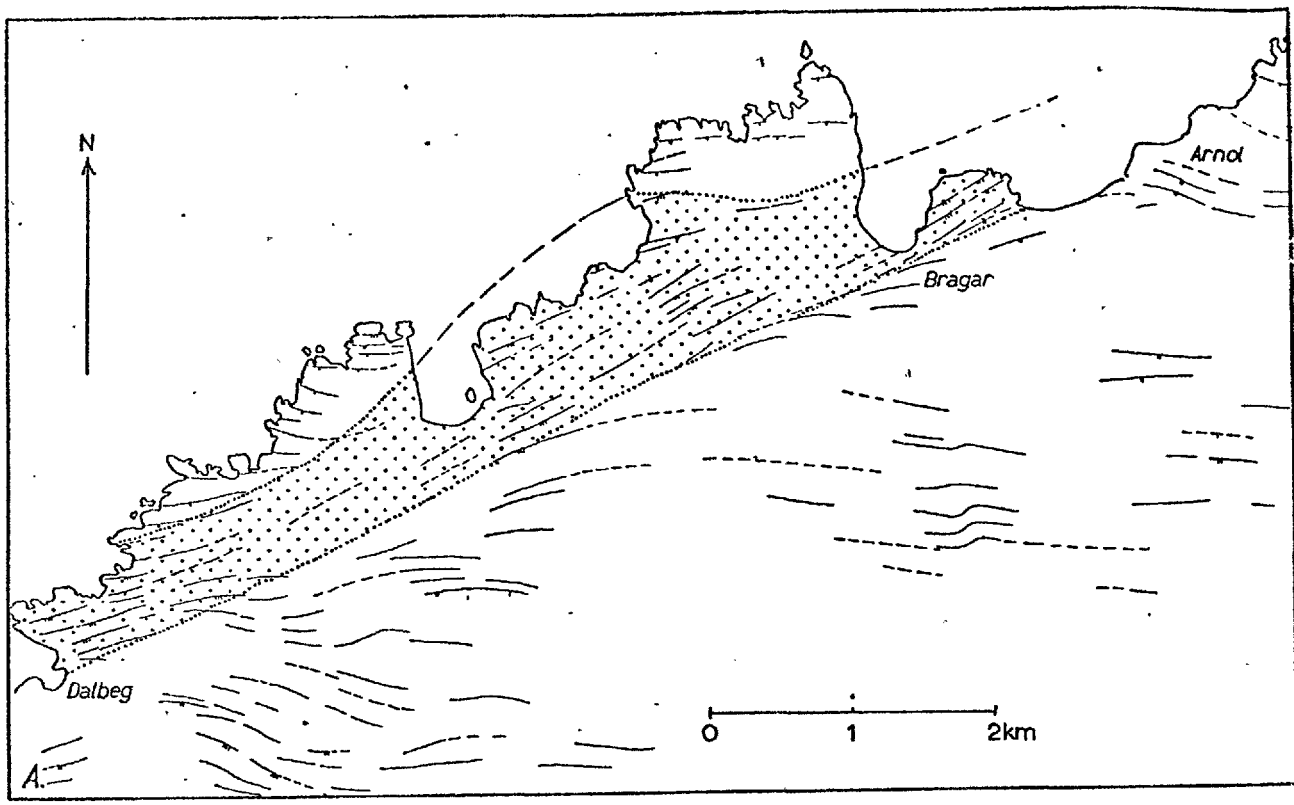


FIGURE 28

Exposure map of the summit of Ben Rahacleit showing F3 effects on outcrop patterns.

Coarse stipple - Scourie Dykes, Fine stipple - quartzo-feldspathic gneiss, Cross-hatched - older basics, Lined - pegmatites.



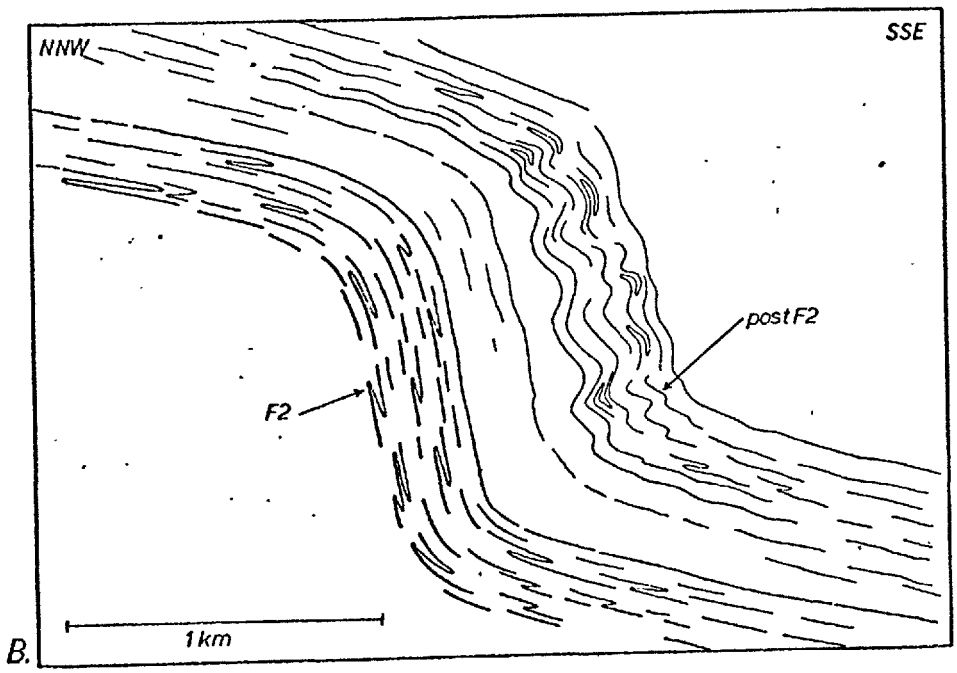


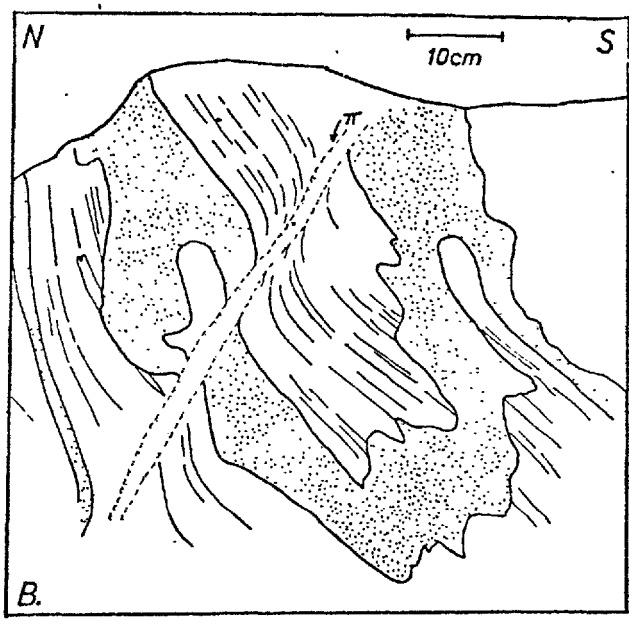
FIGURE 29

THE BRAGAR MONOCLINE

A. Outcrop of steep limb - shaded.

B. Idealized section through the monocline showing refolding of F2 by post F2 folds.





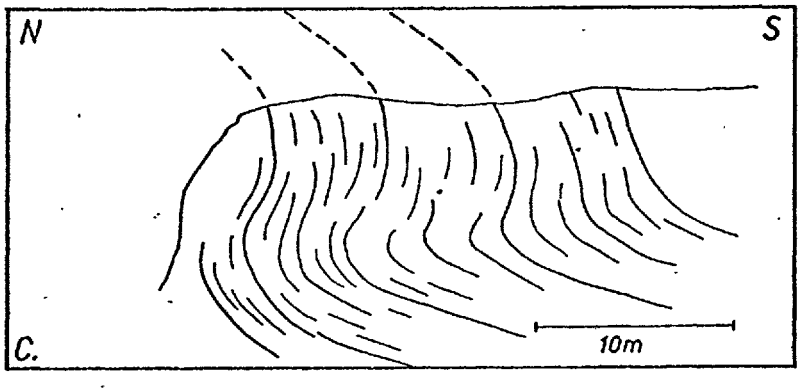


FIGURE **30**

STRUCTURES ON THE BRAGAR MONOCLINE

A. F2 fold with boudinaged limbs tilted southwards on steep limb of monocline. Development of post-D2 folds with flat axial surfaces.

B. F2 folds with south-dipping axial surfaces cut by pegmatite shear zone.

C. Minor monoclinal structure on N.W. part of Bragar Peninsula.

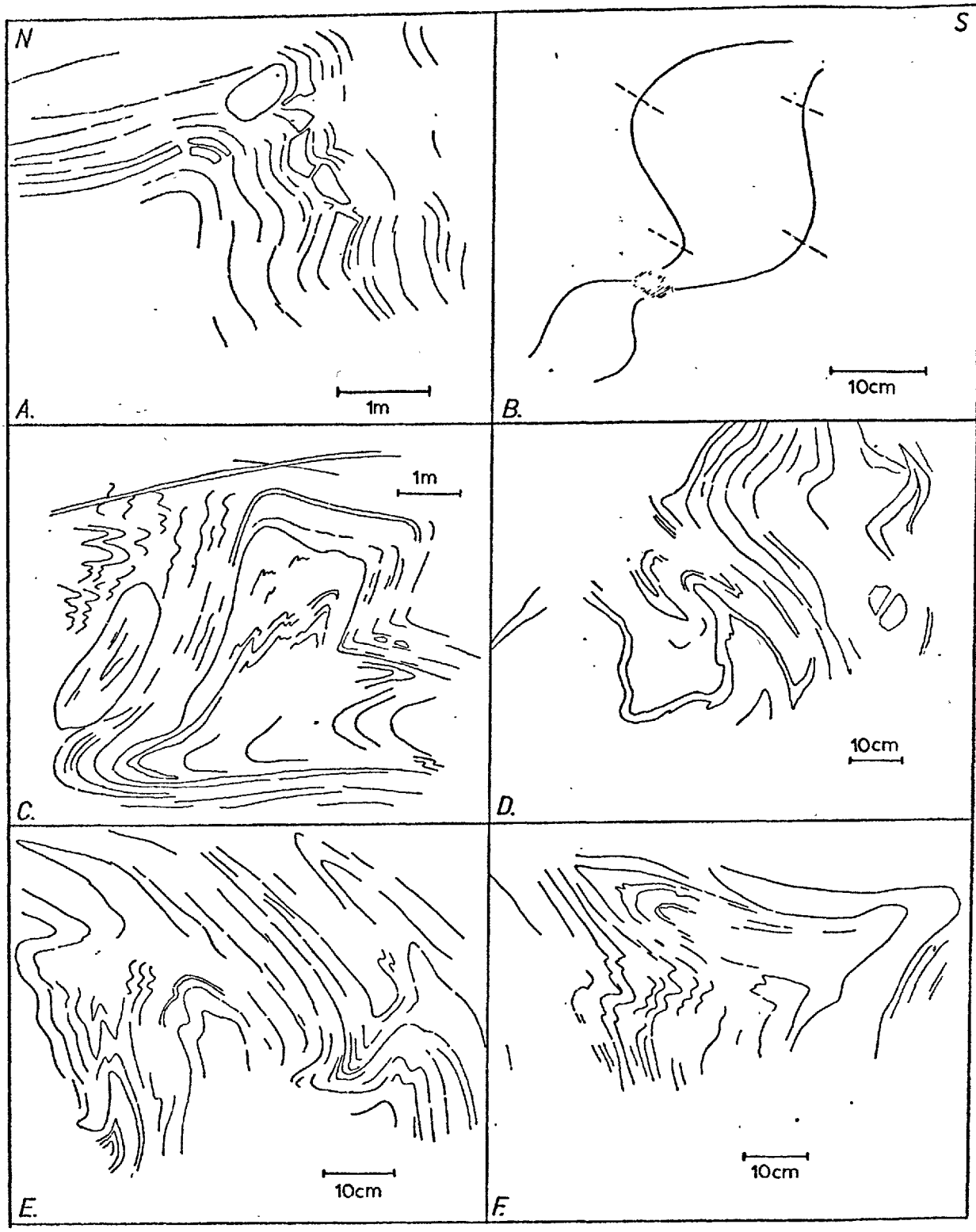


FIGURE **31**

POST - D2 FOLDS FOLDING D2 STRUCTURES ON NORTHERN COAST.

A. D2 boudins shunted together by post D2 movements, South Shawbost.

B. D2 boudinage refolded by post D2 folds, N.E. Bragar Peninsula.

C&D. Refolded folds, E. side of Dalbeg.

E. Refolded folds, N.E. Bragar Peninsula.

F. Refolded folds, North Shawbost.

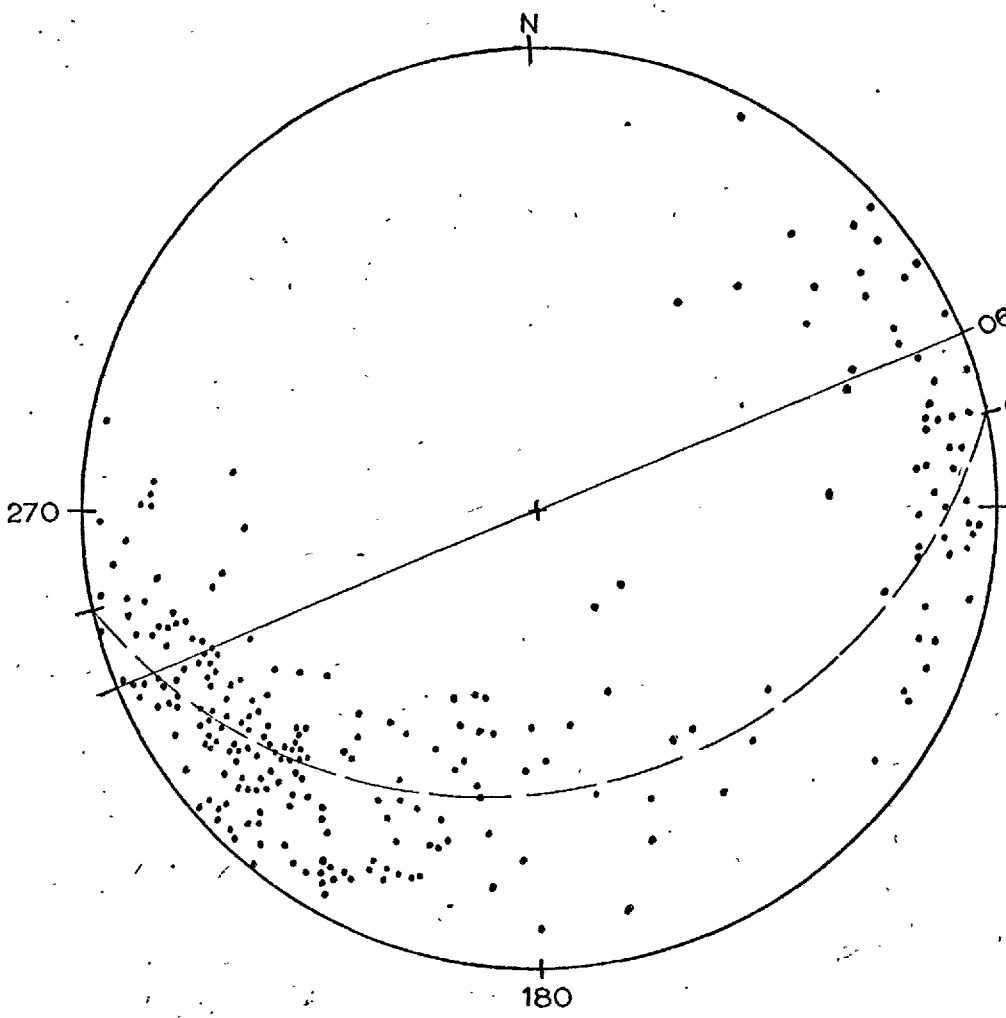


FIGURE 32

ORIGINAL STRIKE OF BRAGAR MONOCLINE

Given by best-fit plane through post-D2 fold axes.





FIGURE 33
SYN-CATACLASTIC FOLDS

A. Labost Peninsula, North Bragar

B. S. Shawbost

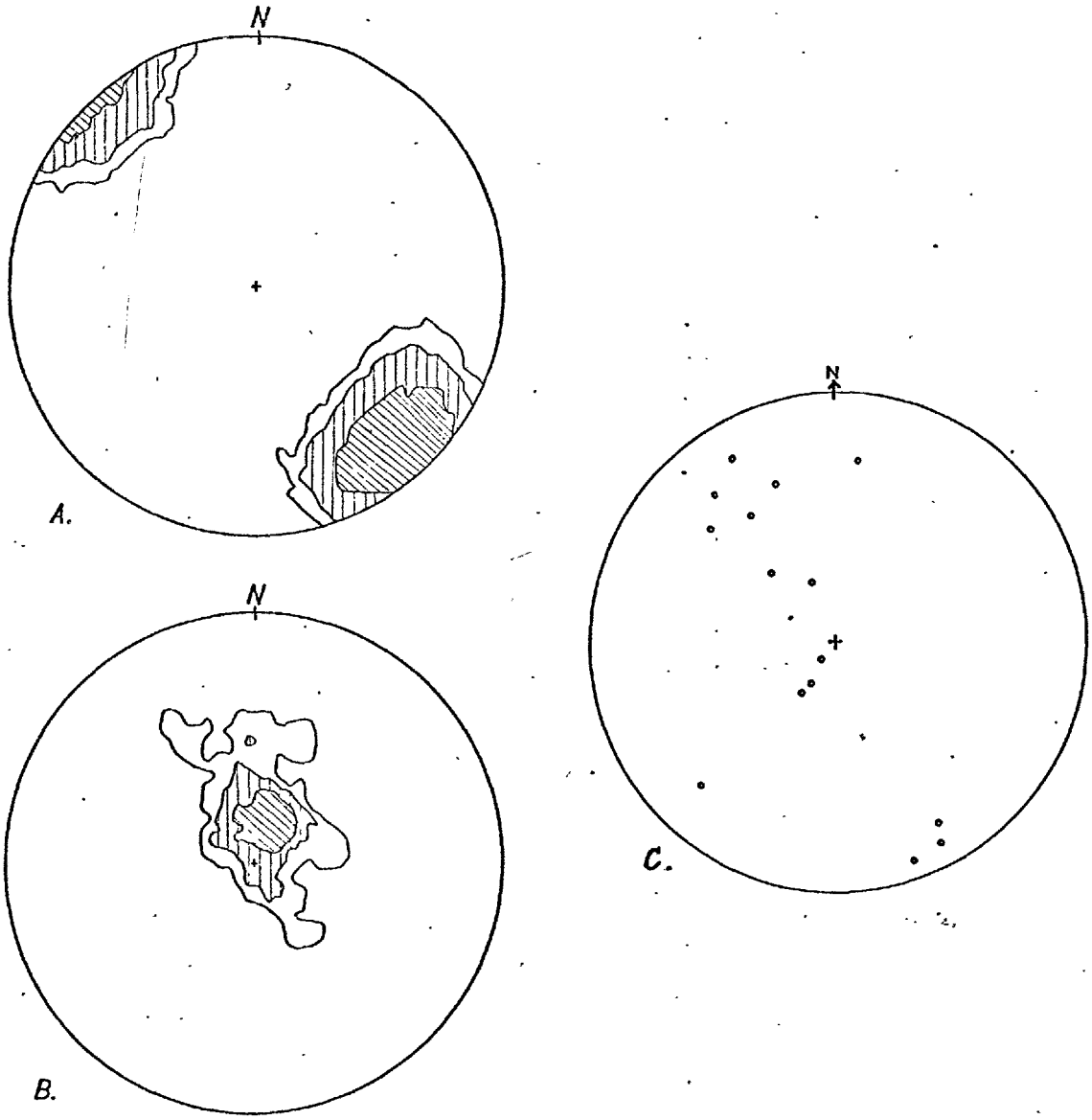


FIGURE **34**

A. Cataclastic lineations N = 357

B. Poles to flinty-crush surfaces N = 131

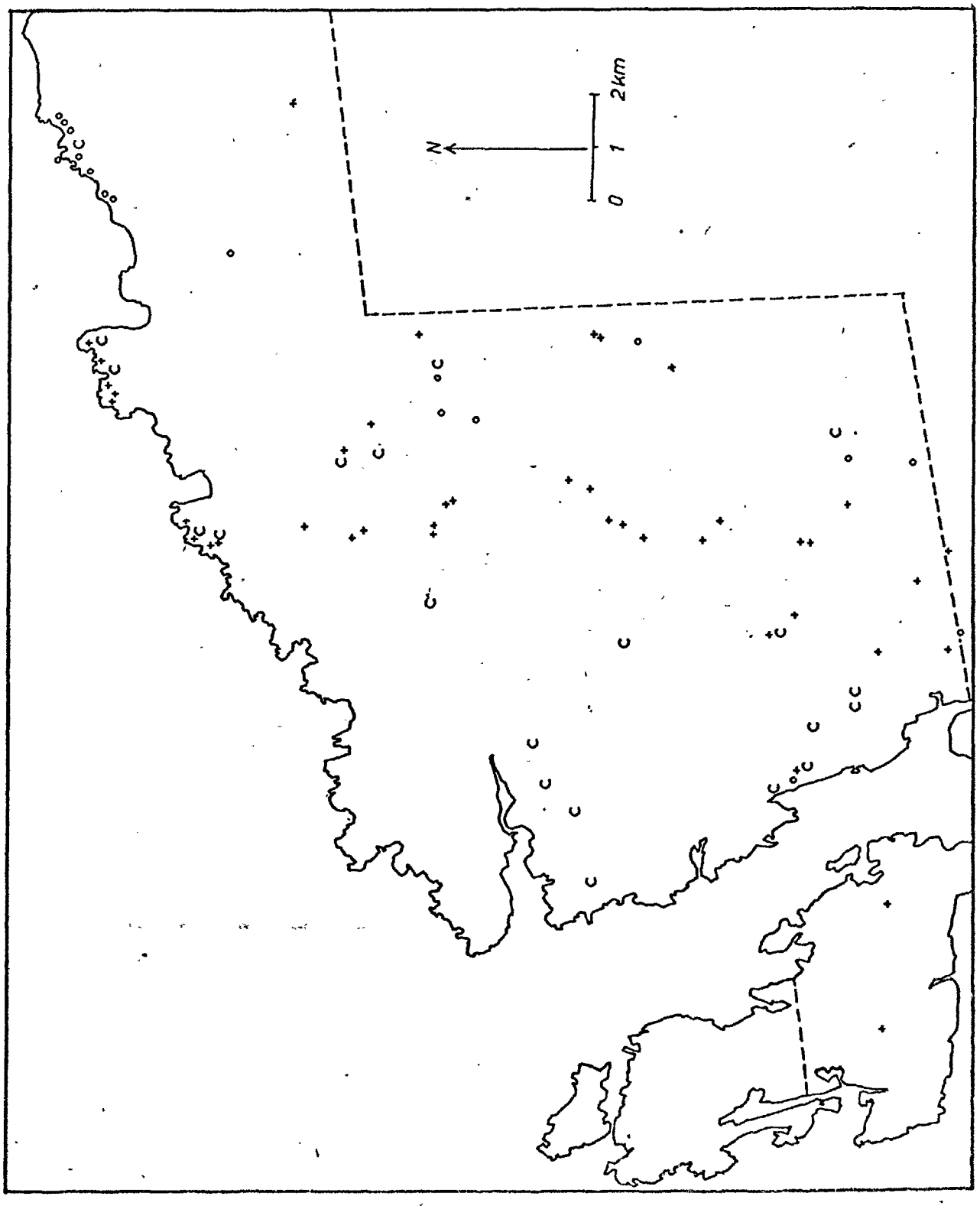
} Contours at 2,4 and 10% / 1% area.

C. Poles to granite foliation.

FIGURE 35

DISTRIBUTION OF PRODUCTS OF THE CATACLASTIC PHASE

Crosses = flinty-crush, c = cataclastic textures, circles = pseudotachylite.



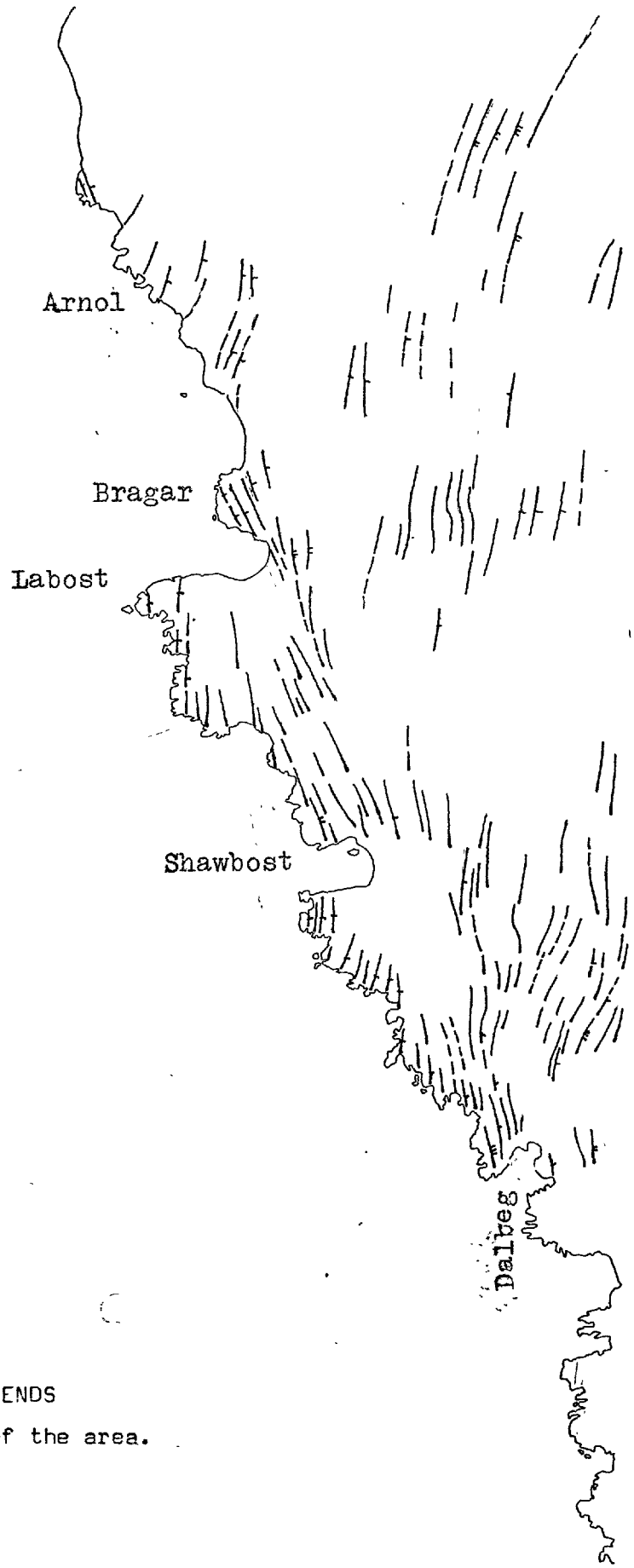


FIGURE 36A

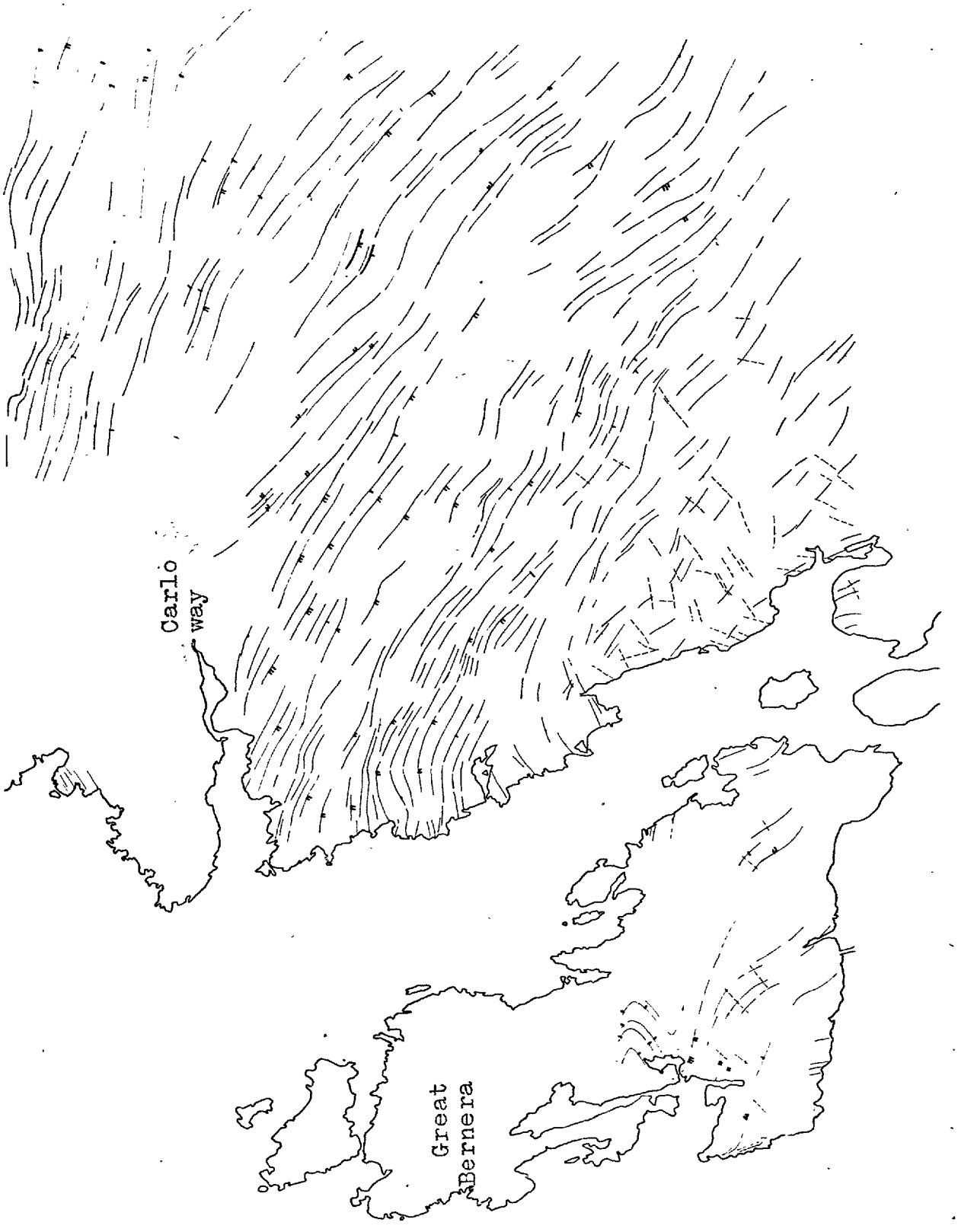
GNEISSIC BANDING TRENDS

Northern part of the area.

FIGURE 36B

GNEISSIC BANDING TRENDS

Southern part of the area.



PART TWO

CHAPTER 4 - LOCATIONAL ELEMENTS AND SHAPE-FABRICS

1. INTRODUCTION

Interpretation in structural geology relies on the recognition of certain geometrical features (for example planes, lines, etc.) whose significance and hence whose behavioural pattern during deformation is known or is assumed. Structures involving these features can be explained only when the features themselves have been assigned some significance.

This section examines various types of s-surfaces, lineations and shape-fabrics observed in the area so that such a reference framework can be constructed. Interpretation of other mesoscopic (Turner and Weiss 1963 page 16) structures can then proceed.

2. THE GEOMETRICAL DESCRIPTION OF LOCATIONAL ELEMENTS AND SHAPE-FABRICS

An 's-surface' (Sander) is any kind of penetrative planar structure in rocks (Turner and Weiss 1963). (A penetrative structure is one repeated frequently and consistently within the area (or volume) of the selected domain.) From the viewpoint of likely deformation behaviour, it is convenient to distinguish between two particular types of s-surface (or lineation):

Locational Elements are specific planes (or lines) defined in position. As they can be located, their geometry can be observed directly. Each s-surface is defined by the material points contained within it. During deformation the s-surface does not "move through" the material but continues to be defined by the changing positions of the material points; in other words, it moves with the deforming material.

Shape-fabrics are defined by "populations" of elements rather than by specific planes, lines etc. The shape and orientation of the elements

defines the fabric but the positions of elements are not important. The population as a whole may be assigned certain abstract geometrical properties but because these are combined products of each individual's contribution to the fabric, the geometry is more difficult to evaluate than in the case of locational s-surfaces.

In the Lewisian we have examples of both locational elements (dyke contacts, lithological boundaries) and shape-fabrics (fabrics defined by the alignment of crystal aggregates, enclosed basic blocks etc.).

3. EVALUATING THE GEOMETRY OF SHAPE-FABRICS

Very few quantitative investigations have been done on shape-fabrics to calculate their total geometry though many observations have been made on the shape of individual population members. Deductions about total fabric geometry have then proceeded in one of two ways; either an assumption is made that its total geometry is that of individual members or it is assumed that the fabric geometry is related to the geometry of the deformation that produced it (the application of the symmetry principle to fabrics).

These assumptions have frequently led to the adoption of an ellipsoidal model for shape fabric geometry. Fig. 38 shows fabrics which are difficult to assign to such a model.

An attempt was made to assess the geometry of a shape fabric in a Scourie Dyke. The method of measurement is illustrated in Fig. 40 Although the shape fabric measured in this way is not perfectly elliptical (measurements were made in two dimensions only), it is probable that an ellipse is the simple geometrical figure which best fits the data.

4. IMPLICATIONS OF ELLIPSOIDAL SHAPE-FABRICS

Important implications arise by reason of the different properties of shape-fabrics and locational elements. Firstly more parameters are required to describe an ellipsoid (ellipsoidal shape-fabrics) than are required to define a plane or a line (locational elements). Secondly, these structures are affected differently by the imposition of strain upon them. Fig. 41 attempts to illustrate this difference in two dimensions. Both elements are assumed to behave passively. Essentially a very weak shape-fabric will be rotated more than a locational element by the same amount of homogeneous strain. On the other hand a strongly developed shape fabric will rotate less than a locational element. Finally, the two structures differ in their outcrop pattern on two dimensional outcrops. The line (or trace) produced by the outcrop of a locational element is, by definition, a line contained within the plane of the locational element. Only two such traces are required to define a planar locational element. However with an ellipsoidal shape-fabric the fabric direction on a two dimensional surface (called here the fabric trace) only in special circumstances lies in the XY plane of the fabric ellipsoid. There is generally no simple relationship between the fabric traces and the XY plane of the strain ellipsoid. This effect can be illustrated with a geological example. If an intrusive rock has an ellipsoidal shape-fabric developed within it so that the XY plane is parallel to the plane of contact (a locational element) then on a two dimensional outcrop it will generally appear that the fabric and the contact are inclined to one another (i.e. the fabric trace and the contact trace will not generally be parallel).

5. THE ANALYSIS OF SHAPE-FABRICS BY THE FABRIC-TRACE METHOD

A. The Concept of a Fabric-Trace. The fabric trace (or apparent

lineation) is the long axis of the fabric ellipse produced by the intersection of an ellipsoidal shape-fabric with the exposure plane. Fig. 42 is a stereographic projection with contours representing the loci of lines of equal radii in an ellipsoid. Imagine the great circle ABC to be an exposure plane. The intersections of the great circle with the contours reveal the state of elongation along various lines contained within that plane. Point C represents the line of maximum elongation within the plane and hence is the direction of the long axis of the ellipse on that plane. Point D is perpendicular to C and represents the short axis. In Fig. 42 then, the line C represents the fabric-trace on the plane ABCD.

B. The Method in its simplest form. The aim of the method is to reconstruct the fabric ellipsoid using the orientation of fabric-traces on variably-oriented planes through a tectonite. All measurements are assumed to be made within the boundaries of a homogeneous domain. Attempts have previously been made to determine fabrics (planar and linear) from the arrangement of fabric traces, e.g. Lowe (1946), Clark and McIntyre (1951), Den Tex (1953) and Cruden (1971) but the method has not previously been applied to ellipsoidal shape fabrics.

The layout of fabric traces is controlled by

i) the orientation of the fabric axes,

ii) the type of the ellipsoid as expressed by Flinn's k number and

iii) the departure from sphericity shown by the ellipsoid as expressed by a newly defined parameter - the m number. m is the distance from the origin on a Flinn ellipsoid diagram

$$m = ((a - 1)^2 + (b - 1)^2)^{1/2}$$

where $a = \frac{1 + e_1}{1 + e_2}$ and $b = \frac{1 + e_2}{1 + e_3}$

When the fabric ellipsoid is of the perfect prolate-type ($k = \infty$) the fabric trace can mark any direction with respect to the fabric axes with the exception that they cannot lie in the Y = Z plane. Each trace is an orthographic projection of the X direction onto the exposure plane.

Generally speaking, as the ellipsoid becomes more oblate (i.e. as the k value decreases) the fabric-traces become more restricted in their possible distribution. When the fabric ellipsoid is perfectly oblate (k = 0.0) all fabric-traces are contained in the XY plane of the fabric ellipsoid. In summary then, the amount of deviation of fabric traces from a planar arrangement is a reflection of the "prolateness" of the ellipsoid.

C. Statistical Methods. Depending on the nature of the data, the interpretation of fabric-trace patterns can proceed in one of two ways. If the exposure planes are randomly oriented, the concentrations of points representing fabric traces can be calculated by contouring on a stereographic projection and the contoured plot can then be compared with reference concentrations calculated for various ellipsoids (e.g. Fig. 43A,B). If abundant data are available, fabric traces can be plotted on a stereogram to define areas (if they exist) in which no fabric traces occur. The shapes of these "no fabric trace fields" are characteristic of particular ellipsoid shapes (Fig. 43C).

D. Restricted Data Methods. Usually the small numbers and restricted orientations of exposure surfaces will make the "statistical methods" impracticable. Providing the orientation of one of the fabric axes is known however, it is still possible to infer the shape of an ellipsoidal shape fabric.

The exposure planes (great circles, Fig. 44A) and their corresponding fabric traces are plotted on a transparent overlay to a stereographic projection which is rotated to position the known axis of the fabric ellipsoid at the centre. This overlay is placed in turn over several reference diagrams computed for various ellipsoids (for example, Fig. 44B) and rotated about the central axis until simultaneously all exposure planes intersect the highest valued extension contour at the position where the fabric trace is plotted. For only one reference diagram will the process be successful and the fabric shape will be given by the fitted reference diagram. This fitting process is illustrated in Fig. 44C and D.

E. Application to fabrics in Scourie Dykes.

The fabric trace method was applied to two specimens of foliated Scourie Dykes purely as a test of the usefulness of the method in practice.

One of the specimens had a dominantly linear type of fabric (specimen number 531) whilst the other had a fabric of a more planar nature (specimen number 620). Variably-oriented flat faces were cut on large hand specimens and the orientations of these faces were measured with respect to the main lineation direction (X) in the rock using a goniometer. The traces of the fabric (or apparent lineations) were measured on these faces. The cut faces are shown as great circles (dashed) in Fig. 45 with the fabric traces as the dots on these great circles.

In neither example do the fabric traces lie on a single great circle. This indicates that neither fabric is of a purely planar type ($k = 0.0$). On the other hand, neither of the specimens has its fabric traces arranged as orthographic projections of the main lineation direction (X) in the rock. We can add then that neither of the specimens has a fabric which is totally linear ($k = \infty$) either.

We must conclude that the fabrics are shape-fabrics which can be represented by triaxial ellipsoids ($X \neq Y \neq Z$). Specimen 620 has fabric traces which show a greater tendency to plot on a great circle and we can deduce that this rock has a lower k value than specimen 531.

This method has not been applied on a regional scale to the analysis of shape fabrics because the method in its present form is somewhat cumbersome. The method could be improved so that measurements of planes and fabric traces could be made more accurately and quickly (for instance by the use of a universal rotating stage device) and the graphical technique of fitting the fabric trace information to the reference plots for various ellipsoids could be replaced if a computer program was developed to perform this process mathematically. The method is described here as a foundation upon which further developments can be based.

6. THE SIGNIFICANCE OF BANDING

The term banding is used here for the configuration of the compositional units within metamorphic rocks. The term is defined here in a deliberately broad sense in order to embody structures which in the field can be seen to be of a transitional nature.

A. Field observations

The following structural variations of the banding structure have been noted:

i) Variation in an L/S fabric system. Complete transitions from gneisses with a linear fabric to those with a planar fabric have been mapped. The linear fabric is usually emphasized by mineral alignment (e.g. rods of quartz, crystals of hornblende) but is usually also a true banding structure (as defined above) defined by lensoids of basic material in a quartzo-feldspathic gneiss host (Fig. 46). Prolate lensoids give way to more flattened bodies in a continuous sequence. This modification

seems to go hand in hand with the modification of discordance relationships with Scourie Dykes. Where the planar type of banding is best developed it is difficult to recognize the modified equivalent of the lensoid gneiss. The variations are visualized as analogous to changes of Flinns k number. Sometimes the k value can be quantified by reference to the structure of the banding. Fig. 47 shows measurements of the axial ratios and orientation of lensoids on mutually perpendicular two-dimensional outcrops. These measurements are plotted on graphs of axial ratio versus orientation (i.e. R_f/ϕ graphs).

ii) Variations of "intensity" of the development of banding

The degree of development of banding was also recorded. Rocks were classified in a transitional sequence

massive gneiss → stabby gneiss → flaggy gneiss

As with the variation in fabric type, these changes are accompanied by a parallel sequence of discordance modification in the Scourie Dykes. This textural change is analogous to a change in "m" number (defined earlier in this chapter). The "flaggy" end of the scale represents high values of m.

These two types of banding modification are closely associated. The observed changes of gneiss aspect can be summarized on a Flinn ellipsoid diagram (Fig. 48). Totally massive (fabricless) gneisses are not often observed so we can infer that the "gneiss field" does not include the origin (1,1) on the diagram. This point becomes significant in later discussion.

The fact that some gneiss types observed in the field lend

themselves to this sort of classification signifies that we are dealing with fabrics with the geometrical properties of shape-fabrics. However some gneiss types do not lend themselves to this geometrical treatment. The flaggy, intensely-developed bands have more of the characters of locational elements than of shape-fabrics. Populations of particles appear to be replaced by continuous partings by a process of strong planarization. This strong planarization effect has caused a fundamental change in the nature of the banding structure which is likely to affect subsequent reaction to deformation.

B. Conversion of shape-fabrics to locational elements

Changes of the nature of banding are more difficult to explain than the transitional variations outlined above. The process of planarization is linked with the development of layer continuity which suggests more than just intense flattening of a shape-fabric.

These changes may be the combined effect of several mechanisms:

1. Passive rotation - rotating of small-scale s-surfaces and shape-fabrics into quasi-parallelism. This process would not lead to the development of new locational elements.

2. Rotation during folding - where the new banding is composed of the limbs of isoclinal folds. There is some evidence that some areas in the Tolstachaolais-Breasclete flat belt have banding which is defined essentially by isoclinal F2 fold limbs. This does not necessarily apply everywhere because the fold closures are only rarely seen. Again such a mechanism would not replace shape-fabrics with location elements.

3. Growth of new banding with a parallel alignment of the compositional layering (by processes of localized metamorphic differention e.g. Wynn-Edwards 1963). This would lead to the replacement of flattened shape-fabrics by a more continuous layering persumably related to the axial surfaces of folds, that is the change from modified shape-fabric to

locations elements would be achieved. This, or a related process, has to be invoked to account for secondary concordance of intrusive bodies.

C. Conclusions

Banding is a structure of varied origin in the area. Within a certain range, the variability can be accounted for by strain modification of a shape-fabric. At the extreme however, a fundamental change of the nature of the banding occurs producing a set of locational elements: such a change must require an origin which involves a reconstitution process. It is predicted then that the banding will be inconsistent in its response to deformation and is therefore not a fixed datum for structural interpretation. The use of populations of banding surfaces to define a regional fabric will be discussed in a later section (Chapter 5).

7. AGE AND EVOLUTION OF FABRICS IN N.W. LEWIS

A. The distribution of fabrics

The variability of the fabrics developed in the gneisses has been described in section 6 of this chapter. The spatial aspect of this variability is shown in Fig. 49. The assessment of fabric type is based on field observations of gneiss aspect.

B. Origin of regional variability

Two essentially different theories can be put forward to account for the observed variability.

i) Single phase theory. This would involve the generation of the fabrics in one deformation episode. This fabric-forming episode may produce fabrics heterogeneous in terms of k and m. Already in the Outer Hebrides (e.g. Coward 1969, 1973b) inequalities of strain intensity (m) in single episodes have been observed. The possibility of heterogeneities of k

in a single phase has been given little consideration. In fact in any three dimensional geological system there must be some compatibility restraints on k values. Before this theory can be implemented some knowledge of the components and size of the deforming system must be made.

ii) Polyphase evolution theories. The concept of strain superimposition involves the summing up of increments of strain to produce a total finite strain. Using Flinn's concept of relating the shape of the fabric ellipsoid to the strain that produced it, a comparable theory has been used for fabric evolution.

Coward (1969, 1973a) has attempted to explain the finite fabric pattern in South Uist in terms of fabric "increments" related to a polyphase deformation. Ramsay (1967, p. 220) refers to the modification of initial fabrics by strains due to folding and Graham (1969) attributed local fabric variations within folds to a similar process. Graham explained the occurrence of a linear fabric in fold hinges by the co-axial superimposition of non-linear fabrics. Watterson (1968, especially Fig. 46) has given consideration to the modification of shape fabrics about folds.

This work has been extended to consider the superimposition of heterogeneous strains due to folding upon rocks showing effects of an initial strain (≈ fabric, by symmetry concept, see Fig. 50). The subject has been dealt with in some depth (Lisle 1974) but only some of the more relevant conclusions will be discussed here. The theoretical predictions are given in the hope that they may explain some observed fabric patterns.

i) Because the superimposed strains are heterogeneous, the total strains (≈fabrics) will be variable in k and m about the fold.

ii) In contrast to the effects of the superimposition of homogeneous strains in a co-axial fashion, the finite fabric axes will not be simply

related to the axes of the increments.

iii) As a result of the difference of behaviour of locational elements (e.g. lithological layers) and shape fabrics (e.g. hornblende lineation) the two structures will generally achieve a different attitude after the deformation even where they were initially parallel. The aspect of an inclined fabric as seen on an intersecting surface will be that of an "apparent lineation". Apparent-lineation loci have been calculated theoretically for various mechanisms of folding and various initial strains (Lisle 1974). Simple small- or great-circle loci are rarely produced in this way.

iv) If the initial fabric was inclined to the s-surface before folding an asymmetrical finite fabric pattern will result. This can be seen in profile, for instance a fold at the Port of Ness in northern Lewis shown by Hopgood and Bowes (1972, Fig. 11b) shows such asymmetry. The asymmetry can also be expressed on the folded surface, that is the apparent lineation will have unequal development on each limb. The phenomenon has been reported from the Ness area (Watson 1969) where folded lineation is better displayed on one limb of the later structure.

It is believed that this model for folded fabrics (including some kinds of folded lineations) is more relevant than "passive-line" theories (Weiss 1959, Ramsay 1960) in basement regimes where fabrics appear to be cumulative in nature (e.g. Watterson, 1968, p. 69).

C. Age of fabric generation

If a cumulative (superimposition) theory is adopted to account for the evolution of the fabrics in this area it would be interesting to deduce the age of the first fabric increment. In the areas where the discordant state of the Scourie Dykes suggests that the Laxfordian strain is relatively low, the gneisses usually possess a highly linear fabric (k is high). Coward (1969, 1973) has made similar observations

in low Laxfordian finite deformation areas of South Uist.

There is evidence in N.W. Lewis that a linear fabric was in existence in the gneisses before the dykes were intruded:

i) Intersection lineations (of discordant dykes with the banding) are sometimes considerably oblique to the lineation direction. This is not foolproof evidence but it suggests either that the lineation formed at lower strains than were required to rotate the dyke contact close to the X direction of the ellipsoid or that the lineation was present before the dykes were intruded.

ii) Pre-Scourie Dyke basic bodies show boudinage axes parallel to the lineation whereas dykes in the same area do not. Again this evidence is somewhat questionable - for example the presence or absence of boudinage could reflect relative ductility differences of the materials involved.

iii) On planes perpendicular to the lineation in low Laxfordian deformation areas the maximum dyke discordance is seen. This would suggest either that a constrictional strain ($1 < k < \infty$) had been imposed or that the dyke swarm had a preferred orientation in its undeformed state. This argument will be dealt with when discordances are looked at in more detail (Chapter 7). However it should be mentioned that the dykes, viewed on that plane rarely take part in structures which can be attributed to deformation. An explanation may be put forward that the deformation was of a perfect constrictional type so that the strain ellipse on the plane perpendicular to the lineation is in fact a circle. However in such a case all lines in that plane will have undergone finite contraction in length and only if the dyke/gneiss system behaved as a perfectly homogeneous material could it be expected that deformation structures would not develop.

Coward (1973a) put forward the idea that the linear fabric in the low Laxfordian deformation areas may be due to the superimposition of

two non-linear strains. In other words considerable Laxfordian deformation has occurred during the development of the low finite Laxfordian deformation areas. The evidence above, although not conclusive, suggests that in N.W. Lewis the low finite Laxfordian deformation areas could be areas where little Laxfordian deformation has occurred.

On the evidence above, a pre-Laxfordian age for the first recognizable fabric increment is suggested. Other workers in the same area (Hopgood and Bowes 1972) suggests that strong fabrics developed prior to the intrusion of basic dykes. The pre-Laxfordian grain in N.W. Lewis has essentially been retained in the rocks of the area, the Laxfordian events serving only to bring about modification to it.

8. EXAMPLES OF SHAPE-FABRIC IN THE AREA

Gneiss shape-fabrics have already been described on a mesoscopic scale. The shape-fabric is defined on varying scales by different fabric elements. This feature is summarized in the table in Fig. 51.

Gneiss fabrics on a subarea scale will be discussed in Chapter 5. Shape fabrics are developed in intrusive bodies into the gneisses, for example the Scourian Dykes and Laxfordian granite sheets and these will be discussed in the following section.

9. THE DEVELOPMENT OF SHAPE-FABRICS IN THE SCOURIE DYKES

i) Observations. We are mainly concerned with the type of fabric shown in Fig. 39 which is pervasive on a mesoscopic scale. Most of the dykes show foliation parallel to the dyke margins (Fig. 52). Rare exceptions to margin-parallel foliation occur at dyke contacts (Fig. 53A) or within shear zones of the type described by Ramsay and Graham (1970) (Fig. 53B).

Other oblique patterns are shown in Fig. 54.

As seen from the measurements shown in Fig. 39 and Fig. 40 earlier in this chapter, the fabrics can be classified as ellipsoidal shape-fabrics and can be described by parameters such as k and m. Relatively high k values are prevalent in dykes which occur in areas of low Laxfordian strain. The fabrics in concordant dykes generally have lower k values in areas of higher Laxfordian deformation. This suggests that these fabrics, like gneiss shape-fabrics, are capable of being modified by subsequent strain.

ii) Margin-parallel foliation: Theories. Foliation parallel to the margins of Scourie Dykes seems to be a common phenomenon in the Outer Hebrides (Francis 1969, Coward 1969 and Graham 1969). Graham (1969) relates this fabric to an early Laxfordian deformation event (F1) which had its XY strain plane oriented parallel to the plane of the dykes. The fact that dykes of varying orientation show margin-parallel foliation in N.W. Lewis is difficult to reconcile with this theory.

A second possible explanation assumes that the fabric pattern developed as a result of stress or infinitesimal strains (as opposed to finite strains). This view has been put forward by Watterson (1968) to account for fabric patterns in deformed dykes in the Ilordleq area of S. Greenland. Stress distributions with σ_1 invariably oriented normal to the dyke contacts, irrespective of dyke orientation are required to account for margin-parallel foliation patterns. It is difficult to visualize such specialized stress distributions.

A third theory assumes that the fabric pattern is related to the finite strain trajectories. It has frequently been observed in the deformation of multilayer systems that refraction of the strain trajectories occurs between layers of different competence. Less competent layers show refraction of the trajectories towards the

plane of the layering. Experimental work was done to investigate this phenomenon and to decide whether margin-parallel foliation could be accounted for by extreme trajectory refraction in an incompetent layer (the dyke).

These experiments were performed using boxes with movable sides which imposed a bulk strain on the material inside according to a simple shear configuration. The box was filled with plasticene into which a thin planar layer of softer plasticene was introduced the normal of which was parallel to the XZ plane of the bulk strain of the box. Marks were impressed on the surface of the plasticene in order to assess the local strain variations in the XZ plane of the box during the progressive application of a bulk strain to the deformation box.

The strain trajectories calculated from these markers were almost parallel to the expected bulk strain directions in large areas of the matrix plasticene, which enclosed the soft layer. In the layer, however, refraction of the strain trajectories occurred away from the bulk strain direction towards the direction of the layer contacts.

The amount of refraction of the strain trajectories as it is traced through the softer plasticene layer increases

i) as the undeformed angle between the layer and bulk strain was increased,

ii) as the bulk strain increased, and

iii) as the competence difference of the layer and matrix was increased.

The refraction of the trajectories could be seen to be due to a component of shearing which was set up within the layer parallel to the contacts. The shearing was an outcome of a curvature of the layer which developed progressively with the deformation. In other words a flexural-flow mechanism was operating - the amount of shearing parallel to the

margins being related to curvature (or differential rotations) of the enclosed layer.

