CORRELATION OF EVENTS AFFECTING THE MOINE ROCKS BORDERING THE SOUND OF SLEAT, INVERNESS-SHIRE, SCOTLAND

A thesis presented for the degree
of Doctor of Philosophy by
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1976

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ABSTRACT

The study area lies within the marginal part of the Caledonian orogen of the Northwest Highlands of Scotland. The aim of the thesis was to attempt to correlate events from the marginal Moine thrust zone eastward into the Mobile Belt. The correlations included stratigraphy, structure and metamorphism.

Stratigraphic correlations were restricted to Moine lithologies hitherto undifferentiated; they included rocks on the Sleat Peninsula of Skye, and in Eastern Knoydart.

Structural and metamorphic events are closely related, and developed as a result of two distinct orogenic episodes.

The earliest of these orogenic episodes occurred during the Pre-Cambrian and resulted in deformation on a regional scale producing tight, often flat lying structures. The metamorphic grade increased from west to east. Microfabric studies enabled a close correlation between the second phase of deformation and the advance of the metamorphic front.

The youngest orogenic event is the Caledonian event which produced open profile, upright structures, associated with a second metamorphic event, which also advanced from east to west.

It has proved possible to correlate structural and metamorphic events over an area of some 1,100 sq.kms. within the Moine nappe.

Further studies established that structural and metamorphic events recorded in the Moine nappe may be extended to include the underlying Tarskavaig nappe.

Wider correlations were also attempted; firstly in immediately adjacent areas and subsequently on a more regional scale. The discussion of regional correlations includes data presented in the literature for areas both within the Moine thrust zone and within the Mobile Belt. Although the suggested correlations may be only tentative, there would appear to be some basis for regional correlation.

ACKNOWLEDGEMENTS

The project was initiated and supervised by Dr. D. Powell to whom thanks are due for help in the field and later discussions. I am grateful to him for constant enthusiasm and for providing the opportunity to work in the Highlands. His advice and criticisms during the final stages of this project were particularly appreciated.

The study was financed by a Natural Environment Research Council grant which is gratefully acknowledged.

Of the many colleagues in the Geology Departments of Bedford College (London University), and the University of Adelaide, South Australia, especial thanks are due to N. Charnley, B. Jackson and Dr. P. Banham (Bedford College), and J. Cottle, R. Glen and W. Laing (University of Adelaide) for advice and assistance. Appreciation is extended to Dr. T. Hopwood and Professor R.W. Rutland for helpful criticism of the final manuscript.

During the field work, numerous people provided hospitality and kindness. In particular, I am deeply grateful to Shaunehan MacDonald, Isabel Moore, Kirstie McInnes, Angus Peter McLean, Don and Alison Pomfret, Mr. E. Bailey, the staff at Camusrory Adventure School, and the factor of Knoydart, Mr. Lewis. I would also like to thank Shoras and Roddie for their almost constant attention to my unreliable car.

I am indebted to Mrs. L. Clark and Mrs. J. Brumby for typing the thesis.

Finally, I extend my sincere thanks to my parents, family, and especially to Patrick, for their constant optimism and encouragement, and their unfailing belief that it was all possible.