In order to produce strain trajectory patterns truly parallel to the layer contacts, an infinite shearing component would be required - an obviously unrealistic situation. So if the Scourie Dyke foliation is equated with the local strains in the layer in the experiment, we succeeded only in reproducing oblique foliation patterns in dykes. Figure 55 shows a photograph of the surface of the plasticene during one of these model experiments. Lines drawn perpendicular to the layer before the deformation was imposed give an indication of the shear parallel to the layer contacts.

There are two main problems with this mechanism. Although trajectories at a low angle to the layering are achieved by high bulk strains and high ductility contrasts, truly margin-parallel patterns are not obtained by this method. Furthermore, in the experiments, trajectory refraction simultaneously took place with the formation of other structures (the dykes themselves became curved). These structures would seem to be essential if different parts of the system are to show differential deformation. In the field dykes appear to possess foliation even in the absence of such structures. For example, Graham (1969) reports that structures coeval with the Scourie Dyke foliation (F1) are rarely seen.

It is concluded that this theory does not satisfactorily explain the occurrence of margin-parallel foliation - a feature which is of widespread distribution. However the theory may be applicable to some cases of oblique foliation (e.g. Fig. 53B) especially those showing sigmoidality. The fact that fabrics inside an intrusive body and those in the country rock are differently oriented should be used with care as a criterion in chronological work.

Windley (1970) has suggested that some foliation in dykes in the Sukkertoppen area of W. Greenland was due to slight compression during crystallization of primary amphibolites. Again in this theory the stress or strain trajectories required to produce the fabric pattern present a problem, but his suggestions prompt the consideration of a syn-intrusive theory for fabric development.

Fabrics may develop due to the shearing involved while a fluid is intruded between parallel walls. This is essentially an internal deformation theory. The strain configuration due to intrusion of viscous and pseudoplastic materials is shown in Fig. 56. If the fabric axes are related to the strain ellipsoid axes, near-parallelism of the fabric with the wall is soon achieved during continued flow (especially near the wall, Fig. 56). The inclination of the trajectories to the wall will soon become undetectable. If the fabric axes and finite strain axes are related then the flow direction (the a direction) must have been almost horizontal in this area (refer to Fig. 53C).

Alternatively during the process of intrusion the fabric directions may be related to the kinematic axes of flow. A mechanism involving rolling of the first-crystallized minerals (or groups of minerals) would produce this relationship. A system of rigid ellipsoidal particles suspended in a fluid undergoing simple shear has been investigated theoretically by Jeffery (1923). According to his predictions an L/S fabric would be defined by the suspended particles as a result of shear. The planar (XY) component of the fabric would be perfectly parallel to the dyke walls (i.e. parallel to the ab plane). The linear component (X) would be perpendicular to the flow direction (a) in the ab plane. Unlike fabrics related to finite strain trajectories, the fabric axes remain constant in orientation regardless of the amount of shear γ. However the k value of the fabric increases with the shear (γ)

so that according to these predictions, fabrics should be linear near the contacts of the dyke than at the dyke centre. Fabric intensity (m) should increase with increasing γ. If this sort of mechanism operated in the dykes, the orientation of the lineation suggests that the flow direction was vertical (Fig. 53C).

These syn-intrusive internal deformation theories most easily account for the following observations:

i) the foliation is parallel to dyke walls,

ii) the foliation is early in the Laxfordian structural sequence,

iii) other coeval structures in the gneisses are rare,

iv) the foliation orientation relative to the margins is independent of dyke orientation,

v) the foliation is sometimes better developed at the dyke margins (Fig.

However we earlier discussed how these fabrics are capable of later modification by subsequent strains. The deformed sub-ophitic textures seen in the dykes could date from subsequent periods of strain imposition.

FIGURE 37

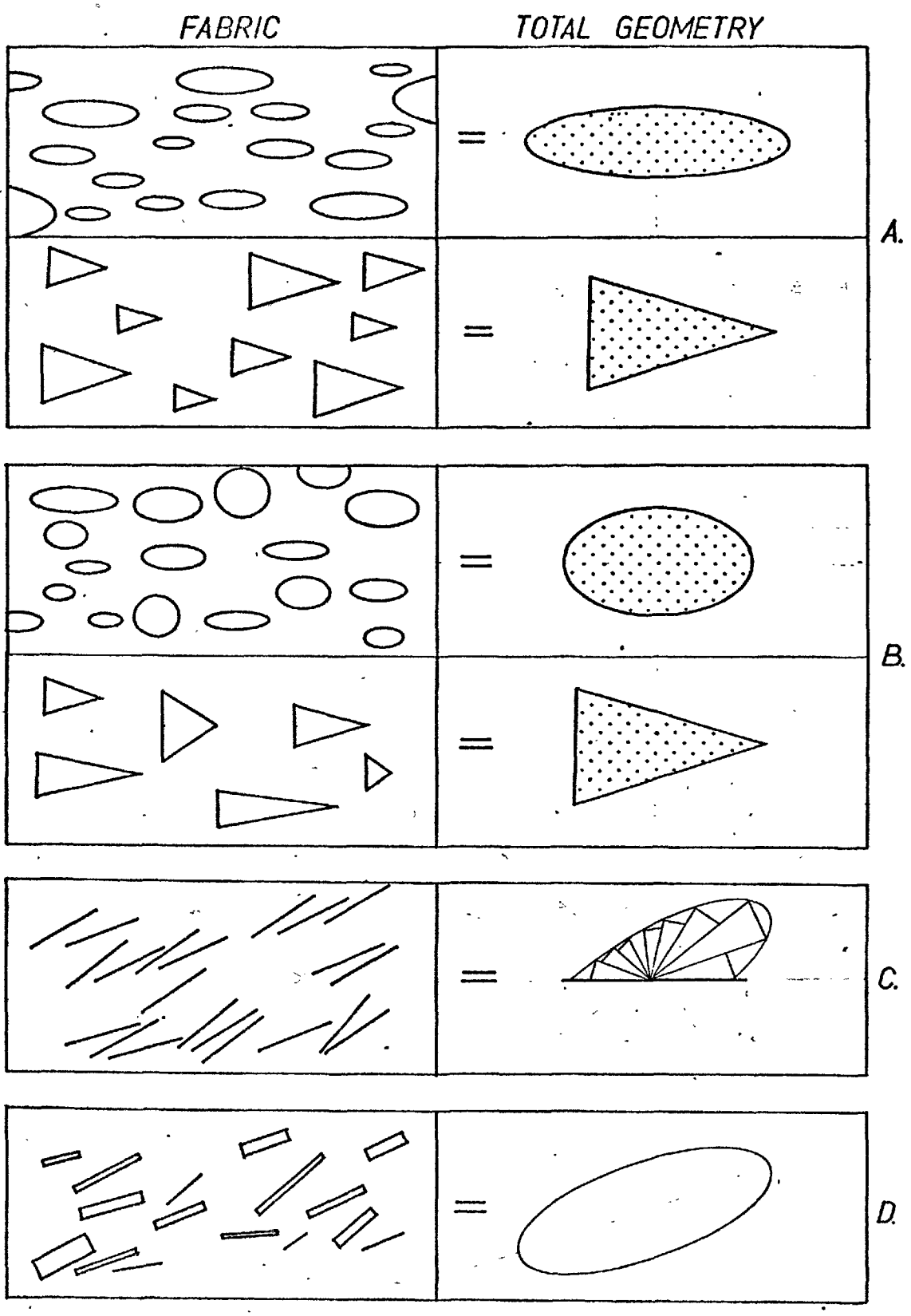
ASSIGNING GEOMETRY TO A SHAPE - FABRIC USING THE CONFIGURATION OF THE POPULATION MEMBERS.

A. Orientation of the population members constant. Each particle has a'similar'shape to the total fabric geometry.

B. Orientation of population members constant. Particles have different shapes. Total fabric geometry is some kind of an average.

C. Shape of population members constant but particles have different orientation. Total fabric is some kind of an average e.g. a'rose diagram' form of representation.

D. Shape and orientation of the population members variable. Total fabric is some kind of an average e.g. an Rf / Ø method of representation.


FABRIC
TOTAL GEOMETRY
A.
B.
C.
D.

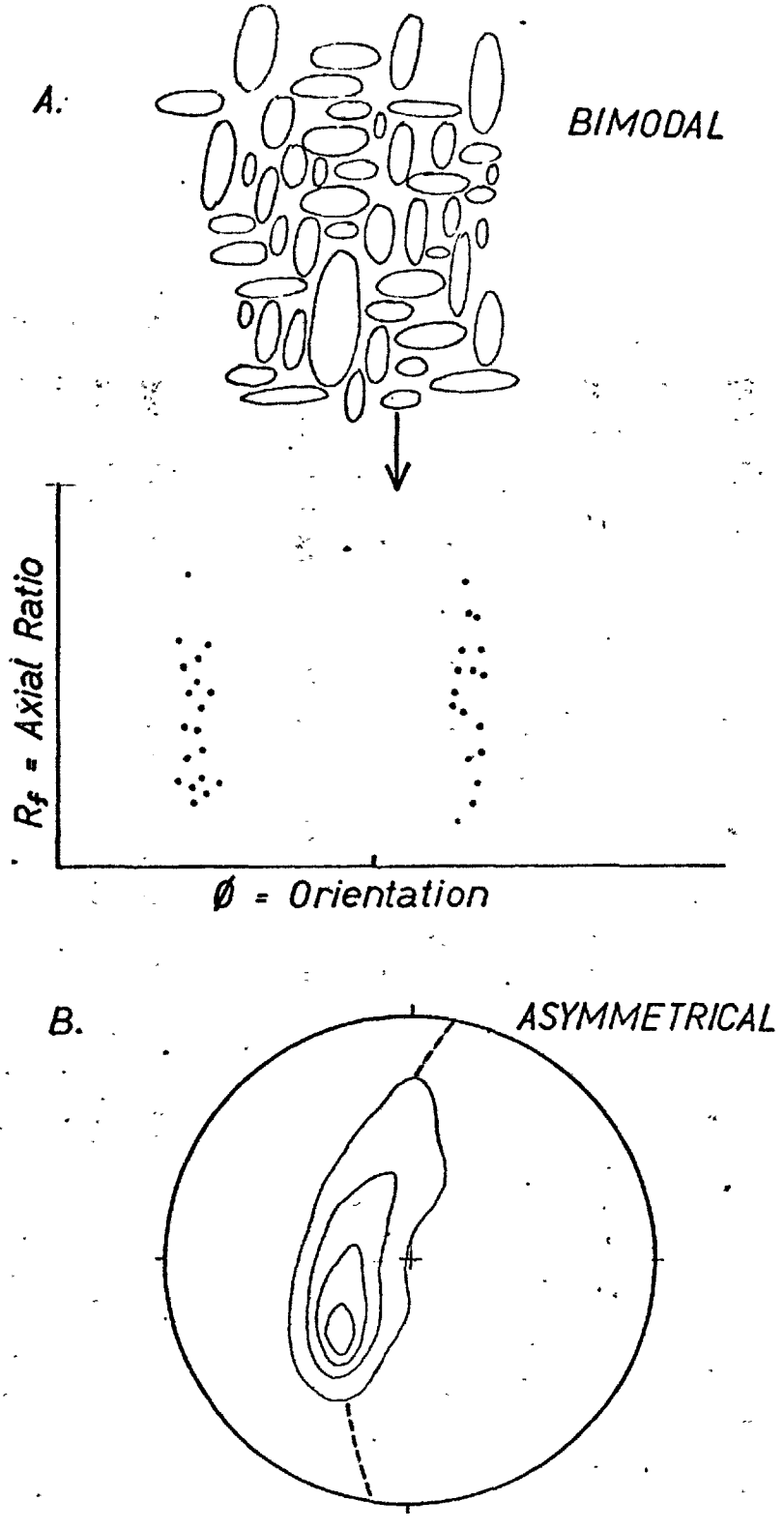


FIGURE 38

EXAMPLES OF NON-ELLIPSOIDAL SHAPE FABRICS

A. Bimodal distribution. This is fabric of type D (see previous figure). The bimodal character is incompatible with an ellipsoidal shape fabric.

B. Asymmetrical. The fabric has a lower symmetry than that of an ellipsoid.

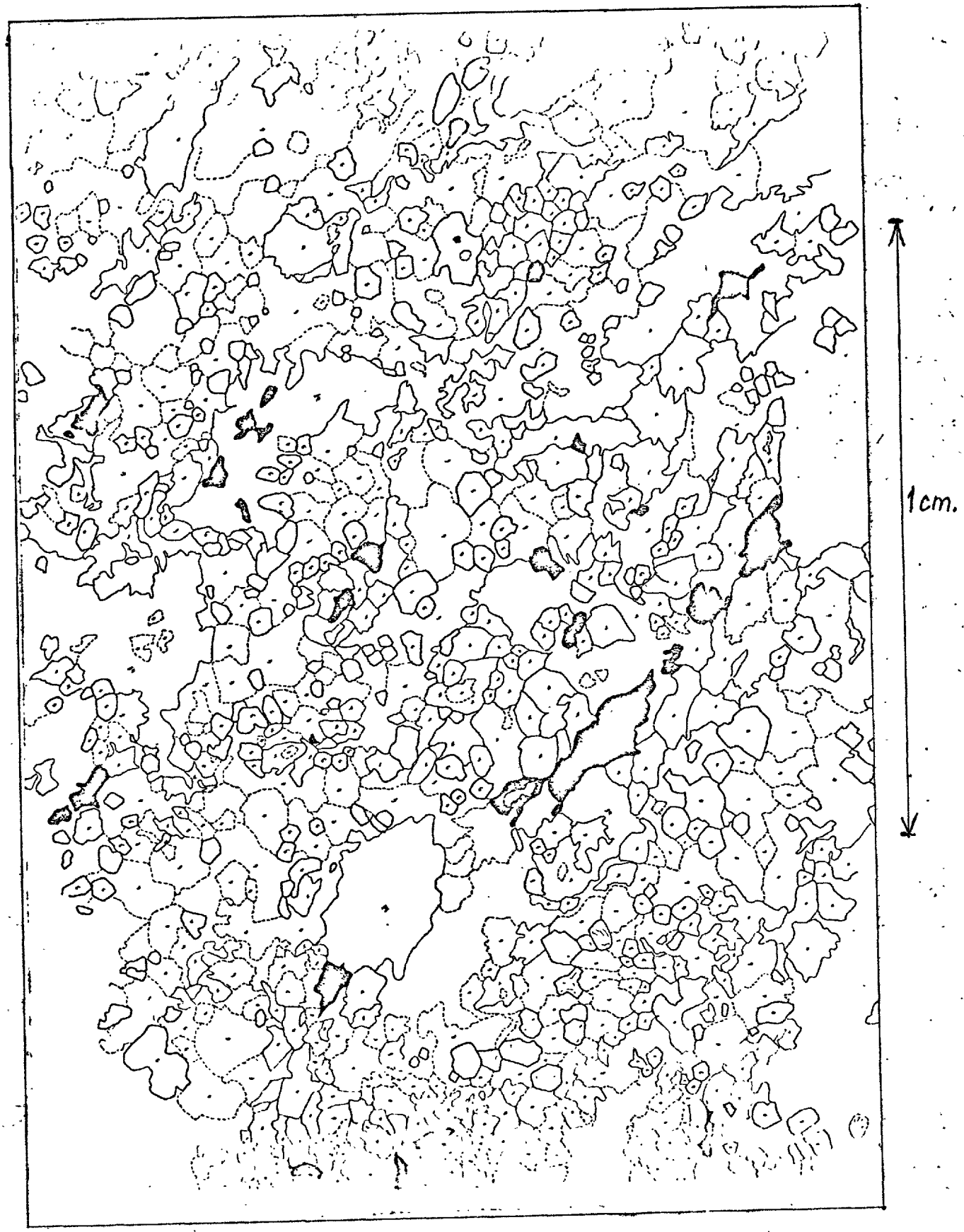
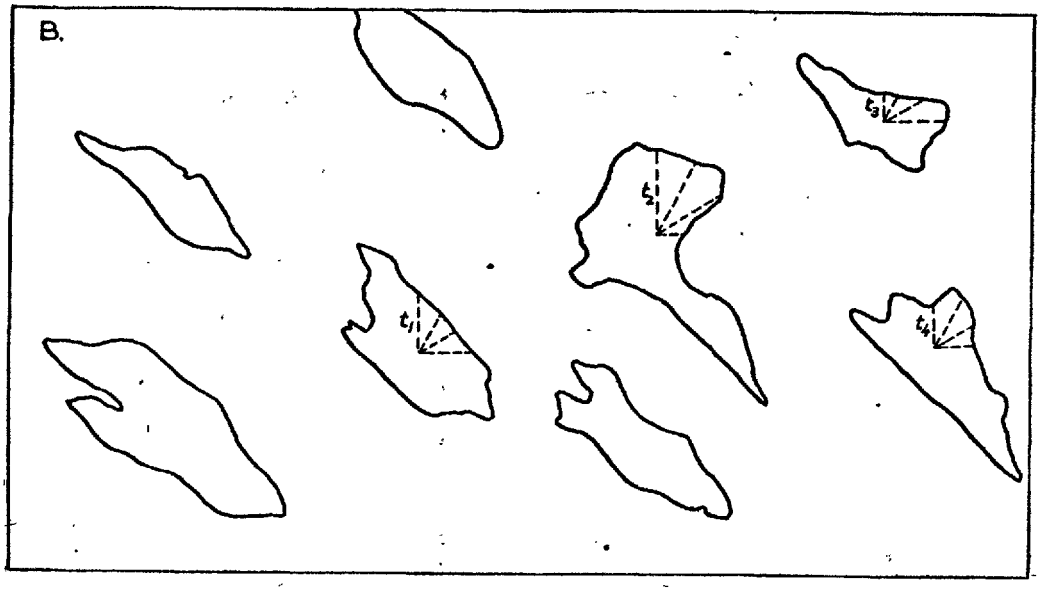


FIGURE 39

A shape-fabric in a Scourie Dyke metadolerite.

Hornblende + pyroxene aggregates are shaded. The shape defined by this fabric is assessed in Figure 40



$T = \sum t$ in any particular direction

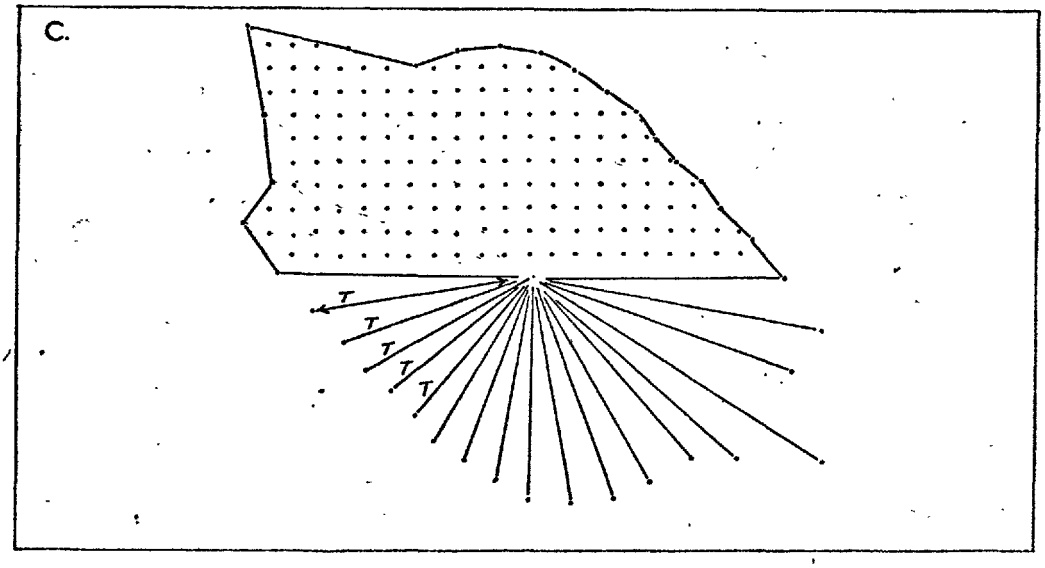


FIGURE **40**

The Total Geometry of the Scourie Dyke fabric shown in Figure 39

B. The outlines of mineral aggregates defining the fabric. Distances, t, were measured from the centre of gravity of each particle to the perimeter in various directions.
$T = \sum t$ in any direction.

C. The total shape of the fabric is constucted by radii T in length for each direction.

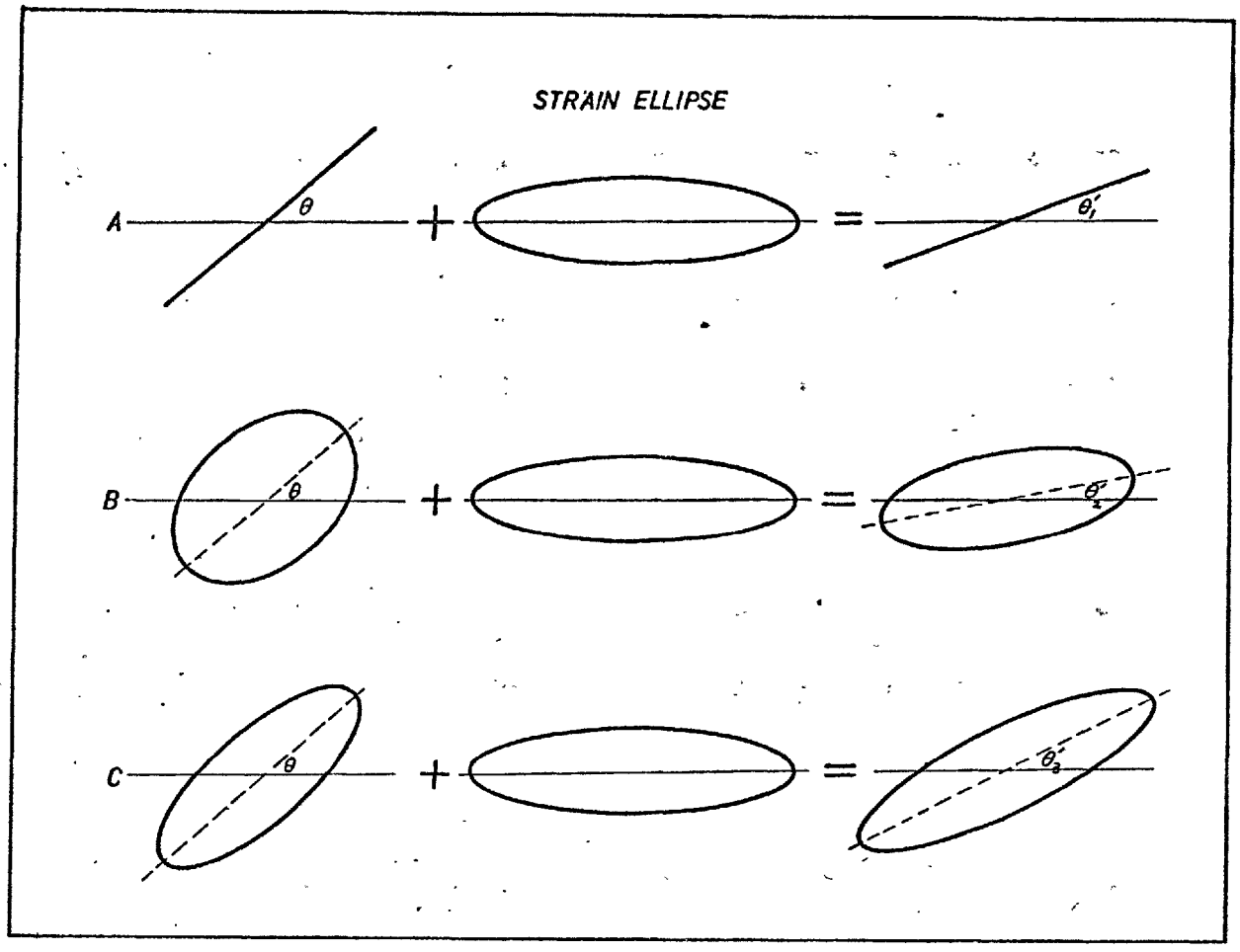


FIGURE 41

THE DEFORMATION OF SHAPE - FABRICS AND LOCATIONAL ELEMENTS

A. This represents the imposition of a strain on a line (a locational element).
θ = original angle between element and extension direction.
θ'= final angle " " " " " .

B. An ellipse (representing an elliptical shape - fabric) is superimposed upon by a strain ellipse. The shape - fabric resulting from the superimposition is shown on the right.

C. A stronger shape - fabric (than B) is strained. Final shape - fabric intensity and orientation differs from that of B.
$\theta = \theta = \theta$ and $\theta_3 > \theta_1 > \theta_2$.

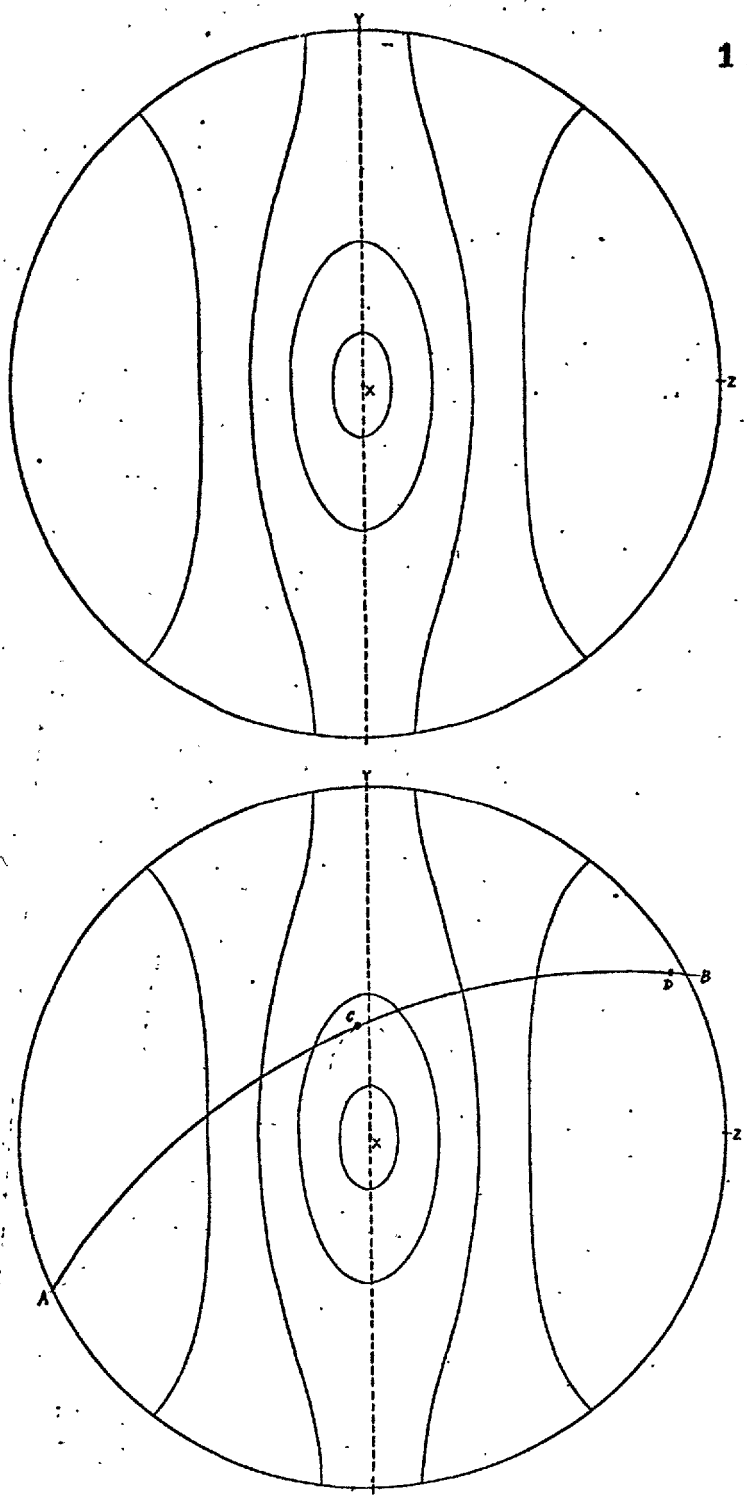


FIGURE 42

THE CONCEPT OF A FABRIC TRACE

A. A stereographic projection with contours showing the orientation of lines of equal length in a triaxial ellipsoid.

B. The same ellipsoid intersected by a plane (ABCD).

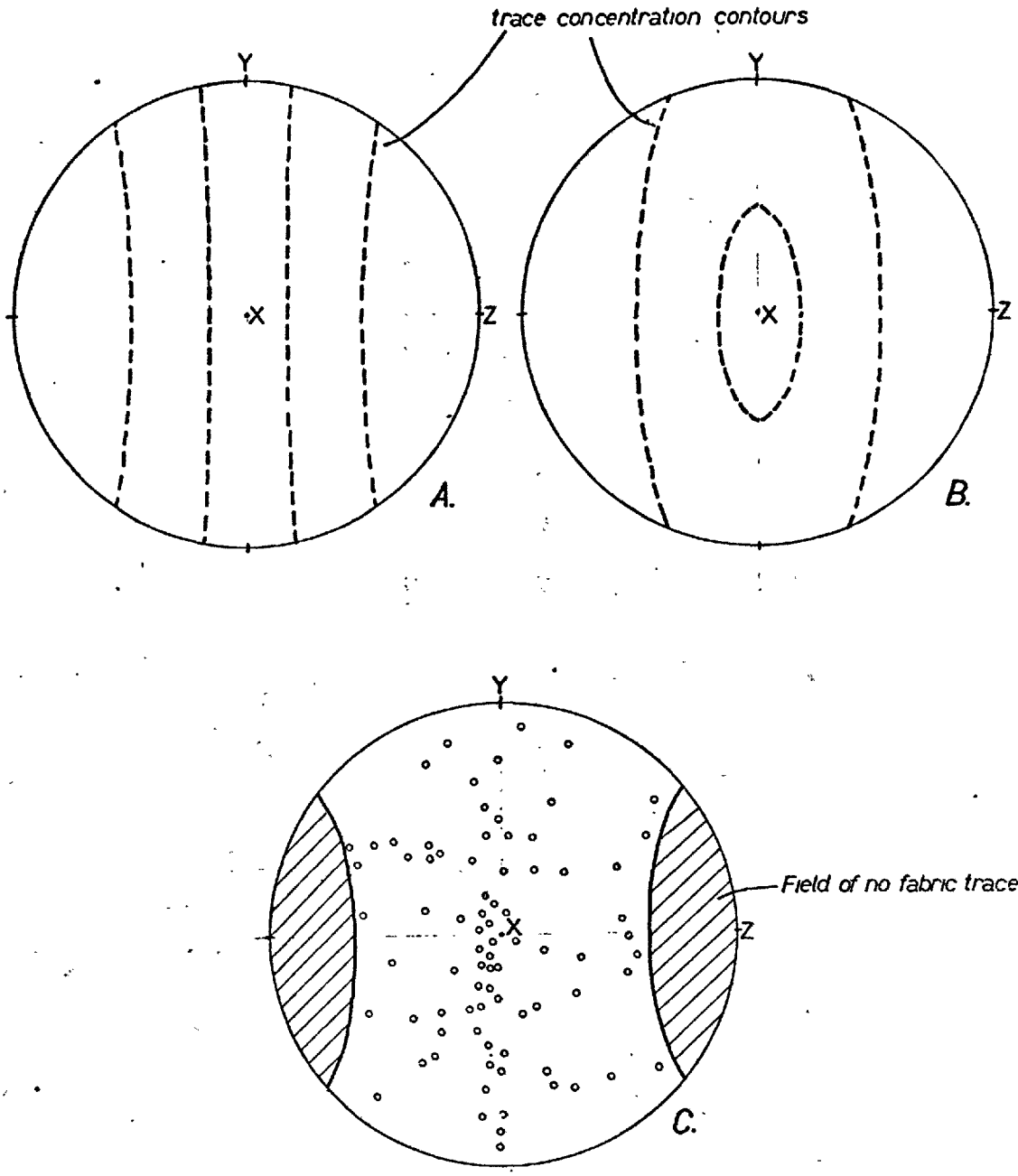


FIGURE 43

STATISTICAL METHODS - Examples of reference plots.

A and B show contours of equal concentration of fabric traces. The value of the contours increases toward X (the long axis of strain ellipsoid).

C. Circles represent plots of fabric traces.

Shaded areas are areas where no fabric traces occur.

FIGURE 44

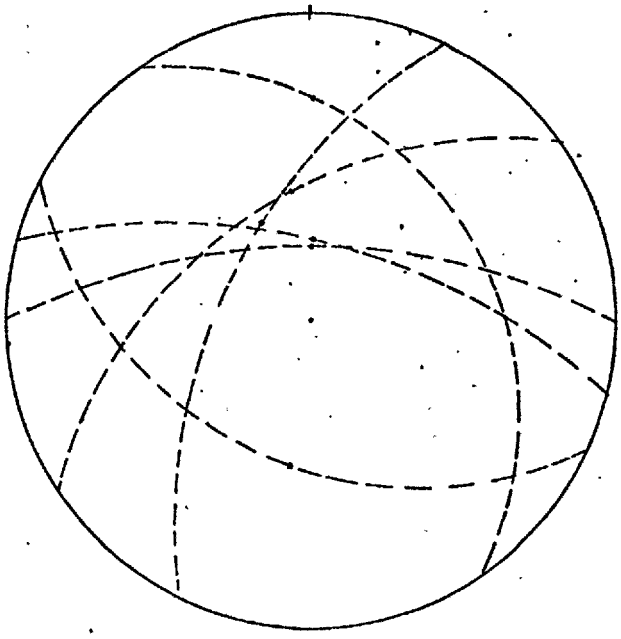
THE FABRIC TRACE METHOD WITH RESTRICTED AMOUNTS OF DATA

A. Outcrop planes and fabric traces plotted so that X direction of fabric is vertical.

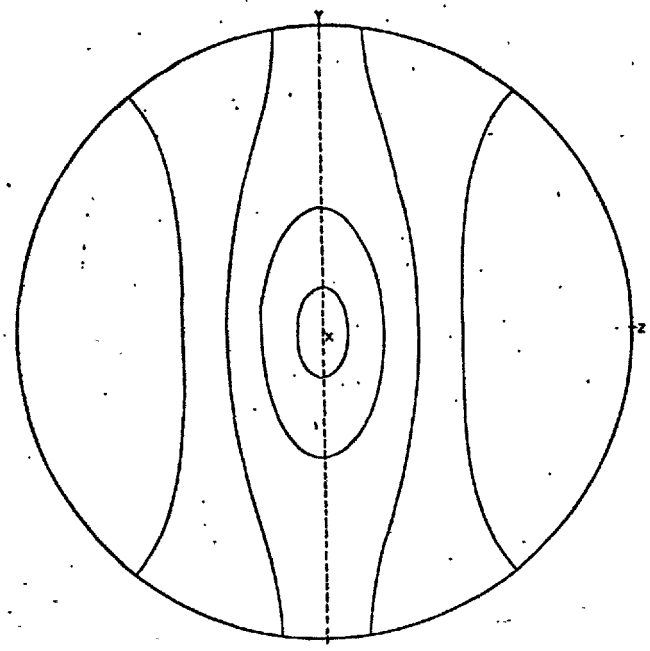
B. A stereogram - one of a reference set of stereograms referring to various ellipsoids.

C. Superimposition of A and B with an overlay and rotation until

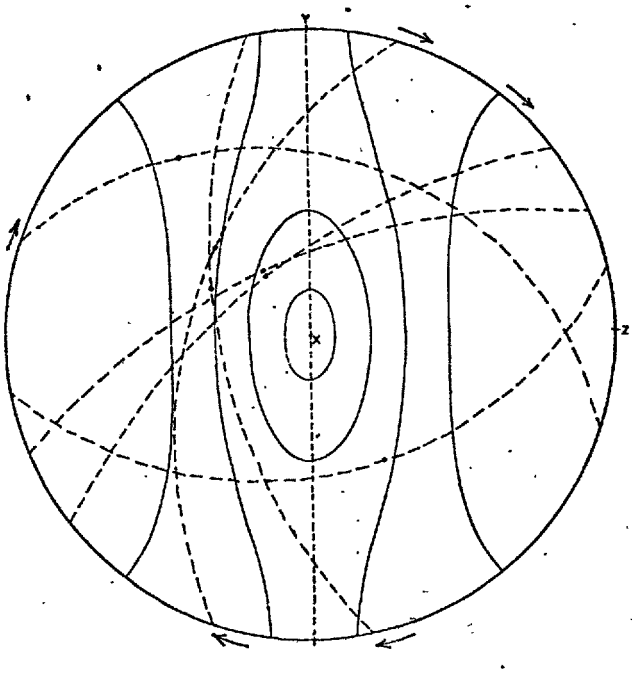
D. Fabric traces all simultaneously fall on contours of a higher value than any point on their outcrop plane.



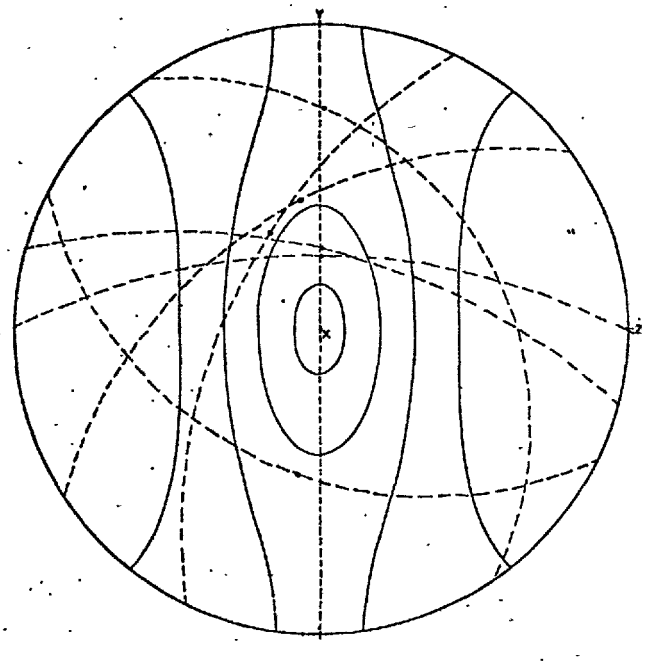
A



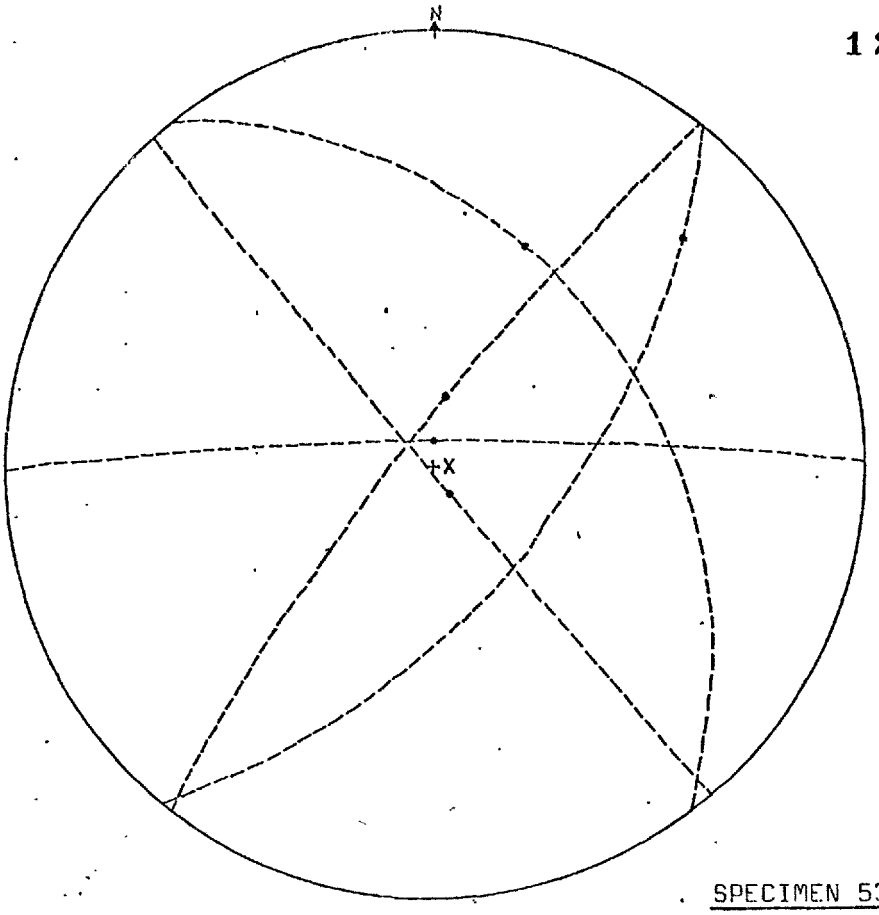
B



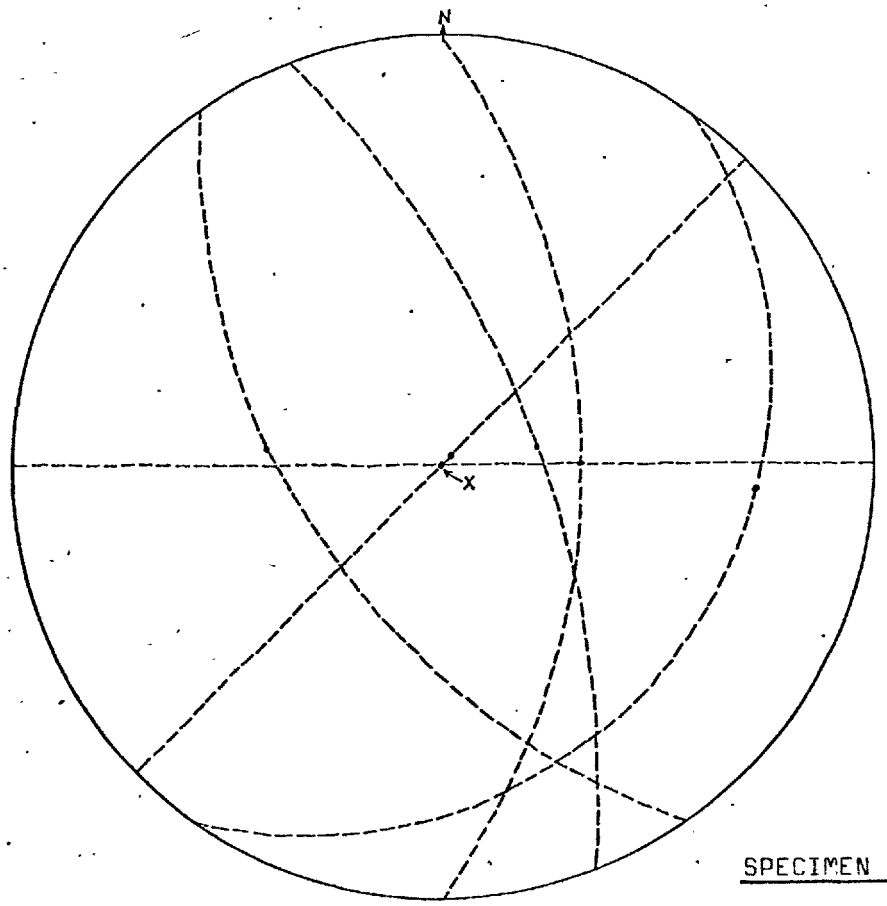
C



D



SPECIMEN 531



SPECIMEN 620

FIGURE 45

PLANES OF OUTCROP (great circles) and FABRIC TRACES (dots) on two specimens of foliated Scourie Dyke.

The X direction corresponds to the observed total lineation in the rock, and is plotted as a vertical line on the stereogram.



FIGURE 46

Lensoid gneiss
East of Loch Shawbost

FIGURE 47

FABRIC ANALYSIS ON AN OUTCROP OF LENSOID GNEISS

Measurement of the orientation (ϕ) of the long axis of basic lensoids (in a quartzo-feldspathic host) is plotted against the axial ratio (Rf).

A is the YZ shape-fabric plane 0^{o} = Y direction
B is the XZ shape-fabric plane 0^{o} = X direction

Total Fabric on YZ plane is approx. 2.7 : 1
Total Fabric on XZ plane is approx. 5.0 : 1

$$\text{i.e. } \frac{Y}{Z} = 2.7 \quad \text{and} \quad \frac{X}{Z} = 5.0$$

$$\frac{X}{Z} = \frac{Y}{Z} \times \frac{X}{Y}$$

$$\therefore \frac{X}{Y} = 1.85$$

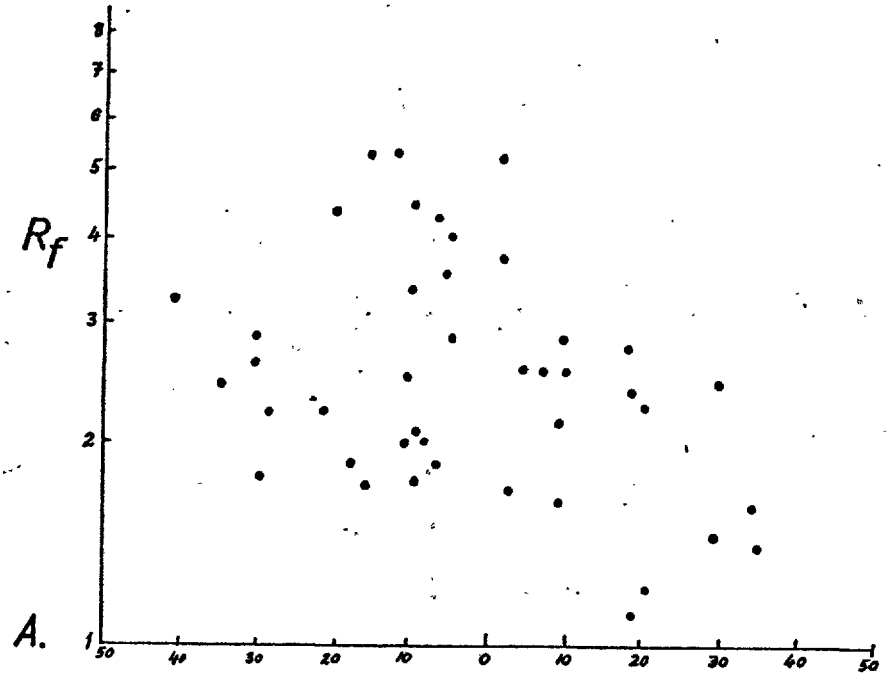
Flinns number, $k = \frac{a}{b}$ where $a = \frac{X}{Y}$ and $b = \frac{Y}{Z}$

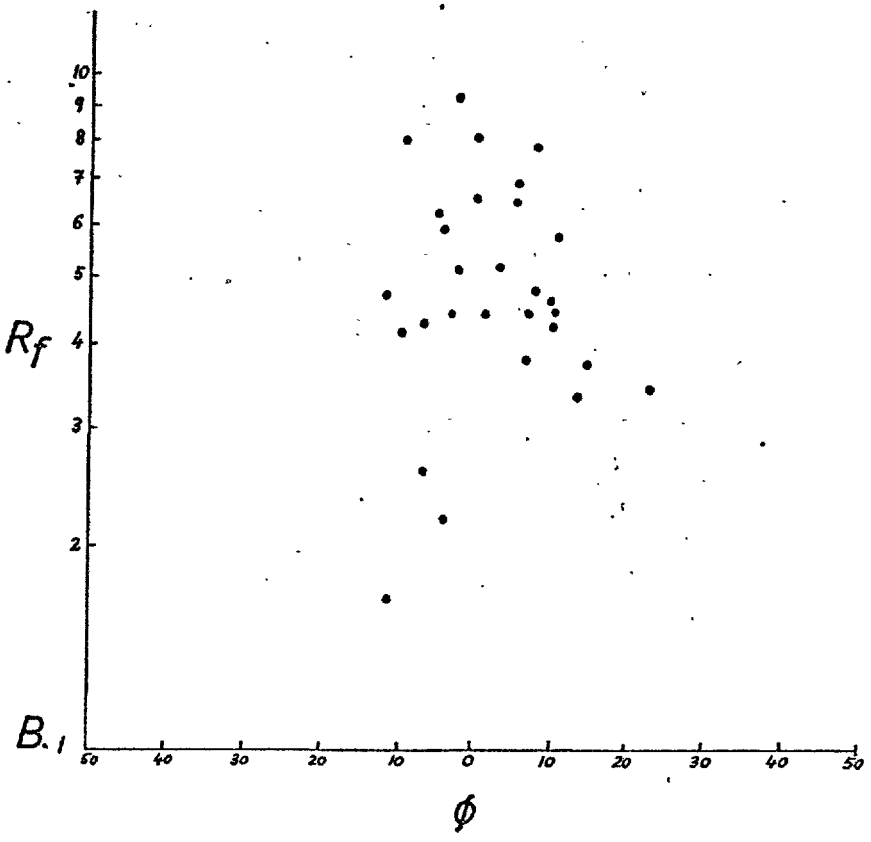
Then $\underline{k = 0.685}$ That is the fabric is an LSS fabric.

$$m = ((a-1)^2 + (b-1)^2)^{\frac{1}{2}}$$

$\underline{m = 1.9}$

The lensoid gneiss occurs on the N.E. corner of Loch Shawbost.
The XY plane is upright with an E - W strike.
X is more or less horizontal.


R_f
A.
8
7
6
5
4
3
2
1
50
40
30
20
10
0
10
20
30
40
50


R_f
B. 1
10
9
8
7
6
5
4
3
2
50
40
30
20
10
0
10
20
30
40
50
ϕ

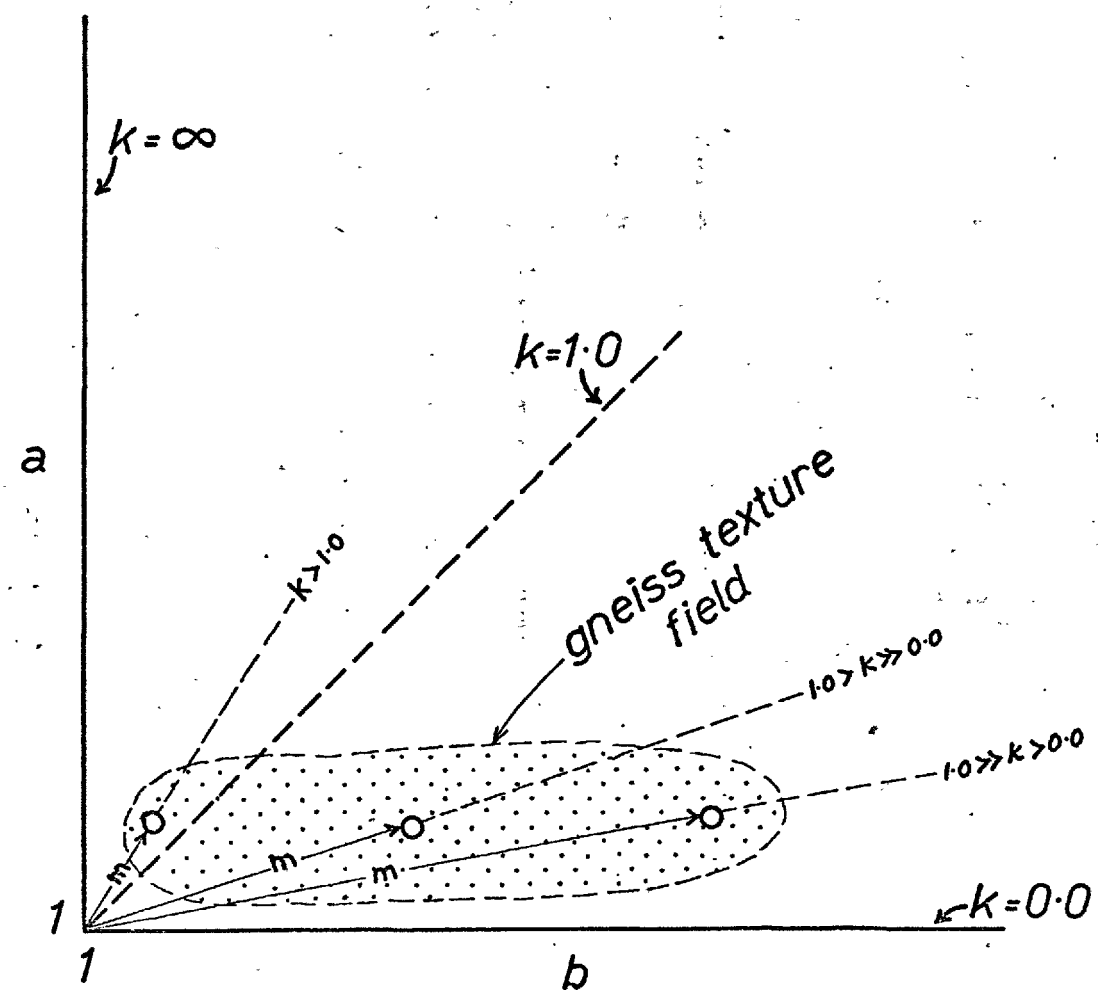


FIGURE 48

OBSERVED STATES OF GNEISS TEXTURE PRESENT IN THE AREA

In general, fabrics with high m values possess low k values.
The field does not necessarily represent a time-deformation path.

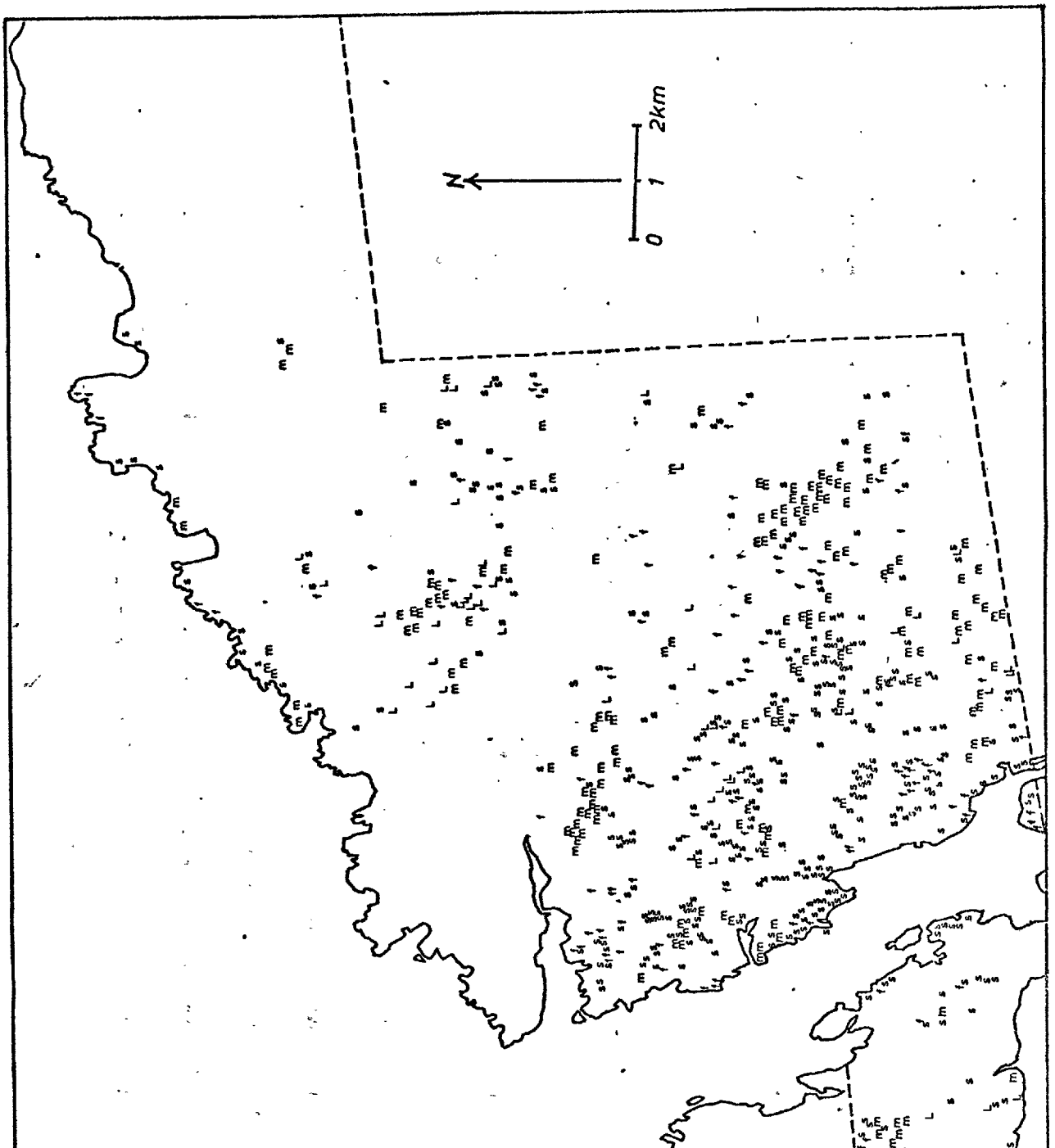


FIGURE 49

GNEISS FABRIC MAP OF THE AREA

m = massive gneiss, s = slabby gneiss, f = flaggy gneiss,
L = lensoid gneiss. See text for explanation.

FIGURE 50

THE SUPERIMPOSITION OF HETEROGENEOUS STRAINS DUE TO FOLDING UPON AN INITIAL STRAIN (OR SHAPE-FABRIC).

A. The initial strain (or shape-fabric) in the unfolded layer.

B. The folded layer and the states of strain due to folding only.

C. The final strains (or shape-fabric) due to the superimposition of B on A.

The trends on the folded surface (dashed lines) represent folded apparent lineations consisting of the curved trajectories of fabric traces on this surface.

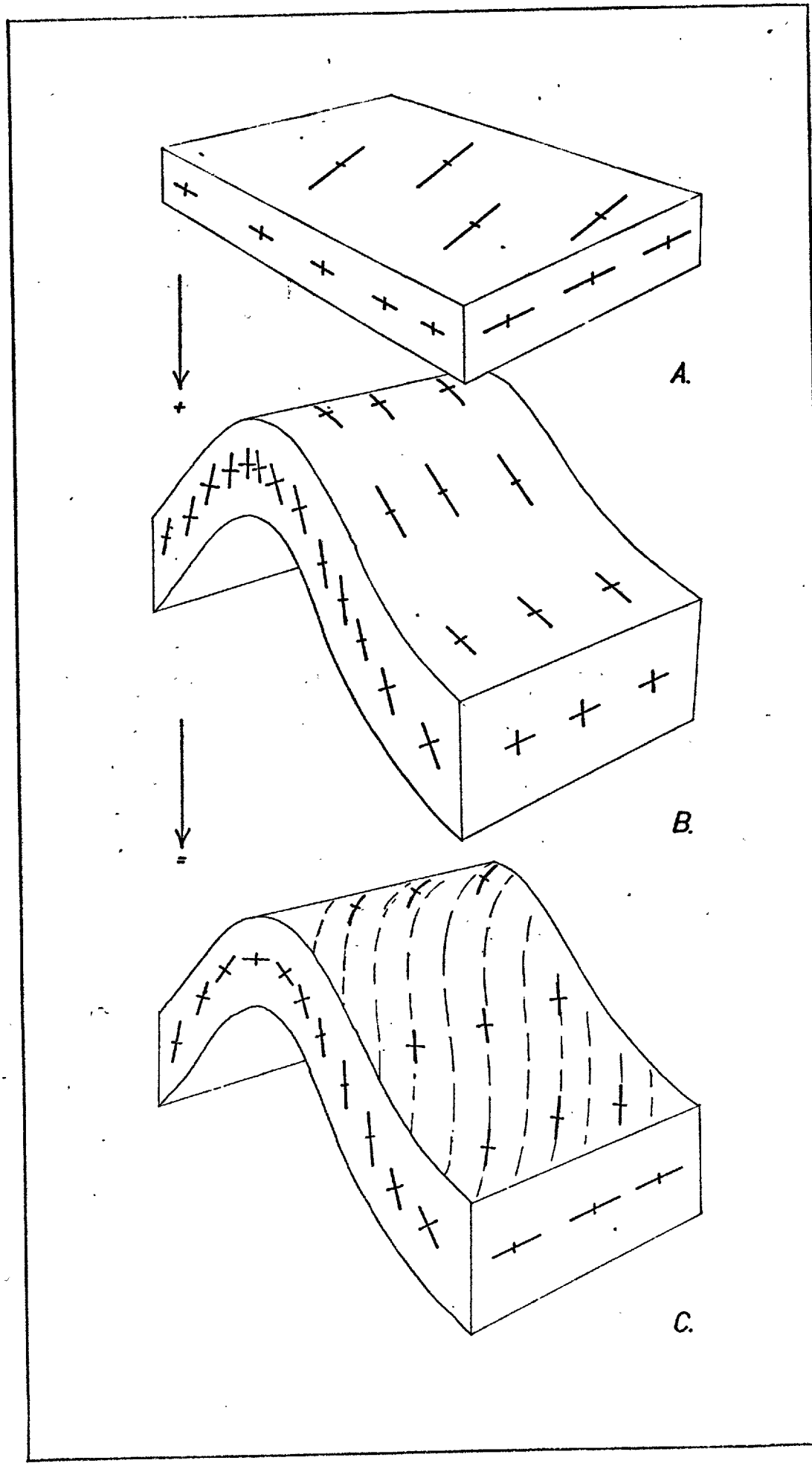

A.
B.
C.

FIGURE 51

SCALE OF GNEISS SHAPE-FABRIC

Mineral scale	Crystal shape defines a fabric
Aggregate scale	Recognisable groups and clusters of minerals
Pod scale	Lithological pods, discs, lensoids, etc.
Subarea scale	Banding itself as an element defining a fabric



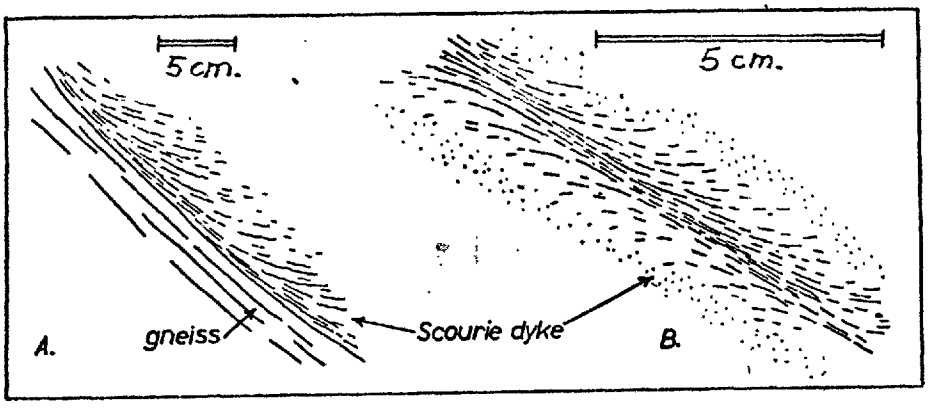


FIGURE 52

FABRICS IN SCOURIE DYKES

A. Margin-parallel foliation

B. Fabric showing planar and linear components, near Dalbeg Granite Quarry



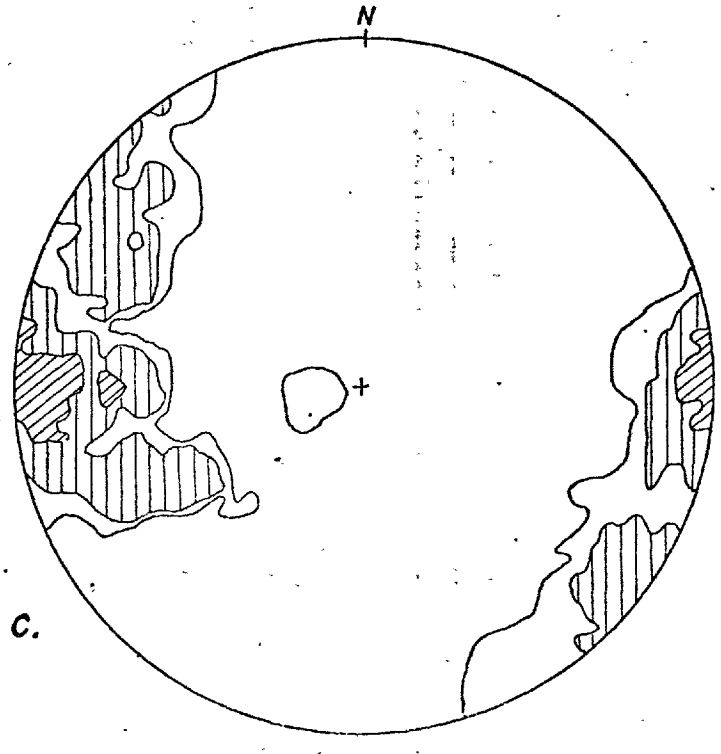


FIGURE 53

A and B. OBLIQUE FOLIATION IN SCOURIE DYKES

A at dyke margins. B is a heterogeneous simple shear zone within the dyke.

C. LINEATION DIRECTIONS(78) IN SCOURIE DYKES

Whole area. Contours 2,4 and 10% per 1% area.

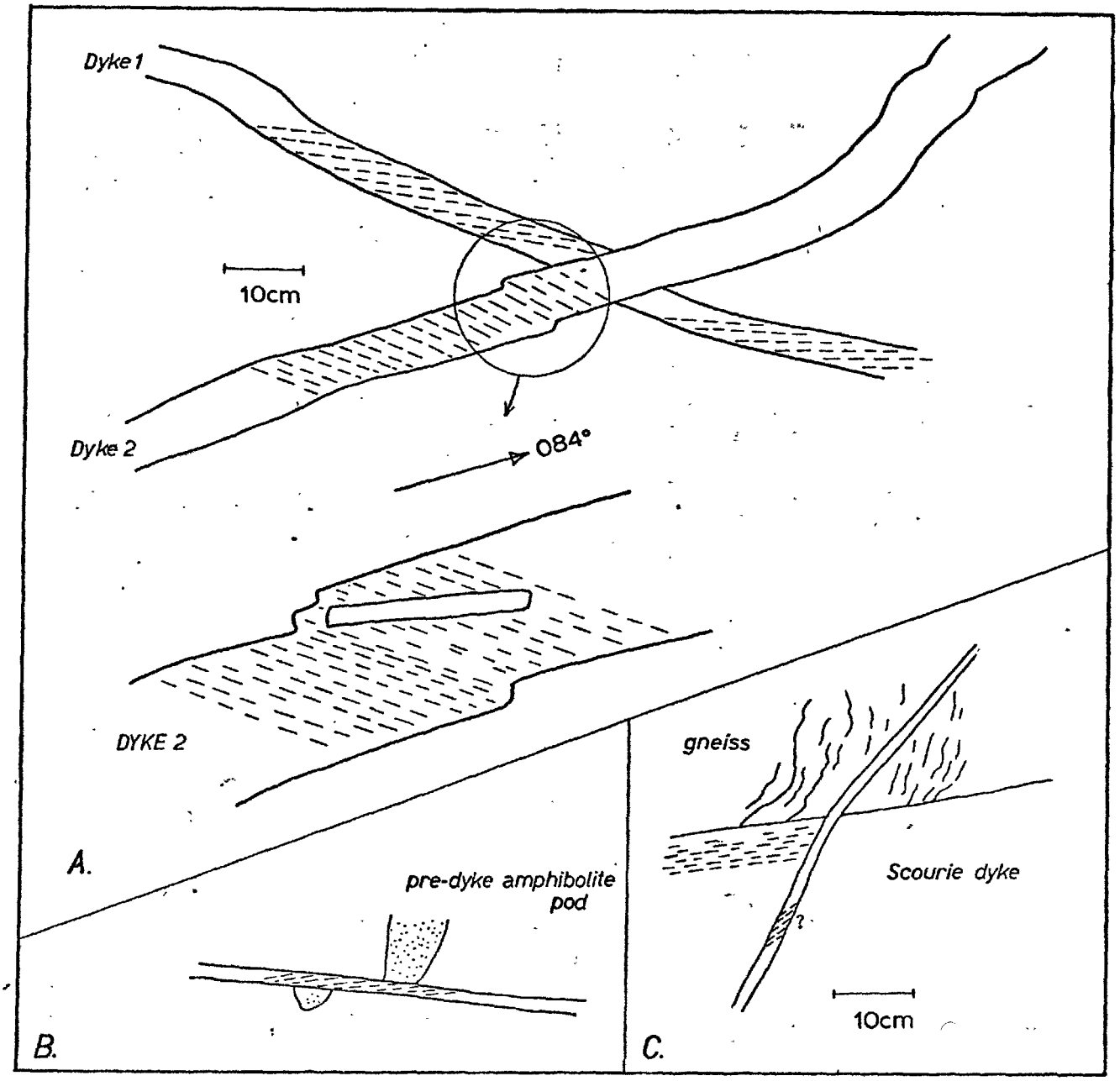


FIGURE 54

A RARE EXAMPLE OF FOLIATION INCLINED TO DYKE WALLS.

From a low Laxfordian deformation area, to the South of the Dalbeg granite (240443)



FIGURE 55

Plasticene model after deformation in a pure-shear deformation box. The undeformed block of plasticene consisted of a soft layer (darker) in a normal plasticene matrix (light).

The surface was impressed with circles (now ellipses) and a large square (now a rectangle) from which calculations of the bulk strain can be made.

Strains within the layer are calculated using lines drawn perpendicular to the layer (now non-perpendicular) dividing the layer into squares. The shapes that were originally squares have a mark at their centre.

Shear has caused a higher rotation of these lines within the layer than in the matrix.

The layer has become curved during the deformation process (see text for discussion).

FIGURE 56

SYN-INTRUSIVE THEORIES FOR FOLIATION PATTERNS IN DYKES

A. VISCOUS FLOW BETWEEN DYKE WALLS

The velocity profile is shown and has the equation

$$\text{velocity, } v = x\,(h - x)$$

where h is the width of the channel and x is the distance from the wall.

B. Expected foliation pattern for A. The strongest foliation will occur where shear strain, γ (given by slope of profile in A) is highest.

C. PSEUDOPLASTIC FLOW BETWEEN DYKE WALLS

Velocity profile

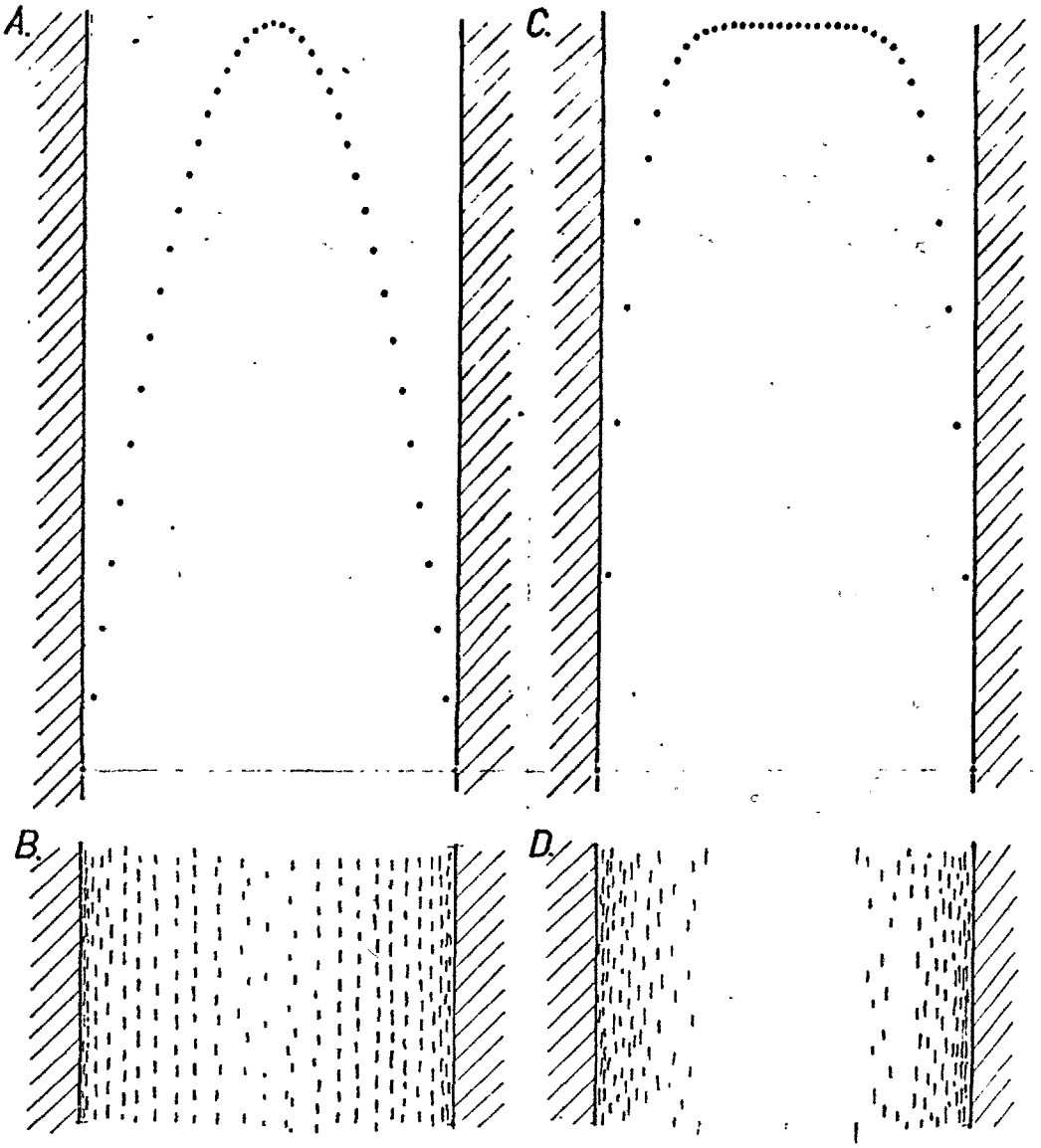
$$\text{velocity, } v = v_{max}\left(1 - \left\{\frac{x}{0.5h}\right\}^{(n+1)/n}\right)$$

where n is a measure of the pseudoplasticity ($n = 0.2$ in this case),

h is the width of the channel,

x is the distance from the centre of the channel.

D. Expected foliation pattern for C.


A.
C.
B.
D.

CHAPTER 5 - FOLDING

1. THE SEQUENCE OF FOLD PHASES

Traditional methods to determine the chronological order of folding events rely on refolding of earlier folds or their related features (e.g. lineations, foliation, etc.) by a set of later folds. The use of these relationships to determine the structural sequence is hindered if the second folding is coaxial with the first. In N.W. Lewis several sets of structures have almost horizontal axes trending southeasterly (for example, some Scourian folds and F2 folds are coaxial). It is often difficult to establish the sequence of these structures and to assign lineations to particular fold sets.

Often with refolded structures it is difficult to derive a unique solution to the folding order. This is illustrated by Fig. 57 which shows a refolded structure in the bay at Garenin (192443). From previous experience it is known that F2 folds usually have approximately horizontal axial surfaces and are sometimes refolded by later folds. Laxfordian folds earlier than F2 (i.e. F1) could possibly exist. With this in mind at least two explanations of the pattern become apparent:

a) the simple case - upright F1 (= F_A) refolded by flat F2's (= F_B), or

b) F2 (= F_A) has been bodily rotated by $F_{(A + 1)}$ so that its axial surface is vertical and then a set of flat folds (= F_B) has been superimposed.

Using this evidence alone it is impossible to specify which of these (or other) alternatives apply: only by collecting data from several localities is it found that the second explanation is the more likely.

Interference patterns do not always give information about the order of the refolding. Fig. 58A shows interference patterns from

N.W. Lewis where the order of refolding can be worked out. Other cases (e.g. Fig. 58B), where the axial surface of the first fold is not distorted by the second fold, provide no evidence of the relative timing of the two foldings. Ramsay (1962) has classified interference patterns produced by the interference of "similar-type" folds. Fig. 59 shows the appearance of interference patterns on two dimensional sections. In general, only interference patterns of types 2 and 3 (Fig. 59 F to I) gives information about the order of the superimposition. However there is the possibility that even these types could be produced by "synchronous refolding" (Wynn-Edwards 1963). This discussion has relevance to areas where basin-and-dome structures have been produced by post-D2 folding in regions of strong D2 flattening (e.g. Fig. 58B). They are similar to Class 1 interference patterns and, as a result, the time-relations of these post-F2 folds are difficult to deduce.

Geometrical patterns produced by refolding have only, as yet, been predicted for a two fold-phase model. Naturally structural elements associated with the first phase of a deformation involving more than two phases will be expected to possess a complex configuration and no guide-lines have been given for their interpretation. As a result, sequences of more than two fold episodes can only be built up on the basis of pairs of structures, for example B folds A at one exposure and C folds B at another. Hence correlation is required to equate B with B.

A detailed discussion of the special problems attending structural correlation in gneisses has been given by Park (1969). He deals comprehensively with the criteria used in correlation. However a further point is made here. Strain heterogeneity shown by a phase of deformation can probably produce a spatial variation of fold style, orientation and fabrics. If strain heterogeneity is suspected (for example during the

F2 phase in this area) then we should anticipate initial variation of fold characters. F2 fold axial surfaces dip more steeply to the southwest near to the low deformation area than they do around Loch Roag where F2 axial surfaces are nearly horizontal (Fig. 60). Is this variation due to primary curvature of F2 XY strain trajectories (which are equated with fold axial surfaces) or is it due to post-D2 refolding?

The problem mentioned above is typical of areas where variations of folds and finite strain can be related to the position in the major fold structure. Elsewhere in other tectonic settings it appears more convenient to consider folds as an expression rather than a cause of the large scale strain heterogeneities. The following sections attempt to discover in which of these ways the folding in N.W. Lewis ought to be considered.

2. THE ROLE OF FOLDS IN THE REGIONAL STRUCTURE

Watterson (1968) has shown that some areas of Precambrian gneisses are better described by reference to the bulk strains than by reference to the patterns of successive fold episodes. The evidence is examined to find out if such an approach is justified in this area.

A. Folding as a manifestation of the bulk strains. The effects of the early Laxfordian deformation in the area consists of flattening with a flat XY plane. This flattening results in structural changes, the most important of which is the modification of shape fabrics which affects the aspect of the gneisses on the outcrop. Folds (F2) are formed but are less reliable than fabrics to indicate this flattening. With increase in deformation they become less, rather than more, conspicuous so that in intensely-deformed areas the hinges of isoclinal folds are rarely seen. F2 folds rarely vary in their sense of asymmetry (observations made looking towards the east usually reveal a Z sense).

The consistent sense of F2 minor folds indicates that F2 folds are usually of low order. Second order folds with wavelengths up to 40 metres are, for example, visible at Dalmore (202460) and on the north-facing slopes of Ben Bragar (266435) and these appear to be the highest order on which D2 folding took place within the area.

Apart from rare reversals of sense due to second order folding, senses can be interpreted as indications, not of the limb of the major structure, but the orientation of the pre-D2 layering with respect of the XY plane of the D2 strain ellipsoid (see Fig. 61).

In this setting, poles to banding have more meaning if they are considered as elements defining a regional fabric rather than s-surfaces from limbs of folds. Fig. 62 demonstrates how the banding, used as a fabric element is interpreted. Girdles of poles define a fabric of linear type and point maxima define planar fabrics.

Fig. 63 shows contoured stereograms of poles to banding in 46 subareas which make up the area. The location of these subareas is shown in the map in Fig. 64 . These plots show a similar variation from girdles to point concentrations. Good examples of girdles occur in subareas 19, 20, 21, 29, 30, 31, 32, 39, 40 and 45 which are all areas of low Laxfordian deformation - regions where the gneisses have a linear fabric on the scale of the outcrop.

A tendency for single maxima is shown by other plots, especially those from subareas 2, 6, 7, 8, 9, 10, 11, 12, 13, 25, 26, 33, 35, 36, 37, 40 and 43. This means that the banding in these areas defines a total fabric which is of a planar type. These subareas are regions of considerable Laxfordian deformation where the gneiss has a planar aspect (see Fig. 49, which shows the distribution of gneiss fabric types).

We can conclude that, by using groups of banding data we are able to define a macrofabric and this macrofabric (which refers to a considerable

area) agrees closely in type with the gneissic mesofabric on the scale of an outcrop. This trend towards planarization with increase in Laxfordian strain, which agrees with trends in the changes of the small-scale fabric in the gneisses, also matches the trend towards planarization of Scourie Dyke orientations (Chapter 7).

B. Interpretation of structural geometry in terms of folds

Where the D2 deformation produced a high degree of co-planarity of the various structural elements, any subsequent folding produces profound effects on the structural geometry.

From the non-cylindrical nature of the folded surfaces produced in these areas by post-D2 folding, it appears that more than one set of folding occurred after the D2 flattening. On the scale of an outcrop it is often impossible to separate these fold sets. The folded surface has no axis or other features which can be related to an individual set but is a compound product of the two sets.

On the scale of the map the same is true. Selection of homogeneous domains whose geometry is the result of only one fold set is impossible because every domain is heterogeneous. Pi-diagrams show considerable scatters away from a best-fit great circle.

A new approach had to be adopted to interpret the pi-diagrams. Instead of the usual assumptions of cylindrical folding embodied even in methods of polyphase folding analysis, the degree of non-cylindricity was measured for the 46 subareas shown in Fig. 63 . A non-cylindricity factor was adopted as a measure of the scatter of the data away from the great circles of pi-diagrams of true cylindrical folds.

If an s-surface forms part of a cylindrically folded surface then its pole should be perpendicular to the axis of the fold. If ℓ_1 m_1 n_1 and ℓ_2 m_2 n_2 are the direction cosines of the s-surface pole and the fold axis respectively, then

$$\ell_1\ell_2 + m_1m_2 + n_1n_2 = 0$$

If the s-surface was not perpendicular to the axis, i.e. if the fold is not truly cylindrical

$$\ell_1\ell_2 + m_1m_2 + n_1n_2 = X$$

The non-cylindricity factor (NCF) is defined as the standard deviation of X for the whole population of s-surfaces

$$NCF = ((X_1^2 + X_2^2 + X_3^2 \ldots\ldots + X_n^2)/(n - 1))^{1/2}$$

where n is the number of s-surfaces measured. A computer program was written to calculate NCF from a population of banding measurements. NCF was calculated for the forty six subareas and Appendix 1 is a table of the results of these calculations and shows the range of values of NCF. These values were contoured and Fig. 64 is a contour map of the degree of non-cylindricity shown by the banding throughout the area. The highest values of non-cylindricity (NCF $>$ 0.35) occur on Ben Bragar, the southern part of Great Bernera and around Breasclete.

Possible origins of the variation of NCF were considered and the most likely cause seems to be the orientation and occurrence of post D2 folds. The areas where NCF is high can be matched with areas where a well-defined set of post-D2 folds has developed with north- and northeast-trending axes which are transverse to the earlier structural grain. These are the F3 folds described in Chapter 3 and Fig. 112 shows their distribution. It can be seen that Ben Bragar, Breasclete and Southern Bernera are areas of pronounced F3 folding.

Consistent with this interpretation of NCF variations are the low values of NCF along the northern coast. It is here that the post-D2 folds are co-axial with the D2 structures and the banding is likely to be arranged in a more 'cylindrical' fashion.

3. CONCLUSIONS

The area can be divided into two types of regions where folding controls the structural geometry to different extents:

i) Regions where D2 flattening was incomplete. The structural geometry was produced by the imposition of bulk D2 strain on an inherited pattern of structural patterns. Folding is inadequate to completely explain the resultant geometry but seems to be just one mode of expression of the bulk strains.

ii) Regions where D2 strains were effective in bringing about virtual co-planarity of early structural elements. Post-D2 folds play a large part in controlling the final structural arrangements in these areas.

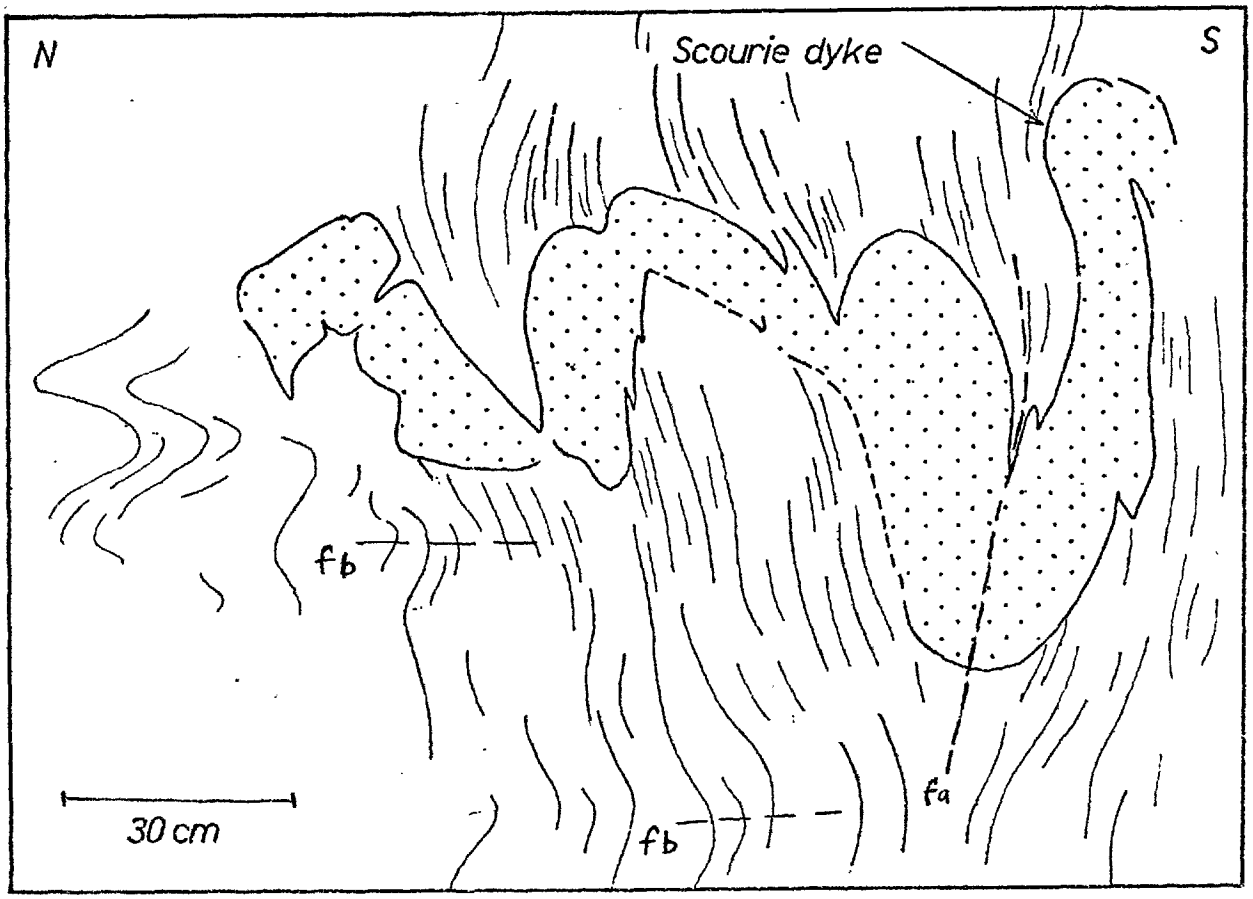


FIGURE 57

A refolded structure on the east side of the bay at Garenin, near Carloway.

FIGURE 58

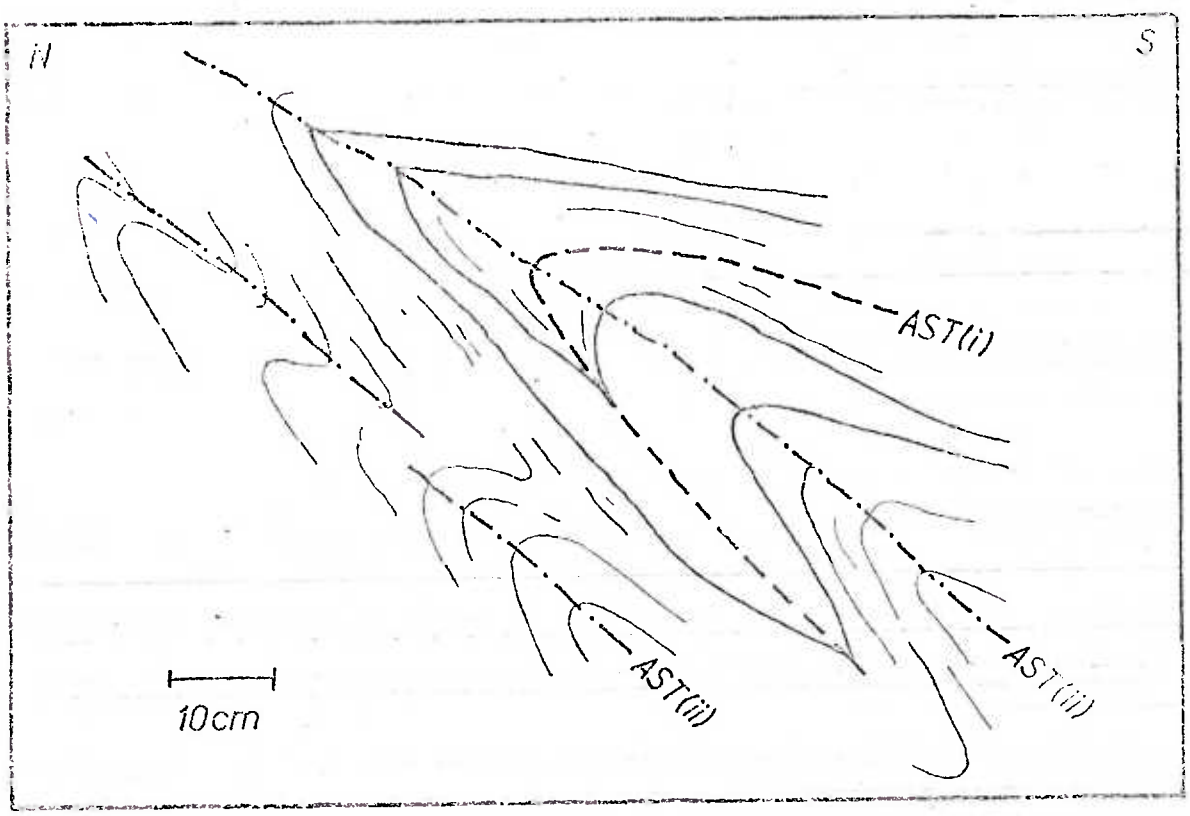
A. Refolded fold in which the order of the folding events can be determined.

AST (i) = Axial surface trace of first folds

AST (ii) = Axial surface trace of second folds.

B. Refolded folds in which the order of the folding events cannot be determined.

A and B are from the Labost Peninsula, North Bragar.


N
S
AST(i)
AST(ii)
AST(iii)
10cm



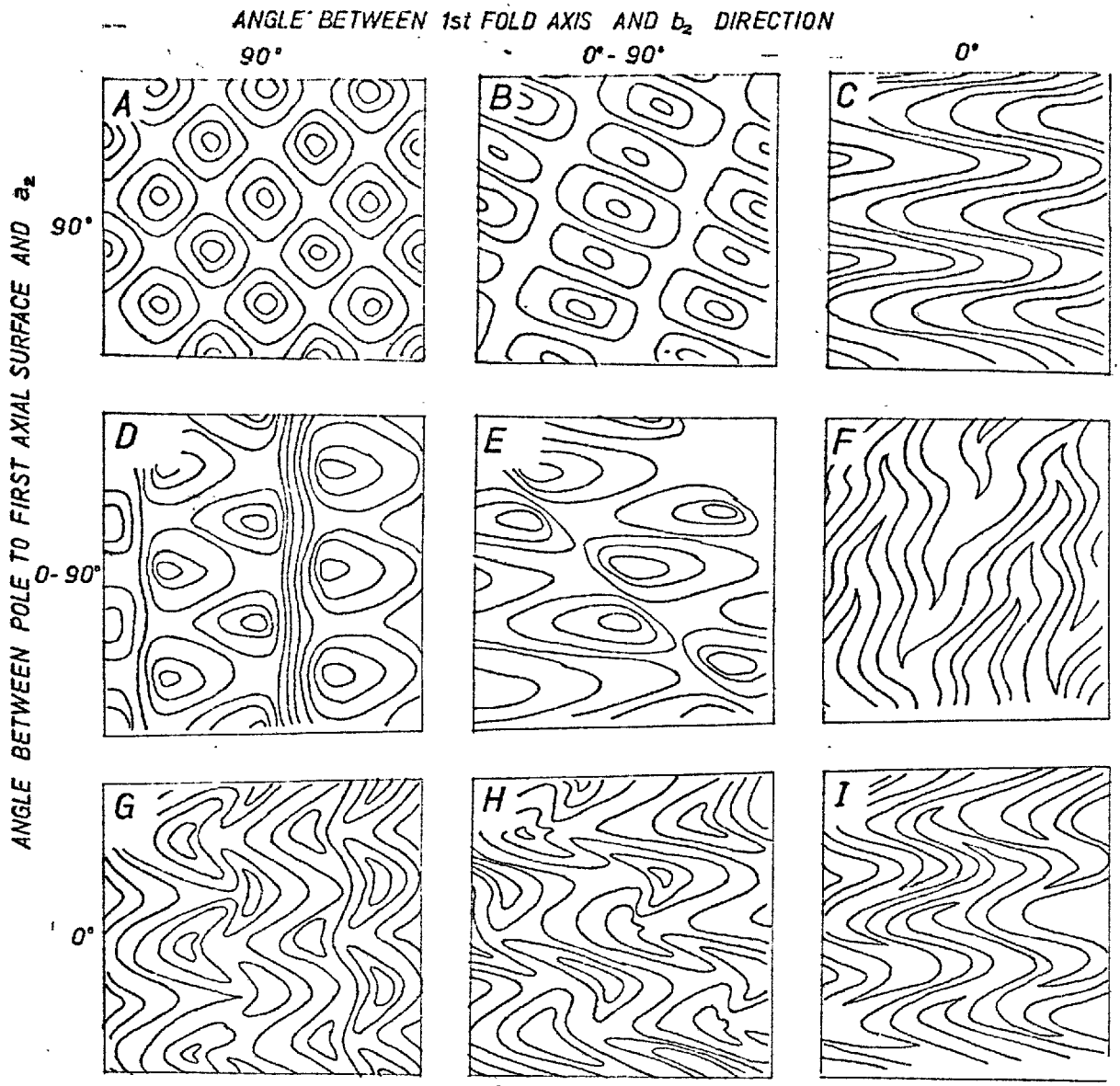


FIGURE 59 (Modified from Ramsay, 1967. Figs. 10-13) APPEARANCE OF INTERFERENCE PATTERNS ON A PLANAR SURFACE. Only with types F to I can the order of the superimposition be determined.

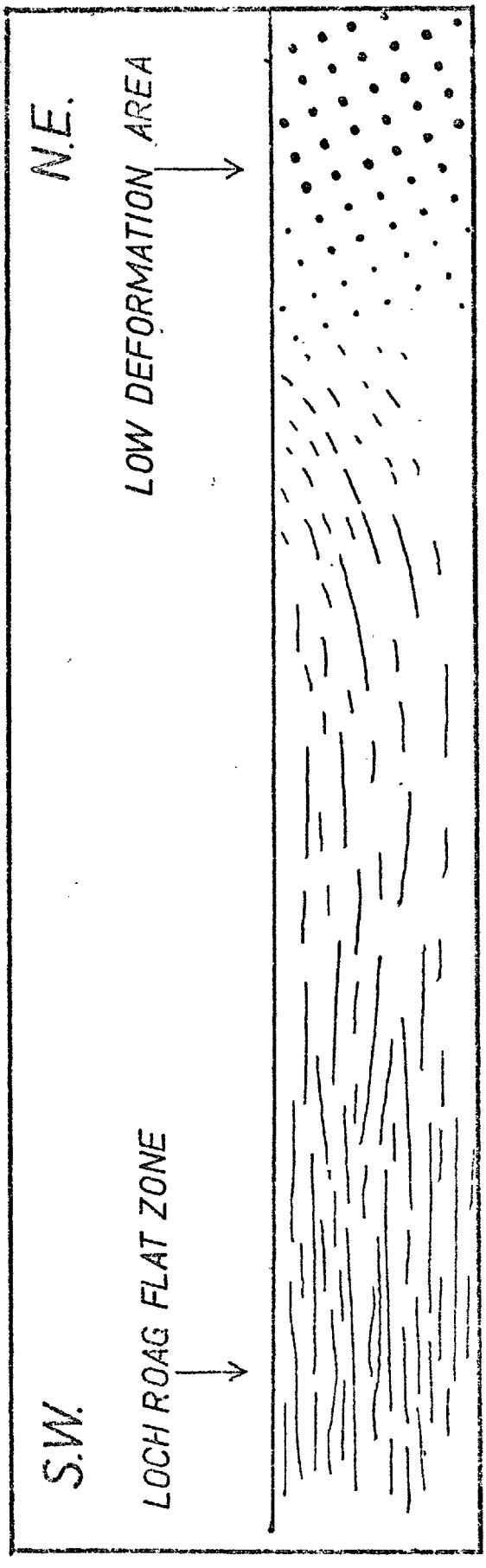
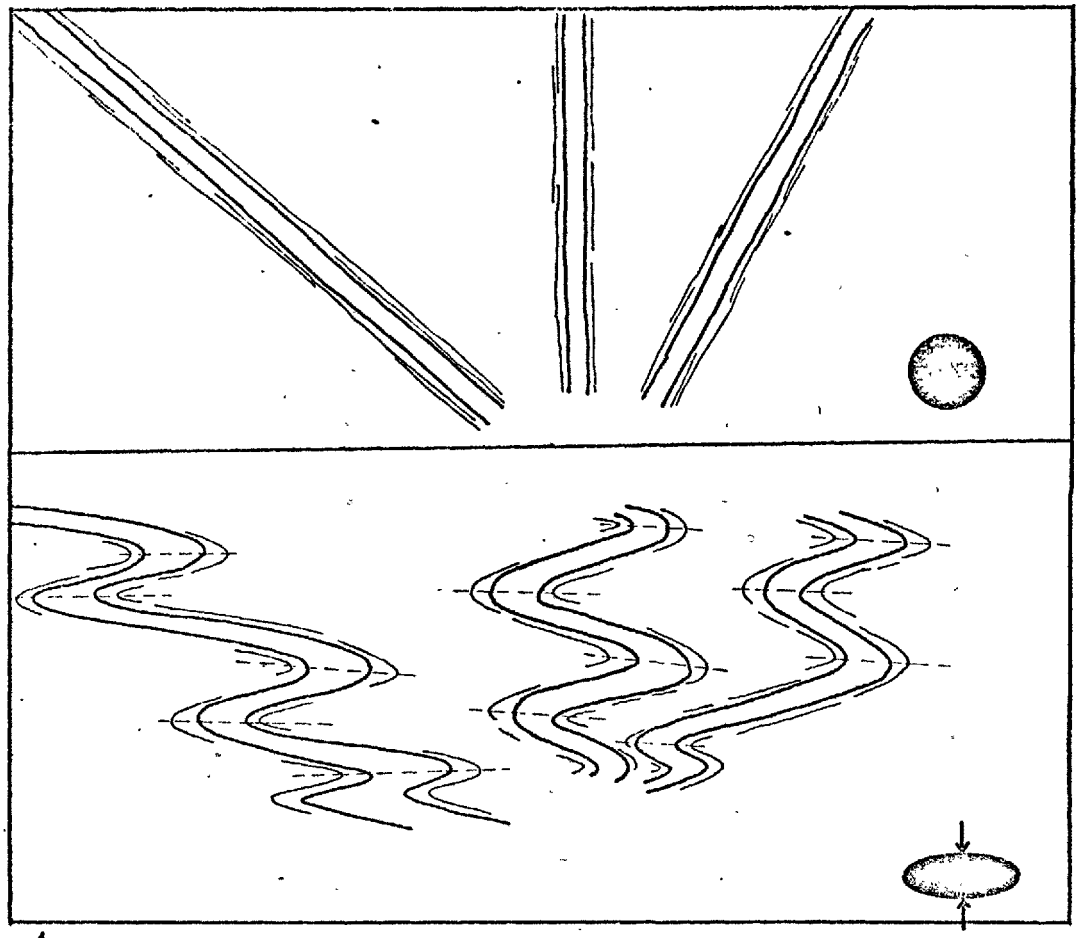
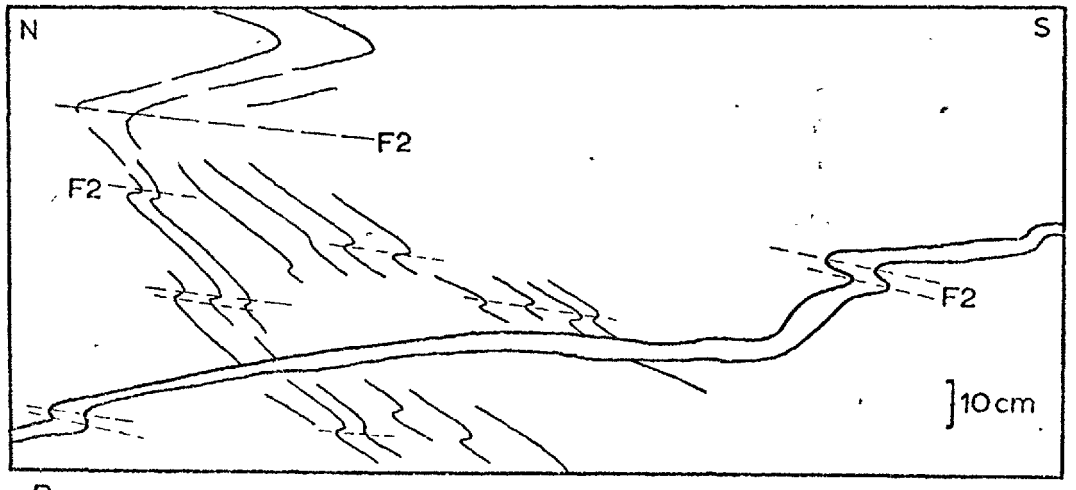


FIGURE 60

The relationship of F2 axial surfaces (lines) to the low deformation area N.E. of the Loch Roag Flat zone. Scale: 2cm = 1 km.



A.



B.

FIGURE **61**

A. Control of fold sense by the arrangement of the banding prior to deformation relative to the strain ellipsoid.

B. Opposing senses of F2 folds, N.W. flank of Ben Bragar. A Scourie dyke cuts grey gneiss.

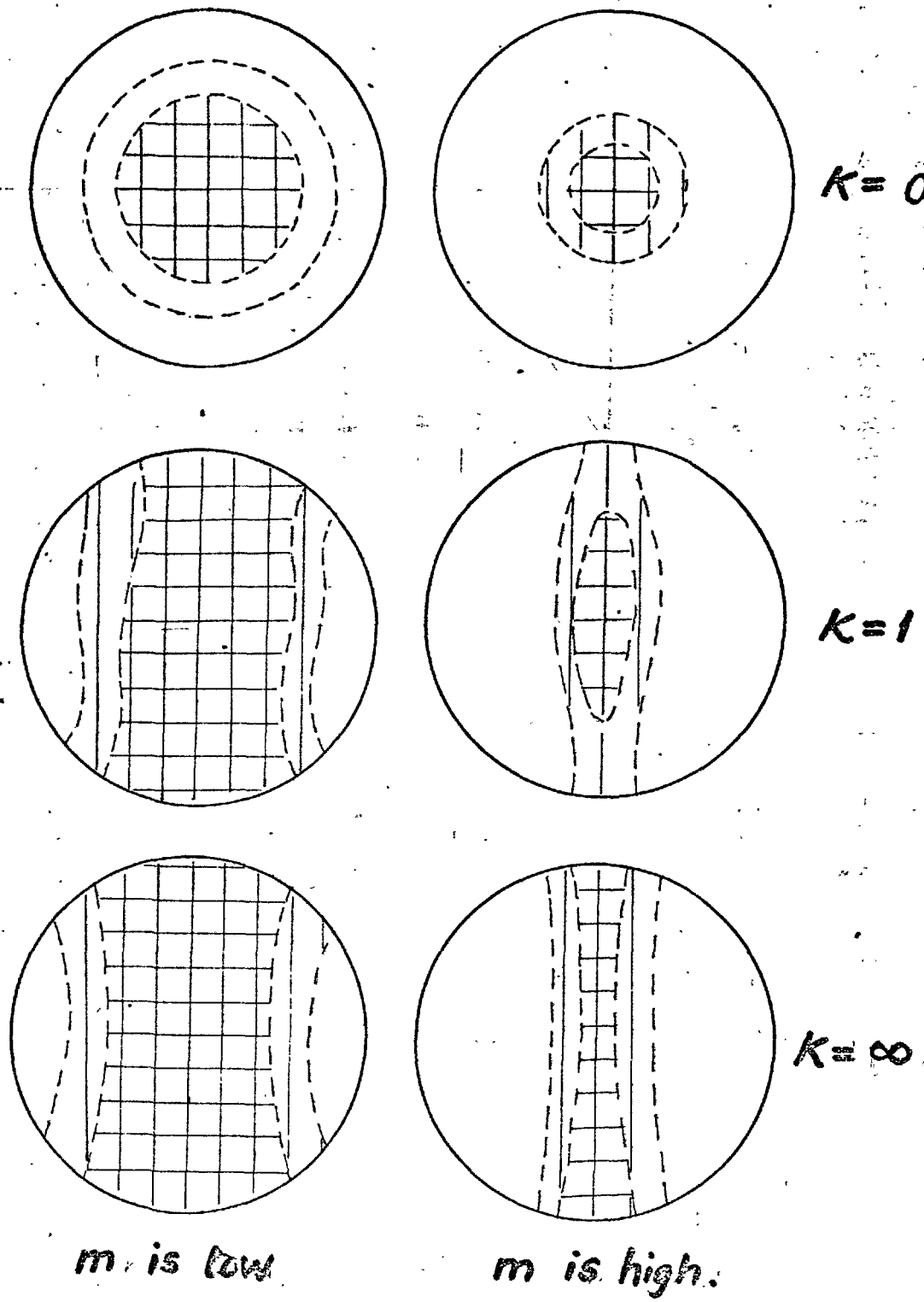


FIGURE 62

POPULATIONS OF BANDING POLES DEFINING A MACROFABRIC

Plots for various k and m values.

These macrofabrics which refer to banding subareas, have the properties of a shape - fabric.