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CHAPTER 1. INTRODUCTION

1.1 Regional setting.

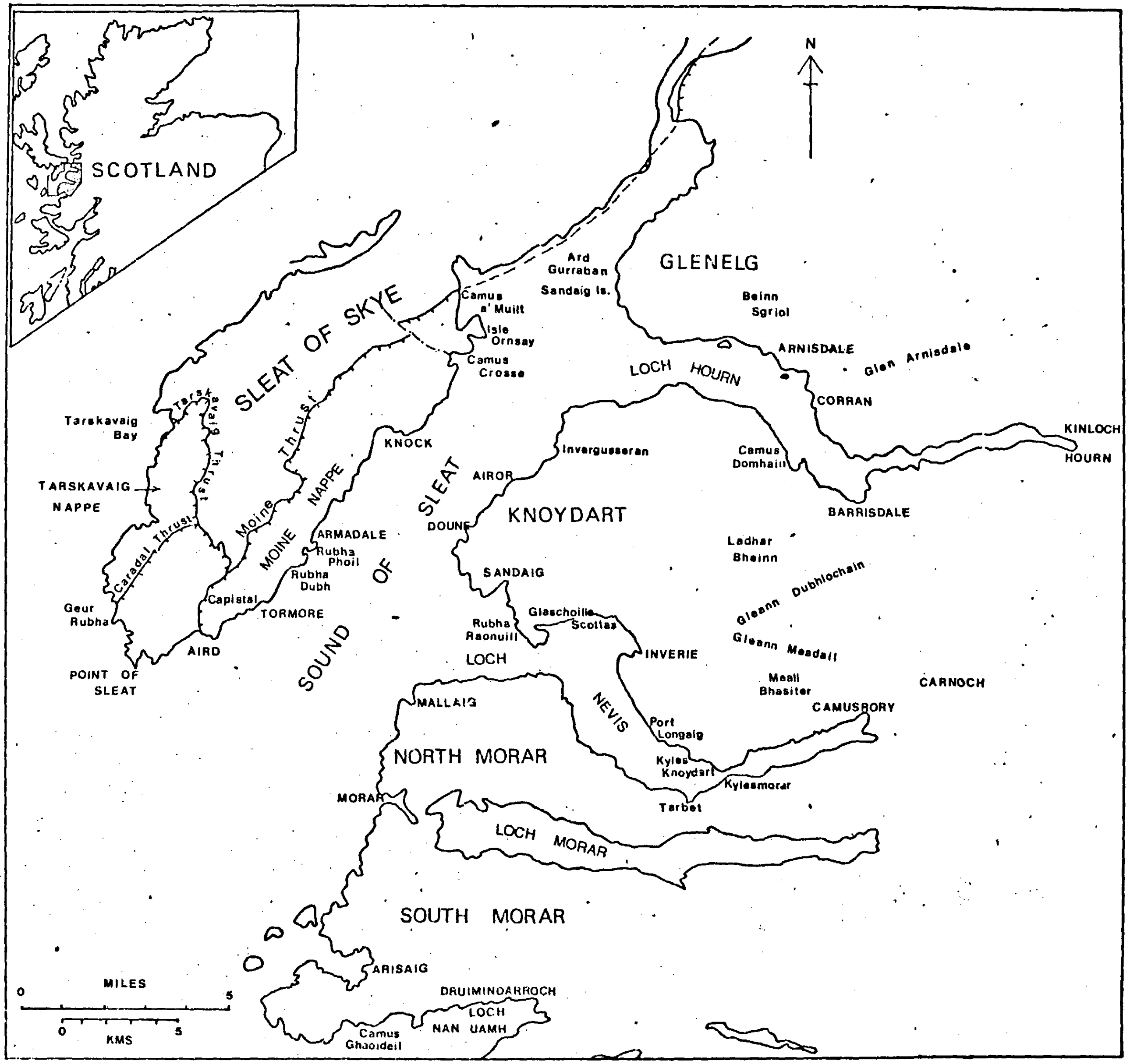
The area of this study lies in western Inverness-shire, and forms part of the North-West Highlands of Scotland. It includes the Sleat Peninsula of Skye and the adjacent mainland, extending eastwards from the coast for some 35 km., and covering a total area of approximately 1,150 square kilometres (see map Fig. 1). Three sub-areas of this ground, southeast Skye, Knoydart and south Morar (Arisaig) have been mapped in detail. Reference is made later to the adjacent areas of Tarskavaig, Glenelg, and North Morar (Chapters 6 and 7).

The altitude of the terrain varies from sea level to over 1000 m. with generally good exposure on the coast, in glacial valleys and on glacial pavements on the higher ground. Some areas of moorlands and peat bogs are very poorly exposed but these do not generally constitute important gaps.