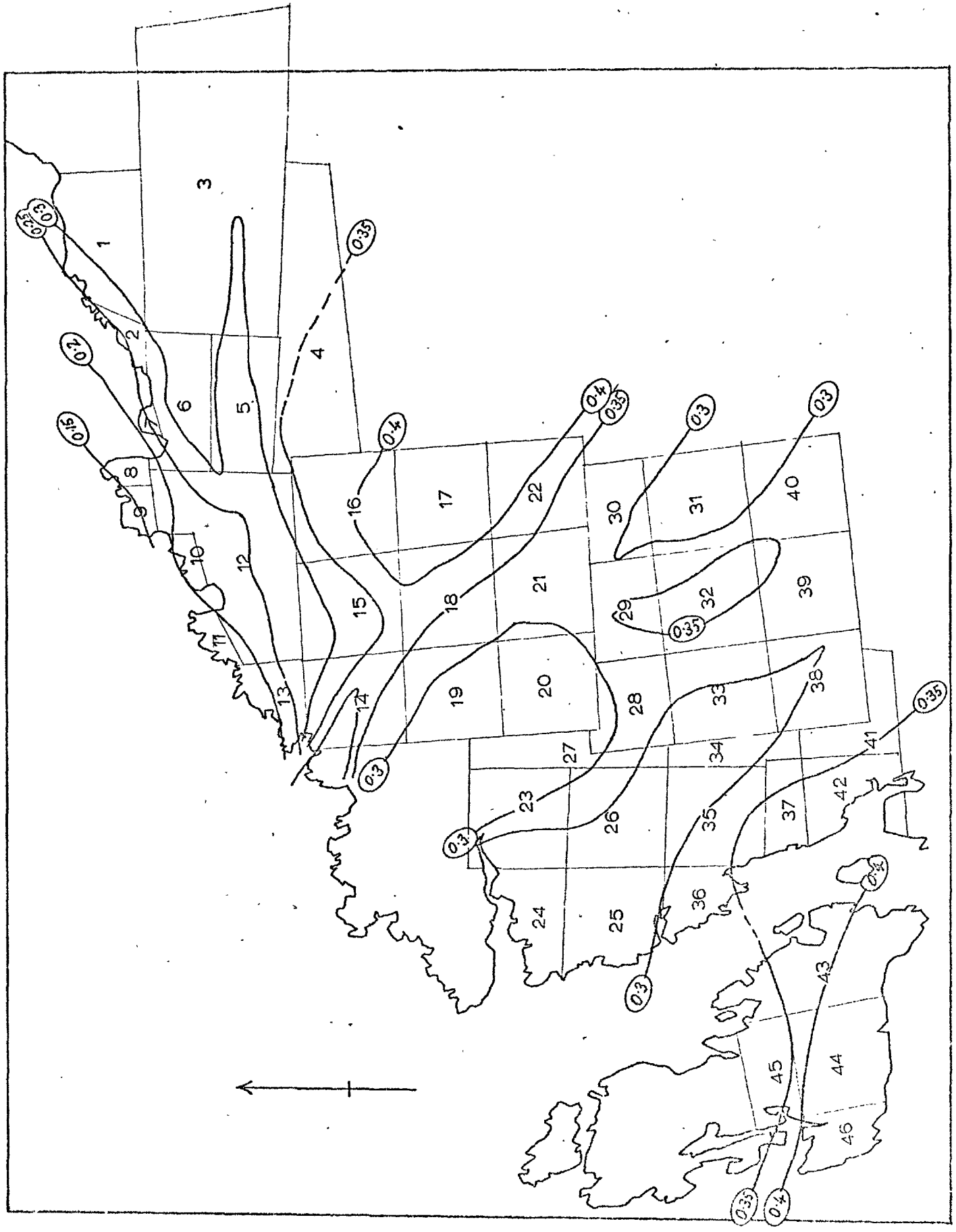


FIGURE **64** The variation of the value of the Non-cylindricity Factor (NCF) of the banding throughout the area. The numbered squares show the boundaries of subareas from which banding were measured. NCF variations are shown by the contour lines. For results see Appendix 1.

CHAPTER 6 - EXTENSIONAL STRUCTURES

1. INTRODUCTION

The following section outlines the morphology of structures apparently formed by extension of the lithological layering. Boudinage and pinch-and-swell structures, together with irregularly arranged boudin-like bodies are common in certain areas. Their form and occurrence have been investigated to obtain information about the competence of the rock-types involved and strain responsible for the formation of these structures.

2A. COMPETENCE VARIATIONS SUGGESTED BY EXTENSIONAL STRUCTURES

It is generally accepted that boudinage and pinch-and-swell structures are produced by extension, within the plane of the layering, of a component layer in a less competent host. Observations on the composition of the boudinaged layers and host therefore provide a scale of relative rock competence (Fig. 66). Scourie Dykes are frequently boudinaged in a variety of gneissic host rocks and these two components provide the best examples of boudinage structure. Dykes invariably appear to be the competent member but it must be pointed out that dykes are rarely in a position to act as hosts to gneiss layers. However other evidence sometimes points to reversed competence relationships between quarto feldspathic gneiss and Scourie Dyke amphibolite. An example occurs at North Shawbost (260484) where a gneissic xenolith is enclosed in the amphibolitic contact of a thick Scourie Dyke. The strain trajectory pattern about the enclosed block, as indicated by the foliation pattern in the amphibolite, reveals that the xenolith behaved more competently (Fig. 67) than the biotite-amphibolite host.

Of the Scourie Dyke suite, the coarse-grained and ultrabasic types appear to have behaved most competently during the extension. Normal basic types show pinch-and-swell structure on the scale of the map (for

example Fig. 72). The ultrabasic dykes occur as stumpy, widely-spaced fragments, suggesting that the deformation involved little stretching within these boudins. The almost total lack of fabric inside these fragments is further evidence for their resistance to deformation.

Pegmatites are boudinaged in most host rocks (Fig. 66), an observation which at first appears unusual because of their quartzo-feldspathic composition. An explanation may lie in the scale of the heterogeneities present in a pegmatite. If the grainsize is large in relation to the thickness of the body, cross-sections rich in quartz will "neck" in preference to feldspar-rich sections. This results in pinch-and-swell where long slender necks separate augen-like feldspathic portions (Fig. 68A). If the explanation of the feature is correct we would expect the "observed competence" (deduced from extensional structures) to increase with increase in the scale of the mineralogical heterogeneity. The pinch-and-swell structure may also be controlled, partly at least, by the bulk competence differences of the pegmatite and host.

A correlation between "observed competence" and thickness of Scourie Dykes has been observed. Thicker dykes show a higher degree of pinch-and-swell than do thin dykes at the same outcrop. Examples of this feature are illustrated in Fig. 68. In support of this, the gneissic fabric intensity variation can be seen to be more pronounced about thick dykes than about thin dykes. Talbot (1970) found that thickness is an important parameter controlling the tendency to neck or to thin uniformly during the extension of quartz veins while Myers (1968) found that within one group of Laxfordian pegmatites in Harris, those with thicknesses of 2 - 4 cms had straight parallel margins while those of 5 - 10 cms usually show pinch-and-swell. The explanation of a thickness control on "observed competence" remains problematical; in the case of Scourie Dykes, evidence

based on different metamorphism and fabric development of thick and thin dykes tends to lead to circular arguments. In many situations, metamorphism and fabric development have been seen to accompany deformation and to be an expression of it. It is therefore dangerous to imply that the one phenomenon causes the other.

The observed shape of boudins provides suggestions for the rheological state of the rocks at the time of deformation. Areas of strong late Laxfordian recrystallization have their own style of boudinage and Scourie Dykes broken up during this phase have a blocky shape, the blocks often lacking a systematic arrangement. This suggests low ductility of the dykes during this recrystallization phase. The final product of this break-up often resembles the lensoid gneiss which developed in pre-Scourie Dyke times. By way of contrast, extensional structures produced in the Scourie Dykes during the early Laxfordian event, more often show considerable necking so that pinch-and-swell structures and lens-shaped boudins are more common. The ability to neck is probably an expression of the high ductility properties of the Scourie Dykes rather than of the competence contrast of the boudin and host.

Fig. 69 shows the deductions about rheology made from the form of extensional structures: it is based on the conclusions of Ramberg (1955) and Ramsay (1967). The distinction between the brittle and ductile behaviour of the competent layer seems to be vital for the correct inference of other rheological characters. In the case of the brittle development of boudins, a short 'wavelength' would suggest that the competent layer had a low tensile strength. However, short wavelengths in a ductile extensional structure would indicate that the layer had a very high competence with respect to the host rock.

Some boudins, formed initially by the brittle failure of a

competent layer, were later modified in shape in a ductile manner. Barrel-shaped boudins (Fig. 70A) are formed where the body behaved as the more competent partner during post-failure modification. Other shapes, however, reveal that sometimes the separated fragments behaved less competently than the host during the later modification. Basic lensoids in the lensoid-gneiss very occasionally show "axe-head" shapes with concave edges facing the shortening direction (Fig. 70B). The dependence of the shape of modified rectangular bodies on relative ductility of the body and its host and on strain orientations is envisaged in a manner shown in Fig. 71.

2B. CONCLUSIONS ABOUT COMPETENCE

The observed competences, as inferred from structures produced by extension along the layering, show considerable variation even in structures involving similar lithologies. Often this can be seen to be related to a scale factor which remains unexplained dynamically. Metamorphism is more complete in thinner competent layers and the penetration of pore fluids from the host to the competent layer may be an explanation of this scale problem. This implies that the metamorphism is the independent variable with respect to the deformation. However, field evidence often shows that fabric development (and metamorphism) go hand in hand with the expected state of deformation.

The shapes of extended layers provide information about the rheology of the system. Nevertheless there are problems, for instance, interpretation of the wavelength of boudinage structure will depend on whether the boudins formed in response to ductility variation of the layers in a sense related to brittle/ductile behaviour (stress-strain behaviour) or to ductility variation (contrasts) in terms of "viscosity" ratios (Fig. 69).

3. STRAIN MEASUREMENT FROM EXTENSIONAL STRUCTURES

The present body of knowledge concerning boudinage formation indicates that strain amount is only one of many factors controlling its final form. However attempts are made in this section to use extensional structures to glean information about the finite strain. The type of data obtained depend on the method used - it can be a vague regional comparison of the relative strain amount or a minimum value of the strain amount at a particular outcrop.

A. The regional variation of strain

The degree of boudinage of the thicker Scourie Dykes can be seen on map scale. Fig. 72 (a and b) indicates two selected areas which show different degrees of continuity of Scourie Dyke outcrops suggesting different amounts of boudinage. The distribution of outcrop-sized boudinage structure in Scourie Dykes is shown in Fig. 73. Not surprisingly areas of abundant boudinage correspond with areas of strong Laxfordian strain. The dominant orientation for boudinage consists of a flat enveloping surface and low-dipping axes trending east to south-east.

B. The strain on the scale of an outcrop

Ramberg (1955) discusses a model for the development of boudinage structure where the competent layer is assumed to deform elastically before rupture. If the boudin also suffers no permanent deformation subsequent to failure, then it is possible to use the structure to estimate the amount of stretching. Methods similar to those used with stretched belemnites (Badoux 1963) may be employed to calculate the amount of extension along the layering (Fig. 74).

If the boudins have undergone internal stretching either before or after separation, the sum of the lengths of the separated fragments

will not record the unextended length of the layer. It is the uniform stretching of both layer and host which presents the most difficult problem in this type of strain analysis. Homogeneous stretching before the formation of 'necks' can be undetected if parallelism of the layers is maintained. With folds, estimates of this pre-instability deformation are made using ductility contrasts calculated from the wavelength/thickness ratios of the folds. Before wavelength/thickness ratios can be measured, post-buckle strains are subtracted by assessing the amount of modification from a fold of a "standard shape"; a fold of equal orthogonal layer thickness (Ramsay 1967).

Attempts to apply a similar method to pinch-and-swell structures meet with several problems. Firstly no "standard shape" has been suggested for embryonic pinch-and-swell structure and secondly there are not sufficient theoretical or experimental data with which to interpret wavelength/thickness ratios of pinch-and-swell in terms of viscosity ratios, etc.

Homogeneous stretching of both layer and host also gives rise to problems when other methods of strain analysis using extensional structures are tried out. Talbot (1970) uses the orientation of envelopes of folded and stretched veins to define sectors of finite elongation and contraction in the strain ellipsoid and hence to discover the shape of the strain ellipsoid. Fields of shortening, of no change in length and of extension have been assumed to produce respectively: folding, "no-structure" and extensional structures (Fig. 75). Recent ideas suggest that homogeneous deformation can take place in both the shortening and extension fields thus producing a zone, rather than a line, of "no structure" on the stereographic plot (Fig. 75). If this is correct, then the location of the surface of no finite longitudinal strain (a procedure upon which accurate strain calculation depends with this

method) becomes hazardous.

With the knowledge that homogeneous stretching has probably played a significant part in the total deformation, measurements of the amount of the "structure-producing" component of the strain have been carried out using extensional structures. The "belemnite" method has been applied to boudins and a new method was devised for necked boudins and pinch-and-swell structure. In two dimensions, assuming there has been no cross-sectional area change and that the competent layer was originally of constant thickness, measurements of the cross-sectional area (A) occupied by the competent layer and its present maximum thickness (t_{max}) allows assessment of the heterogeneous stretching component. (Only if the relationship $t_{max}/t_{original}$ is known can the total stretching be calculated.) Fig. 74 shows the basis of the method and Fig. 76 shows the method applied to examples of extensional structures. The results are compared with those derived by the belemnite method.

Only in rare circumstances can an estimate of the homogeneous strain be made. Fig. 77 shows an outcrop where a layer appears to have separated into boudins which later changed orientation relative to one another before flattening. The local foliation pattern suggests fairly homogeneous flattening. Assuming that the stretching direction is parallel to the trace of the foliation, it is possible to use these data to calculate the strain ratio of the flattening which modified the shape of the layer fragments. The Mohr circle solution to this strain problem is shown in Fig. 77.

4. BOUDINS ON THE LIMBS OF FOLDS

Occasionally boudins occur which have their maximum individual length inclined to the orientation of the envelope of the string of boudins (Fig. 78).

Recent experimental work (K.M. Hossain, personal communication) shows that asymmetrical boudins may be formed when the long axis of the finite ellipse is inclined to the line defined by the boudinaged fragments. This reflects the different rotation rates of boudin and matrix, the boudins showing the slower rotation rate towards the finite extension direction (Fig. 79). Pinch-and-swell, likewise, may be expected to develop symmetrically by the oblique flattening of existing pinch-and-swell. Fig. 79 shows the geometrical product of pinch-and-swell subjected to oblique extension. It is interesting to note that the axial surfaces of bending folds become non-perpendicular to the pinch-and-swell envelope. Although this has been described as a two-stage process, with the oblique flattening superimposed upon the extension structure, there is no reason to believe that a single stage of oblique stretching would produce very different structures.

From this discussion, it appears possible that asymmetrical extensional structure could be used to determine the structural "way-up" of fold limbs in the same way as asymmetrical folds have been used. However, certain aspects of the asymmetry seem to depend on the type of extensional structure under consideration. For instance the relationship of the effective long axis (in section) of the structure with respect to the run (or envelope) of a series of boudins seems to be different from rectangular boudins and for pinch-and-swell structure (Fig.79a and b). Furthermore, findings by Ghosh and Sengupta (1973) suggest the probability that the sense of rotation of competent fragments on fold limbs may depend on the mechanism of folding. This would make the interpretation of asymmetrical boudinage structures in terms of limb sense more difficult.

Although the boudinage of variably-oriented competent bodies (e.g. belemnite fragments, etc.) often give rise to an asymmetric

arrangement of the disrupted fragments, reports of asymmetrical extensional structures of lithological layers (for instance on the limbs of folds) seem to be rare. Ramberg (1955), for example, found that most boudinage structures he observed, mainly in gneissic areas, are of a symmetrical type. Field observations in Lewis confirm that symmetrical or near-symmetrical extensional structures are more common than asymmetrical extensional structures. This point will have significance in the later discussion.

Some folds of D2 age contain boudinage on their limbs. One example is shown in Fig. 80 (which is the same fold as that figured in Plate 7, Fig. 1, Dearnley 1962) which occurs at the roadside at Duone Carloway (196401). It would seem that quite a considerable amount of bulk deformation is required during D2 to produce such folding with boudinaged limbs because the strain has to be sufficient not only to produce a rather tight fold but also to rotate the limbs well into the extension field where the boudinage was formed.

Let us calculate the effects of two mechanisms by which limb rotation could take place. The first is a body rotation of the limbs without change of limb length which consists of a "hinge-like" tightening of the fold, similar to that suggested for the development of chevron folds. Considering a part of a fold limb, the strain due to this mechanism is given by

$$1 + e_2 = \frac{l_1}{l_o} = \sin \frac{\alpha}{2}$$ See Fig. 81A

where $1 + e_2$ is the length of the short axis of the strain ellipse, l_o is the length of the section of fold limb, l_1 is the distance perpendicular to the fold axial surface subtended by the limb section and $\alpha/2$ is the angle of dip of the limb section with respect to the fold axial surface.

Assuming no area change, $1 + e_1 = \frac{1}{1 + e_2}$, so that R_{BODY}, the strain due to this body rotation mechanism becomes

$$R_{BODY} = \frac{1 + e_1}{1 + e_2} = 1.0/\sin^2 \frac{\alpha}{2}$$

The variation of R_{BODY} with changes of α is plotted in Fig. 82

The second mechanism involves the homogeneous flattening of the fold which tightens a fold formed by the first mechanism. The contraction or stretching of the limb section will now depend on its initial orientation relative to the homogeneous "flattening" ellipse and on the amount of this homogeneous strain (Fig. 81 b). This can be expressed by the equation

$$\lambda = \lambda_1 \cos^2 \theta + \lambda_2 \sin^2 \theta \qquad \text{(Eqn. 3-29, Ramsay 1967)}$$

where λ is the quadratic elongation of a line which made an angle θ with a strain ellipse (with axes of quadratic extensions λ_1 and λ_2) before the deformation. If there is no area change $\lambda_1 = {}^1/\lambda_2$.

Therefore, $\lambda = \lambda_1 \cos^2 \frac{\alpha}{2} + \frac{1}{\lambda_1} \sin^2 \frac{\alpha}{2}$

because the flattening is parallel to the axial surface of the fold, i.e. $\frac{\alpha}{2} = \theta$.

This can be expressed as a quadratic in terms of λ_1

$$\cos^2 \frac{\alpha}{2} \lambda_1^2 - \lambda . \lambda_1 + \sin^2 \frac{\alpha}{2} = 0$$

Therefore, assuming constant area

$$R_{HOMOG} = (\lambda_1/\lambda_2)^{\frac{1}{2}} = (\lambda_1^2)^{\frac{1}{2}} = \lambda_1 + \frac{(\lambda^2 - 4 \cos^2 \frac{\alpha}{2} \sin^2 \frac{\alpha}{2})^{\frac{1}{2}}}{2 \cos^2 \frac{\alpha}{2}}$$

so we have the homogeneous strain ratio expressed in terms of the quadratic elongation of the limb section (λ) and the limb attitude attained after the first mechanism was completed ($\frac{\alpha}{2}$).

The absolute minimum value of the quadratic elongation of the limb (λ) is indicated by the measurement of boudinage in Fig. 76 . If we take $\lambda = 3.0$ as a value of the quadratic elongation shown by the boudinage at the outcrop, it is possible to calculate the amount of homogeneous strain required to cause boudinage, for various initial limb dips, using the equation above. This component is plotted in Fig. 82.

For any value of limb dip ($\frac{\alpha}{2}$) produced by the first component, the total strain required to produce boudinage of the specified quadratic elongation is

$$R_{TOTAL} = R_{BODY} \times R_{HOMOG}$$

The variation in R_{TOTAL} with change of α is shown in Fig. 82 . The absolute minimum strain ratio (R_{TOTAL}) to produce folds with boudinaged limbs seems to be around 12:1. This minimum strain corresponds to the case where the limb closes to an interlimb angle of 90° before homogeneous flattening takes over as the mechanism for fold amplification. A greater or lesser contribution from the body limb rotation mechanism will lead to a greater strain required to produce boudinage.

The final interlimb angle is produced by the homogeneous strain acting on the interlimb angle produced by body rotation (α). The angle between the limbs varies with the strain required to produce the structure. The minimum total strain value corresponds with the maximum interlimb angle. In this case the folds produced have a maximum interlimb angle of about 19.5° (Fig. 83). Each limb therefore was at a maximum angle of 10° from the finite stretching direction - a fact which could explain

why asymmetric boudinage is relatively rare on folds with boudinaged limbs.

These calculations imply that the presence of folds with boudinaged limbs, for instance some F2 folds in this area, indicates a considerable amount of bulk strain. Without a knowledge of the mechanism of folding the strain value cannot be estimated but an absolute minimum strain ratio is obtained which is of the order of 12:1. The rarity of strongly asymmetrical boudinage suggests that much boudinage forms in connection with tight folding.

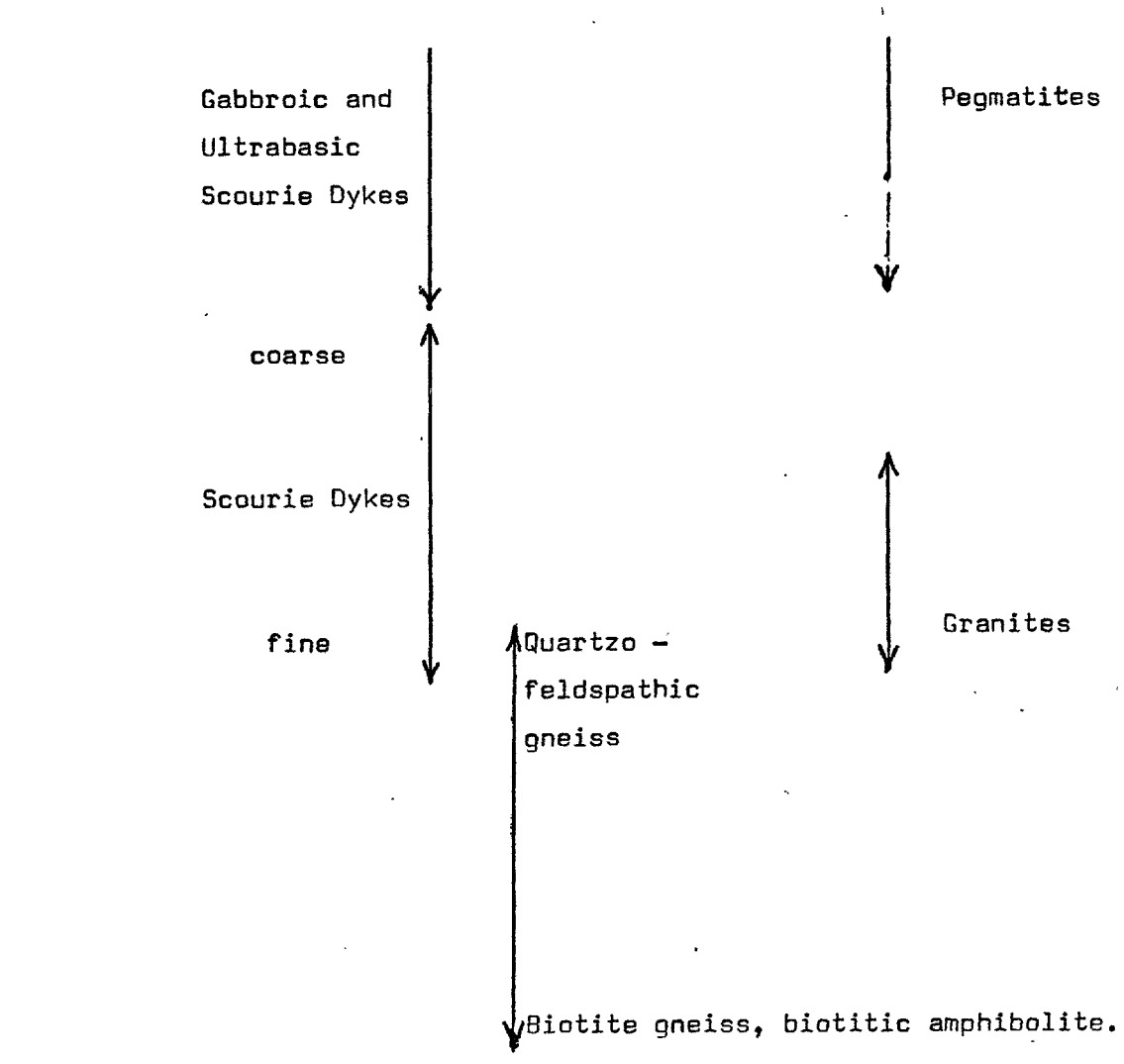


FIGURE 65

BOUDINAGE
Coast between South Shawbost and Dalbeg
Camera facing east.

FIGURE 66

COMPETENCE ORDER OF ROCK - TYPES INFERRED FROM EXTENSIONAL STRUCTURES



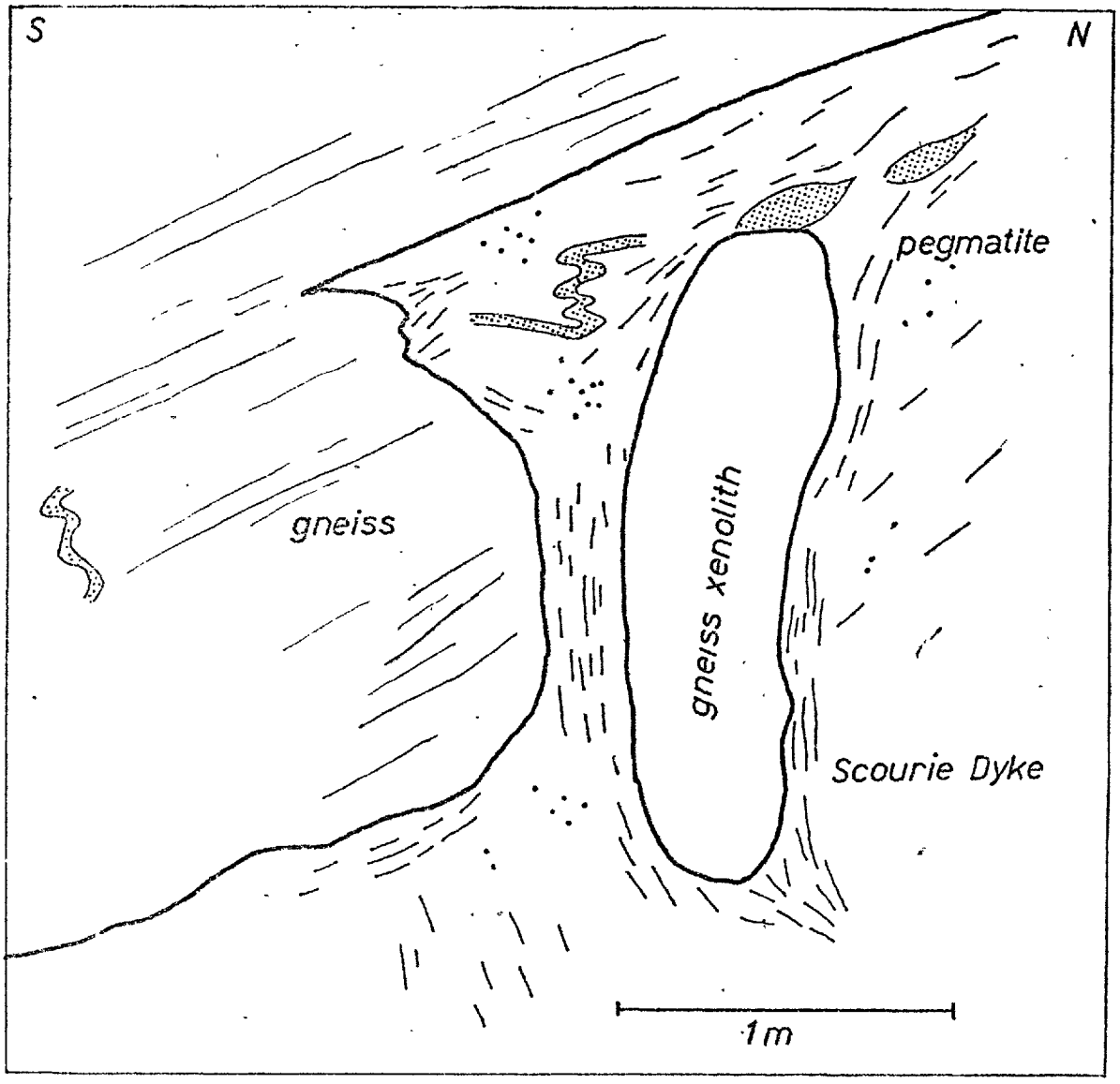


FIGURE **67**

GNEISS XENOLITH IN SCOURIE DYKE (BIOTITIC) AT NORTH SHAWBOST.

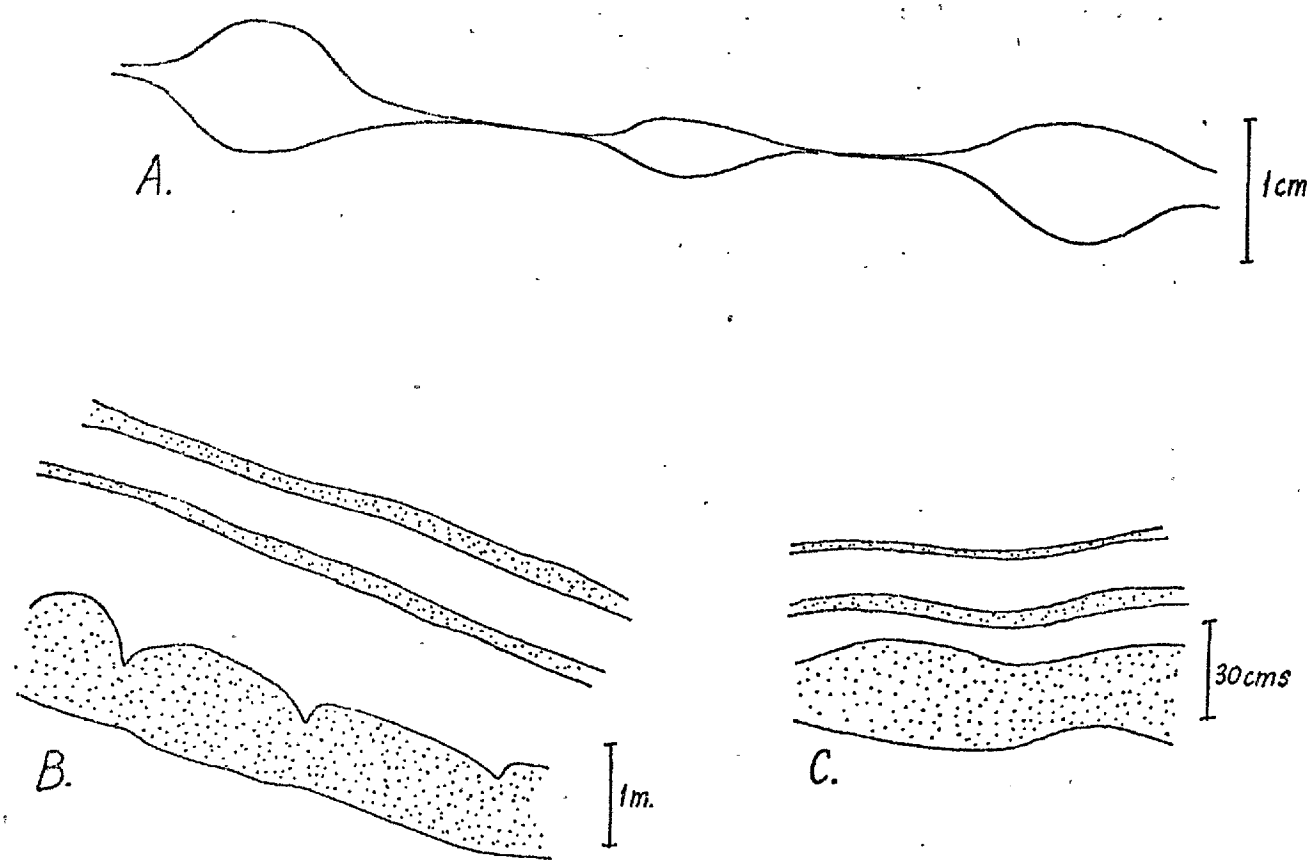


FIGURE 68

A. Pinch - and - swell structure with augen-like feldspathic sections, South Shawbost.

B and C. Differential pinch - and - swell of thick and thin Scourie Dykes.

B. Labost (208499) , near Bragar.

C. Roadside near Tolstachaolais (200397)

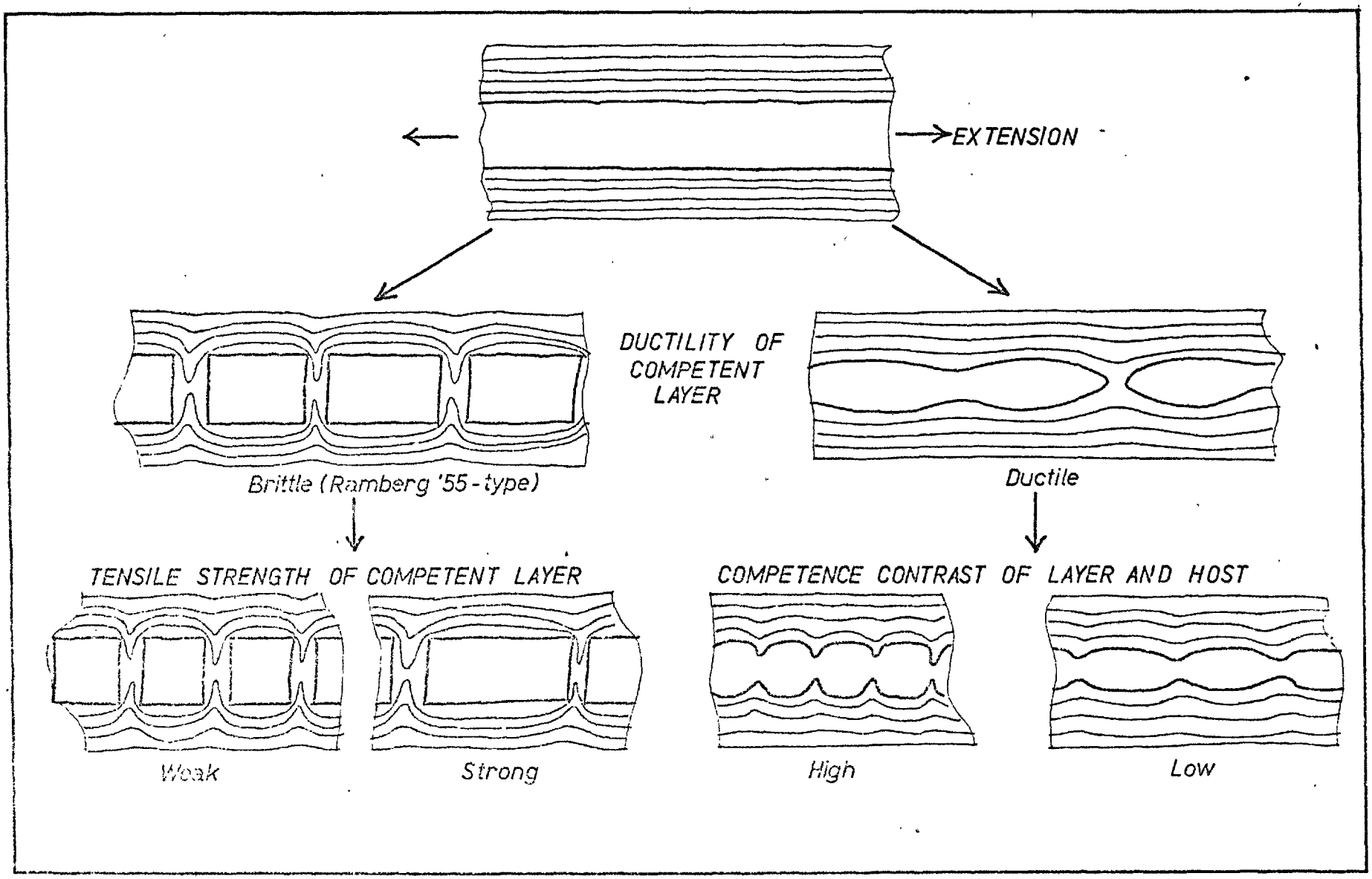


FIGURE 69

THE MORPHOLOGY OF EXTENSIONAL STRUCTURES - A GUIDE TO ROCK RHEOLOGY.

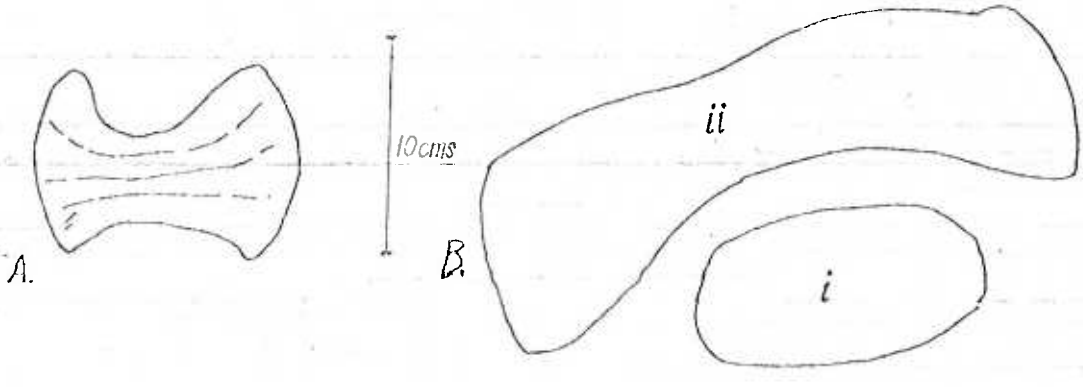
FIGURE 70

PHOTOGRAPH showing boudinage with barrel-shaped terminations, North Bragar.

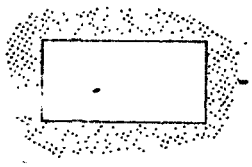
A. Axe-head shaped basic body from an outcrop of lensoid gneiss, South of Dalbeg

B. Two bodies from lensoid gneiss.
(i) is more competent than (ii) which has an axe-head shape.




10cms
A.
B.
ii
i

DUCTILE MODIFICATION OF RECTANGULAR BODIES

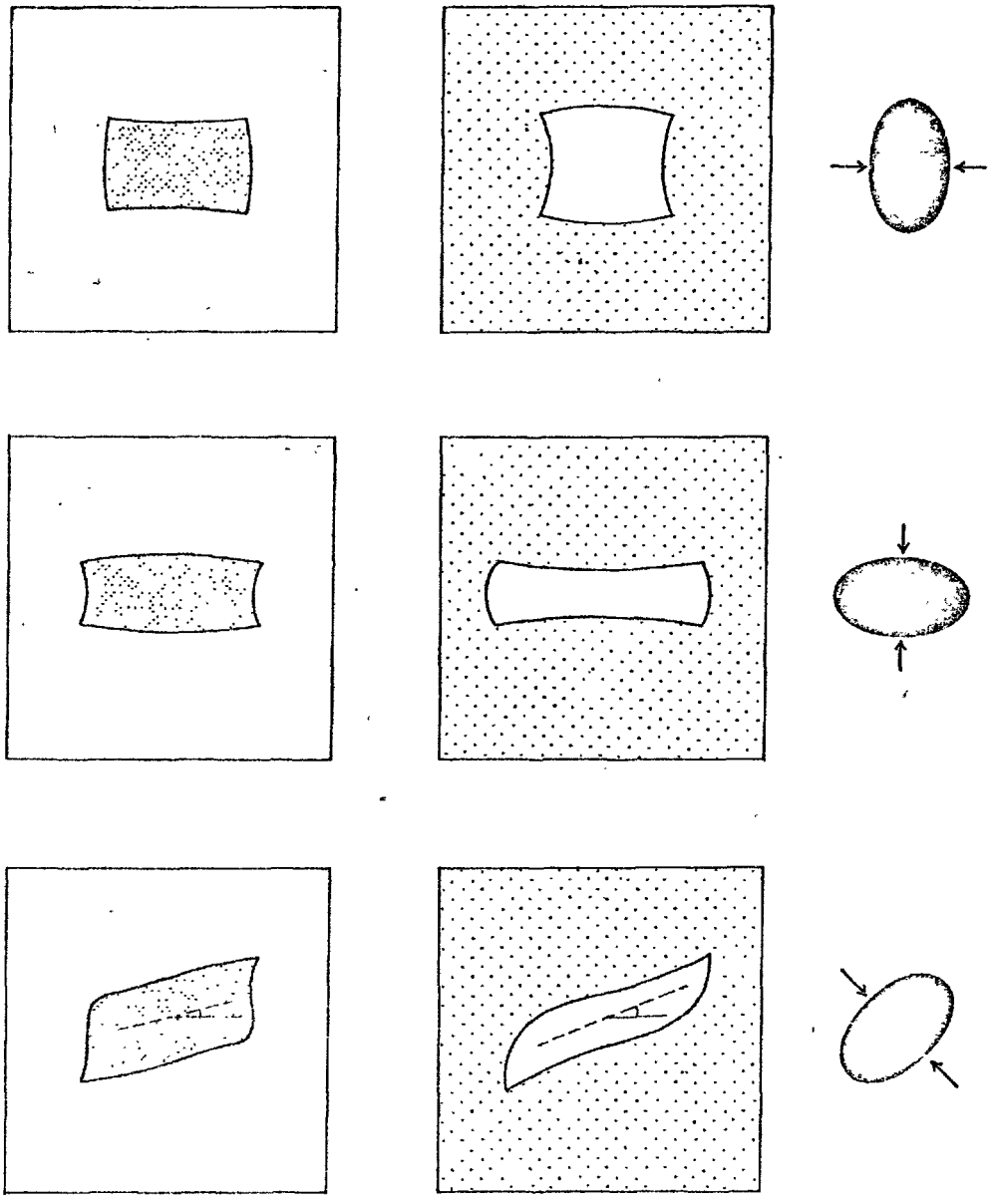


- Before deformation

—Relative Competence of the Body—

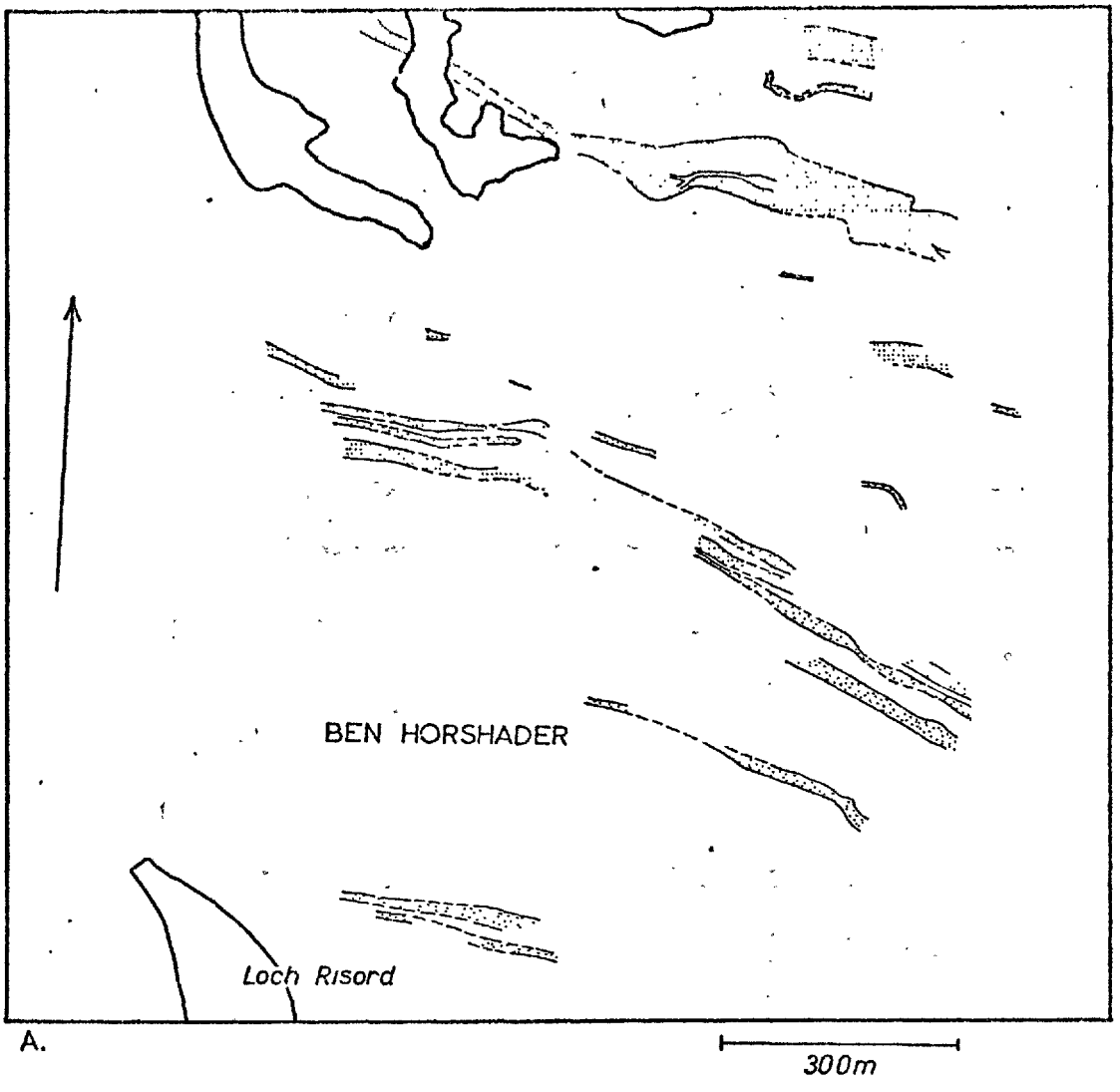
Competent

Incompetent



— Orientation of the Strain Axes —

FIGURE 71



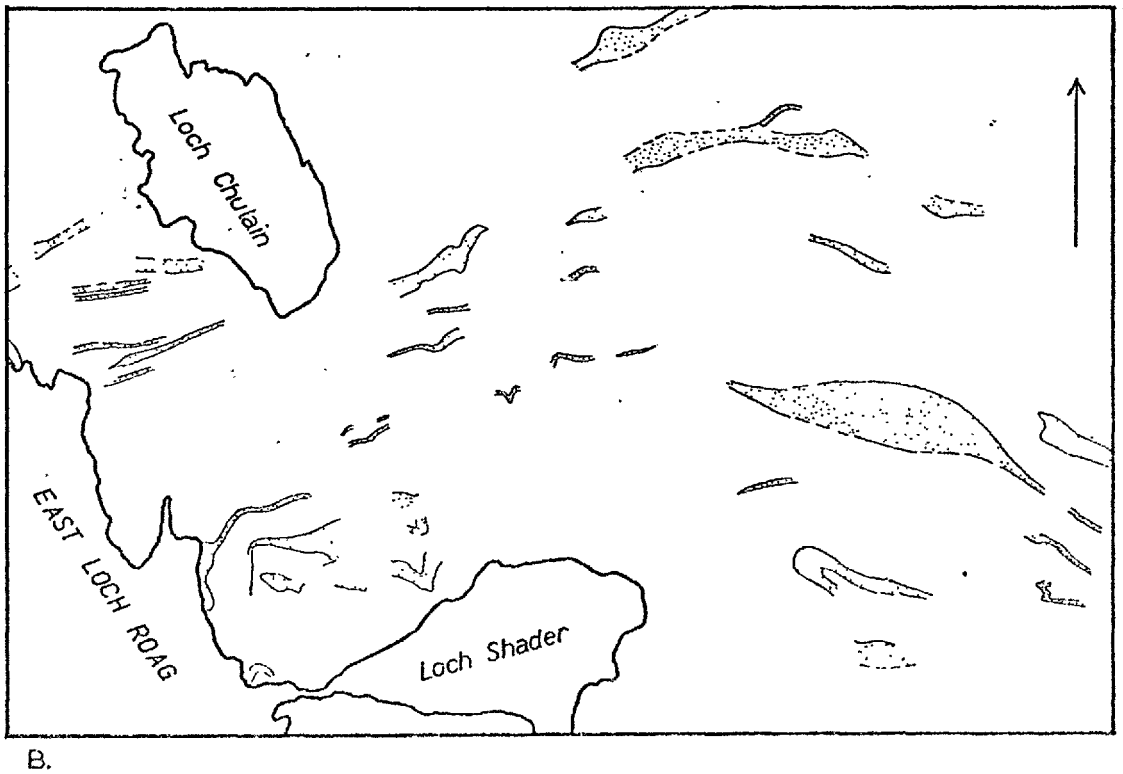


FIGURE 72

AREAS SHOWING CONTRASTING AMOUNTS OF CONTINUITY OF SCOURIE DYKES.

A. Area around Ben Horshader (245433) with fairly continuous and parallel-walled dykes.

B. Area around Loch Shader (187389) with strongly boudinaged dykes.

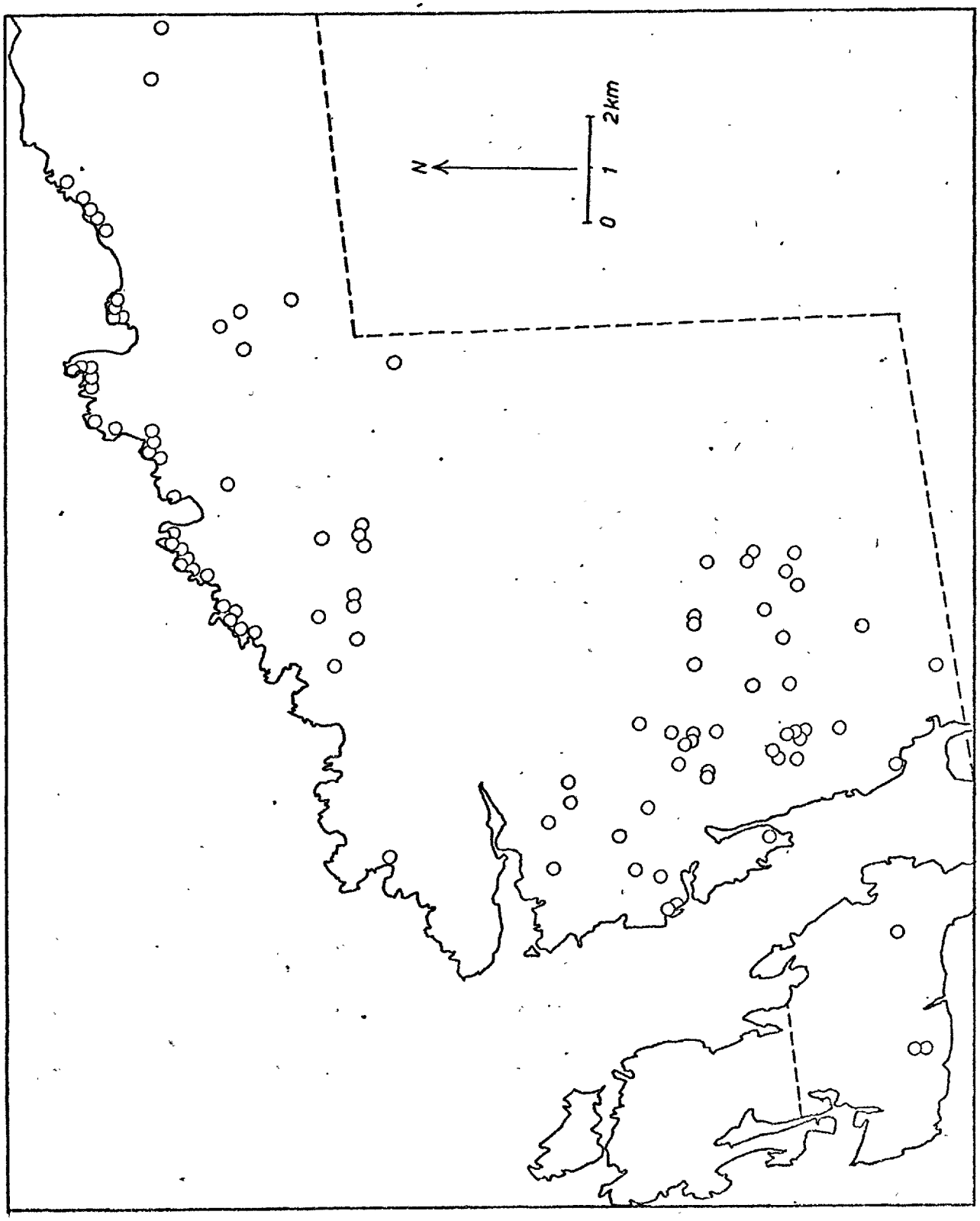
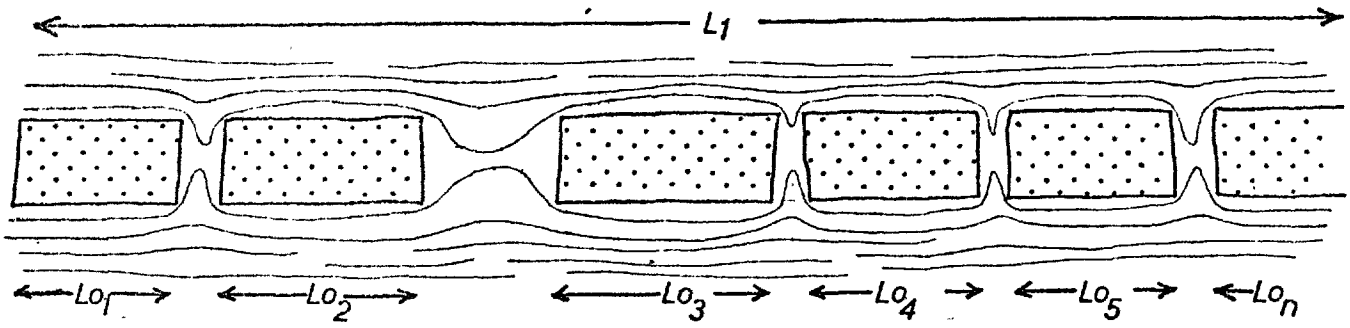


FIGURE 73

DISTRIBUTION OF BOUDINAGE AND PINCH-AND-SWELL STRUCTURE IN SCOURIE DYKES.

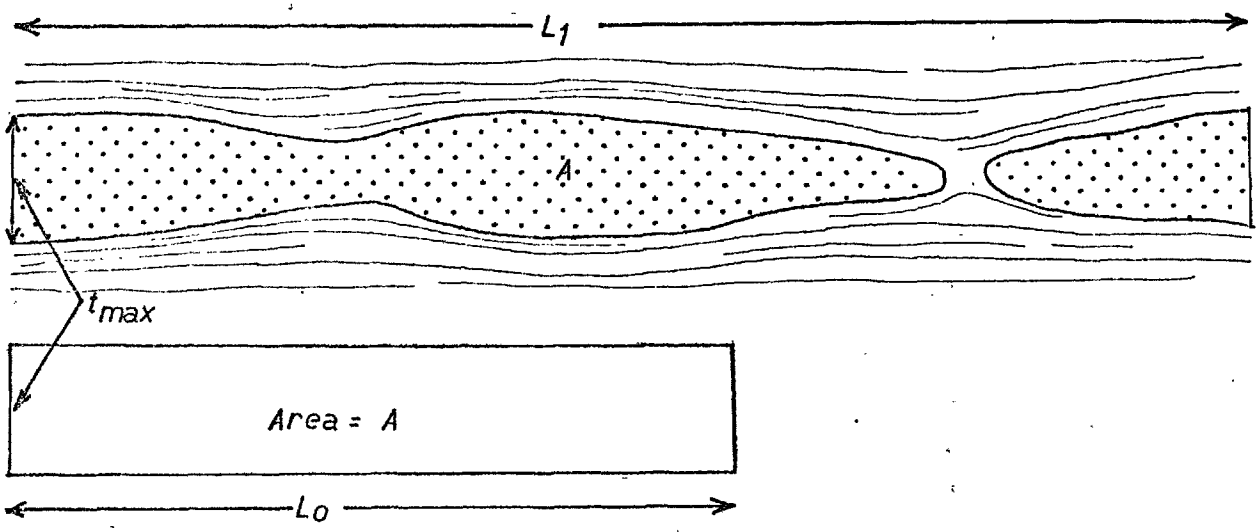
FIGURE 74

A. THE 'BELEMNITE' METHOD OF STRAIN DETERMINATION USING BOUDINS



$$1+e = \frac{L_1}{\sum_{0}^{n} Lo}$$

B. THE 'AREA' METHOD



$$L_o = \frac{A}{t_{max}} \quad 1+e = \frac{L_1}{L_o}$$

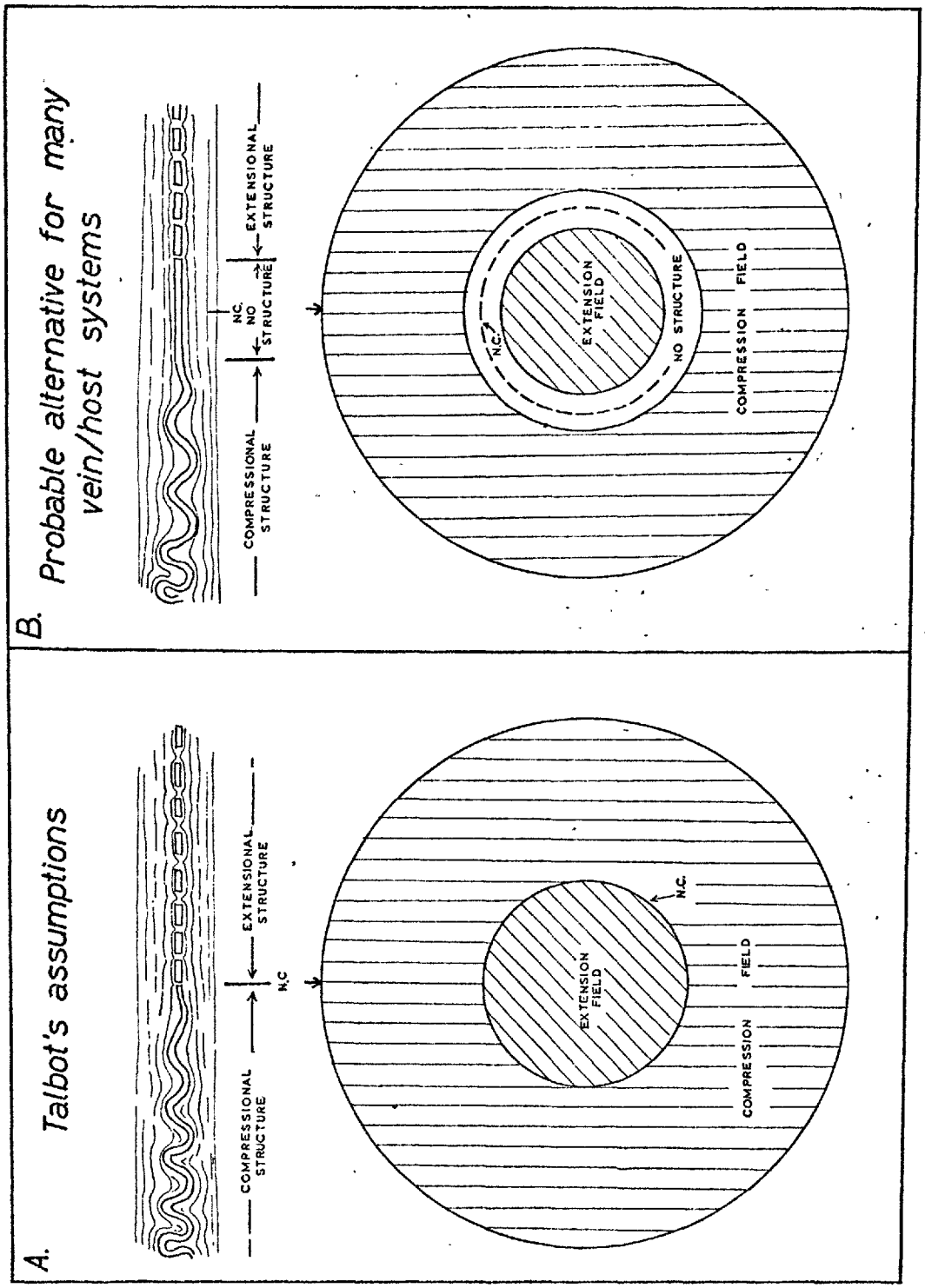


FIGURE 75

DEFINING FIELDS OF EXTENSION, COMPRESSION AND "NO STRUCTURE" IN THE FINITE STRAIN ELLIPSOID.

NC = surface of no change in length.

RESULTS OF "AREA METHOD" OF STRAIN ANALYSIS

a) Pinch-and-swell (opposite)

Present area = 12594 sq.m.m.

Maximum thickness = 66 mm

If max thickness = original thickness,

$\therefore$ original length (ℓ_o) = $\frac{12594}{66}$ = 190.8 mm

Present length (ℓ_1) = 275.0

$1 + e_1 = \frac{\ell_1}{\ell_o} = 1.4411$ If no area change

$R_s = (1 + e_1)^2$

$\therefore$ $R_s = 2.077$

b) Boudinage of Scourie Dykes - South Shawbost (opposite)

Present area = 2208 sq.m.m.

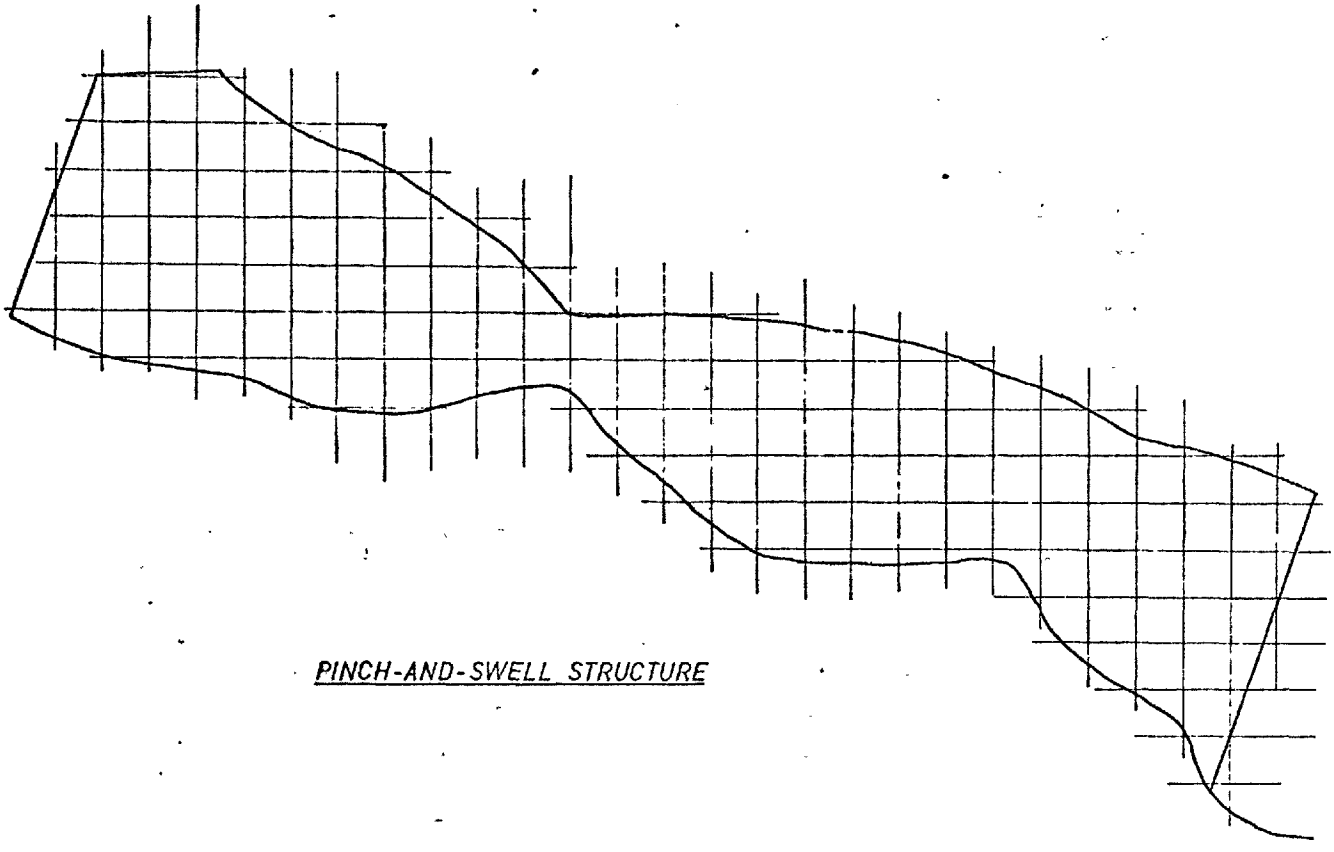
Maximum thickness = 13 mm

original length (ℓ_o) = $\frac{2208}{13}$ = 169.8 mm

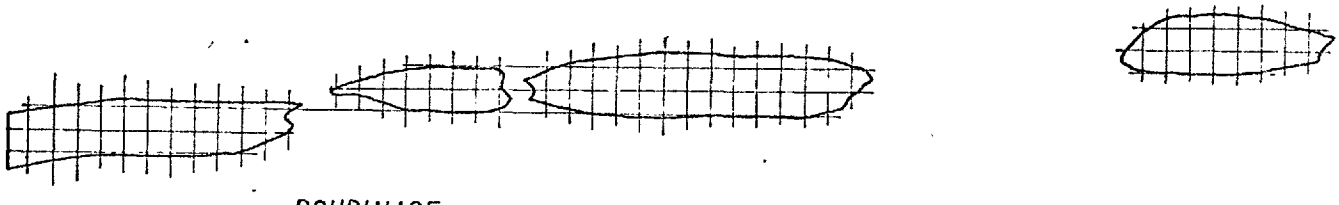
Present length (ℓ_1) = 280.0 mm

$1 + e_1 = \frac{\ell_1}{\ell_o} = \frac{280.0}{169.8}$ = 1.65

$R_s = (1.65)^2 = 2.7225$



PINCH-AND-SWELL STRUCTURE



BOUDINAGE

FIGURE 76

APPLICATION OF THE "AREA METHOD" OF STRAIN ANALYSIS TO EXTENSIONAL STRUCTURES.

FIGURE 77

Neighbouring boudins which were rotated before a homogeneous strain was imposed.

ta = 14.3 tb = 35.5

$\theta a = 76^{o}$ $\theta b = 11^{o}$

$$\frac{\lambda_a}{\lambda_b} = \frac{\lambda'_b}{\lambda'_a} = \left(\frac{ta}{tb}\right)^2 = \left(\frac{35.5}{14.3}\right)^2 = 6.163$$

Mohr Circle Solution

An arbitrary circle was drawn on the ' axis of the graph. The graph has no origin yet.

Lines were then drawn at angle $2\theta a$ and $2\theta b$ from the λ' axis.

Values of $\lambda'b$ and $\lambda'a$ are now marked on λ' axis.

But we know that $\frac{\lambda'_b}{\lambda'_a} = 6.163$,

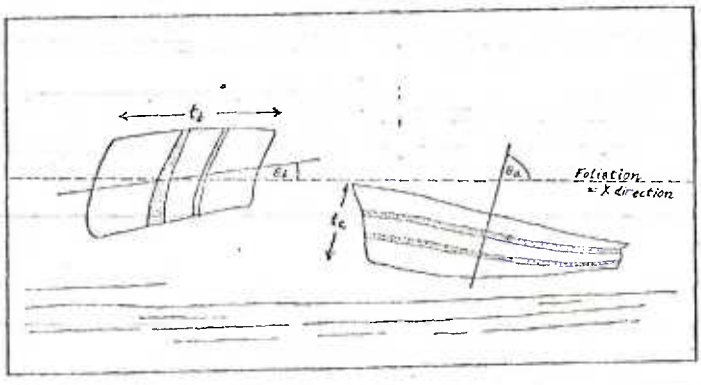
therefore we can locate the origin (and γ' axis).

When we have the origin, we can measure ratio.

$$\frac{\lambda_2'}{\lambda_1'} = 8.281$$

$$R = \frac{1 + e_1}{1 + e_2} = \sqrt{\frac{\lambda_2'}{\lambda_1'}} = \underline{2.877}$$




t_a
ε_L
t_c
θ_a
Foliation
= X direction

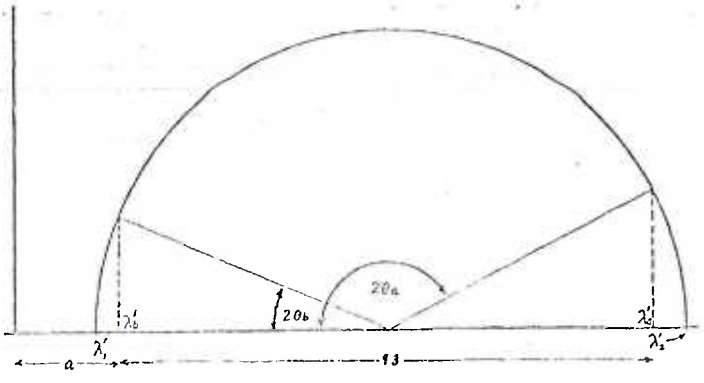

$2\theta_a$
$2\theta_b$
λ_b'
λ_3'
λ_1'
λ_2'
a
13



FIGURE 78

ASYMMETRICAL BOUDINAGE

North of Fivig, N. Shawbost

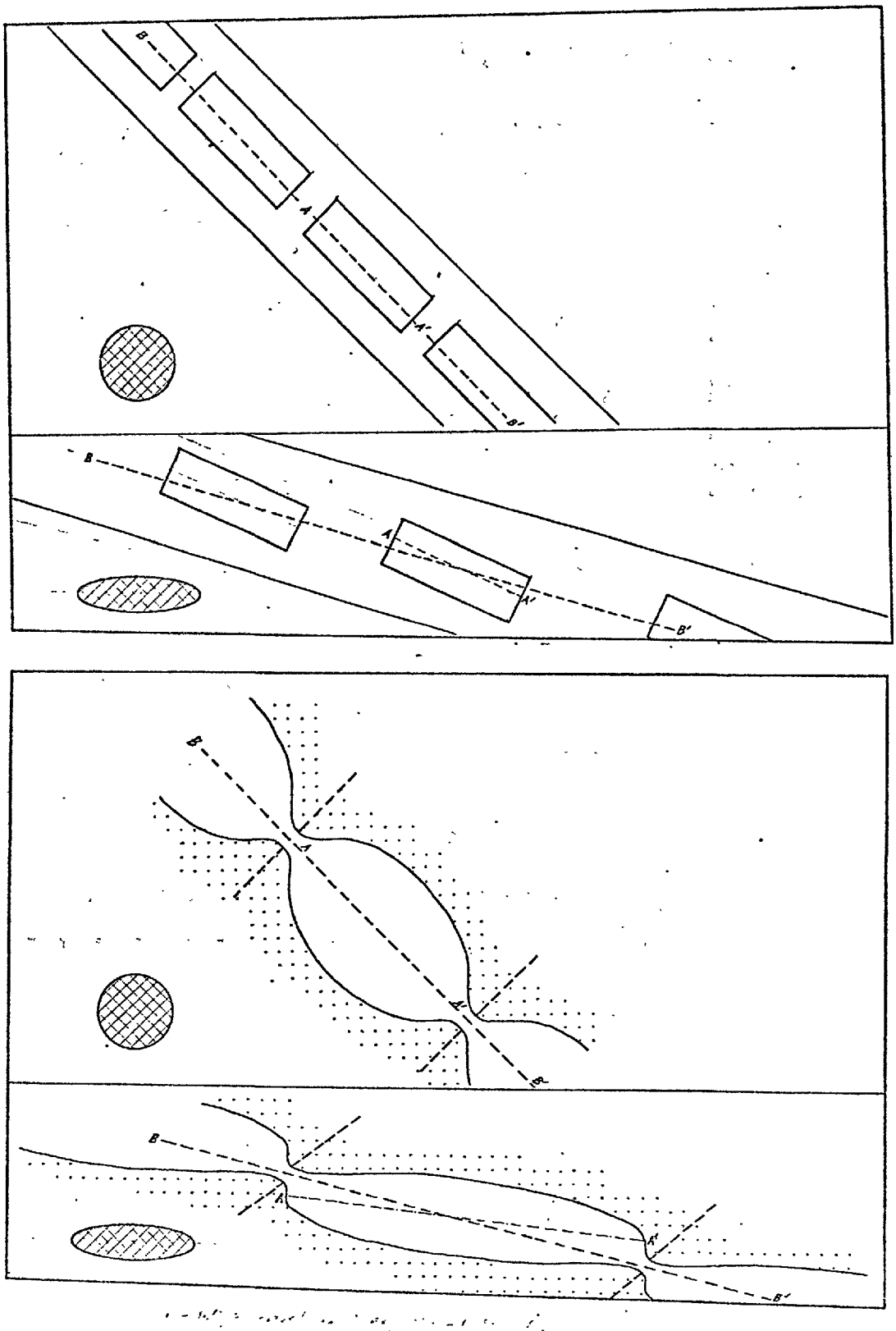


FIGURE 79

THE PRODUCTION OF ASYMMETRICAL BOUDINAGE (A) and PINCH-AND-SWELL STRUCTURE (B) by the oblique flattening of symmetrical extensional structures.

B - B' = envelope of the set of structures.

A - A' = long axis of individual sections.

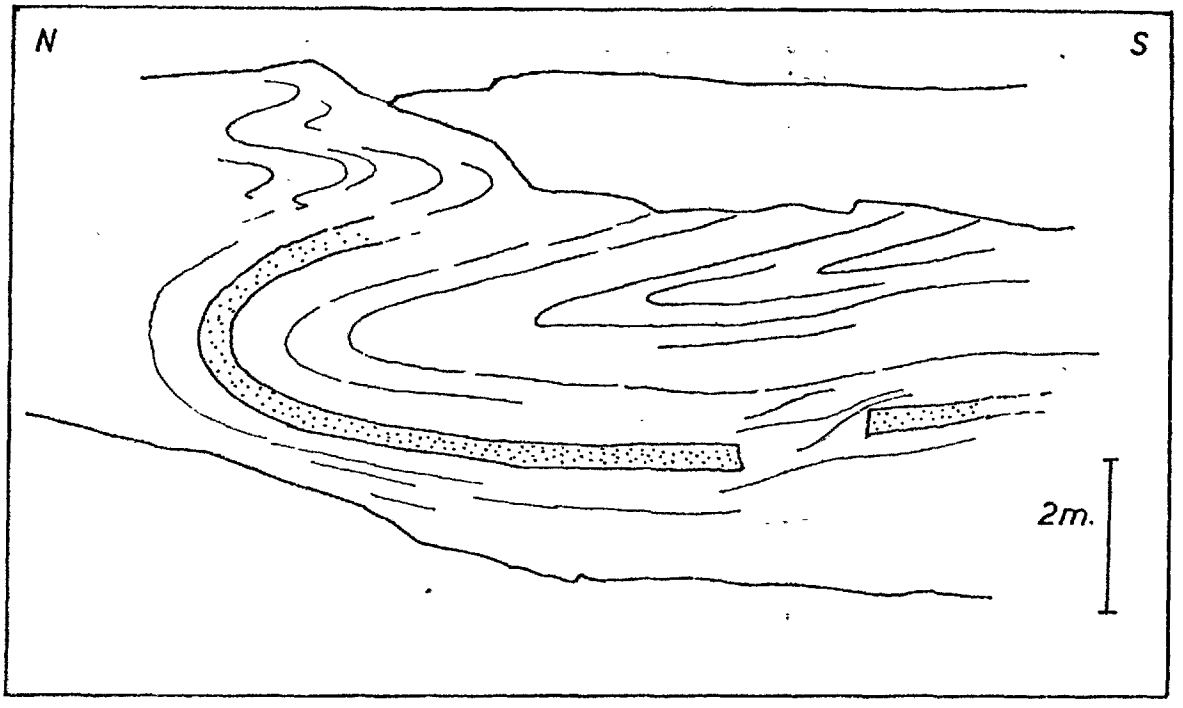


FIGURE 80

AN EXAMPLE OF AN F2 FOLD WITH BOUDINAGED LIMBS.

Roadside opposite the hotel at Duone Carloway.

Stipple - Scourie Dyke.

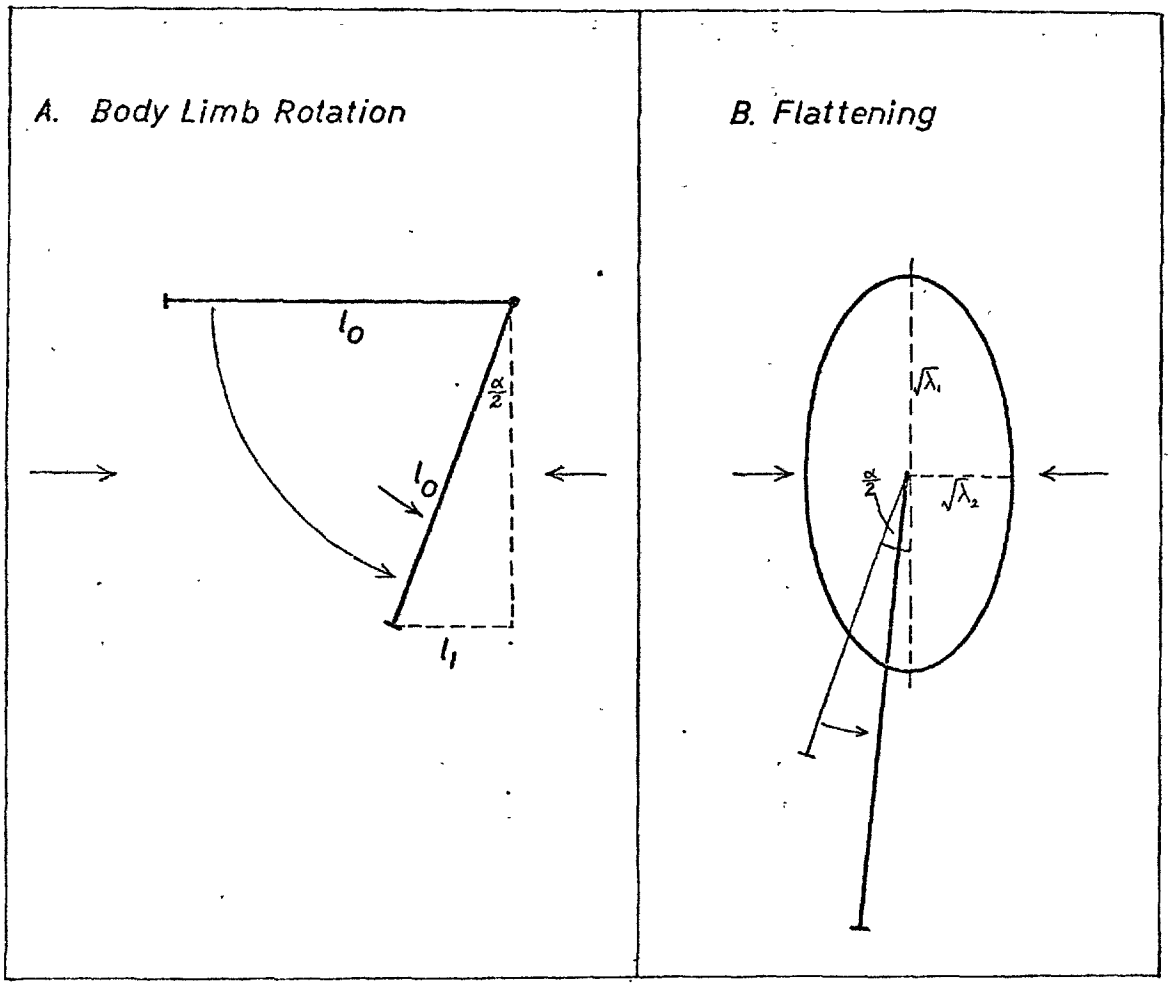


FIGURE 81

MECHANISMS OF LIMB ROTATION

See text for explanation.

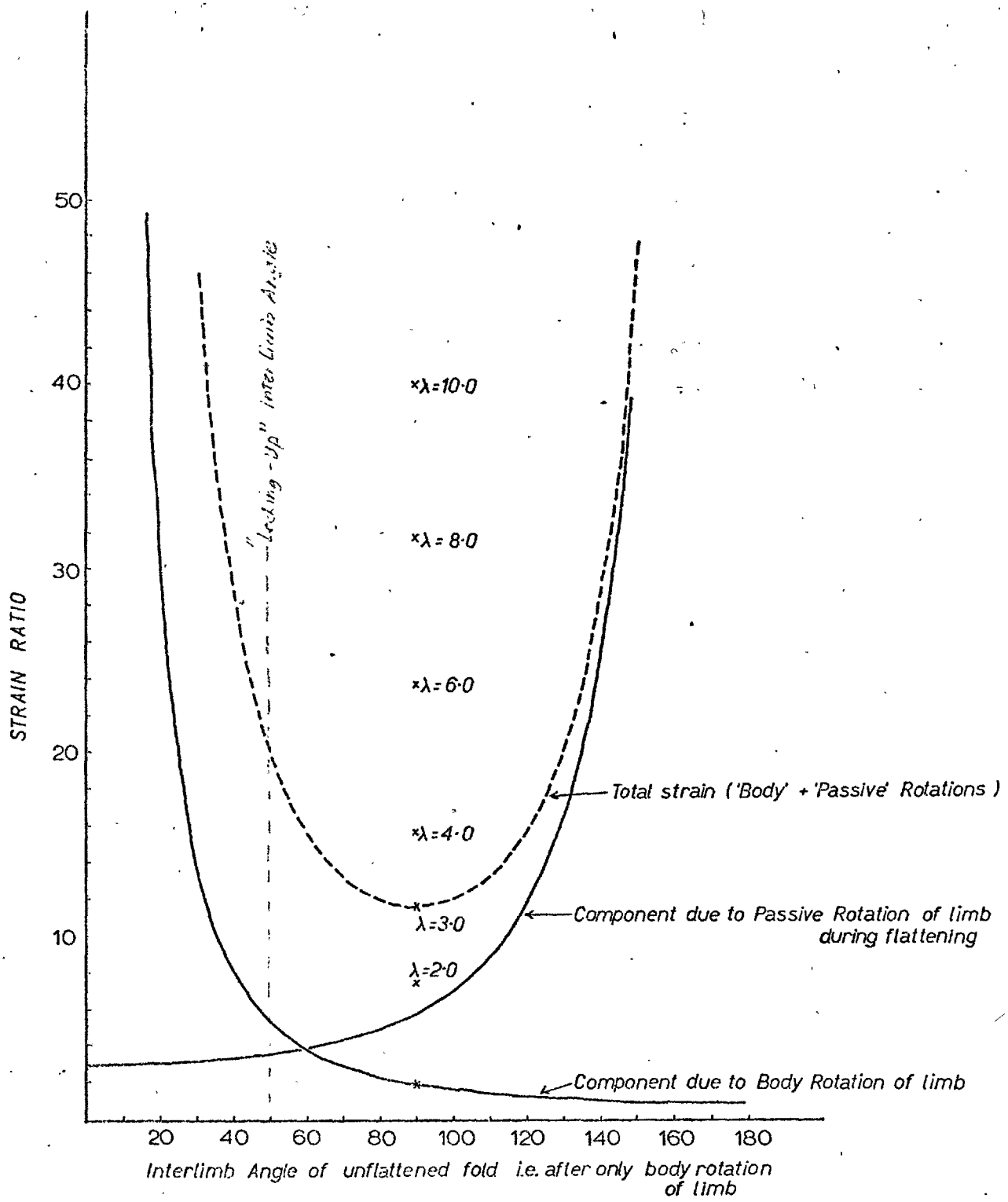


FIGURE 82

STRAIN IN FOLDS WITH BOUDINAGED LIMBS.

λ = quadratic elongation shown by boudinage.

Crosses represent the minimum total strain in folds with boudinage of a particular quadratic elongation (λ).

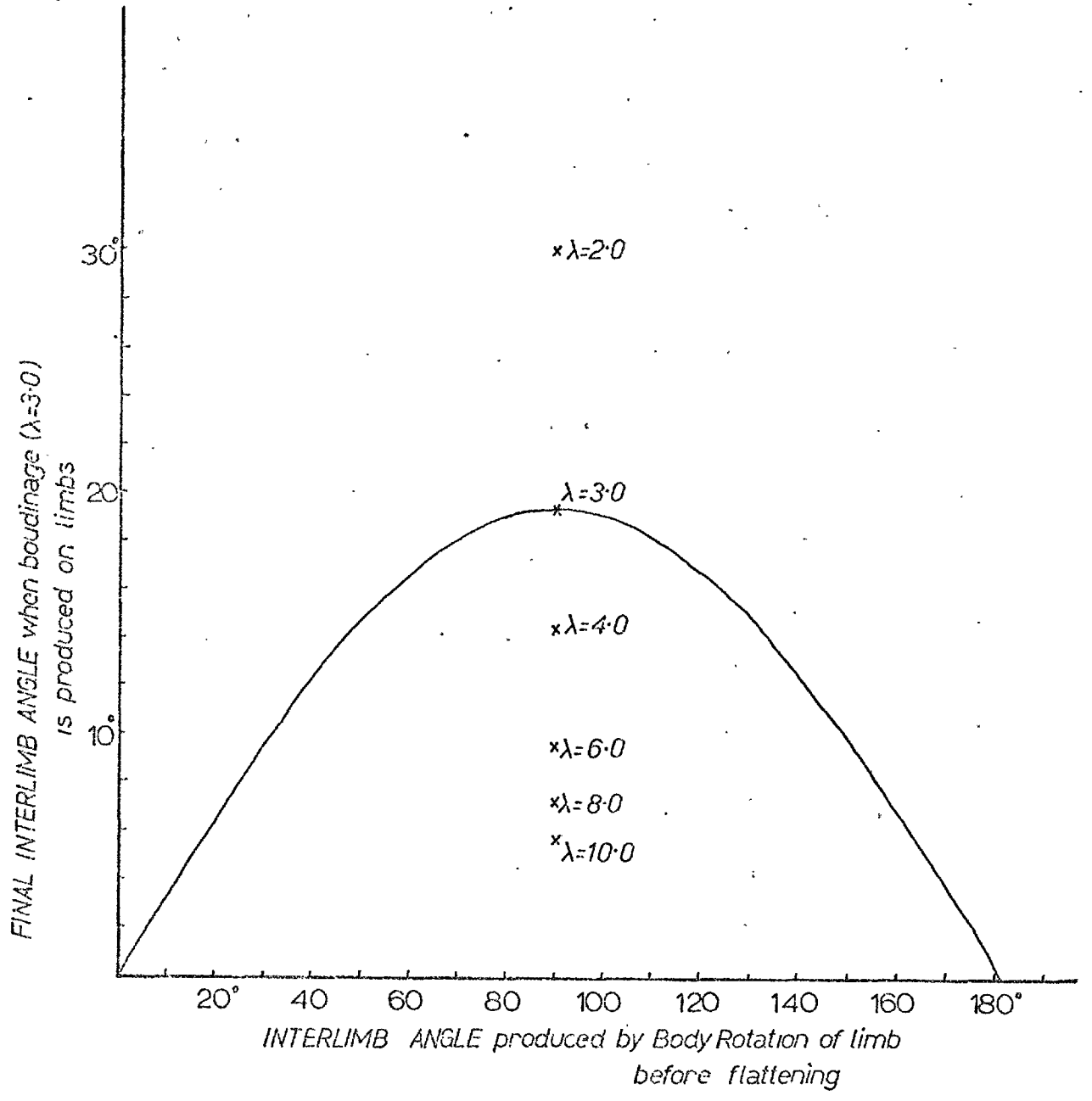

FINAL INTERLIMB ANGLE when boudinage (λ=3·0) is produced on limbs
30°
20°
10°
×λ=2·0
λ=3·0
×λ=4·0
×λ=6·0
×λ=8·0
×λ=10·0
20°
40
60
80
100
120
140
160
180°
INTERLIMB ANGLE produced by Body Rotation of limb before flattening

FIGURE 83

CHAPTER 7 - DISCORDANCE

1. INTRODUCTION

The angular relationship of a suite of basic dykes (the Scourie Dykes) to the banding in the gneisses which they cut has provided an important criterion for the chronological division of events in the Lewisian. Supposed representatives of the Scourie Dyke suite occurring in this area vary in thickness, the largest being hundreds of metres in thickness. Abundant thin dykes (0 - 3 metres) which occur throughout the area provide ample data for the study of gneiss/dyke angular relationships. Other sheet-like bodies (e.g. granites, pegmatites) provide additional information.

The inclination of a dyke to an s-surface can be described by the ANGLE OF DISCORDANCE (AD), the angle between the dyke and s-surface measured in the plane perpendicular to their line of intersection. The acute angle on that plane (or the dihedral angle) is usually referred to as the angle of discordance. The angle between the dyke and an s-surface measured on any general outcropping plane is defined as the APPARENT ANGLE OF DISCORDANCE (AAD). Fig. 85 shows the variability of AAD on different outcropping surfaces. The diagram refers to an example when AD = 60° and the line of intersection is E-W horizontal. Values of AAD refer to the pole of an outcropping surface. In general, there is no restriction on the range of values of AAD regardless of the value of AD. AAD = AD only for very restricted outcrop orientations. This emphasizes the need for careful observation when assessing the amount of the angle of discordance (AD).

Variations of the angle of discordance of Scourie Dykes have been observed throughout the area. Although at least part of this

variation must be due to variation in the original dyke orientation relative to s-surfaces, a contribution to the variation is probably made by deformation.

The aim of this section is to look at the possible ways the modification of original discordances can be brought about and to look at the geometry of the structures produced during modification with reference to North West Lewis. The observed modifications of discordances are then used to infer the nature of the Laxfordian deformation in the area.

2. THE MODIFICATION OF ANGULAR DISCORDANCE

During the process of irrotational homogeneous strain, planes which are inclined to the principal planes of the strain ellipsoid will undergo rotation. However the rate of change of orientation is a function of the actual orientation of the plane so two inclined planes will show an inclination which changes continuously during the deformation.

Consequently deformation has been invoked to account for dyke/gneissic banding angular modifications. Sutton and Watson (1962) likened the rotation of dykes and the gneissic banding in the Loch Laxford area of the mainland to the closing of a garden trellis. In detail, the "garden trellis mechanism", although illustrating certain aspects of rotation during deformation is not a realistic analogue to the geometry of the strain because both sets of "crosspieces" (the dykes) show considerable thinning as a result of deformation.

Hopgood (1966) considered the tectonic reorientation of dykes in Barra and concluded that the attitudes of the Lewisian dykes relative to the banding are parallel to those occupied at the time of intrusion. His conclusions, however, are based on theoretical consideration of a specific strain mechanism viz simple shear with the shear (ab) plane parallel to the gneissic banding.

The modification of inclined surfaces (e.g. dykes, banding or other surfaces) by heterogeneous strain will generally give rise to variable angles of discordance. The states of discordance will depend on the type of structure which gives rise to a state of heterogeneous state of strain and on the nature and position of the mutually inclined s-surface systems. A classification of the types of discordances based on these factors is shown in Fig. 86. Most of the types shown have received little or no attention but Ramsay (1961,1967) has considered the geometry of discordances which belong in groups A(I) and A(II). The mechanics of the deformation of discordant systems are largely unknown. This is especially true where both of the inclined systems possess significant physical anisotropy and the total anisotropy therefore possesses low symmetry.

3. THE GEOMETRY OF DISCORDANT STRUCTURES

A. The axes of discordant structures. Only when the fold axis is parallel to the line of intersection of two inclined layers can it be expected that both layers will have parallel axes of folding. Also the axes of boudins formed in discordant layers will usually deviate from the regional trend. Coward (1973, Fig. 11) noted that a discordant dyke and the surrounding banding from Ardivachar, South Uist are folded about different axes. This same phenomenon has been observed in North West Lewis where the F2 axes of folded Scourie Dykes deviate from the F2 axes in the folded gneiss.

A folded discordance is generally a structure of low total symmetry and usually possesses no true profile. This is to be borne in mind when calculating and comparing the arrangement of two dimensional discordance about folds.

Because the geometry of discordant structures is usually complex,

interpretation based on two-dimensional exposures should be made with caution. Apparent amplitude differences of discordant layers (as seen in Fig. 87 and Ramsay (1967) Fig. 7.2) can be accounted for in one of three ways. Firstly, the discordant layer could be folded co-axially so that the discordant folds have different real amplitudes. This interpretation was favoured by Myers (1971) for discordant zones of abundant Scourie Dyke fragments in Western Harris. An alternative explanation may be that the real amplitudes are the same and the layers are folded non-coaxially. Finally there is the possibility that both amplitudes and the axes of the inclined layers are different. Interpretation of the time relation of folding and the formation of discordant layers (e.g. the intrusion of pegmatites) should involve these considerations.

B. Intrusion irregularities. Straight lines remain straight when subjected to homogeneous strain. Unmodified basic dyke contacts usually possess a high degree of rectilinearity and irregularities tend to be angular in shape. Discordant Scourie Dykes in the areas of low Laxfordian deformation show angular contact irregularities (Fig. 88 With an increase in the Laxfordian deformation these irregularities are more smoothed out in appearance with curved contacts more common than planar ones. In areas of high post-dyke deformation, signs of intrusion irregularities are almost completely lost. It appears then that modification of these irregularities is best accounted for by heterogeneous rather than homogeneous strain.

The heterogeneous deformation of the dyke contacts may be the result of a passive reaction to external strain heterogeneities or it may develop in response to the differential behaviour of materials of different competence, i.e. the dyke and the surrounding gneiss. Often it will be difficult to distinguish these two types of heterogeneity.

However, in some cases it is possible to match the configuration of the contact with that observed in experiments involving the deformation of materials of different competence. Fig. 89 shows a discordant dyke from Ben Bragar (236434) where it has been inferred from other evidence that the bulk strains are closely related to the axial planes of F2 folds and that the XY plane of the strain ellipsoid is more or less horizontal. The shape of the irregularities look similar to those produced experimentally by the deformation of an incompetent layer (soft plasticene surrounded by a harder plasticene matrix) with a right-angled bend in it (Fig. 89). Fabric intensities in the surrounding gneisses match closely the amounts of strain observed in the experiments (Fig. 89). It is tempting to suggest that the shape of the dyke on Ben Bragar (Fig. 89) developed in a similar way to the one in the experiment.

However structures similar in appearance can develop by different processes and generally there are too many unknowns in the field structure to specify the actual route by which a structure developed. Nevertheless experiments are useful because they give information about at least some of the possible ways in which structures could have developed.

The experiments illustrated in Fig.89 verify that curvatures develop during the deformation of contacts between materials of different competence. Apophyses and off-shoots are common in the Scourie Dykes of the Outer Hebrides (Dearnley and Dunning 1968, Coward 1973). As yet no criterion has been devised to distinguish off-shoots from cusps produced by deformation. This point is of considerable importance because deductions about the relative competence of dykes and gneiss have been made on the basis of the recognition of cusps (e.g.

Francis 1973). Structures resembling cusps have been observed in the Dalbeg low deformation area (Fig. 90A/84A). They are developed only on parts of the dyke which are at a high angle to the finite extension direction but this may mean that these irregularities have been smoothed on the thinned lengths of the dyke. As yet no solution has been found to distinguish tectonic cusps from original off-shoots of the dyke.

C. Chronology of structures using discordance patterns. Sometimes there is evidence that curvatures in discordant bodies are due in part at least to original non-planarity of the discordant sheet. True deformational folds can sometimes be distinguished from these effects of original curvature by the arrangement of discordance. Fig. 90B shows an amphibolite cutting the banding and quartz veins figured by Myers (1968, Fig. 20, pp. 81). Myers interpreted the amphibolite as an isoclinal fold. However the pattern of discordance is incompatible with such an explanation. The amphibolite was probably originally bifurcated although some deformational modification may have taken place.

Sometimes the pattern of discordance (Fig. 90C) reveals that the banding cut by the discordant sheet was non planar. In general, however, slight initial curvatures of the discordant layer and the surrounding banding will go undetected. Most methods of separating original from deformational effects are hampered by the possibility that the discordant layer was initially not of uniform thickness. One such method is the use of dip isogons to calculate the amount of homogeneous flattening.

D. The nature of the discordance. Locational elements and shape-fabrics show a different geometrical response to deformation (Chapter 4). Ramsay (1961, 67) has calculated theoretical patterns of discordance about folds assuming that both discordant surfaces have the properties of locational elements. If, however, one (or more) of the discordant

elements is a shape fabric different patterns of discordance will arise. This is relevant to some areas of low Laxfordian deformation where Scourie Dykes cut a banding which has more of the character of a shape-fabric than of a locational element.

E. The variability of the angle of discordance. Fig.91,92 shows examples of discordance variation about folds. As a rule, maximum discordance is visible in the vicinity of the fold hinge. Coward (1973) has made predictions about the mechanisms of folding using the variation of the dihedral angle between the gnessic banding and the dyke contact. The pattern of discordances is produced by the strains within the gneisses at the function of the folded dyke. Therefore, it is only permissible to suggest a mechanism for the folding of the gneiss which was probably different than that operating in the dyke.

Ramsay (1961, 1967) has analysed the folding of some types of discordant structure (see Fig. 86). Structures other than folds, possessing heterogeneous states of strain will, in general, also give rise to variable angular discordance. Examples are pinch-and-swell structure and cusp structures. Some basic dykes were not orientated favourably for the development of folds but instead gave rise to pinch-and-swell in response to D2 deformation. Fig.93A shows one such dyke from the Dalbeg area. The observed discordances are compared with the prediction of discordance based on a simple pinch-and-swell model in Fig. 94 . Another pattern (Fig. 93B) however, does not fit this model. It may be by the careful study of discordance about pinch-and-swell that we can analyse the mechanisms of formation of this type of extensional structure.

4. DISCORDANCE AS A STRAIN INDICATOR

Probably the most successful method for comparing regional variations of the amount of Laxfordian deformation has been based on the

discordant relationships of Scourie Dykes and the gneiss into which they were intruded (e.g. Sutton and Watson, 1951). Discordance of Scourie Dykes have been utilized for two different methods of regional strain analysis. One of these methods yields information about the 'k' value as well as the 'm' value (the amount) of the Laxfordian strain.

A. The Maximum Degree of Discordance Method. During the field mapping, the maximum degree of discordance in any particular area was recorded. A map (Fig. 95) was produced showing the variation of discordance. Areas where highly discordant dykes are preserved are taken to represent areas of low finite Laxfordian deformation and areas of 'concordant' dykes are equated with areas of high finite Laxfordian deformation.

This method is not ideal for several reasons. The value of the actual maximum angle of discordance will depend on initial angles of discordance as well as on the strain amount. Furthermore, the observed maximum angle of discordance may not be the actual maximum angle of discordance. This is a sampling problem.

In spite of these downfalls, the method gives results which correlate well with those derived from other sources, for example fabric changes in the gneisses. The degree of discordance was classified as "strongly", "moderately", "slightly" discordant or "concordant" (though actual angles of discordance were often accurately measured). Used in this general way, the method was a valuable one to assess crudely the Laxfordian strain (Fig. 95 and 114).

B. Methods based on the modification of orientation populations of discordant dykes. If it can be assumed that the population of dykes were intruded as a suite random in orientation, comparison of sampled

dyke populations with diagrams such as those in Fig. 96 should give an estimation of k and m for the strain which brought about modification to the orientation of dykes in that particular area.

However a stereographic plot of highly discordant dykes reveals that the Scourie Dyke suite (like most other dyke swarms) had a strong original preferred orientation in an E-W direction. With this in mind another was devised which takes into account initial non-random populations. Field evidence shows that the most widespread Laxfordian episode (D2) was associated with an XY plane which was near horizontal in attitude and an X direction which was approximately SE-NW trending. Using these restrictions on the strain orientation, strains of various k values and m values (see Chapter 4 for an explanation of these parameters) were superimposed mathematically on the population of 'highly' discordant dykes. The population hence undergoes rotation. A computer program (PRØGRAM ØRIENT) has been written to perform this process. Calculated deformed populations for various strains are then compared with a field deformed population (for example, the population of 'moderately' discordant dykes), until a least squares best-fit is achieved. The superimposed strain for this best-fit is then taken as an approximation to the finite Laxfordian deformation for areas from which the field deformed population was sampled.

The populations of field and calculated orientation data are plotted and contoured for comparison (Fig. 97). The strain required to bring about the modifications of the 'highly' discordant dyke populations to match those of other degrees of discordance are shown in a Flinn diagram (Fig. 98). They are the calculated states of Laxfordian finite strain in areas of "moderately", "slightly-discordant" and "concordant" Scourie Dykes marked on Maps 75, 95 and 114.

The changes from 'highly' to 'moderately' discordant dykes involved a strain with high k values (k = 4.1) which represents an ellipsoid with a strong linear shape component. This accounts for the early loss of discordance in planes containing the X direction (horizontal in a SE direction). Further modification required deformation ellipsoids of more oblate types (k = 0.75, then k = 0.25) and this agrees well with the fact that discordances in the plane perpendicular to the X direction are the last to be lost.

From field evidence, the strong linear gneiss fabric was probably inherited, in part at least, from pre-Scourie Dyke times (Chapter 4). The results of strain analysis using discordances suggests that a contribution to this linearity was likely to have been made in the Laxfordian in areas where the most discordant dykes occur. In areas of less overall discordance, the Laxfordian deformation was more planar in nature and this agrees with the observation that the linear component of the gneiss fabrics is less strong.

This method of strain assessment cannot be an ideal one for this area of study. The assumption embodied in it is that the dyke re-orientation was due to regional bulk homogeneous deformation. This assumption is not strictly valid because it can be seen that at least some of the dyke re-orientation was caused by F2 folding. Values of the strain ratios and the variation of m values derived by this method are suprisingly low. If the dykes rotated as limbs of F2 folds, substational pre-buckle homogeneous strains may go unrecorded by dyke re-orientation.

FIGURE 84

VARIATION IN AMOUNT OF DISCORDANCE OF SCOURIE DYKES

A. Highly discordant dyke with cuspy contacts

B. Slightly discordant dyke

C. Concordant dyke







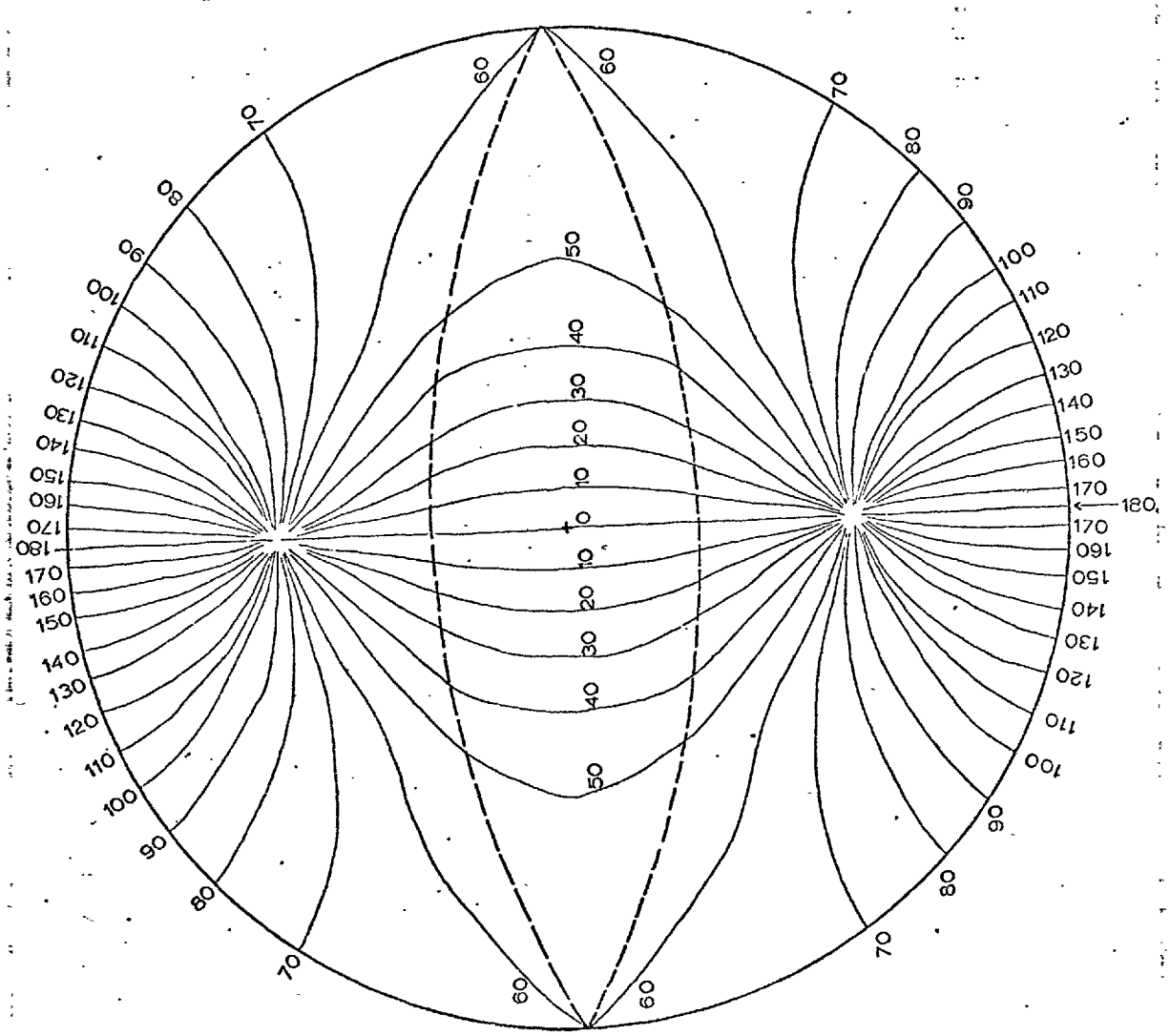


FIGURE 85

THE RELATIONSHIP BETWEEN APPARENT ANGLE OF DISCORDANCE AND OUTCROPPING PLANE ORIENTATION.

Stereographic projection. Discordant planes shown as dashed great circles. Angle of discordance = 60°. The contours shown refer to values of AAD - these values are sited at the pole of the outcropping plane.

STRUCTURES GIVING RISE TO HETEROGENEOUS STRAIN

e.g. Folds, boudins, etc.

	A	B	C
GEOMETRY OF INCLINED S - SURFACE SYSTEMS	Both systems are locational element systems	One system is composed of locational element, one is a shape fabric	Both systems are shape fabrics
PHYSICAL NATURE OF INCLINED S - SURFACE SYSTEMS	I Both systems are passive, e.g. shear folding model	One system has a physical anisotropy, one is passive	IV Both systems possess physical anisotropy. Discordance geometry complex and little known.
POSITION OF PASSIVE SYSTEM	II Passive system inside more competent layer of active system	III Passive system inside a less competent layer of active system	

FIGURE 86

DISCORDANCES AND HETEROGENEOUS STRAIN STRUCTURES

Dyke discordances in gneiss could fit into categories A (I - IV) or B (I - IV) depending on the system.