Geologically the area lies within the mobile belt of the Scottish Caledonides; the larger part of the study being devoted to rocks within the Moine nappe, which represents the highest member of the pile of nappes or thrust sheets, thrust over the foreland during the culmination of orogenic events of the Caledonian orogeny (Bailey 1955, Kennedy 1955, Richey & Kennedy 1939). Study of the Moine thrust zone, which in this area outcrops on the southeast side of the Sleat peninsula, and marks the northwest limit of the mobile belt,has also been undertaken. The two main rock groups of the area comprise the older Pre-Cambrian Lewisian basement gneisses and schists, and the younger Moine metasediments. The Lewisian rocks record intense prograde metamorphic events prior to the deposition of the younger Moine sediments, and in some areas retrogressive events of Caledonian or later age. The Moine rocks show a progressive increase in metamorphic grade from west to east throughout the region; from biotite-garnet grade in the west, to kyanite-sillimanite in the east.

The younger group of rocks comprising the Moinian assemblage is the most relevent to this study. They are metasediments belonging to the Morar division of Western Inverness-shire (Johnstone et al. 1969), which is considered to be the oldest of the Moine divisions, which overlies Lewisian "basement" in the west. This division is succeeded eastward by the younger Glenfinnan and Loch Eil divisions, but suggested age relations between the three Moinian groups has yet to be proven.

FIGURE 1. LOCATION OF RESEARCH AREA AND PLACE NAMES REFERRED TO IN TEXT



The Morar division contains four main lithostratigraphic units; - the Basal Pelite, the Lower Morar Psammite, the Morar Schists (or Striped and Pelitic Group) and the Upper Morar Psammite (Richey & Kennedy 1939, Ramsay & Spring 1962, Powell 1964).

Limited study has been made of the underlying Tarskavaig nappe on the Sleat of Skye. This involved investigation of the Tarskavaig "Moines" whose stratigraphic and structural relationships with the Moines (s.s.) and significance will be discussed following that of the main investigation of the Moine nappe (Chapter 6).

1.2 Outline of problems and of thesis aims

The Moine rocks of the N.W. Highlands have been the subject of geological investigations since 1892 (see Geikie et al., 1892, Chapter 2); however, little attempt has been made to produce a synthesis of the results emerging from these, and subsequent, investigations. In this study an attempt has been made to correlate the stratigraphic, structural and metamorphic events which have affected the Moine and Tarskavaig Nappes of this part of the Caledonides. Critical areas were selected in Skye, Knoydart and Morar, and details of the geological histories within these areas have been elucidated, with a view to correlating events from the Moine thrust zone in the west, into the centre of the mobile belt further east. As this area represents one of both polyphase deformation and metamorphism, the unravelling of these events forms the bulk of the investigation undertaken.

The reappraisal of the structure and metamorphism in the three strategic sub-areas has permitted a wide correlation of events to be made. A history of four main phases of deformation and two major metamorphic peaks has been established within the area. Stratigraphic correlation was largely achieved by Richey and Kennedy (1939), Ramsay and Spring (1962), Powell (1964) and Poole (1966) and summarised by Johnstone et al. (1969). This was followed by the publication of the Geological Survey Sheet 61 (in 1971) which covers the Knoydart, Morar and Moidart area. Discussion of problems of stratigraphic correlation is therefore limited here to the recognition of different members of the Morar division in Skye and east Knoydart, and their regional implications.

Finally an attempt has been made to correlate events established within the area of research with adjacent areas, on a more regional scale (Chapters 6 and 7). This has included investigations of selected areas within the Moine nappe in Glenelg, North Morar and North Knoydart (Chapter 7), and the study of the events which have effected the underlying Tarskavaig nappe. The investigation has attempted to determine whether the two nappes have structural and/or metamorphic histories in common, and if so, the regional implications of these in the overall evolution of the Caledonian orogenic belt (Chapter 7).

The increasing number of radiometric age determinations has recently raised the argument of there being more than one orogenic episode represented in this area. Using the published radiometric ages and detailed analyses of field relations, and especially structural and metamorphic relationships, it is proposed that both Pre-Cambrian and Caledonian orogenic events have affected the area (Chapters 4, 5 and 8).