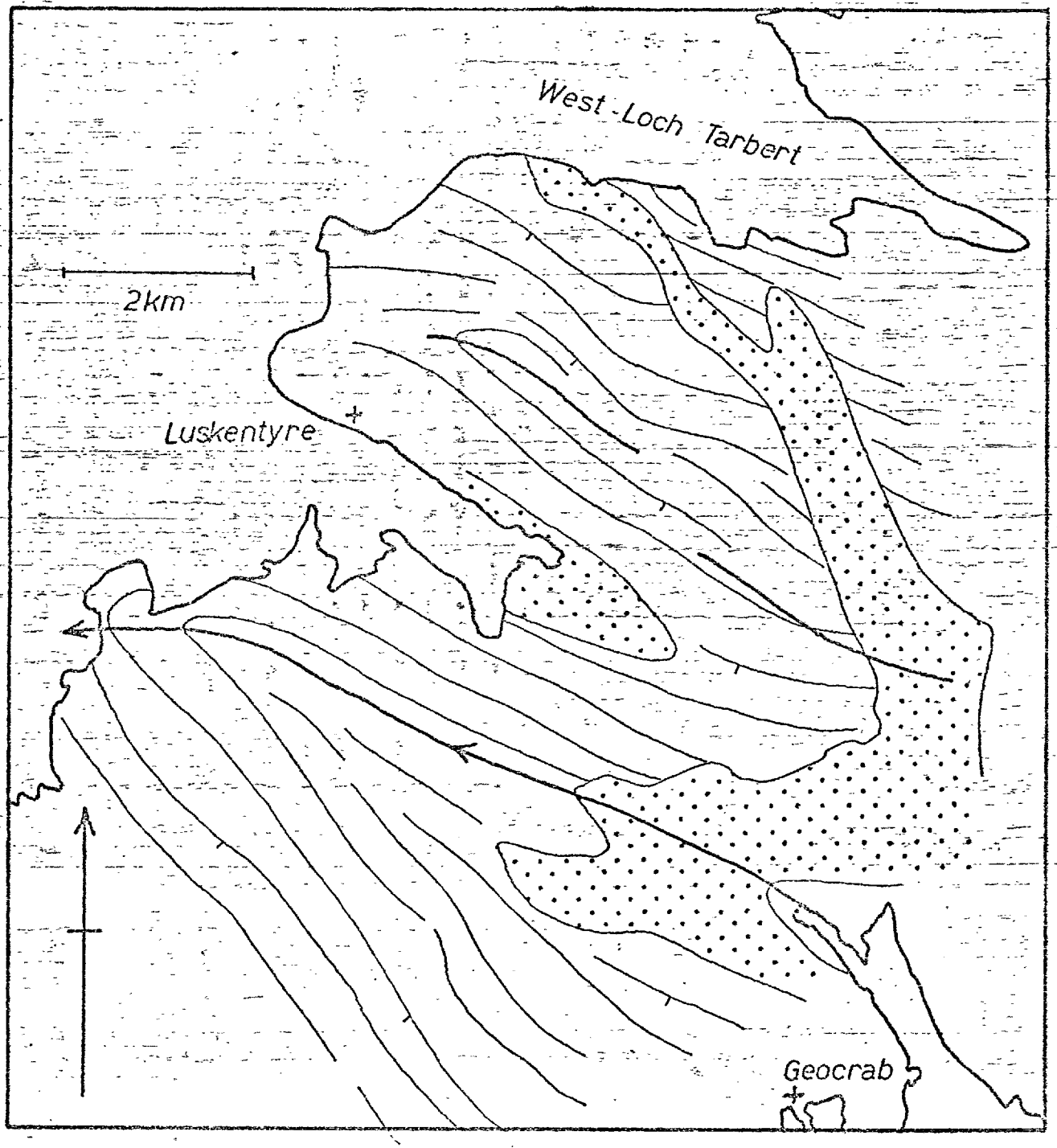


FIGURE 87

A FOLDED ZONE OF ABUNDANT SCOURIE DYKE FRAGMENTS (DOTTED) IN RELATION TO STRUCTURES IN THE GNEISSES, WESTERN HARRIS. Adapted from Myers, 1971.

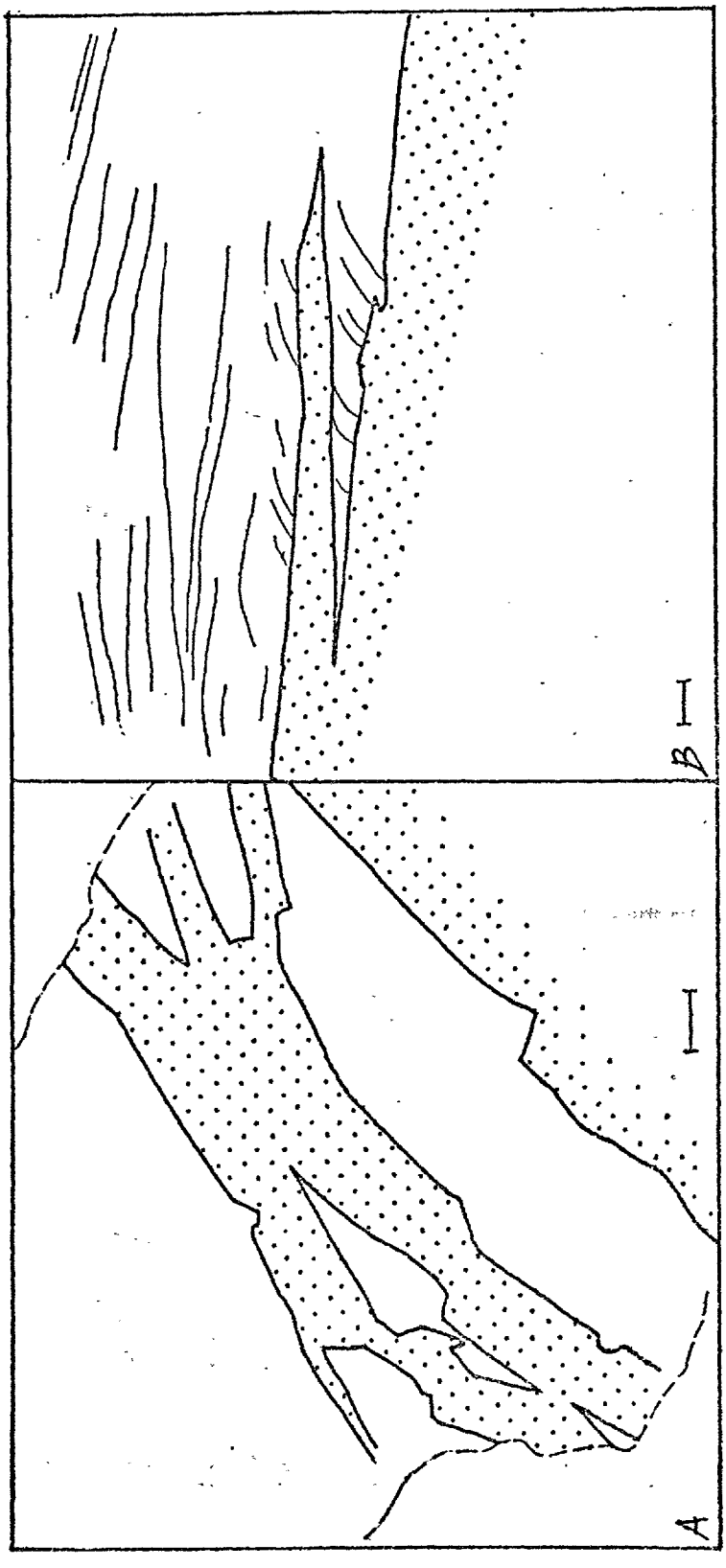


FIGURE 88

Sketches of dykes (dotted) from areas of low post-dyke deformation. These dykes show rectilinear contact irregularities. Scale = 10 cms. Banding in the gneisses is shown in B.

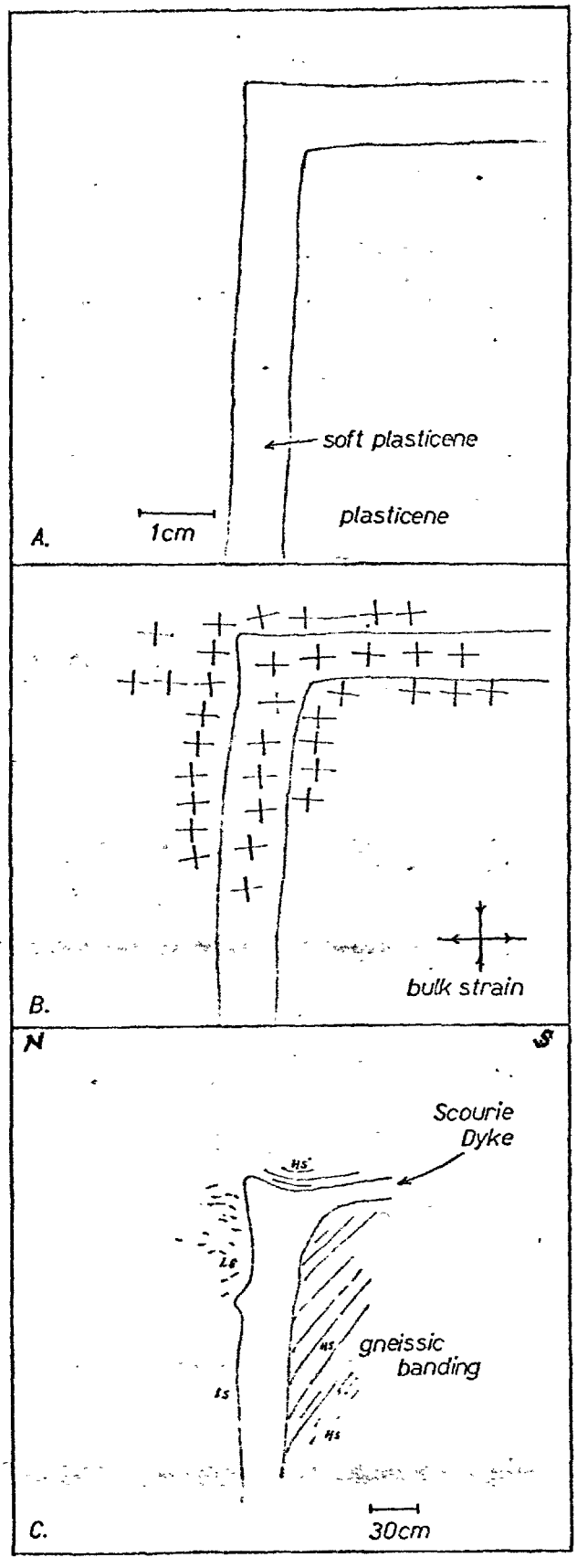
FIGURE 89

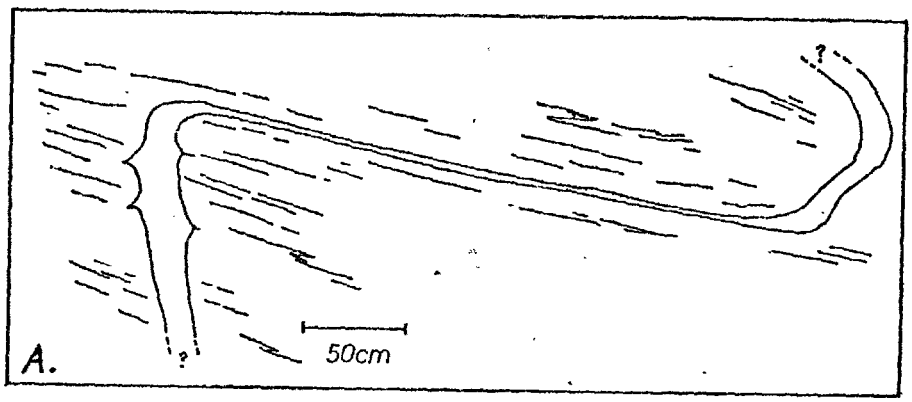
Experimental work investigating the pure shear of a right - angled junction in relatively incompetent material (dykes) in a more competent host (gneiss) and a comparison with a structure in the field.

A. The undeformed model.

B. Deformed. Crosses represent the axes of the local strain ellipses.

C. Deformed dyke from Ben Bragar. Vertical section.
LS = Low strain areas
HS = High strain areas indicated by gneiss fabric.


soft plasticene
plasticene
1cm
A.
bulk strain
B.
N
S
Scourie
Dyke
gneissic
banding
30cm
C.



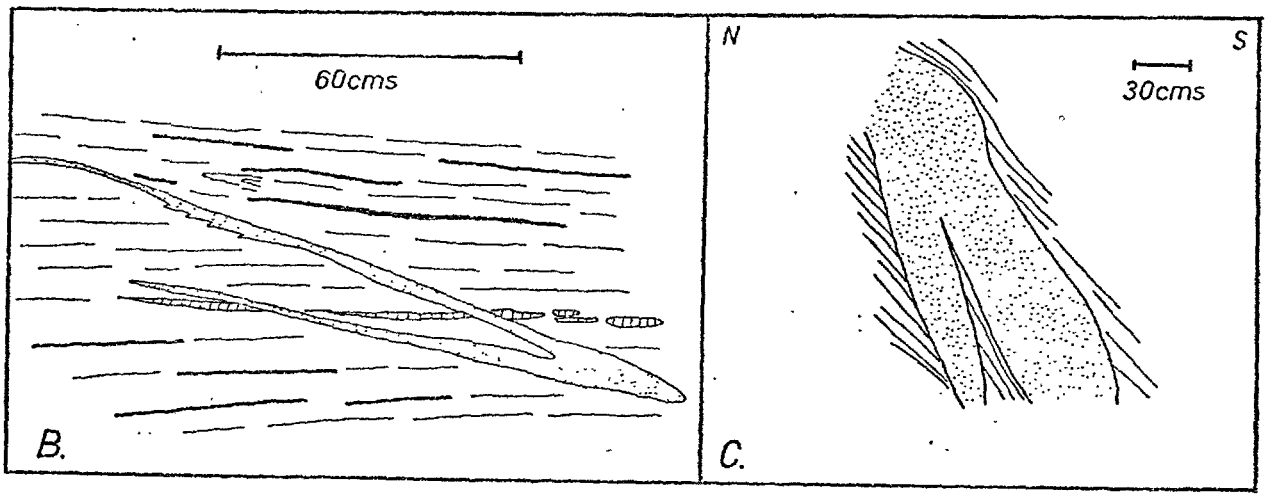


FIGURE 90

A. Cusp-shaped structures on thickened sections of a deformed dyke from the Dalbeg Low deformation area.

B. Deformed amphibolites cutting the banding of the Epidote Schist group, Langavat belt of Metasediments (S. Harris). From Myers, 1968, Fig. 20. p. 81.

C. Discordant dyke, East side of Loch an Duna, near Bragar (286470)

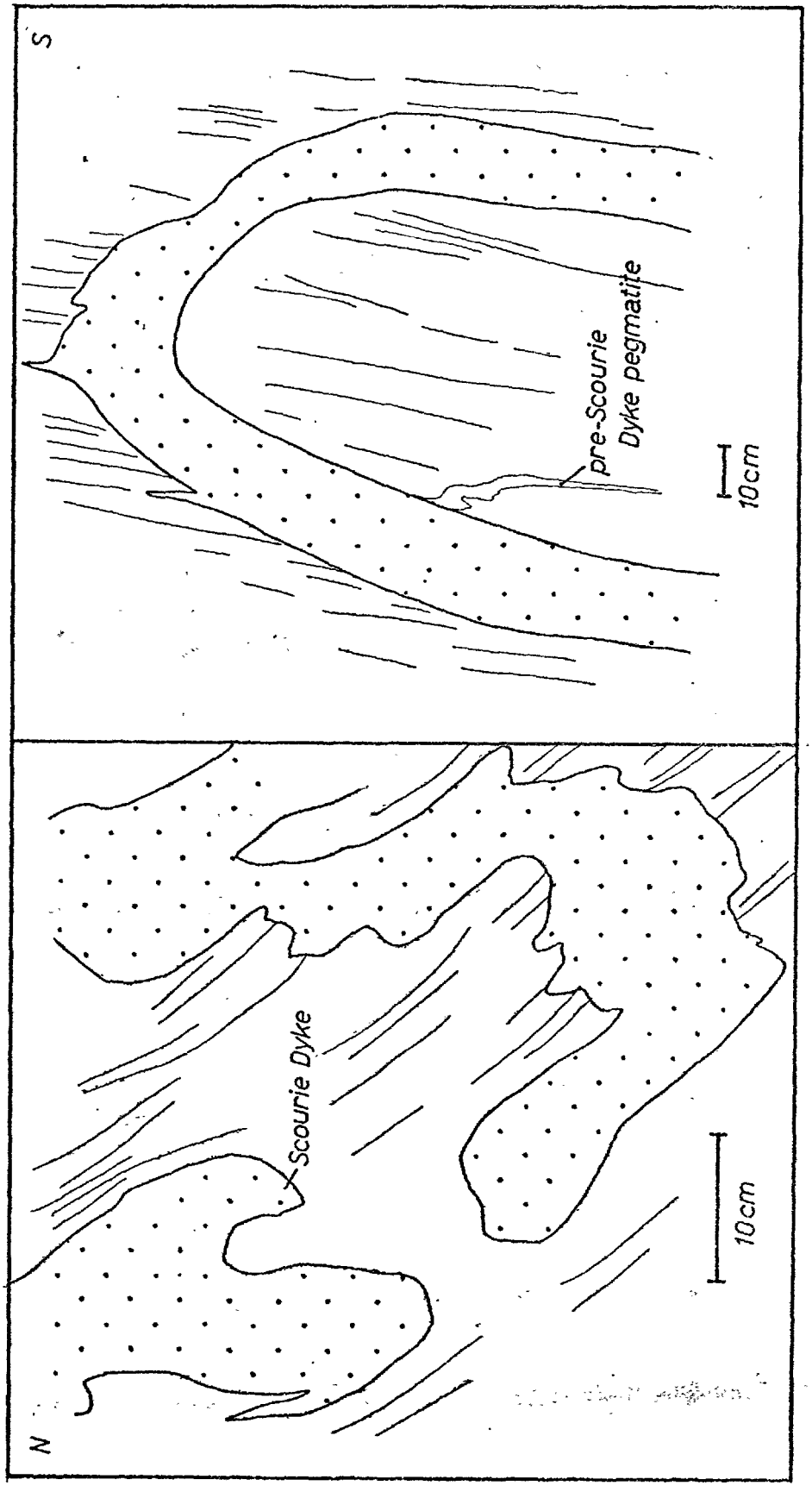


FIGURE 91 DISCORDANCE ABOUT FOLDS.

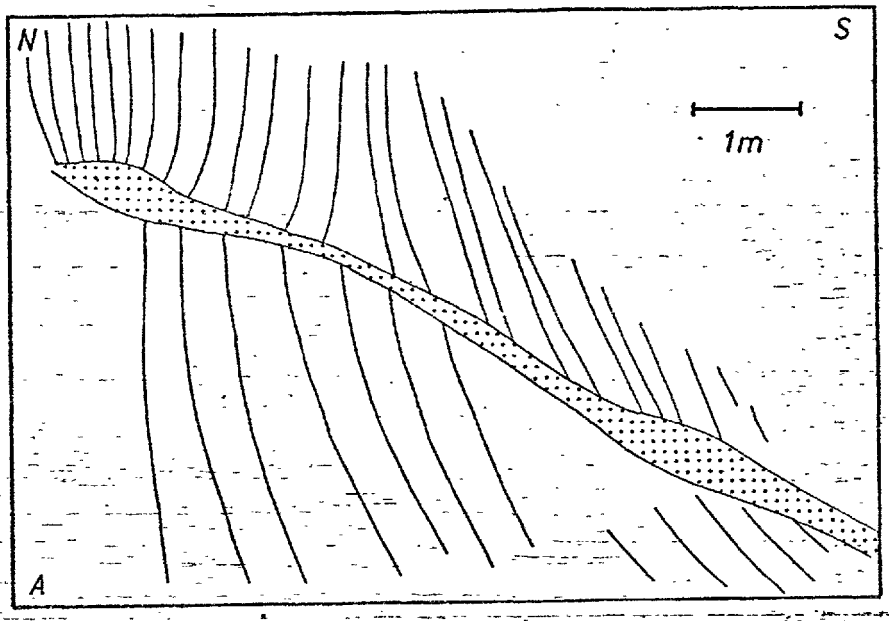
Folded dykes from the coastal outcrops at North Shawbost. Note the relationships between the folded dykes and the gneissic banding.



FIGURE

FOLDED DISCORDANCE

Cliffs east of Dalbeg Bay



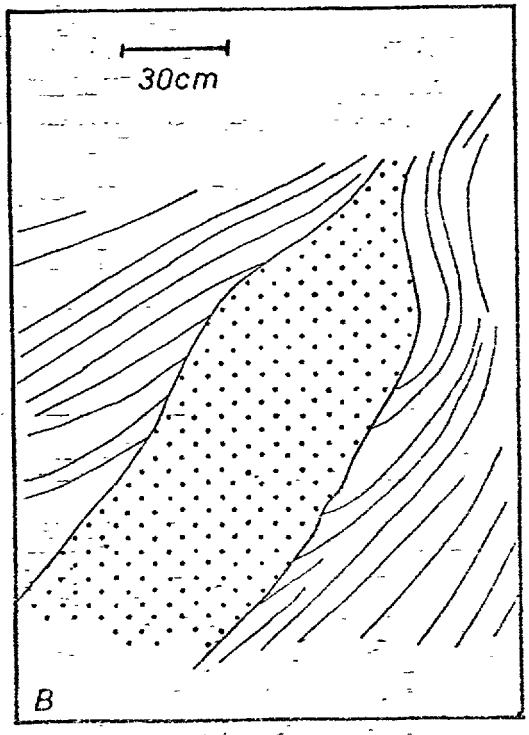


FIGURE 93

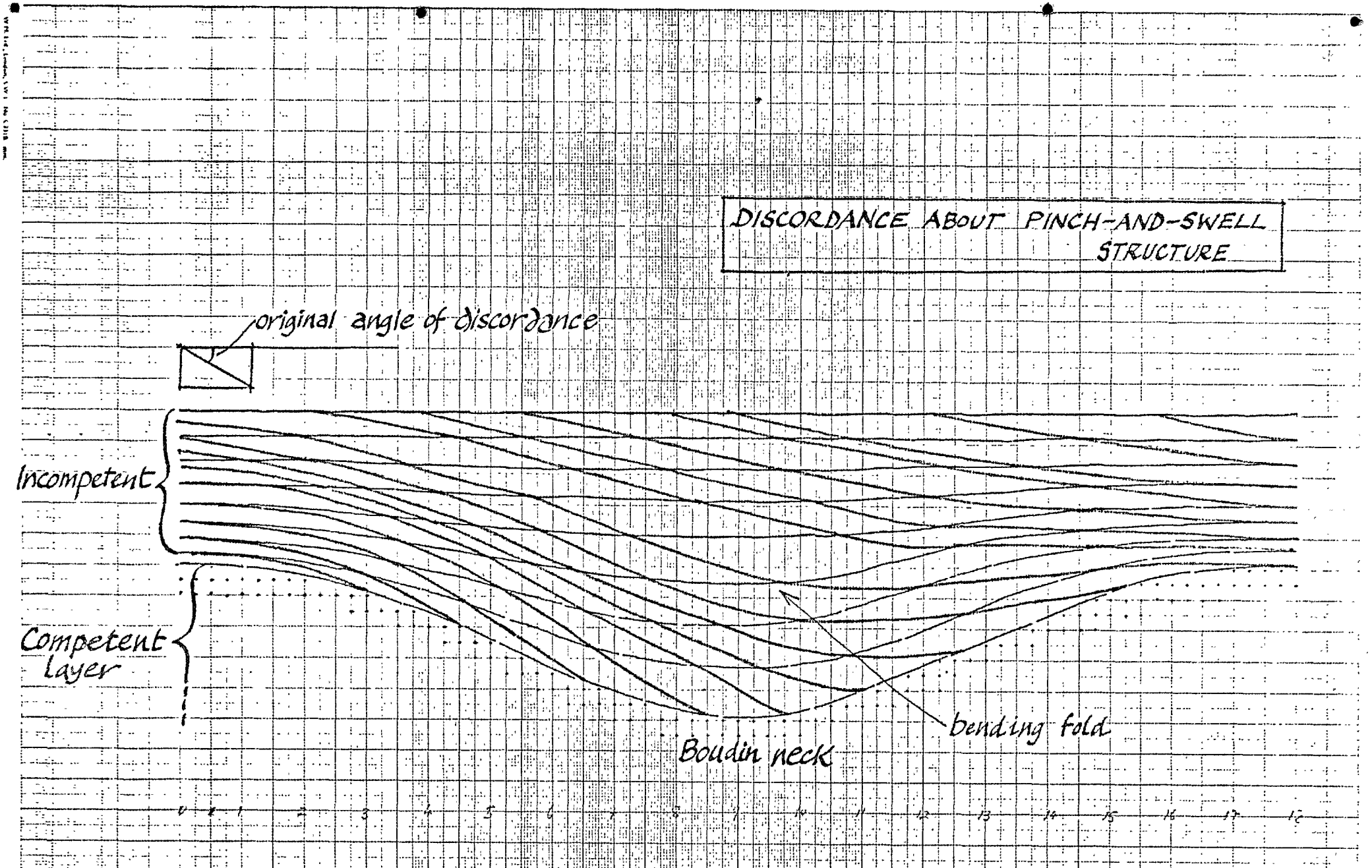
DISCORDANCES AROUND PINCH-AND-SWELL STRUCTURES IN SCOURIE DYKES

A. Dalbeg

B. Western Harris (From Myers, 1968, Fig. 35A).

FIGURE 94A

A simple model to predict discordance variations about pinch-and-swell structure. The competent layer showing pinch-and-swell structure is dotted. The incompetent layer which has flowed into the pinched part shows two sets of inclined surfaces. One set was parallel to the competent layer contact before extension.
The other set represents a set of inclined s - surfaces.


DISCORDANCE ABOUT PINCH-AND-SWELL STRUCTURE
original angle of discordance
Incompetent
Competent layer
bending fold
Boudin neck

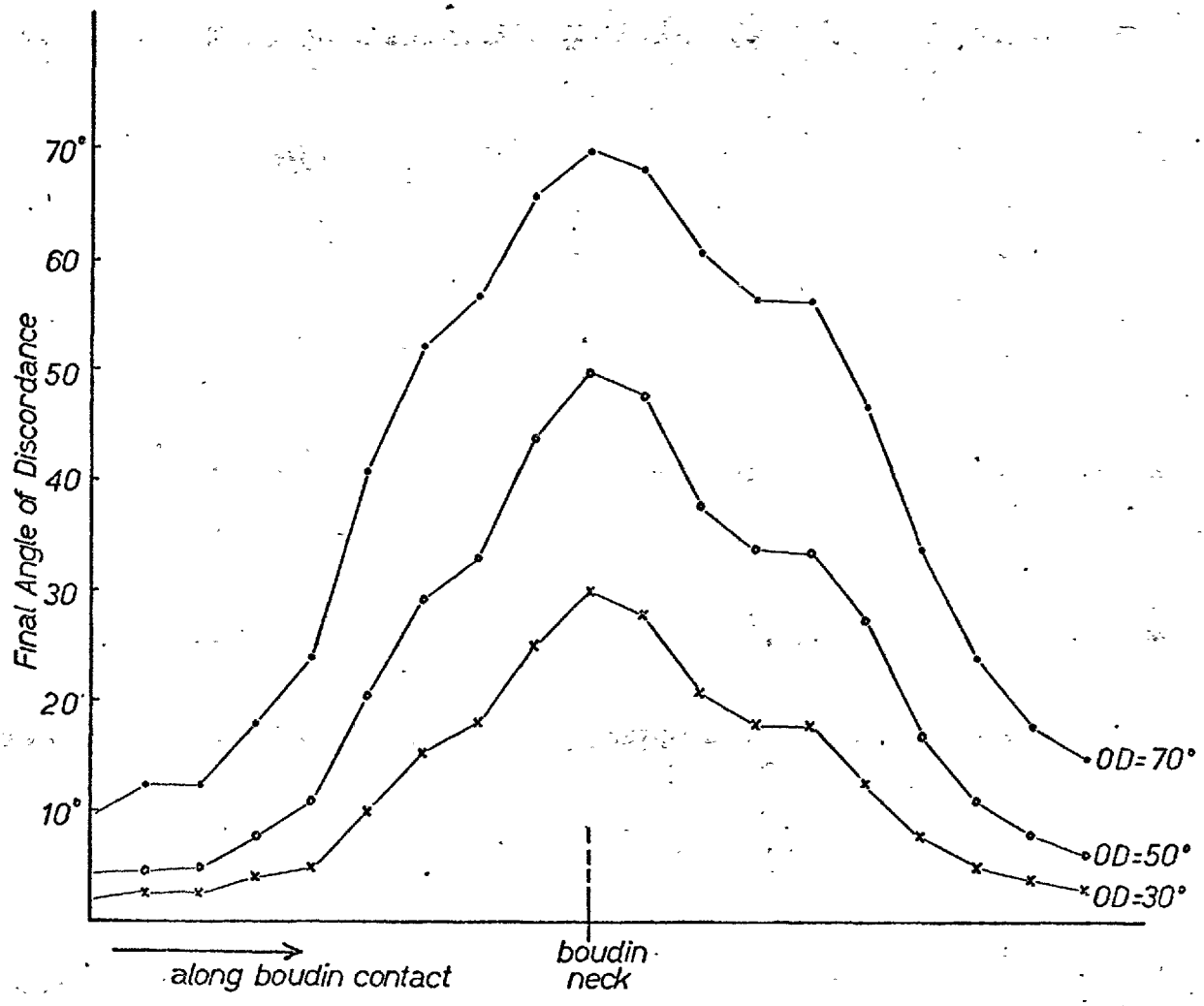


FIGURE 94B

ANGLES OF DISCORDANCE PREDICTED BY THE MODEL IN FIGURE 94A

The final angle of discordance is plotted against the distance along the boudin contact.

Maximum discordance in this case occurs in the neck region of the pinch and swell structure.

OD = original angle of discordance.

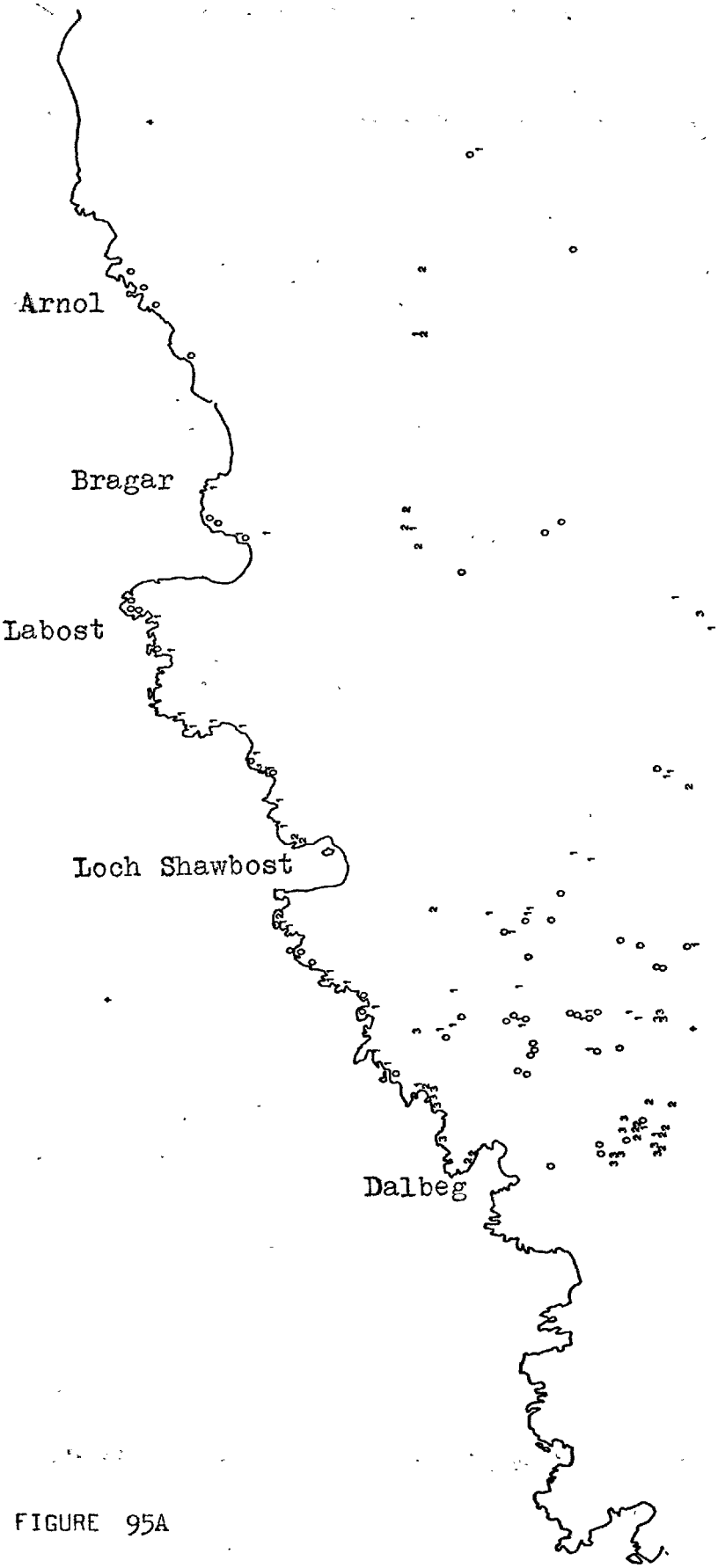


FIGURE 95A

Northern part of the area –
variation of the degree of discordance shown by the Scourie Dykes.

0 = concordant dykes
1 = slight discordant
2 = moderately discordant
3 = highly discordant

FIGURE 95B

Southern part of the area - variation of the degree of discordance shown by the Scourie Dykes.



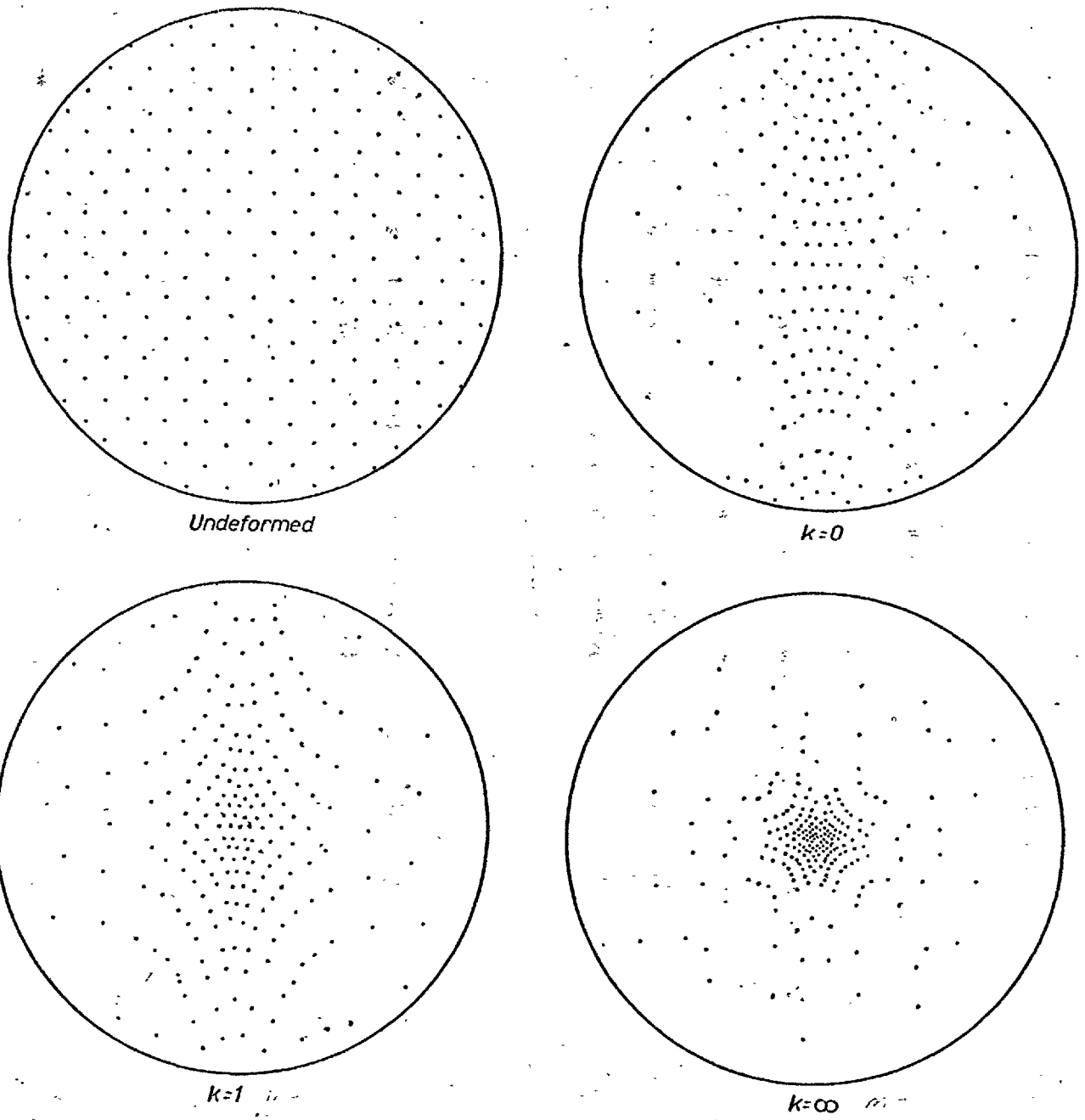


FIGURE 96

THE MODIFICATION BY STRAIN OF RANDOM DYKE ORIENTATIONS
(after Ramsay, 1967. Fig. 4 - 28).

Dyke poles are plotted. Each diagram refers to modification by strain of a particular k value.

FIGURE 97

THE RE-ORIENTATION OF DYKES AND LOSS OF DISCORDANCE

The top row (A,B, and C) are contoured stereographic plots of poles to dykes showing different degrees of discordance measured in the field.

The larger plot represents field measurements of highly discordant dykes and this population has been 'strained' to give plots D,E and F.

Plots D, E and F are the computed best-fit distributions to diagrams A, B and C respectively.

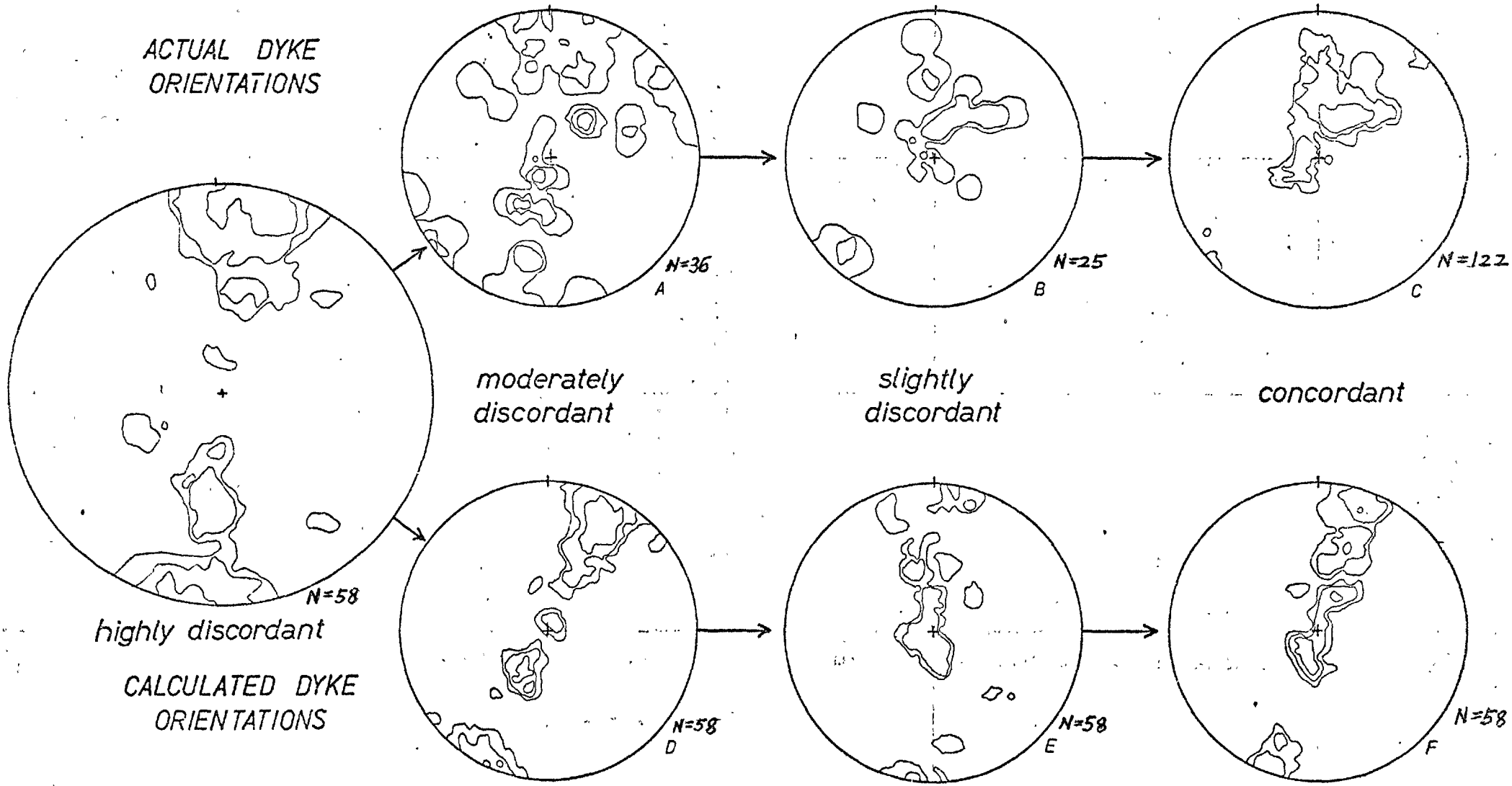


FIGURE 97

THE RE-ORIENTATION OF DYKES AND LOSS OF DISCORDANCE.

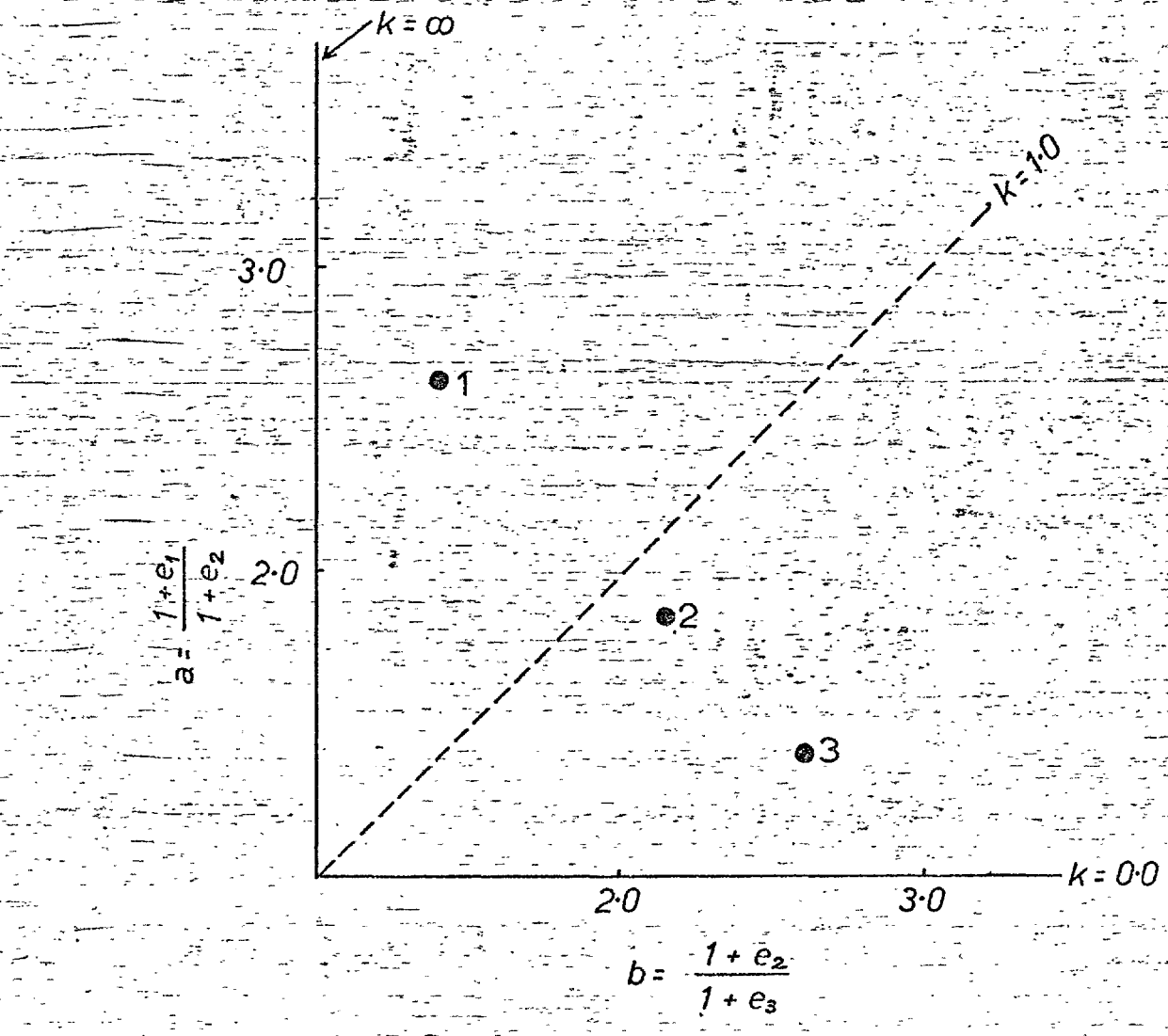


FIGURE 98

THE STRAINS REQUIRED TO THEORETICALLY DEFORM THE POPULATIONS OF DYKES IN FIG. 97 PLOTTED ON A FLINN DIAGRAM.

1 = strain required to modify population of highly discordant dykes to match the population of moderately discordant dykes.

2 = highly discordant population ⟶ slightly discordant population.

3 = highly discordant population ⟶ concordant population.

CHAPTER 8 - THE RECONSTRUCTION OF EARLIER STRUCTURAL AND LITHOLOGICAL TRENDS

This part of the thesis, so far, has dealt with specific structural elements and their use in the structural analysis. This section looks at a subject of a somewhat different nature, namely, the orientation of structural and lithological markers at intermediate times in the deformational history. Deductions are made about these earlier trends using conclusions reached in the preceding sections.

Basically, the reconstruction of earlier trends must be done by using two variables; the final trend and the finite strain. The nature of the relationship between the original trend, the finite strain and the final trend is shown by a simple mathematical example,

$$\tan \theta = \tan \theta' \left(\frac{1 + e_1}{1 + e_2}\right) \qquad \text{(Wettstein's Equation)}$$

where the trend, in this case, is a passive line subjected to a strain in two dimensions (strain ratio = $\frac{1 + e_1}{1 + e_2}$). The original orientation (or original trend), θ, can only be calculated if we have measured the present trend θ' and we have independent evidence about the state of strain (the orientation of the strain axes and the strain amount ($\frac{1 + e_1}{1 + e_2}$)). However enough independent information is rarely available because many of the methods of strain calculations use equations similar to

$$\frac{1 + e_1}{1 + e_2} = \frac{\tan \theta}{\tan \theta'}$$

that is, the calculation of the strain usually involved some knowledge about the initial trends (θ). Furthermore all the methods use equations

which involve only the 'internal strain' part of the deformation and they neglect any body rotation that the rock units may have undergone.

As a result of these limitations, the conclusions about original trends drawn from the following section are usually incomplete and sometimes only a 'relative orientation' with respect to another trend is suggested. Any such deductions, however vague, are of great value because they add greatly to our knowledge of the structural evolution of the area.

Most of the strain data so far worked out relate to the deformation suffered during post-Scourie Dyke times. By 'subtracting' this Laxfordian deformation we can attempt to reconstruct the structural and lithological trends as they were after the dykes were intruded. Firstly we will try to calculate the original intrusive trends of the Scourie Dykes themselves and then we will look at the preLaxfordian trends of the lithological visits into which the dykes were intruded.

1. THE ORIGINAL TREND OF THE SCOURIE DYKE SUITE

Throughout most of the Outer Hebrides the Laxfordian deformation has distorted what is believed to be a swarm of basic dykes which are usually correlated with the Scourie Dykes of the mainland. This distortion sometimes gives rise to complex outcrop patterns in the modified dykes which are very unlike the patterns shown by underformed dyke swarms. The map of Northern Great Bernera (Watson 1968, Fig. 2) shows an example of the effects of Laxfordian deformation on this set of basic intrusions.

In spite of these widespread deformation effects, attempts have been made to discover the original intrusive trend of the Scourie Dykes in the Outer Hebrides (e.g. Watson 1968, Coward 1969 and Graham 1969). We will now look at the kinds of methods used in these reconstructions

and at the results of these methods applied to various areas in the Lewisian.

1.a. Methods In the northern part of Great Bernera, Watson (1968) found that the axes of post-dyke folds in the gneisses were more or less parallel to the clustering of β axes constructed from the orientation of discordant dykes. Because the fold axis is generally assumed to define one line in the unfolded surface, it follows that the gneisses and the dykes shared at least one line in their undeformed state (their line of intersection) and this is parallel to their common axis. The axis was measured from the β diagram given by Watson (1968) as plunging 10° towards 109°N. Providing the dykes had a dip which was not shallow, we can conclude that the approximate original strike of the dykes (and of the gneisses) was in a direction 109°. This method ignores any effect the strain may have had in rotating the fold axes on a regional scale.

In this area, the line of intersection of the gneissic banding and the cross-cutting dykes was either directly measured in the field or was later constructed from the measurements of the mutually inclined planes. This line of intersection, termed the 'contact lineation' would seem to be capable of being 'unfolded' like other folded linear structures to give information about the original gneiss/dyke intersection. However there are several reasons why the contact lineation is unsuitable for the purpose. Firstly the population of contact lineations is likely to have shown originally a considerable degree of variability due to the variation both of the orientation of the dykes and of the banding they cut. If, for example, both sets of planes had tended to scatter about its own 'mean orientation', the lineation produced by their intersection would also tend to scatter within the great circles representing these 'mean planes'. A plot of 66 contact lineations measured from the whole

area is shown in Fig. 99. It is difficult to decide whether the variability of the lineations is original or is due to deformation. If the distribution is partly controlled by folding, a clustering of the contact lineations about a single maximum would be produced if the majority of the original lineations were at a small angle to the axis of the folding. This point alone seems relevant to the present discussion. Any more exact inferences would have to take into account the nature of the banding that is, whether it had the properties of a shape fabric or a location element (see Chapter 4) because this would affect the geometrical patterns exhibited by the contact lineation.

One of the most direct and widely-applied methods of determining the original run of the dykes is by measurements of dyke orientations in areas where they have been least modified, that is, in areas of low Laxfordian strain. Dearnley and Dunning (1968) who mapped in South Uist and Benbecula point out that the least-altered dykes trend northwest. Coward (1969, Fig. 71a) plots a rose-diagram of the strikes of apparently undeformed dykes at Garry-a-Siar, Benbecula; an area where tectonic orientation is likely to have been minimal. The diagram shows a clear preferred orientation of dykes with a strike of 138°. Applying the same methods to an area of N.W. Lewis, highly discordant dykes show a mean strike of 100° (Fig. 100A). For comparison with these trends the method was then applied, using published maps, to two areas of low Laxfordian strain in the Lewisian of the mainland; the area around Scourie (using maps published by the Geological Survey) and an area just north of Loch Torridon (from Cresswell, 1972). The results are presented in a table in Fig. 108.

It is from these low Laxfordian areas that we can also try to establish the original dip of the Scourie Dykes. Coward (1969), for example, found that dykes in the areas of least Laxfordian tectonic

activity generally dip steeply. Fig. 100B is a histogram relating the degree of discordance to the mean angle of dip of dykes in N.W. Lewis. As in Coward's area, the least modified dykes tend to be upright.

It seems then that both strike and dip information can be inferred using this method. A contoured pole diagram (Fig. 101A) of all highly discordant dykes within the area suitably summarizes the data.

Another approach to the problem of the original strike of the dykes uses the variation of the proportions of the total outcrop areas occupied by the dykes. Watson (1968) observed that there were tracts in Gt. Bernera where dykes took up a large proportion of the outcrop area. These run roughly east-west across the northern part of the island (Watson 1968, Fig. 3) and this is used as evidence for the original trend of the dykes. In Western Harris, Myers (1971) recognized zones rich in Scourie Dyke fragments but concluded that the zones themselves underwent folding in the Laxfordian. It appears therefore, that only in certain circumstances where the scale of the largest order of folding is small in comparison with the thickness of the zone, can this method be reliably used to indicate trends of the intrusions.

Although the value of these belts rich in dykes was appreciated by Watson (1968) and Myers (1971) the actual demarcation of these zones was done rather subjectively. As an alternative, direct measurement of the areas on the map of each dyke fragment can be made using a planimeter but the process is time-consuming. In a more rapid method, squared tracing paper was placed over the map allowing the intersections of the grid to be sampling points for the outcropping rock-type. In a particular area, the number of sample points falling on Scourie Dyke outcrops should be approximately proportional to the percentage of the total area occupied by dykes. By the use of subareas, preferably containing one hundred grid intersections so as to permit easy

calculation of area percentages, this method is capable of revealing regional variations of Scourie Dyke concentrations (Lisle, note to Myers 1971).