1.3 Methods of investigation

Much of the investigation was carried out during the field seasons of 1972, 1973 and 1974, with a total of 15-16 months spent in the field. Mapping was carried out using aerial photographs (scale approximately 1:25,000) and Ordnance Survey maps 1:10,560 (6" = 1 mile), 1:10,000 (metric where available) and 1:25,000 (2½" = 1 mile). Where more detailed mapping proved necessary enlarged maps at 1:2,500 (25" = 1 mile) were used.

Detailed mapping of the rocks above the Moine Thrust on Skye was undertaken. Lewisian rocks immediately overlie the Moine thrust plane, and these in turn are structurally overlain by Moine metasediments along parts of the southeastern seabord of the Sleat Peninsula (see Fig. 22, Chapter 3). Retrogression of the Lewisian metamorphic rocks during the Caledonian orogeny and late stage brittle deformation, especially prominent in the Lewisian schists adjacent to the thrust plane, precludes any clear synthesis of events prior to thrusting in these rocks. Unretrogressed Lewisian rocks east of the thrust plane were mapped to establish their structural history in relation to the Moine "cover" rocks. Mapping was also carried out to determine the nature of the boundaries between adjacent, but discordant, areas of Moine rocks; and the Moine and Lewisian.

In south Morar an east-west traverse along the northern shore of Loch-nan-Uamh, across the western limb and into the core of the Morar Dome, was carried out. Part of this area was mapped by Lewry (1964, unpublished Ph.D. thesis), and given his basic geological mapping the concern of this study was to establish local structural/metamorphic relations, and to relate these, if possible, to those already established in Skye.

The field seasons of late 1973 and the major part ~~majority~~ of 1974 were spent in Knoydart which lies due east of the outcrop of the Moine nappe on the Sleat of Skye, but is separated from the island by the six kilometres width of the Sound of Sleat (Fig. 1). Western Knoydart, north of Gleann Dubhlochain (between grid refs. 700990/700100 and 830010/830100, Fig. 1) was mapped by Spring (1960, unpublished Ph.D. thesis). The present survey includes the majority of Springs' area and in addition the ground lying to the south of Gleann Dubhlochain, southwards to the north shore of Loch Nevis. Little detailed mapping has been previously undertaken since the work of the Geological Survey in 1939 (Kennedy et al.). This sub-area passes from metamorphosed low-grade rocks with recognisable sedimentary structures in the west, into migmatised, high grade rocks in the east, where detailed sedimentary structures are not preserved and gneissic banding represents metamorphically modified sedimentary layering. The method of investigations in this area again consisted of mapping of selected, essentially east-west (across-strike) traverses. An arbitrary eastern limit of mapping occurs at the head of Loch Nevis.

The textural relationships of minerals throughout the area have been investigated in order that details of the structural evolution in relation to the progressive metamorphism evident from west to east could be evaluated.

1.4 Thesis Plan

Evidence will be presented to show that structural and metamorphic events are closely related, and that two distinct tectono-thermal events may be recognised. It is assumed that this distinction is valid and the evidence pertaining to each of these events is presented and discussed separately (Chapters 4 and 5).

The implications of this subdivision is then discussed in relation to the possibility of the presence of the effects of both Pre-Cambrian and Caledonian orogenies represented in the area (Chapter 8).

Chapter 2 deals with the evolution of ideas on the Moine rocks since 1888 (Geikie 1888), and covers stratigraphy, structure, metamorphism and radiometric age data. This synthesis shows that the information although often very detailed, is restricted to localised areas, with understandably little attempt by previous workers to correlate events within the Moine nappe as a whole. The available age determinations are analysed to show the two broad peaks of ages at approximately 420 Ma and 750 Ma, suggest two main separate thermal events.

Chapter 3 presents stratigraphic correlations in the light of the present research, and proposes correlations of the Moine rocks on Skye, east of the Moine thrust plane, with different groups of the Morar Division of the Moine assemblage.

Sedimentary and structural evidence in east Knoydart also permits confirmation of the stratigraphic position of the rocks in this area with members of the Morar succession.

The relationship between the Moines (s.s.) and the Tarskavaig Moines which occur within the Tarskavaig nappe beneath the Moine thrust, is discussed in Chapter 6. Stratigraphic correlations are tentatively suggested, and the structural and metamorphic events which affected this group of rocks are correlated with those recorded in the Moine nappe (Chapters 6 and 7).

Finally, overall correlations concerning the evolution of the Moine nappe are dealt with in Chapters 7 and 8. Regional implications dealing especially with the adjacent areas of Glenelg, Loch Alsh, Kinloch Hourn and the Tarskavaig nappe are discussed, as well as more general problems dealing with Moine, Torridonian and Dalradian relations.

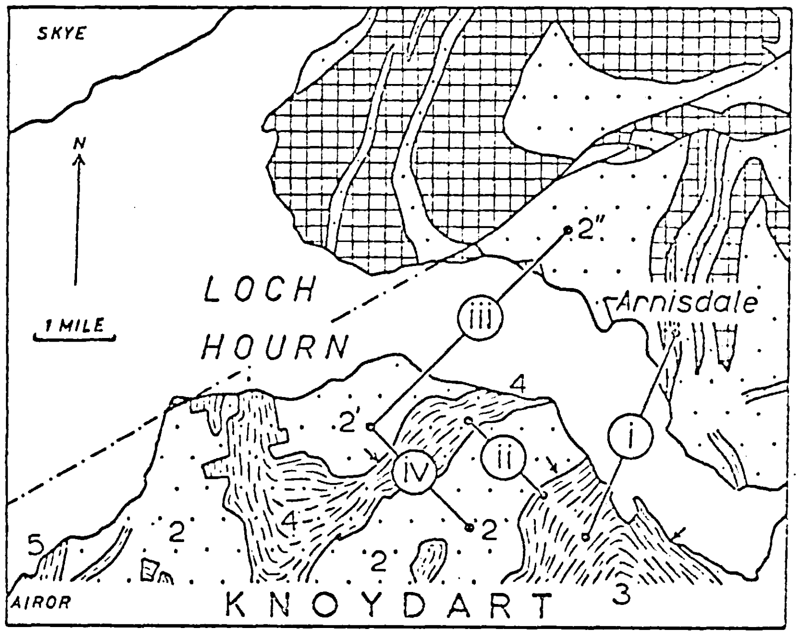
CHAPTER 2 PREVIOUS RESEARCH AND GEOCHRONOLOGY

The rocks of the North West Highlands of Scotland have been the subject of geological discussion since the late 1800's. Members of the geological survey of Great Britain first commenced investigations into the complexities of the geology of the N.W. Caledonian belt, publishing the results of these early surveys in Summaries of Progress of the Geological Survey (1897-1910). This publication was an initial attempt to summarise the facts that had been gradually accumulated by officers of the survey (i.e. Peach, Clough, Anderson, Carruthers and Geikie) over the previous decade for the Glenelg, Loch Alsh and southeast Skye areas (see Summaries of Progress for 1897, 1898, 1899 and 1904). The final report (Peach et al. 1910) outlined the fundamental difference between basement Lewisian rocks and the cover of the Moine series. The subdivision of the Moine rocks outlined by Clough (in Peach et al. 1910) is shown in Figure 2.

Although the two major groups of rocks represented in this area (the Lewisian gneisses and the Moine schists) had many features in common in both structure and metamorphism, it was conclusively established that the Moine series was younger than the Lewisian. Clough noted the amount of gneissose material and unusual rock types (eclogite, marble, kyanite schist and hornblende gneiss) and the occurrence of deformed basic dykes in the Lewisian, none of which occurred in the adjacent Moine rocks. The additional discovery in 1899 of a conglomerate at the Moine-Lewisian junction further supported his proposal for an older Lewisian basement overlain by younger Moine sediments.