Contour maps showing the regional variation of Scourie Dyke concentrations were produced for maps of areas of good exposure where even small dyke outcrops have been marked. The maps of Watson (1968) of Northern Gt. Bernera and Myers' (1968) map of Western Harris met these requirements and the contoured maps of dyke concentrations are shown in Fig. 102 and 103 respectively. The interpretation of these maps is not necessarily straightforward, but assuming that the dyke swarms originally consisted of parallel dykes of even width, contours of equal concentration should parallel the original trend or its rotated equivalent.

The map of Northern Bernera (Fig. 102) supports the conclusions of Watson that the zones are approximately east-west trending. The contours show a preference for a direction trending 107°.

The map of Western Harris (Fig. 103) has been simplified and shows only the 3%-area contour. Fold-like curves in the zones are picked out by the contours and this may indicate that the folds which deflect the Scourie Dykes in W. Harris are of a larger scale than those of Gt. Bernera. In the area which lies north of Loch Tarbert, the zones rich in dyke fragments, although irregular (possibly folded) in their individual shape tend to line up in a discontinuous zone of a higher order along a SE-NW direction (Fig. 103). The alignment (trend 116°) shows through in spite of the folding and may indicate the original dyke trends.

Fragments of the Cleitichean-type of Scourie Dykes (see chapter 2) are restricted in their distribution - the larger fragments lead in a more or less westerly tract away from Cleitichean Beag (270367) across to the southern end of Great Bernera. Contoured area-percentages

for this rock-type would confirm this roughly east-west trend. However, there are occurrences of fragments of Cleitichean-type just south of Duone Carloway (196401) which lie west-northwest of the main outcrops at Cleitichean Beag. Fig. 104 is a different type of map showing the frequency of fragments of rock of Cleitichean-type. Each body of this rock-type is considered as a single occurrence making this contour map independent of the area percentage. The map indicates the fragments occur in zones trending ESE . In short, dykes of the Cleitichean-type provide differing conclusions about original trends depending on the method of interpretation used. It may be worthwhile to point out that the trends shown by Scourie Dykes in the Scourian block of the mainland Lewisian depends somewhat on rock-type. For example, the ultrabasic dykes have more of an east-west trend than the more typical dolerites.

Most of the methods so far described give information about the original run of the Scourie Dyke swarm on a horizontal surface. Watson (1968) however attempted to estimate the original dip of the dykes by noting the dip of the envelope. It dipped steeply and on rare occasions where the attitude of the envelope is visible in the Carloway area, for example on the north side of Ben Bragar, it appears to dip steeply northwards. This dip is also shown by many discordant unfolded dykes on a smaller scale.

In N.W. Lewis, the observation has been made that the present trend of outcrops of the dykes is close to the finite extension direction of the strain in a horizontal plane. It would be interesting to find out if the dykes were originally inclined in a clockwise or anticlockwise sense with respect to the extension direction.

Two attempts have been made to solve this problem. The first approach considers the change of strike of dykes as they become concordant

i.e. as they become more deformed. Fig. 105A is a histogram of the mean strike of dykes showing different angles of discordance with their host gneisses. From this it appears that the strain, which produces the loss of discordance, causes a clockwise swing in the mean strike of the dykes. It follows then that the dykes lay in an anticlockwise position in relation to the finite extension direction (Fig. 105B).

The second approach uses the distribution of the strikes shown by the measured population of deformed dykes. If we assume that the frequency of dykes with a particular orientation in the undeformed swarm is related to the orientation itself in a fashion shown by a normal or Gaussian distribution, we can examine the effects of an oblique strain superimposed on the distribution and compare the results with the distribution shown by the dykes' orientations measured in the field.

Recently Sanderson (1973) has calculated the effect of strain on populations of directional elements and his mathematical procedure is outlined here. The height of the normal distribution curve (F) for any particular direction is given by

$$F = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\theta}{\sigma}\right)^2\right)$$

where σ is the standard deviation and θ is the angle of the selected direction from the mean (see Fig. 106A).

Now consider the imposition of a strain on the population so that the X direction of the strain ellipse is at an angle ϕ to the mean of the distribution. The direction under consideration in the undeformed state is $(\phi + \theta)$ degrees away from the extension direction (Fig. 106A).

As a result of deformation this angle will undergo a change so that

$$\tan \theta' = \tan (\phi + \theta) \frac{1}{R} \qquad (1)$$

where R is the axial ratio of the strain. F will therefore be the height of the frequency curve in the deformed state for a line θ away from the extension direction. However before F can be plotted as a function of θ' a correction must be made to the value of the frequency F caused by change in the spacing of the originally regularly-spaced class interval. This change in the size of the class interval is obviously a function of $(\phi + \theta)$, the angle away from the extension direction and this has been called the class-interval function (C.I.F.) (Sanderson 1973 equation 6).

$$\text{C.I.F.} = \frac{R}{R^2 \cos^2 (\theta + \phi) + \sin^2 (\theta + \phi)}$$

so that the corrected frequency distribution function becomes

$$F = \frac{1}{\sigma\sqrt{2\pi}} \exp \left(-\frac{1}{2} \left(\frac{\theta}{\sigma}\right)^2\right) \frac{R^2 \cos^2 (\theta + \phi) + \sin^2 (\theta + \phi)}{R} \qquad (2)$$

By fixing values of ϕ, R and σ we can vary θ in equations (1) and (2) and hence find the relationship between θ' and F.

This relationship constitutes the new deformed frequency distribution. Examples of this distribution is shown in Fig.106B . Here a normal distribution (the dashed line) of standard deviation 30° ($\sigma = 30^\circ$) has been deformed by a strain of 3:1 (R = 3.0) oriented at 30° from the mean of the distribution ($\phi = 30^\circ$). The shape of the deformed distribution curve is shown with a solid line. As predicted it has become skewed and the sense of skewness is such that the mode lies between the mean and the extension direction of the strain.

Figure 107 shows the distribution of orientations of dyke strikes measured in the field. The mean strike of the dykes is 104.77° and the

mode of the distribution is 107.5°. If we were to interpret the curve according to the theoretical predictions given above we must conclude that the mode lies between the extension direction and the mean. In other words we can place the extension direction of the strain which caused re-orientation of the dykes in the field in a clockwise sense with respect to the direction 107.5 (the mode). This is a deduction compatible with deductions based on early methods.

However not too much reliance can be placed on this orientation distribution method in this example for two main reasons

i) the orientation distribution curve of dykes in this area has a complicated shape - more complicated than the theory predicts, and

ii) the assumptions of an original normal distribution for dyke strikes and of homogeneous strain imposed upon it could well involve too much in the way of oversimplification for the reliable application of this method in this situation.

1.b. Conclusions From various lines of deduction consistent results have been obtained from the original trend of the Scourie Dyke swarm in Gt. Bernera and N.W. Lewis. A strike close to 107° is suggested and the dip of individual dips was probably steep. Further south the strike swing from east-south-easterly to south-easterly (W. Harris = 116°, Benbecula = 138°). Measurements from maps of the strike of discordant dykes on the mainland show a similar swing on going south; 119° in the Scourie area, 139° in the Loch Torridon area. These results are summarized in table form in Fig. 108 and the inferred orientations of the swarm in N.W. Scotland is shown in Fig. 109. The trends cannot be projected as straight lines across the Minch; either the dykes were curved or they were originally linear but have been subsequently offset by a Minch Fault with a substantial sinistral displacement.

2. THE ORIGINAL RELATIVE ORIENTATION OF THE PRE-LAXFORDIAN BANDING AND THE CROSS-CUTTING SCOURIE DYKES

Again this attempt at reconstruction applies to the time immediately after the intrusion of the Scourie Dykes. Where Scourie Dykes appear discordant on horizontal outcrops the banding and dykes show a very consistent sense of discordance (Fig. 110). Considering the acute angle between their outcrop traces, the gneiss trend usually has a clockwise sense of inclination with respect to the dyke (22 observations) whereas the opposite sense was rarely seen (2 observations). These almost constant strike relationships put some restrictions on the Scourian structural geometry and suggest that either

i) no large-scale pre-Laxfordian folds occur within the limits of the area, or

ii) the pre-Laxfordian folds have more or less horizontal axes, or

iii) the pre-Laxfordian folds are very tight.

This sense of cross-cutting probably occurs also on a large scale because the trail of Scourie Dyke fragments of Cleitichean type appears to cut across the trend of the banding in the grey gneiss and the strike of the Laxavat supracrustals which runs clockwise from the dyke-trails.

Discordances on vertical surfaces have more variation in their sense. This could be due to several reasons but the inconstancy of the initial dip of the gneisses is probably at least partly responsible.

3. THE ORIENTATION OF THE BANDING IN THE GNEISSES

Firstly we shall try to establish the banding orientation at the end of Scourian times. The most obvious approach is to look at the orientation of the gneiss in areas where the Scourie Dykes show their least tectonic arrangement. Fig. 101B shows poles to such banding. The mean strike of the banding is 113° but the amount and direction of

dip vary greatly. It seems that pre-Laxfordian folds with a low plunge were present so that the second alternative ((ii) above) given to account for the intersection sense of the dykes seems to be the most likely. Arrangement of the banding poles gives a girdle whose axis has an orientation 8/112°. Fig. 111 shows a schematic sketch summing up these deductions.

The attitudes of F2 folds should give clues to the banding configuration before the D2 structures developed, since there appears to have been no folding on a large scale since D2 times to distort them. If we assume that the axis of a fold is parallel to a line contained within the unfolded surface, the low plunge of the F2 folds suggests that the axes are close to the pre-F2 banding strike.

Using this reasoning,

the pre-D2 strike of the area south of Carloway was 110° and the pre-D2 strike of the northern coastal strip (Carloway to Barvas) was 075°,

which suggests that a significant structural difference existed between the north coast and the area inland in pre-D2 times.

The D2 structures are envisaged as "flattening-down" structures strongly controlled by earlier trends. The strong predominance of folds with a z-profile (observed facing eastwards) therefore suggests that south and south-west dips were characteristic of the pre-D2 structure.

In the same way we can use F3 folds to work out the pre-F3 structural framework. The main F3 folds (sensu stricto) have axes striking more or less perpendicular to the F2 and pre-F2 strike direction. The plunges of these folds are low suggesting that the pre-F3 banding had a low angle of dip. This is illustrated in Fig. 112 where the direction of the F3 plunge seems to be related to its position with respect to an area of low Laxfordian deformation. This suggests that the pre-F3 banding tended to 'wrap around' the areas of low Laxfordian deformation.

4. STRUCTURES PRESERVING EARLIER TRENDS

Certain lithological units contain areas of unusually low strain where earlier trends are more likely to have survived modification. Lens-shaped basic bodies showing oblique internal banding surrounded by more intensely foliated grey gneiss occur occasionally and it seems likely that in these bodies the banding is less modified than that of the gneiss outside. An example is shown in Fig. 113B. from a vertical outcrop surface at South Shawbost.

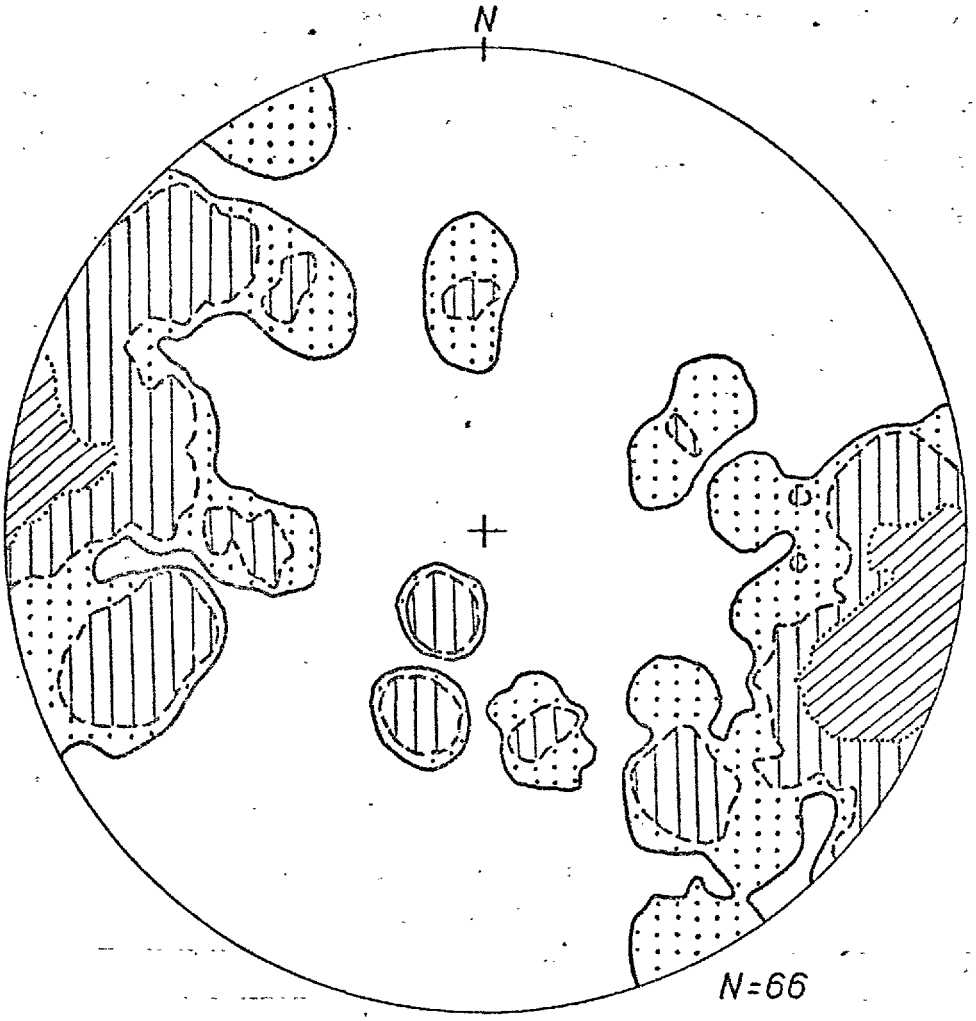
Similar inclusions occur elsewhere in the Outer Hebrides for instance in South Harris (Palmer 1971) and at Melbost Borve (410579) in North Lewis where sigmoidal internal banding is sometimes preserved.

At first glance these structures appear to be valuable 'fossilizers' of ancient trends but in fact interpretation is difficult. For instance, basic bodies within the lensoid gneiss (chapter 2) often show isolated banding trends unrelated to either a banding in the host rock or to banding in neighbouring inclusions. So if the structures are of this type, relict trends within them will only relate to a period of disruption. In addition, body rotation of the inclusion and its internal banding may have occurred during the deformation as a result of the body's higher competence than the enclosing gneiss.

5. THE TRENDS SHOWN BY THE SUPRACRUSTALS

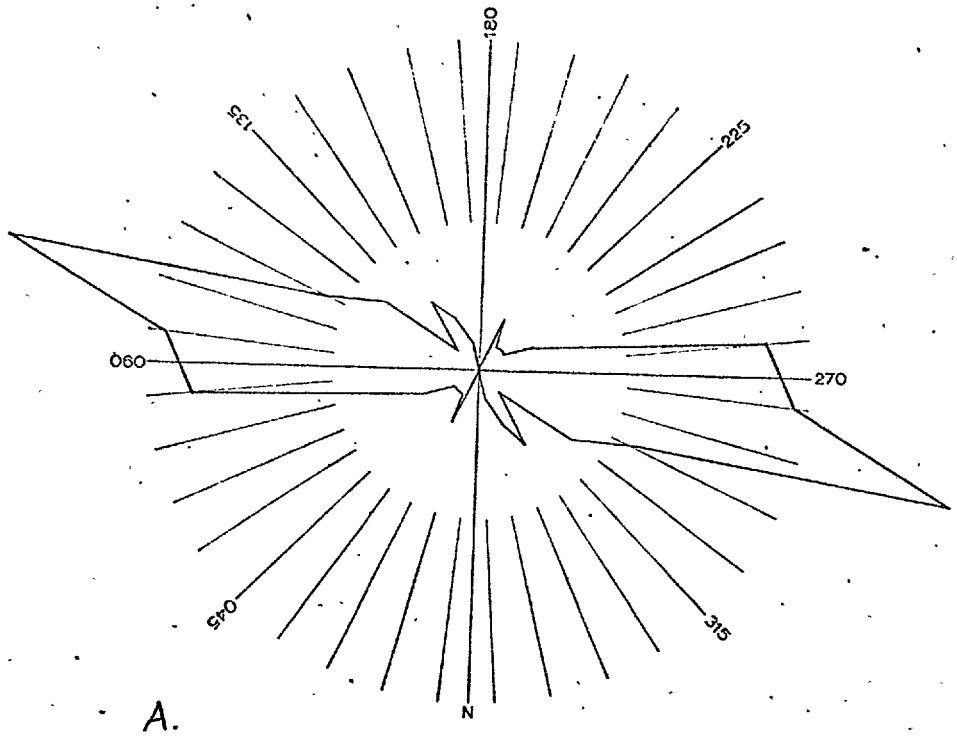
The outcrops of pre-Laxfordian supracrustal rocks map out as horizons dipping southwards to south-westwards and are apparently conformable with the banding in the adjacent grey gneiss. It is unlikely that any significant discordance between the grey gneiss and the supracrustals existed at the beginning of the Laxfordian. Previous discussions about the orientation of the gneissic banding as far back as the end of Scourian times therefore apply equally well to the supracrustal horizons.

No deductions about earlier supracrustal/grey gneiss structural relationships can be attempted.

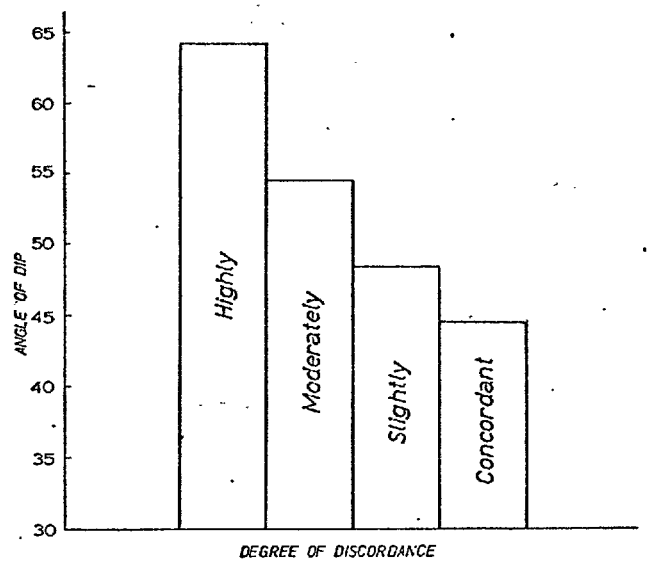


SCOURIE DYKE/GNEISS CONTACT
INTERSECTION LINEATION
(Whole area)

Figure 99



A.

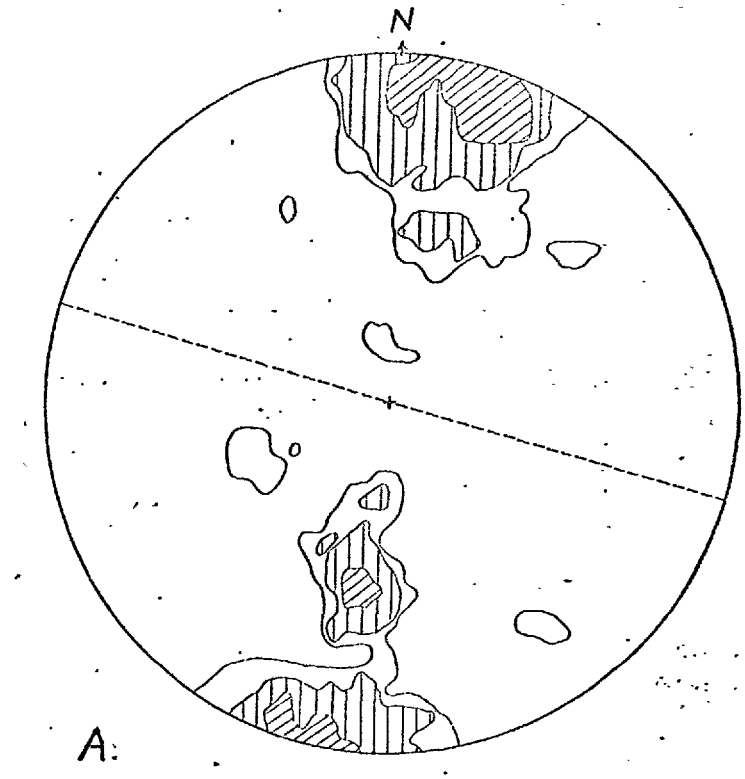


B.

FIGURE **100**

A. Rose-diagram of strikes of highly discordant Scourie Dykes, N.W. Lewis.

B. ~~Histogram~~ showing the variation of mean angle of dip with the degree of discordance of dykes in N.W. Lewis.



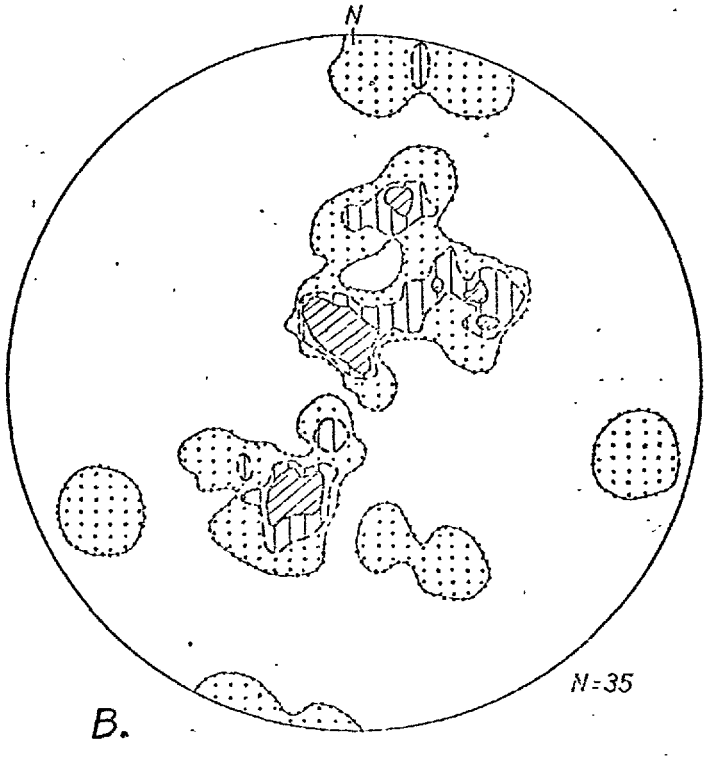
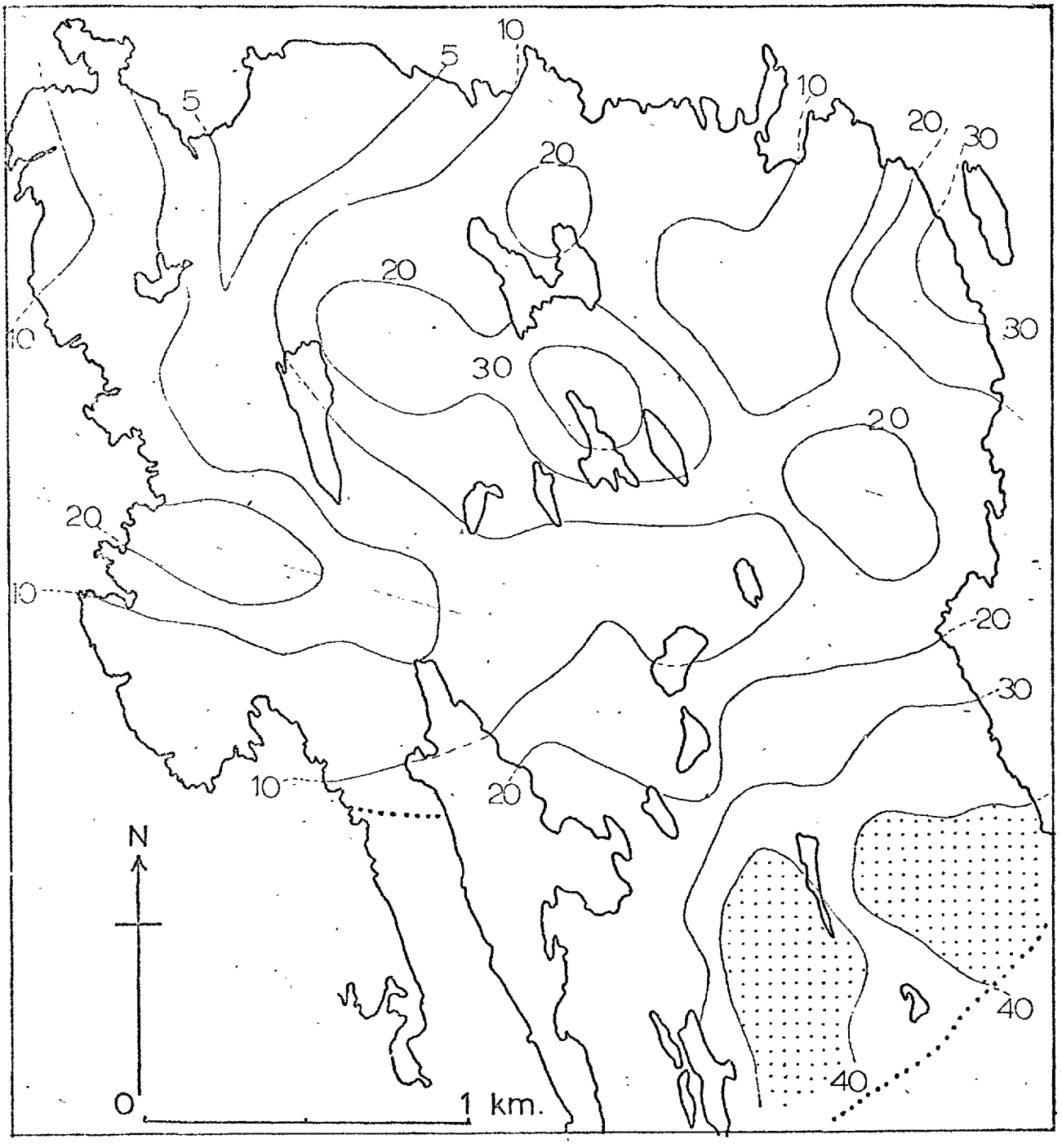


FIGURE **101**

A. Contoured stereogram with poles to highly discordant dykes.

B. Poles to gneissic banding from areas showing highly discordant dykes.

Contours at 2,4 and 8% / 1% area.



THE NORTHERN PART OF GREAT BERNERA

Contours of % area of Scourie Dykes

FIGURE **102**

Map showing proportion of total rock outcrop occupied by Scourie Dykes.

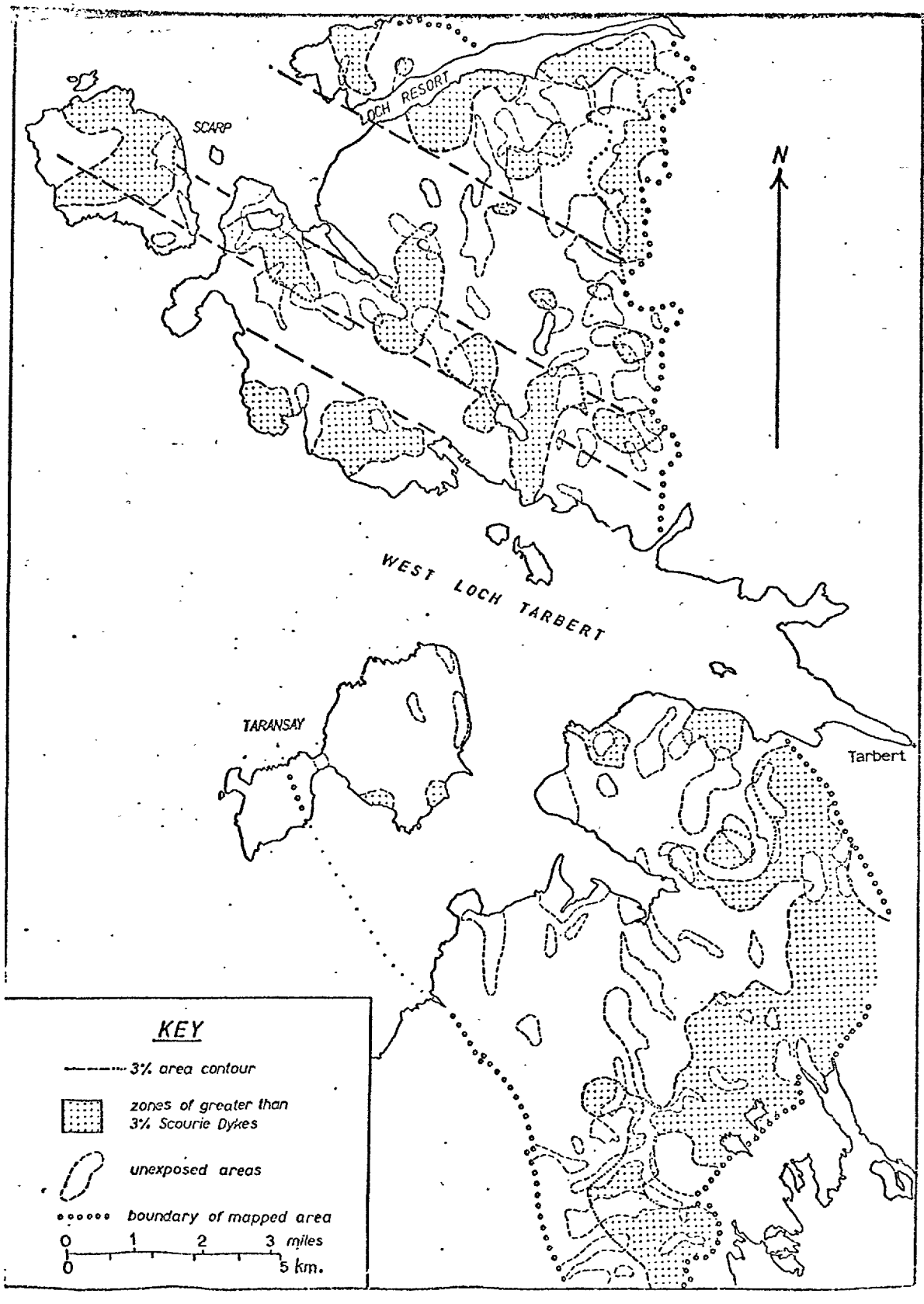
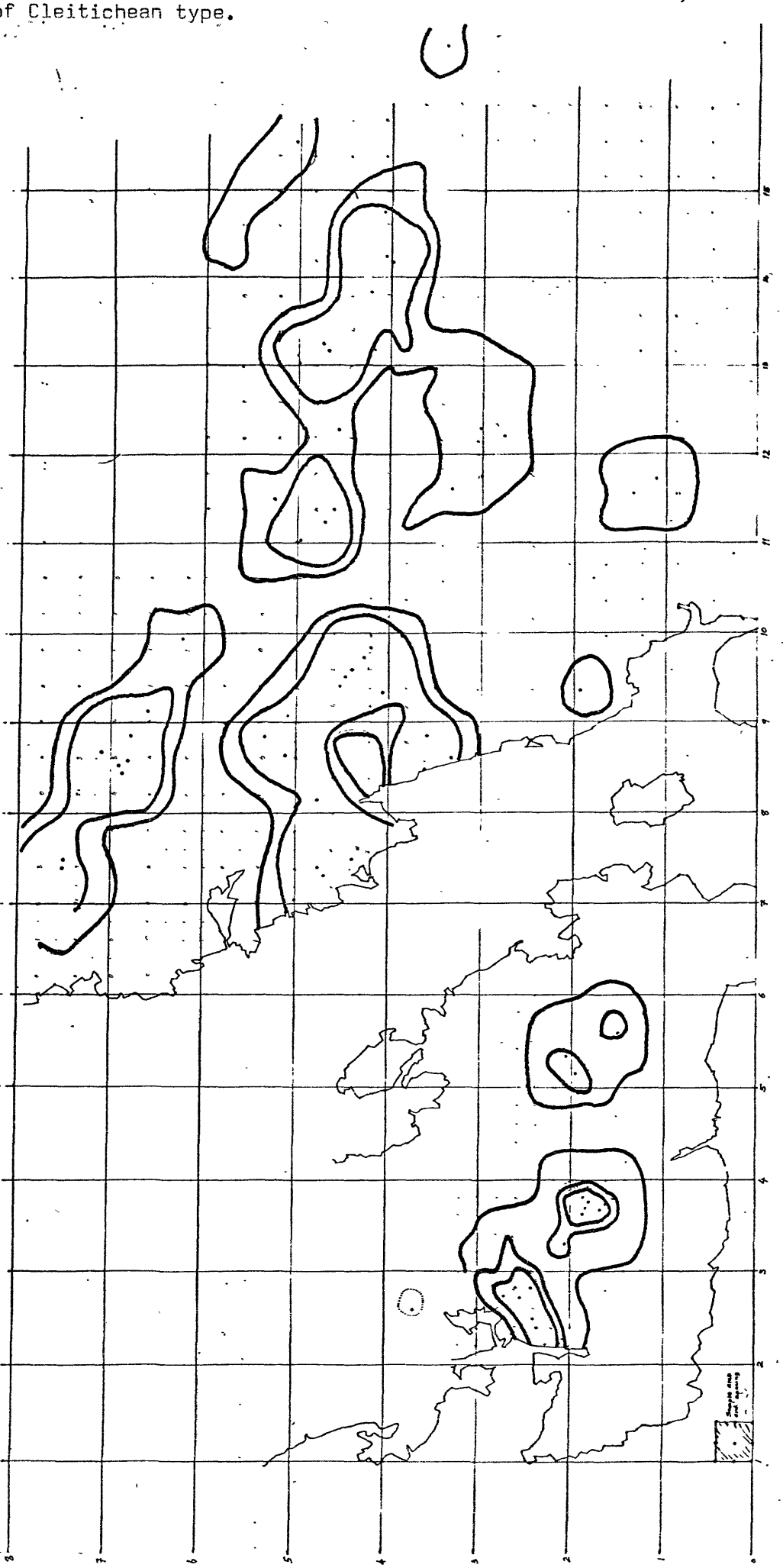


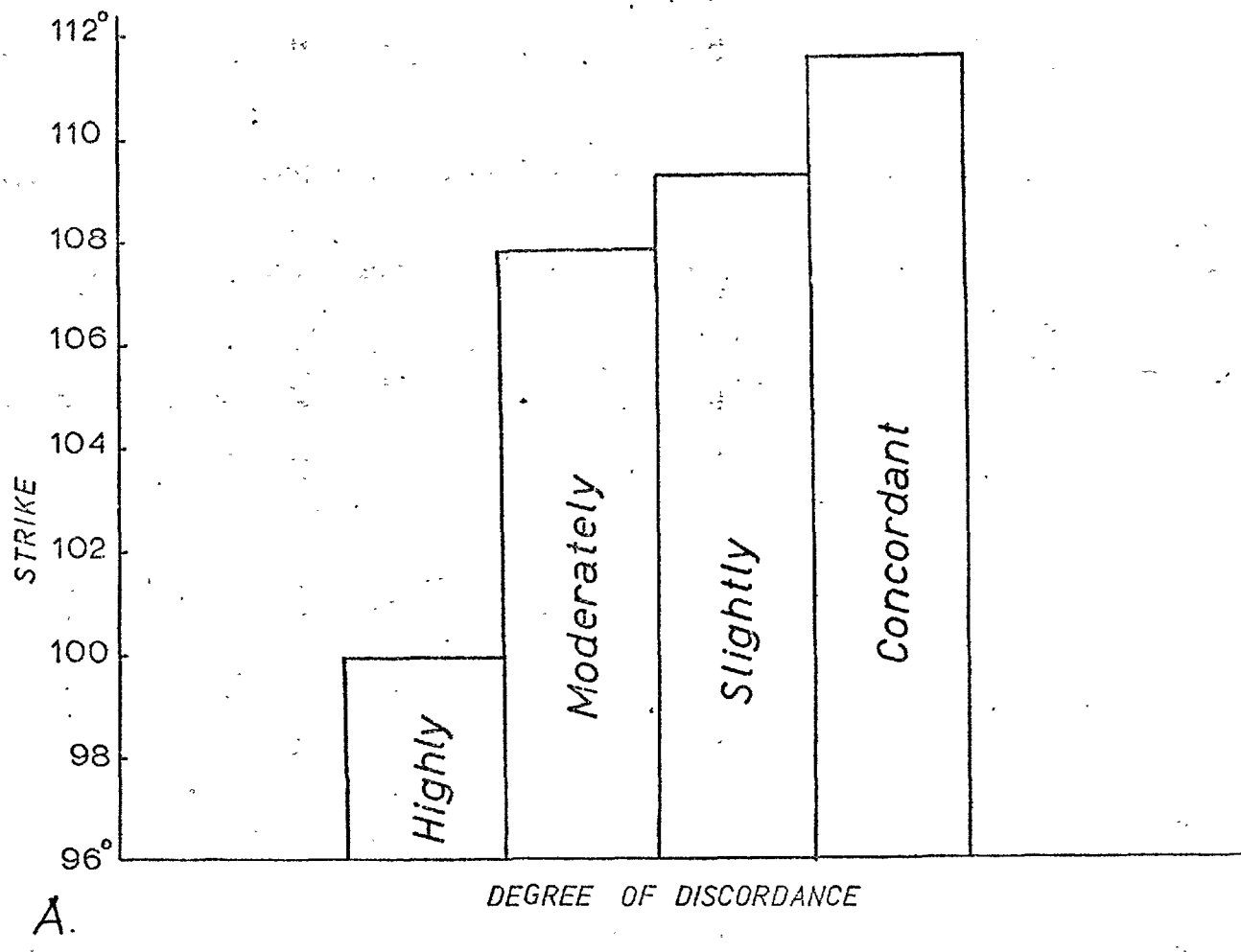
FIGURE **103**

Western Harris. Percentage of total area occupied by Scourie Dykes.

FIGURE 104

Contoured frequency of occurrence of bodies of Scourie Dykes of Cleitichean type.





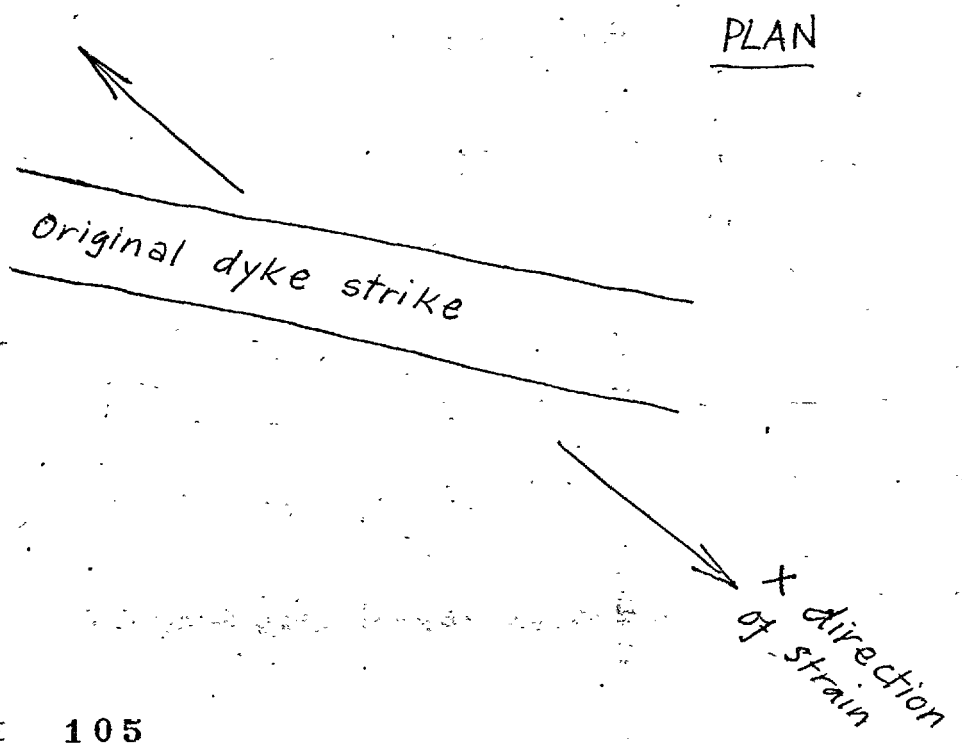
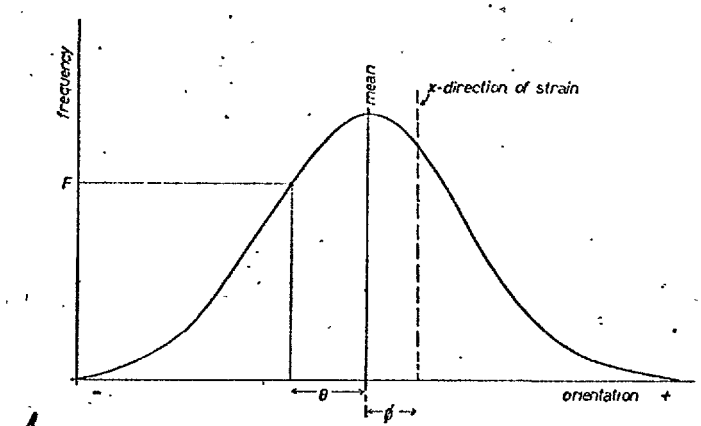


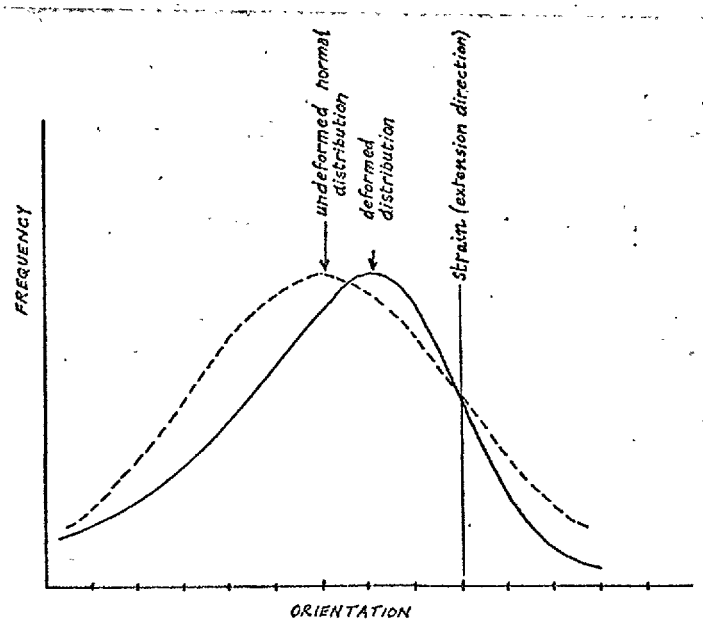
FIGURE **105**

A. Histogram showing the relationship of strike of Scourie Dykes and their degree of discordance.

B. Inferred relative orientation of dyke strike and Laxfordian strain from A above.



A.



B.

FIGURE 106

A. The normal distribution representing the orientation of undeformed dykes.

B. Undeformed normal distribution $\sigma = 30^{\circ}$ deformed by strain ($R = 3.0$, $\phi = 30^{\circ}$).

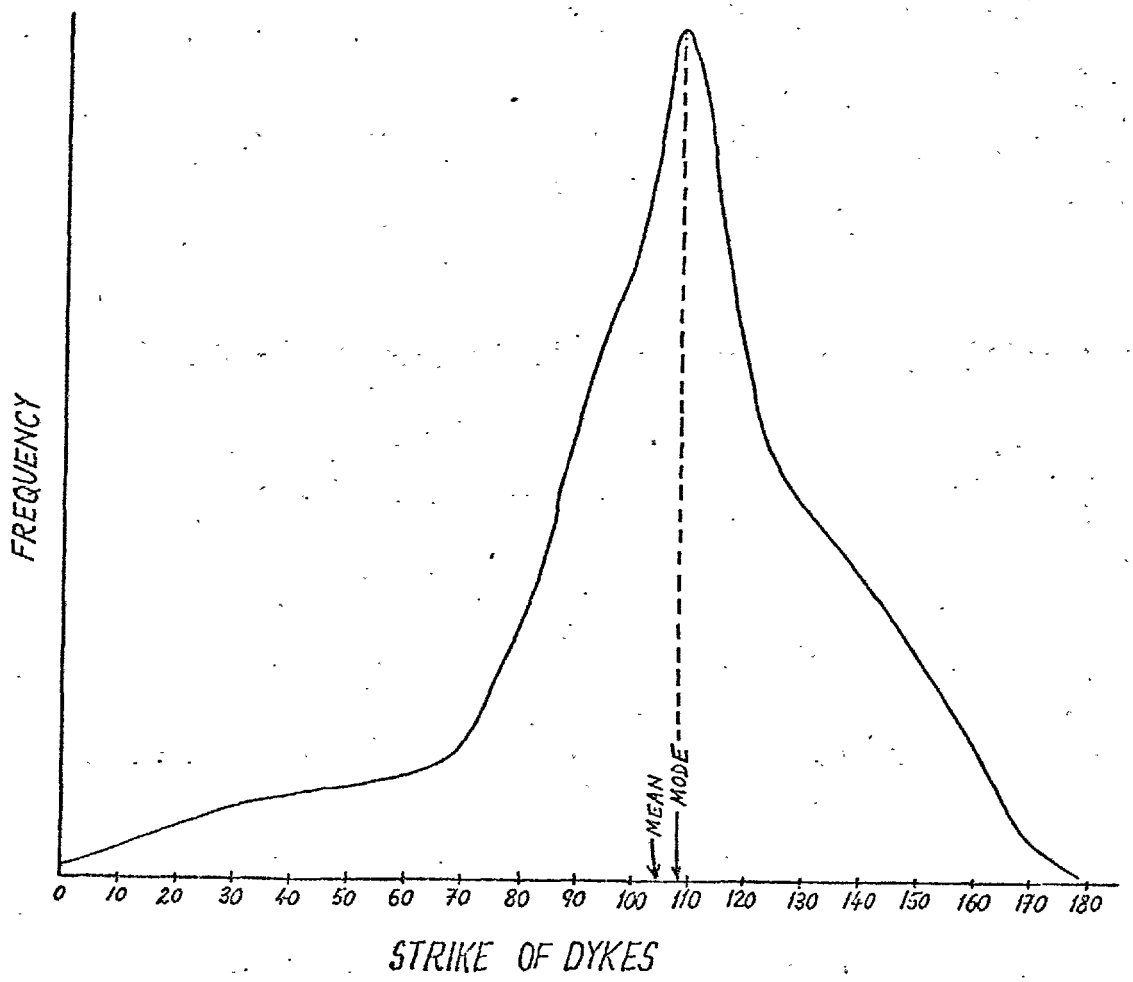


FIGURE 107

Frequency vs. strike orientation curve for Scourie Dykes.

Class interval = 10^{o}

Mean = 104.8

Mode = 107.5

	Area % contour method	Mean strike in Low deformation area	Axes of folded dykes method
GT. BERNERA	107°		109°
CARLOWAY, LEWIS		100°	
WESTERN HARRIS	116°		
BENBECULA		138°	
SCOURIE, SUTHERLAND		119°	
LOCH TORRIDON		139°	

FIGURE 108

DEDUCTIONS ABOUT THE ORIGINAL STRIKE OF THE SCOURIE DYKE SWARM - Results.

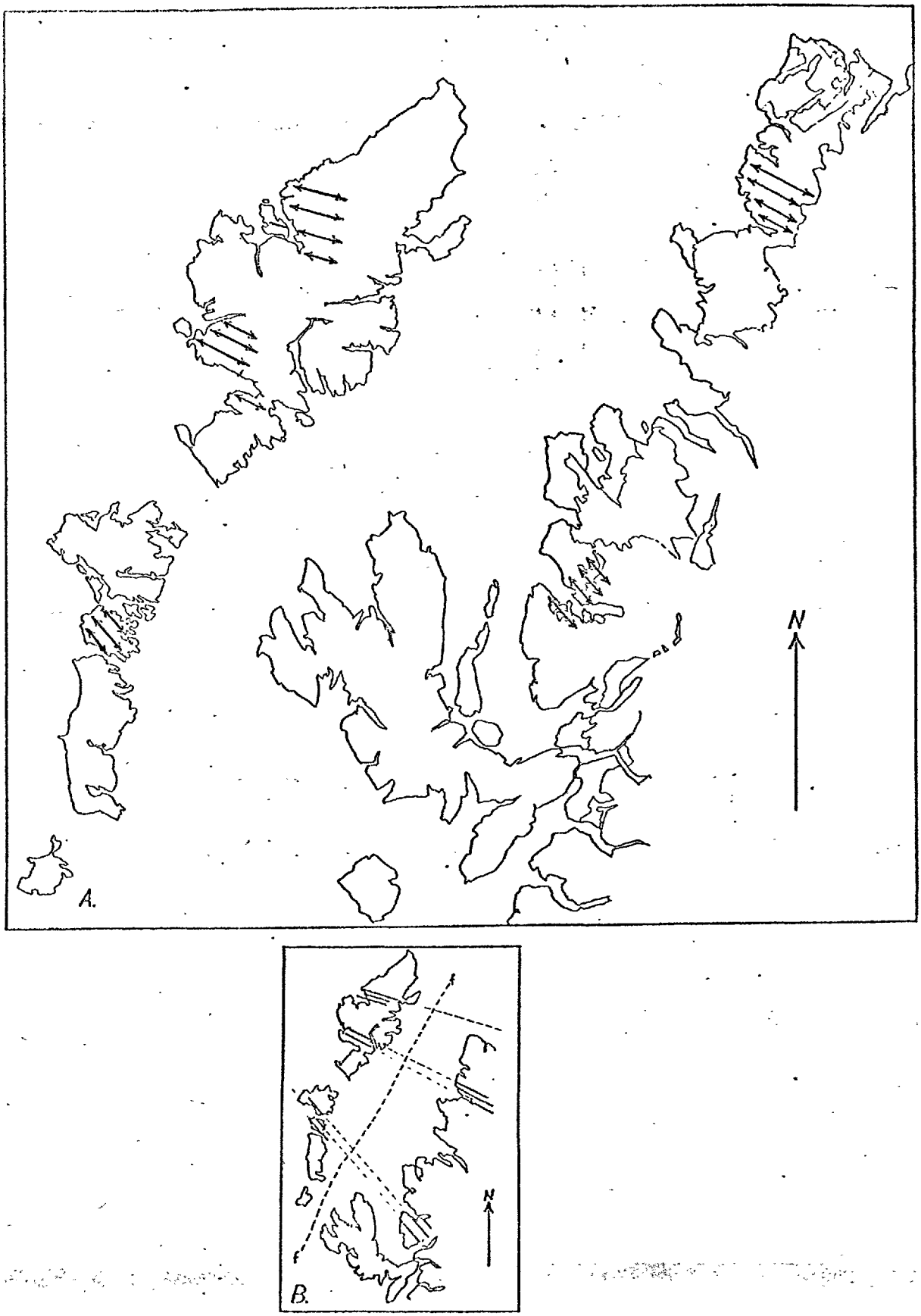


Figure 109

MAP OF N.W. SCOTLAND SHOWING DEDUCED ORIGINAL TRENDS OF SCOURIE DYKE SWARM.

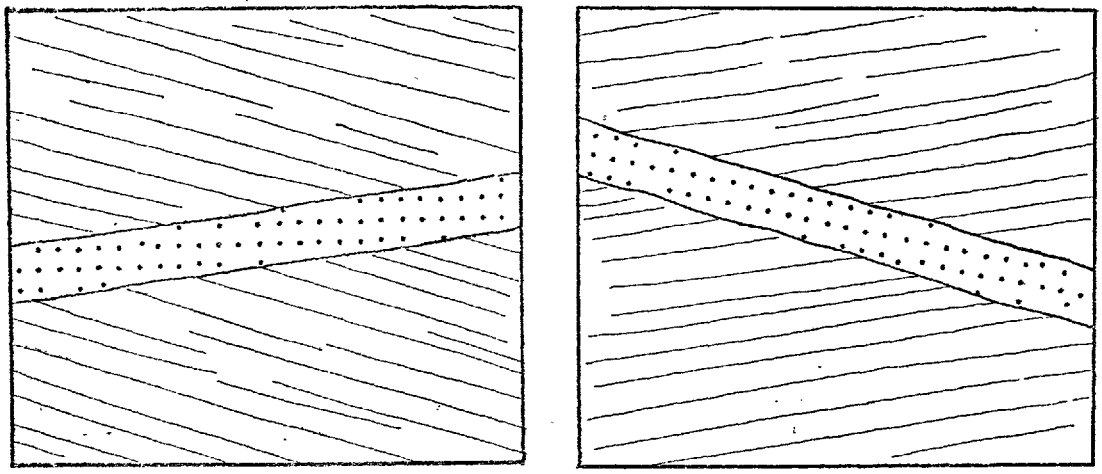


FIGURE 110

The sense of discordance of Scourie Dykes on horizontal surfaces.

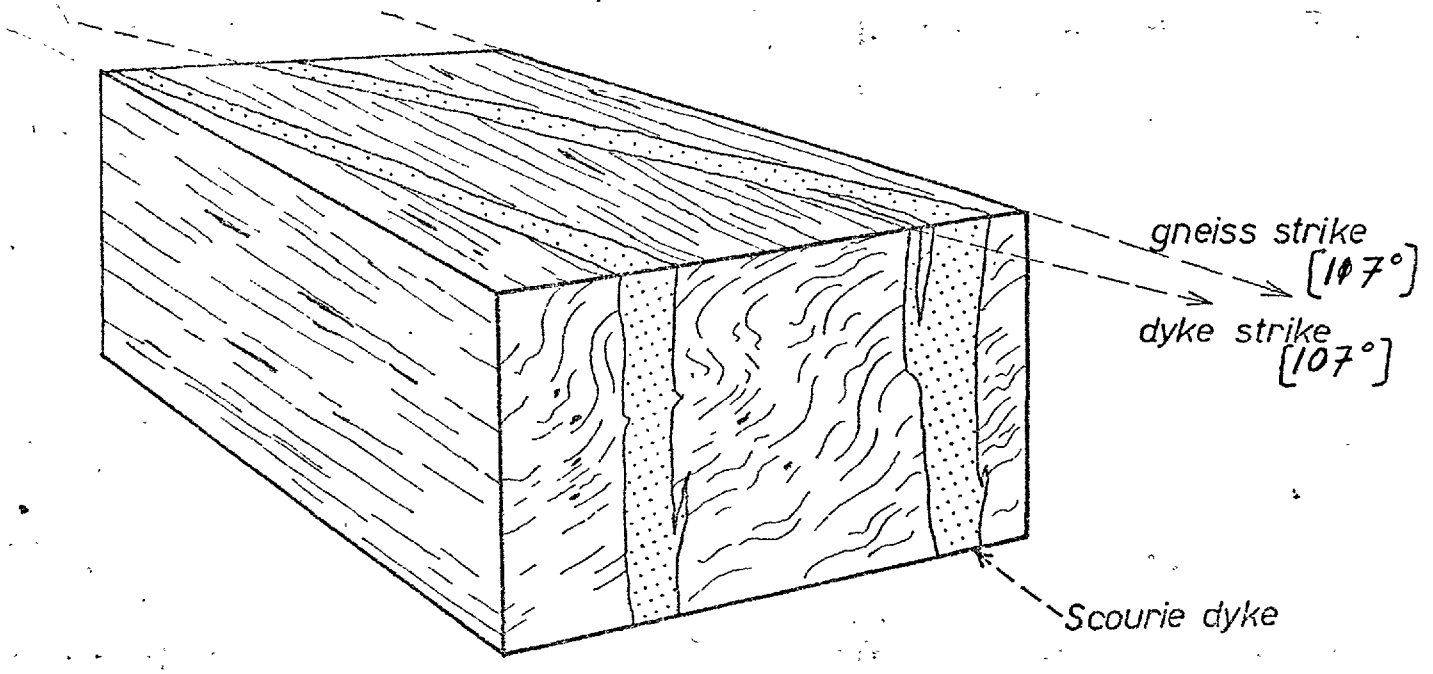
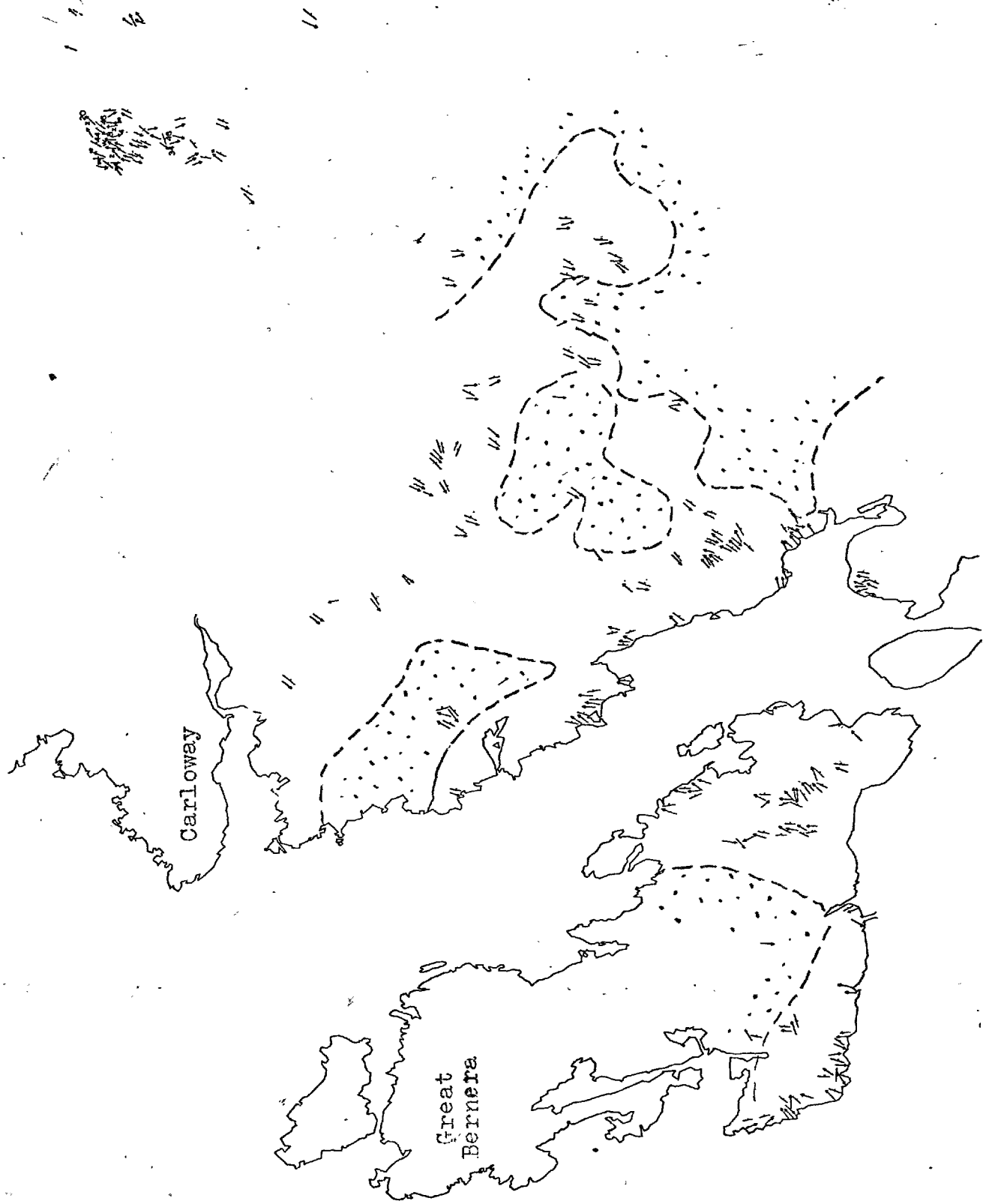


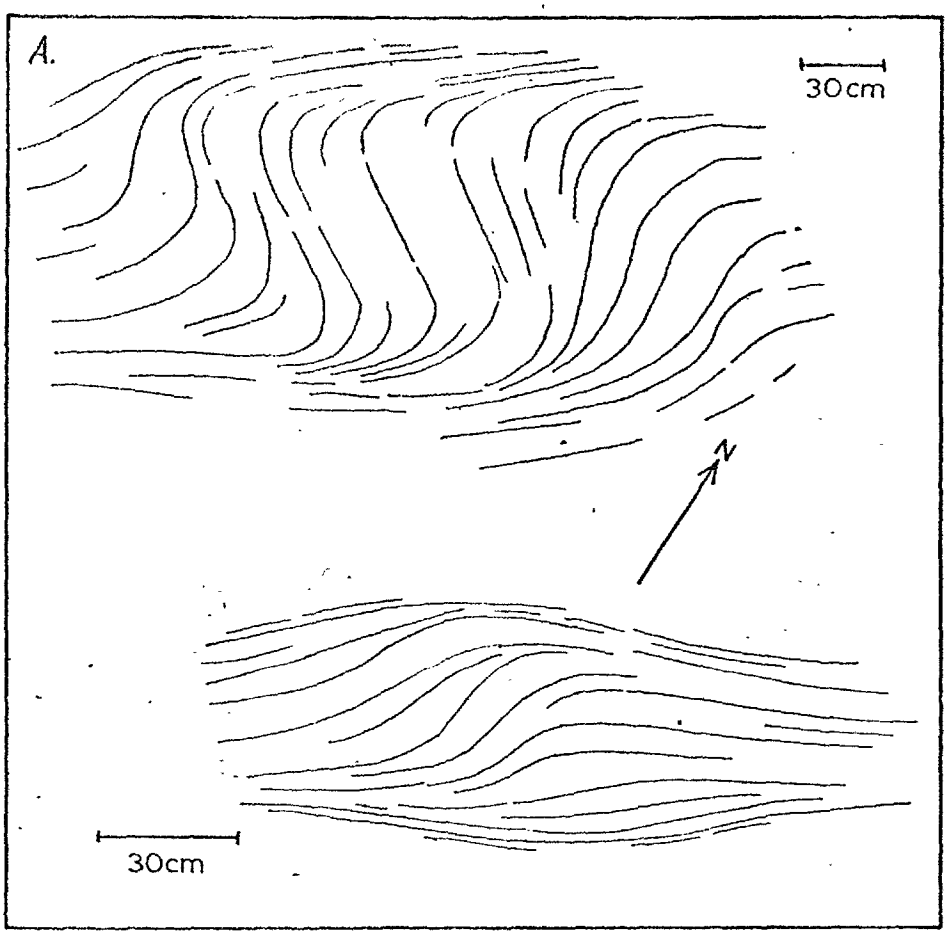
FIGURE 111

Relation of dykes to banding in gneisses in area South of Carloway after dykes were intruded.

FIGURE 112

Direction of plunge of F3 axes and dip of F3 axial planes with respect to areas of discordant dykes (dotted - simplified from fig.





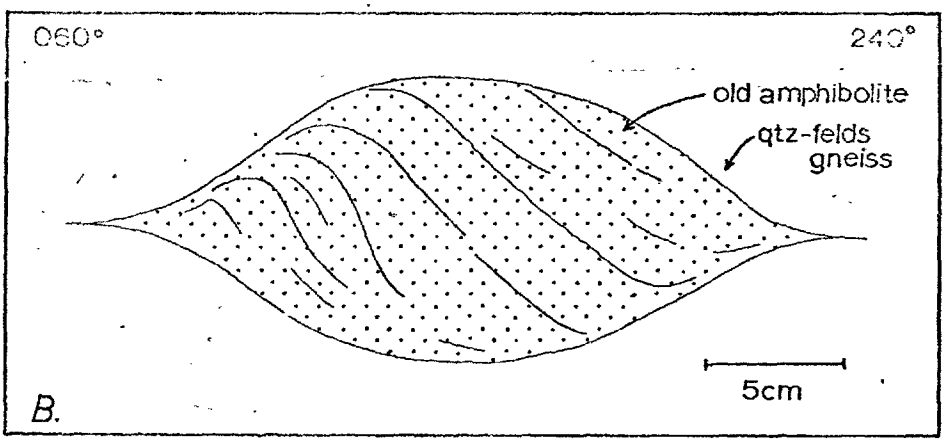


FIGURE **113**

STRUCTURES PRESERVING EARLIER TRENDS

A. Melbost Borve (410579) N.E. of Barvas. Horizontal section.

B. South Shawbost (243476) Vertical section.

See text for explanations.

PART THREE

CHAPTER 9 - CONCLUSIONS

In Part One we have looked at the lithologies of which the complex is now composed and have detected a sequence of structural events which brought about changes in the complex.

In Part Two, particular types of structure were examined in an attempt to specify the conditions under which they were formed. In this way estimates both of the amount and orientation of the strains represented by the structure and the physical properties of the rocks exhibiting the structure have been made. In composite structures revealing several distinct stages of development (for example, refolded folds) it has been shown that only in special cases is the order of the structure-forming stages evident. By this means, a foundation has been built up for the interpretation of regional variations in the morphology of particular structures in terms of factors such as strain, rock-properties and the order of the structure-forming increments.

Part Two described the methods of structural analysis devised for the rocks of this area. They are not necessarily generally-applicable techniques because they hinge on deductions about the conditions under which the observed structures formed. In fact, some of the methods have very limited application, for example it is suggested that folding played different structural roles in different parts of the area and methods of analysis using folds have therefore to be restricted to areas in which all folds are believed to have the same significance. Some existing methods of structural analysis already described in the literature have been criticised because they involve assumptions which are unrealistic in the present situation. Furthermore it is believed that the most realistic assumptions are those embodied in techniques of structural analysis tailor-made to suit the available data in any area.

In many of the methods discussed in Part Two there is an "assumption of homogeneity" problem. Many of the methods used to detect heterogeneities in the complex on a large scale rely on an assumption of homogeneity on a small-scale. This is a problem common to any form of analysis, a complicated system being broken down into simple units for the purpose of description and understanding. The selection of 'homogeneous' subareas then has to be based on observations of the distribution of common field characters and these observations have to be based on detailed regional mapping.

After the application of these methods it was felt that the structural history could only be safely divided into three events (i.e. the pre-dyke, the D2 Laxfordian and post-D2 Laxfordian events). The methods used were inadequate to make possible further divisions.

Other workers in the area (Hopgood and Bowes, 1972) have made more elaborate subdivisions of the history. They have established structural sequences which they have repeatedly observed at various localities in the Outer Hebrides. Although they admit that the characters (e.g. orientation, style, etc.) used in correlation are likely to be inconstant even for contemporaneous structures, they believe by use of pairs (or more) of these parameters they are capable of erecting sequences which can be correlated over large distances.

The work in this thesis throws doubt on these basic assumptions used by Hopgood and Bowes in their technique of "structural sequencing". Earlier it has been shown that the characters of structures belonging to a single phase of deformation do indeed vary greatly. However it has also been shown that regional variation of one character of structures does not go on independently. For example, variation of strain intensity which is likely to give rise to fold-style variation is also likely to cause variation in the degree of development of associated fabrics.

Therefore Hopgood and Bowes' practice of pairing of characters is likely to be unreliable because both characters show variation in a non-independent fashion. Later in this chapter we will summarize the topic of the interdependence of structural characters.

In this section we collect together the results of the devised methods of this structural analysis in order to subdivide this part of the Lewisian complex into tectonic units. The boundaries of the units are arbitrarily chosen because the changes of the state of the complex are continuous. This in itself is an important observation and emphasises the value of more quantitative methods of determining the extent of structural changes.

For the purpose of description, the area can be divided into three units in which regimes of distinctive character are recognized by reference to the amount of Laxfordian deformation.

A. The areas of Low Finite Laxfordian deformation.

The distribution of these areas is shown in Fig. 114 . They include a large area between Carloway, Ben Horshader (245429) and Cleitichean Beag (270368), a strip stretching east from Breasclete and smaller areas on Western Great Bernera and at Dalbeg. The characters of the rocks of these areas can be listed:

1. The Scourie Dykes are often discordant and many are highly discordant to the gneissic banding. Concordant dykes are rare and low deformation of the dykes is indicated by their possession of angular intrusion contacts. The dykes tend to have steep dips.

2. The planar component of the banding is generally poorly developed but the linear component is well developed. This gneiss fabric is that of a shape-fabric defined by populations of fabric-defining elements (veins, pods, lensoids, etc.) and its geometry can be described by a

Flinn k value of considerably greater than 1.0.

3. The main folds are pre-Laxfordian in age with axes parallel to and, in part defining, the main tectonic grain.

4. Boudinage is lacking in the Scourie Dykes and irregularities in the form of the dykes are due to intrusion as much as to later deformation.

5. In places the rocks record practically zero Laxfordian strain. However there are no large areas where Laxfordian strain effects can be thought of as zero. The bulk strain of these areas of low Laxfordian strain is difficult to quantify.

6. Most of the structural features of these areas are inherited from pre-Scourie Dyke times.

B. The areas of Moderate Finite Laxfordian deformation

These areas fringe the areas of Low Laxfordian strain. Another such area occurs in a southeast trending belt from north of Tolstachaolais. The following features are typical:

1. The Scourie Dykes are usually discordant but rarely strongly cross-cutting. The rectilinear angularities of dyke margins attributed to intrusion have been modified and "rounded off".

2. Although the lineation is still strong, the gneiss fabric has taken on a new planarity so that the planar and linear components are more or less equally developed. This can be expressed in terms of a Flinn k value of about 1.0. A banding in a planar sense is now easily detectable. The continuous evolution of this planar/linear fabric system from the areas of low to moderate Laxfordian deformation is compatible with the application of the concept of a shape-fabric to the banding structure of these gneisses.

3. The most spectacular Laxfordian folds in north-western Lewis occur in these areas. They have flat axial surfaces and seem to be

best developed where the dykes provide the necessary anisotropy for the response to stress to be by folding. The greatest discordances of the gneisses and dykes occur in the hinge zones of these recumbent or gently-inclined folds. Some of the tighter folds show extensional structures on their limbs especially where dykes provide the competent layer for boudinage formation.

4. The early Laxfordian phase (D2) was the main episode controlling the banding pattern in these areas. The folds in the gneiss are still defined by the distorted layering dating back in part at least to pre-Laxfordian times.

5. The amount of Laxfordian strain is indicated by folded dykes and pegmatites layers to be at least 10:1 in a plane containing the z direction (Chapter 3) and this absolute minimum value is supported by measurements on folds with boudinaged limbs (Chapter 6). The modification of the gneiss fabrics suggests that the early Laxfordian strain increment had a low k value (possibly approaching zero but definitely less than one).

C. The areas of High Finite Laxfordian deformation

These areas consist of a tract stretching southeastwards from Carloway parallel to the old Carloway-Stornoway road, a tract between Tolstachaolais and Breasclete, the eastern part of Southern Great Bernera together with a discontinuous area of high deformation stretching from the Ben Bragar Hills to Barvas (see Fig. 114 for the more precise location of these areas). The areas about Loch Roag consist of flat-lying gneiss and make up part of the Loch Roag Flat Zone which probably extends to the parts of Central Lewis, south of the island of Great Bernera. These areas have their own special characters, namely:

1. Here the dykes are concordant or nearly so and often occur as boudinaged layers within the gneiss. The lack of visible discordance

poses a considerable problem. Although strain modification can reduce an angle of discordance it cannot eliminate it altogether according to strain theory. It could mean that the angle of discordance had become reduced so as to become undetectable by eye or that it has been eradicated altogether. The latter explanation represents a discrepancy between theory and practice and involves the generation of a completely new banding as opposed to the modification of older banding.

2. The gneiss is now flaggy in aspect with a strong planarity. The early linear contribution is still detectable. The gneissic banding is paralleled by extremely tight or isoclinal D2 fold limbs but although the D2 effects have profoundly modified the gneissic fabrics the banding cannot be termed a "D2 s-surface". It has evolved over a considerably longer time and must be termed a "total fabric".

3. The D2 flattening recorded by the fabrics introduced an anisotropy in the gneiss which made it capable of responding to later stress by folding. The intense flattening down led to a simplification of the structural pattern with earlier features (with the exception of the robust lineation) being modified into obscurity. In this way "the tectonic clock had been reset" in these areas. The interpretation of the geometry of folded rocks which have suffered more than two phases of folding poses enormous untackled problems and it is therefore convenient that in places, virtual obliteration of earlier structures took place allowing study of the later structures in a sequence.

In these areas it is the post-D2 sturctures which are responsible for the arrangement of the banding which became intensified in D2 times, though some variation may date back to D2 times when incomplete planarization took place owing to the presence of bodies of more competent rock (for example, Scourie Dyke boudins) about which the banding wraps. Some of the post D2 structures were oblique to the

earlier structural trend and therefore greatly increased the non-cylindricity of the overall banding geometry.

4. An attempt was made in the chapter on discordant structures to use populations of discordant dykes to determine the Laxfordian strains in these areas. The results were in many ways unsatisfactory probably, I suggest, because the original dyke population had a lack of variety in orientation and was therefore insensitive to modification by strain inclined at a small angle to the orientation maximum.

The extreme re-orientation of planar elements into parallelism or near parallelism is a strong indication that the Laxfordian strains were high. The actual value of the strain ratio is however difficult to calculate. A simple calculation may provide the best guide to the amount of strain involved.

It seems likely that the initial angle of discordance between the dykes and gneiss was variable and the orientation of this discordance expressed as the orientation of the bisector of these inclined planes was probably also highly variable. In these areas of high Laxfordian deformation, the "typical" dyke shows no observable discordance which we will consider to be a discordance of less than three degrees. Let us look at the strains which would be required to reduce the "typical" discordance to "concordance". Taking an "average" angle of discordance (45°) and an average inclination of the discordance to the extension direction of the strain (45°) in a two-dimensional example (Fig. 115) calculations show that a strain ratio of 38:1 is needed to bring concordance about. As the concordance is a three-dimensional feature, the strains are probably approaching those represented by an oblate ellipsoid of 38:38:1.

Figure 116 summarises deductions about the relationship between Laxfordian strains and gneiss shape-fabrics throughout the area. The

lower curve represents the deduced state of strain in the rocks of these tectonic units described. The calculated effects of these strains on a gneiss shape fabric (SSF) are shown by tie-lines linking the lower to the upper curve (which represents the calculated form of the final gneiss fabrics). (Fig. 116). This shows that a theory involving evolution of gneiss fabrics as a result of Laxfordian strain being superimposed on an initially homogeneous Scourian fabric (of linear type) produces results compatible with the field observations of total gneiss fabric types.

Figure 114 shows the configuration of high, moderate and low deformation zones on the map. This map was constructed using the mean discordance shown by Scourie Dykes throughout the area. The low deformation areas are those where the average dyke is moderately or strongly discordant to the banding, the moderate deformation areas are taken as areas where the dykes are on average slightly to moderately discordant and the high deformation areas correspond to areas where the dykes are concordant or slightly discordant.

It is an interesting outcome of this work that many alternative maps could have been used to express these deformation differences, for example,

1) the map showing the occurrence of F3 folds (Fig. 112)
2) the map of gneiss-fabric types (Fig. 49), i.e. massive, flaggy, etc.,
3) the map showing the distribution of F2 fold style (Fig. 18)
4) the map showing the distribution of the dominant fold phase (Fig. 10)
5) a map (not drawn here) showing the areas where the macrofabrics defined by banding populations for the

46 subareas (Fig. 63) reveal girdles (linear macrofabrics) and where they defined point concentrations (planar macrofabrics).

6) a map (not drawn here) showing the occurrence of linear fabrics (on a small scale) in the gneisses and planar fabrics in the gneisses.

All of these maps would have been equally capable of revealing the main tectonic divisions in the area. This underlines the phenomenon of the inter-relation of many structural features, the way certain structures are harbingers of other structures and the way differences in the structures are inherited and used accordingly by later deformations.

The low deformation area boundaries on Fig. 114 follow the regional strike and curvatures of the F2 fold axial surfaces in the neighbourhood of the southwestern margin of the main Cleitichean low deformation area. (Fig. 60) suggests that the boundary of this less deformed block may have a southwesterly dip. The northeast margin of this low deformation area is not so clear. In Chapter 2 we have seen that variation of the dip of F3 fold axes suggests a curvature of the D2 strain trajectories which in turn could be due to refraction about a more resistant (low deformation) block. These deductions led to the suggestion that the rocks trending southeastwards from north of Tostachaolais (an area of moderate finite Laxfordian deformation) could lie just within a low deformation body of gneiss (but on its lower side). This is illustrated in Figure 117 . These deductions are far from conclusive but could indicate that some low areas are disc-like and that the enclosing deformed gneiss could have the form of a megafluxion structure - the low deformation sheets packed like apples in a crate with the more highly deformed rocks wrapping around them (Fig. 117). If the low and high deformation areas have this configuration a deformation

mechanism for the complex of N.W. Lewis as a whole during the Laxfordian may be indicated.

The development of a megafluxion structure could be envisaged in two sets of circumstances: either the complex consisted of more competent masses in a matrix of less competent gneiss, or the gneiss was initially more homogeneous but small differences of competence combined with a strong plastic component in the rheological constitution of the gneiss led to continued yielding of the first-deformed locations in the gneiss leaving less-deformed bodies. No obvious large scale lithological variation occurs to account for this structure by the first option. A strongly plastic model for syn-metamorphic deformation of gneiss could be envisaged if the metamorphism which accompanied deformation reduced the competence of the deformed zone relative to the undeformed gneiss. Rocks which are undergoing changes on the crystalline scale are logically going to be able to yield to strains on a larger scale. In this way, the bulk strain of the rocks would tend to be accommodated locally in high deformation zones.

A suggestion put forward by Coward (1973) that low deformation areas in South Uist correspond with zones rich in Scourie Dykes is attractive because it would account for the initial small competence differences necessary to bring about divergent rates of strain in the plastic material. However, the non-parallelism of zones of abundant Scourie Dykes and zones of low finite Laxfordian deformation casts doubt on the validity of this suggestion in the area under discussion. Nevertheless, smaller scale low deformation strips up to about one hundred metres in width could owe their existence to the presence of larger dykes below the level of exposure. Possible examples of this occur in areas on either side of the valley at Dalbeg, south of the Dalbeg Granite. These low deformation areas, like those on a larger scale, grade into

more deformed gneiss on either side. An attempt to reproduce experimentally this reworking configuration may be a fruitful line of future research. The need for transitional variation in the properties of the material may favour the investigation of a physical analogue using the computer (the finite element method) rather than scale-modelling in a deformation box.

We have seen that many of the diagnostic features of the different structural domains can be accounted for by the varying influence of Laxfordian modification. However, what do we know about the character of the complex in late Scourian times and how uniform was it? The evidence suggests that the area was not at this stage an isotropic block like that of the ganulite facies massif on the mainland at Scourie. Instead, a strong linear structural grain had been imprinted - a grain which was to survive subsequent periods of reworking. Several lines of evidence, already discussed, together with the lack of any strike-swing on moving from low to high deformation zones, suggest that the grain was Laxfordianoid (NW-SE) in the central part of Lewis. The direction of D2 fold axes give some further idea about the pre-Laxfordian strike. They reinforce the northwesterly Scourian strike for the central part of the area and the simple maxima of fold axes point to a relatively simple late Scourian structural pattern. In the rocks south of Carloway the consistent sense of intersection of the Scourie Dykes with the gneisses is evidence in agreement with this deduction. In Harris however (Myers 1968, Graham 1969) it seems that folds supposedly equivalent to D2 folds had axes with less uniformity in orientation which may signify that the late Scourian structural situation was more complicated. The E-W trends of the D2 fold axes in the coastal rocks between Carloway and Barvas prompts the conclusion that the unique strike shown by these rocks had its origins in pre-Laxfordian times.

We have therefore a picture of an area in central Lewis of relatively simple and uniform Scourian structural pattern bounded by peripheral areas with oblique or diverse Scourian trends. On the grounds of strike and structural character which are distinct from the Badcalliqn (Park 1970) of the Scourian block of the Scottish mainland, it is tempting to designate central Lewis an Inverian area (Park 1970) in the Scourian. This is dangerous however, because a distinct event correlatable with the Inverian episode has not so far been recognized here.

The swarm of dykes, the Scourie Dykes, intruded before the Laxfordian, were typically nearer easterly than southeasterly in direction in central Lewis and there is some indication that the original trend of the Scourie Dykes varied on a regional scale within the whole Lewisian from a southeasterly to easterly strike. The original trends of the Scourie Dykes can only be projected linearly across to those of the mainland if a trancurrent Minch Fault is postulated (Chapter 8).

The main effect of the early Laxfordian (D2) was a flattening-down of Scourian structures with strains of an oblate type producing considerable areas of flat-lying gneisses which include the Loch Roag Flat Zone. The Loch Roag Flat Zone appears to extend southwestwards from the current area of study. Other extensive areas of flat-lying gneissic banding have frequently been recorded in Precambrian gneiss complexes (e.g. Pulvertaft 1973). Sometimes it has been possible to deduce that the flat banding is constituted of the limbs of tightly appressed folds (Pulvertaft 1973) but the significance of this intense horizontal flattening in terms of a regional structure is a subject of doubt. It is not necessary to emphasize the 'space' problems involved in accommodating horizontally displaced material away from

large areas of flattening strains of axial ratios of the order of 38:38:1. The diapiric intrusion of upward-moving granitic material which would produce a local stretching within the overlying gneisses with the development of such high strains over small areas seems inadequate to account for large expanses of flattened gneisses. In short, sufficient information about the large scale structure to which the observed strains are related is lacking in this area.

Within the scale of the area, the early Laxfordian event was a structural "modifier" rather than a structure "former". No large scale D2 folds have been detected but if such folds exist, the area as a whole lies on the south-dipping limb of a flat-lying structure. In fact, structures and fabrics evolved in the early Laxfordian from structural "ancestors" dating back to Scourian times. The effects of the Laxfordian strains on the fabric evolution has been summarized already in Fig. 116

A change in the character of the deformation took place after the early Laxfordian. The late Laxfordian (post D2) saw an end to the normal run of fabric and structural evolution. This change was brought about in two ways. Firstly, recrystallization of certain areas was associated with a disruptive tectonic process unable to contribute to the constructive evolution of the gneisses. Secondly, folding started to utilize the anisotropy produced by early fabrics and eventually gave rise to the development of new oblique fabrics rather than the enhancing of original fabrics. If there are such things as cycles of reworking, the late Laxfordian represents the "disordering", "randomizing" or "tectonic retrogression" phase of the cycle. In this respect, the early/late Laxfordian division is of more profound structural significance in this area than the Scourian/Laxfordian break.

In this thesis less emphasis has been placed on a purely historical subdivision of the complex in terms of the enumeration of fold phases

because this method alone has been found to be inadequate to describe the changing state of the rocks in time and space. Instead the variations of structures belonging to particular events have been used to give clues to the layout of the components of the deforming system.

The designation of areas of the Lewisian as Scourian or Laxfordian is impractical in this area owing to the combined contribution made by these events to the structural framework. Instead special attention has been paid to the quantitative assessment of the extent of reworking processes to provide an alternative basis for the subdivision of this part of the Lewisian.

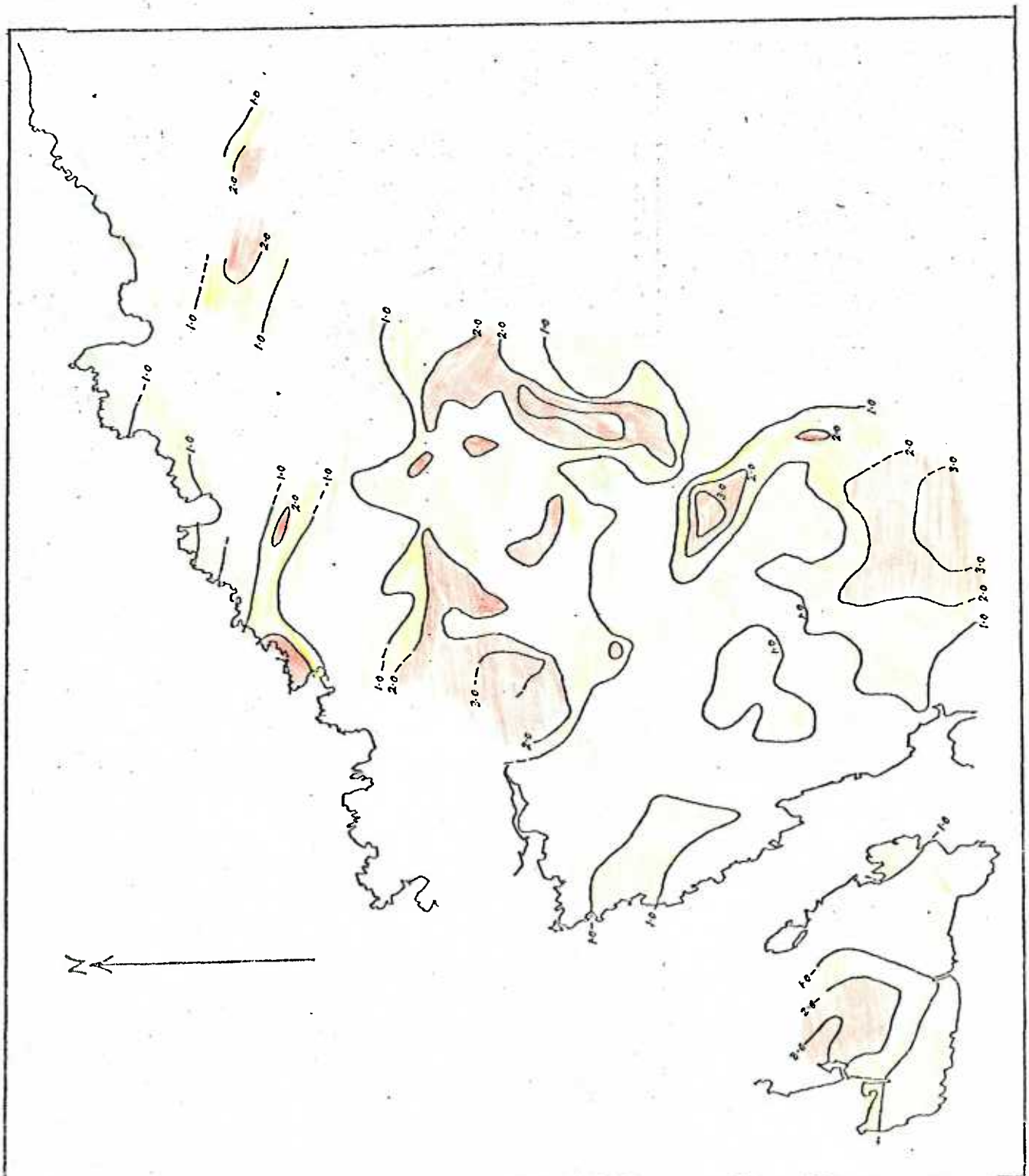
FIGURE 114

STRAIN CONTOUR MAP FOR THE LAXFORDIAN DEFORMATION IN N.W. LEWIS

The contours were calculated from the discordant dyke data shown in Figure 95

1.0 = slightly discordant, 2.0 = moderately discordant, 3.0 = highly discordant.

Red = areas of low Laxfordian deformation (> 2.0)
Yellow = areas of moderate Laxfordian deformation (1.0-2.0)
Green = areas of high Laxfordian deformation (< 1.0)


1.0
2.0
3.0
N

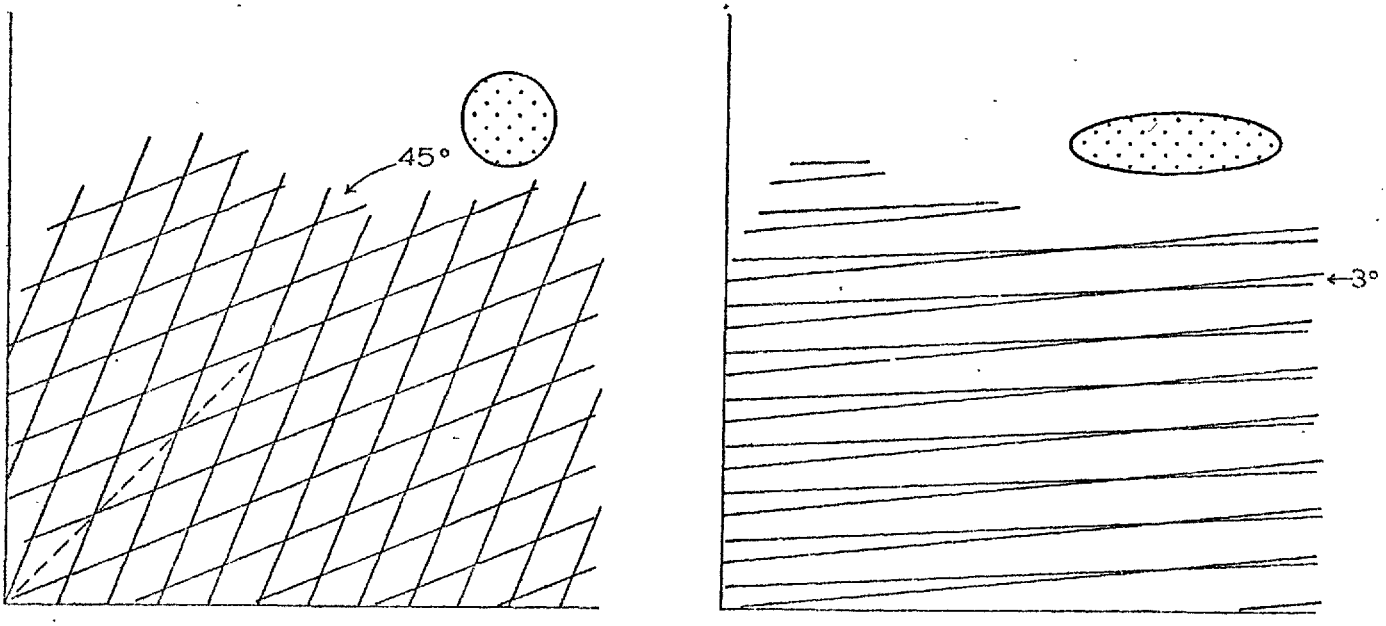


FIGURE **115**

The modification by strain of an 'average' discordance (45^{O}) initially inclined at 45^{O} to the extension direction to less than 3^{O} discordance (or 'effective concordance').

A strain ratio of 38:1 is required to bring about this change.

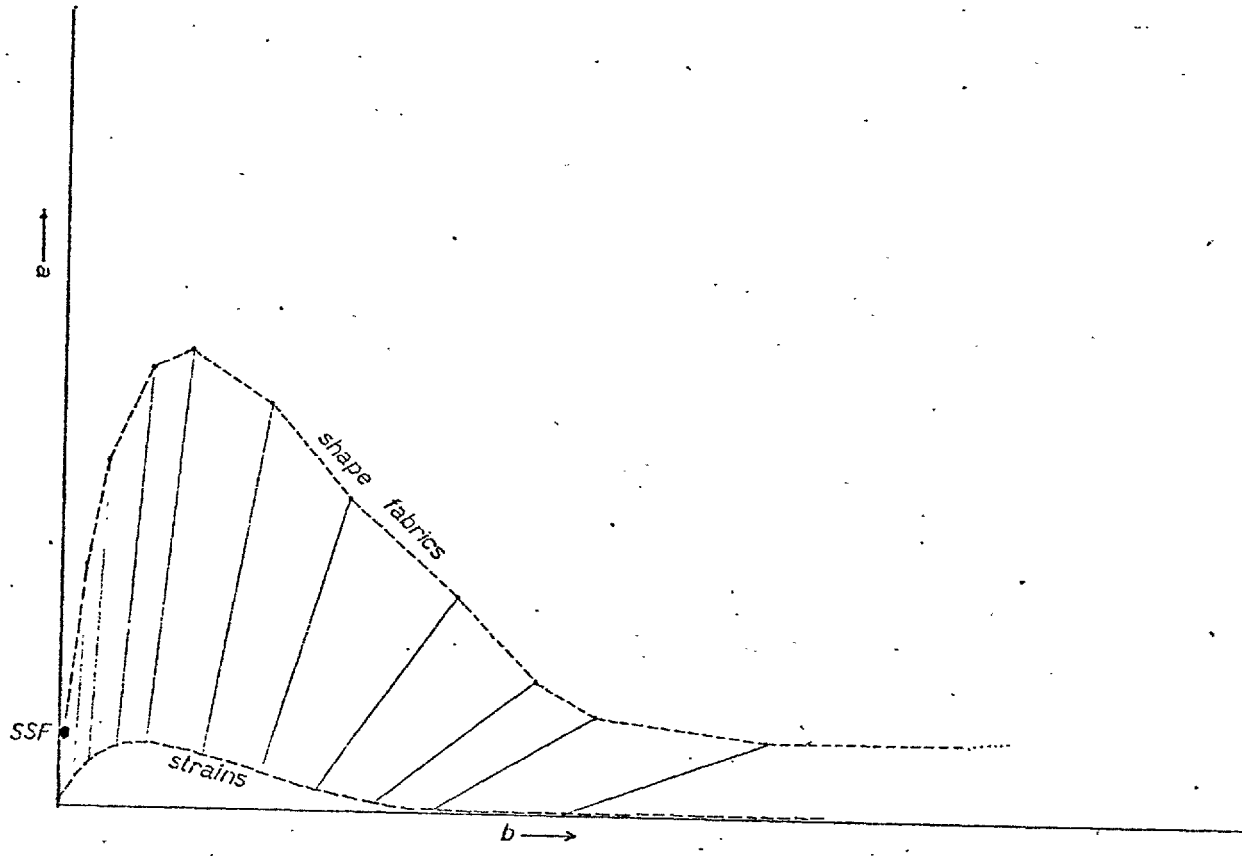


FIGURE 116

THE CUMULATIVE ORIGIN OF OBSERVED SHAPE -FABRICS.

Laxfordian strains (lower curve) are superimposed on a Scourian shape - fabric (SSF) to give observed shape - fabrics (upper curve).

Solid lines link the observed fabric to the required Laxfordian strain for its development.

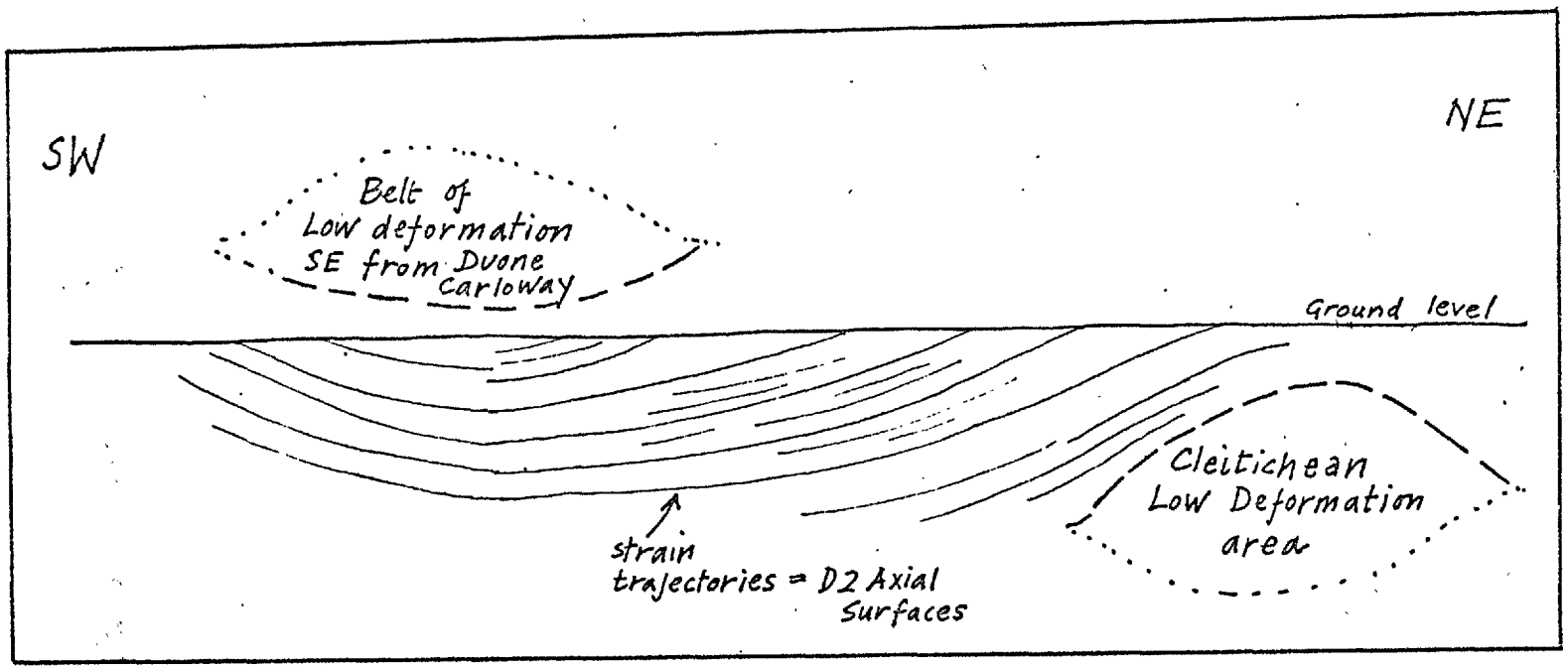


FIGURE **117**

A SECTION FROM TOLSTACHAOLAIS TO THE NORTH-EAST OF THE CARLOWAY-STORNOWAY ROAD showing the envisaged "megafluxion" structure.
The diagram is based on Figures 112, 114 and 60.

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APPENDIX 1

COMPUTED NON-CYLINDRICITY FACTORS FOR BANDING SUBAREAS

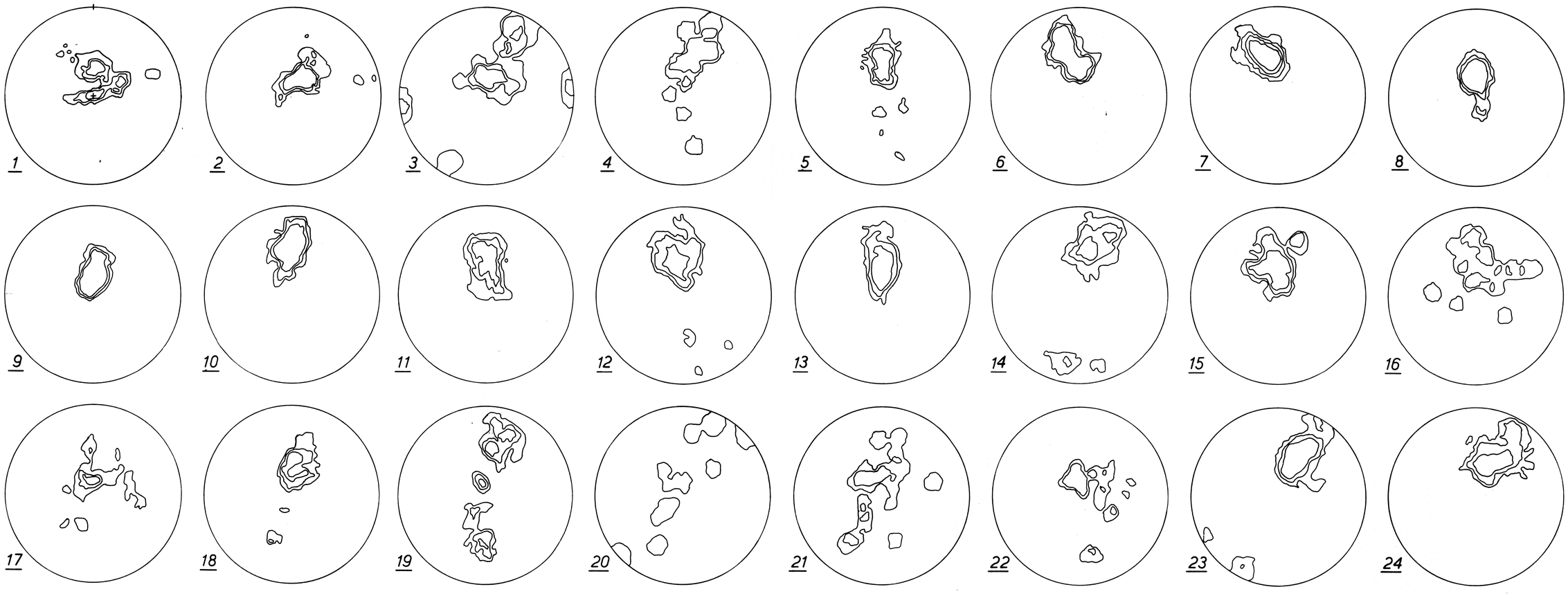
N = Number of data (banding measurements)

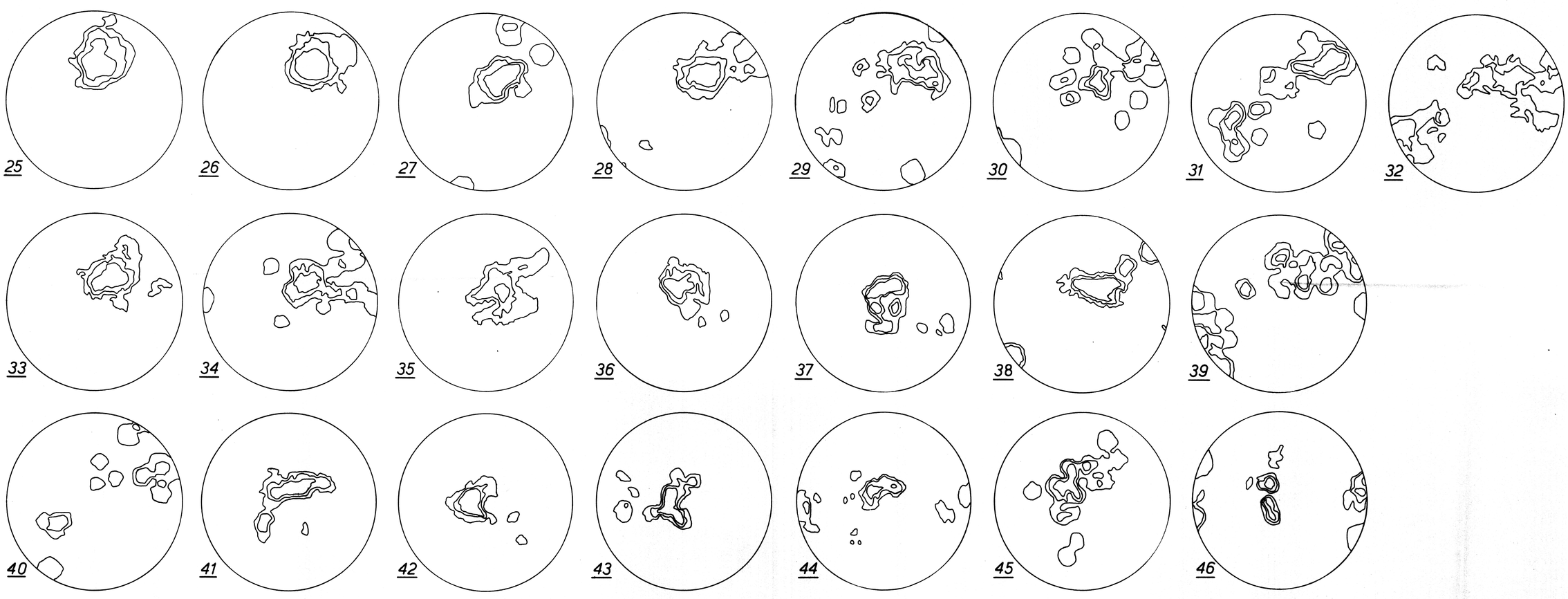
NCF = Non-cylindricity factor

BFGC = Best-fit great circle through banding poles

SUBAREA	N	BFGC	NCF
1	46	90/093	0.39297
2	52	78/346	0.24958
3	32	85/299	0.31354
4	19	70/306	
5	191	90/088	0.27215
6	103	80/066	0.33690
7	435	70/047	0.27345
8	143	86/083	0.16369
9	183	83/290	0.15575
10	89	75/283	0.23168
11	269	80/078	
12	119	85/073	0.26135
13	120	88/275	0.19799
14	159	65/312	0.39513
15	58	85/076	0.24436
16	22	85/281	0.39618
17	84	78/020	0.48276
18	103	85/286	0.36507
19	47	80/100	0.27409
20	14	80/292	0.23277
21	22	75/295	0.32415
22	40	77/031	0.40737
23	132	80/310	0.30559
24	101	70/321	0.26148
25	210	80/286	0.25970
26	197	74/324	0.30016
27	38	80/324	0.22440
28	141	70/344	0.30904
29	59	80/327	0.34624
30	26	81/330	0.32001

31	33	78/326	0.24766
32	125	78/338	0.38088
33	130	80/323	0.28560
34	39	78/342	0.24519
35	242	90/323	0.33329
36		90/254	0.31848
37	58	85/298	0.38656
38	57	85/325	0.30439
39	31	80/330	0.31837
40	15	87/155	0.31860
41	66	80/348	0.29810
42	126	80/325	0.37528
43	50	80/318	0.39668
44	117	78/249	0.58811
45	31	74/297	0.26815
46	43	82/272	0.57438





POLES TO GNEISSIC BANDING Contours 2, 4, 8% per 1% area

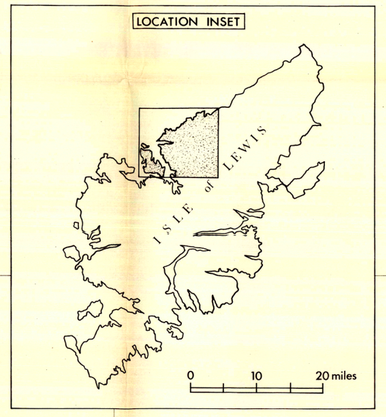
FIG. 63

FIG. 5.

THE GEOLOGY OF CARLOWAY AREA ISLE OF LEWIS

0 1 2 miles

LOCATION INSET



N

20 25 30

45

CARLOWAY

LOCH CARLOWAY

Lt. BERNERA

EAST LOCH ROAG

GREAT BERNERA

Breasclete

40

935000

15 20000 25 30

EXPLANATION

- Grey Gneiss
- Normal dykes
- Cleitichean-type } Scourie Dykes
- Mafic types
- Gneisses of supracrustal origin
- Basic Gneisses & old Amphibolites
- Ultrabasic Gneisses
- Granite
- Early lineation
- Scourian fold axis
- Scourian axial surface
- Banding F = Flat banding
- F3 fold axis
- F3 axial surface
- Boundary observed
- Boundary inferred
- Limit of outcrop