Several other factors were also discussed, including the relationship of the common deformation and metamorphism to later post-Cambrian folding and thrusting evident within the major Moine thrust zone; and also the evidence for earlier phases of deformation affecting the Lewisian gneisses prior to the deposition of the Moine sediments.

Evidence for the culmination of Caledonian orogenic activity prior to or during Devonian times was also postulated in the 1910 memoir, with the statement that, "the general metamorphism of the Lewisian gneisses and the Moine series was completed and was much as it is now, before these (the Glenelg-Ratagain, Old Red Sandstone age) igneous rocks were introduced."



1. Basal Pelite.
2. Beinn na Caillich Psammite.
2'. Psammite correlated with 2.
2". Psammite correlated with 2'.
3. Ladhar Beinn Pelite.
4. Rubha Ruadh Semi-Pelite.
5. Airor Pelite

Fig. 2. The rock divisions of the Loch Hourn area established by Clough and his suggested correlations. (Fig. 2, Ramsay and Spring, 1962).

One of the many controversies concerning the Moine rocks involved their stratigraphic relations with the Torridonian rocks. More than 70 years after Peach (1892, p.262) first suggested that, "the Moine rocks were altered representatives of certain Torridonian rocks", it is interesting to note that research work is still involved with this same problem (Moorbath, 1973), and a universally accepted correlation is still to be established.

Subsequent investigations into the Moinian and Lewisian rocks of the Caledonian fold belt concentrated on a better understanding of the points raised in this early publication (Clough in Peach et al 1910). Research in the 1930's was limited to the Morar-Knoydart area with little further detailed investigations of the Moine and Lewisian of Skye until the 1950's (Bailey, 1955), apart from some microfabric studies carried out by Phillips (1937 and 1945).

The discovery of only slightly deformed Moine rocks on the west coast between Morar and Arisaig by Richey in 1935 enabled a stratigraphic succession (the Morar succession) to be established (Fig. 3) in this area (Richey et al. 1937). Richey and Kennedy (1939) divided the rocks of the Morar-Knoydart area into a sub-Moine series and a Moine series on the basis of differing lithological character, metamorphic state and amount of deformation. The sub-Moines included intensely folded ortho-gneisses and para-gneisses, which outcropped in the core of what is now called the Morar Dome (a north-south trending anticline extending approximately 10 km. north, and 8 km. south of Loch Morar, Fig. 1). The Moines (s.s.) on the other hand were considered to be a group of metasediments which formed the limbs of this anticline, exhibiting well preserved sedimentary structures, e.g. current bedding, ripple bedding and slump folds (Richey, 1936 and Richey and Kennedy, 1939). Sedimentary structures (ripple markings) had already been reported by Tyrrell (1931) from Moine "sediments" at Mallaig.

The presence of abundant way-up criteria in the Moine metasediments enabled Richey and Kennedy (1939) to demonstrate a stratigraphic succession within this area (Fig. 4). They also distinguished a structural succession in the core gneisses, although the order of deposition here could not be ascertained (Fig. 4). Richey and Kennedy (1939 and 1944) advocated that the sub-Moine rocks were recumbently folded before the deposition of the Moines and that the two series were separated by a now folded plane of discordance, which was in all

FIGURE 3a After Richey (1935 and 1937 - Summ. of Progress of Geol. Surv. G.B.)

Stratigraphic succession of the Morar Moines

1935		1937
1. False bedded psammitic schist; interbedded with group 2 at base	b. Massive pink felspathic psammitic schists, often pebbly with frequent false bedding a. Thinly bedded pale or white psammitic schists with abundant false bedding with occasional beds of semipelitic schist	LOWER PSAMMITIC GROUP
2. Semipelitic and pelitic schists; interbedded with group 1 at base	c. Semipelitic and finely striped schists with thin layers of calc-silicate schists and thin seams of magnetite-zoisite rock b. Garnetiferous mica schist a. Finely striped and semipelitic schists	STRIPED AND PELITIC GROUP
3. False bedded pinkish felspathic psammitic schists		UPPER PSAMMITIC GROUP

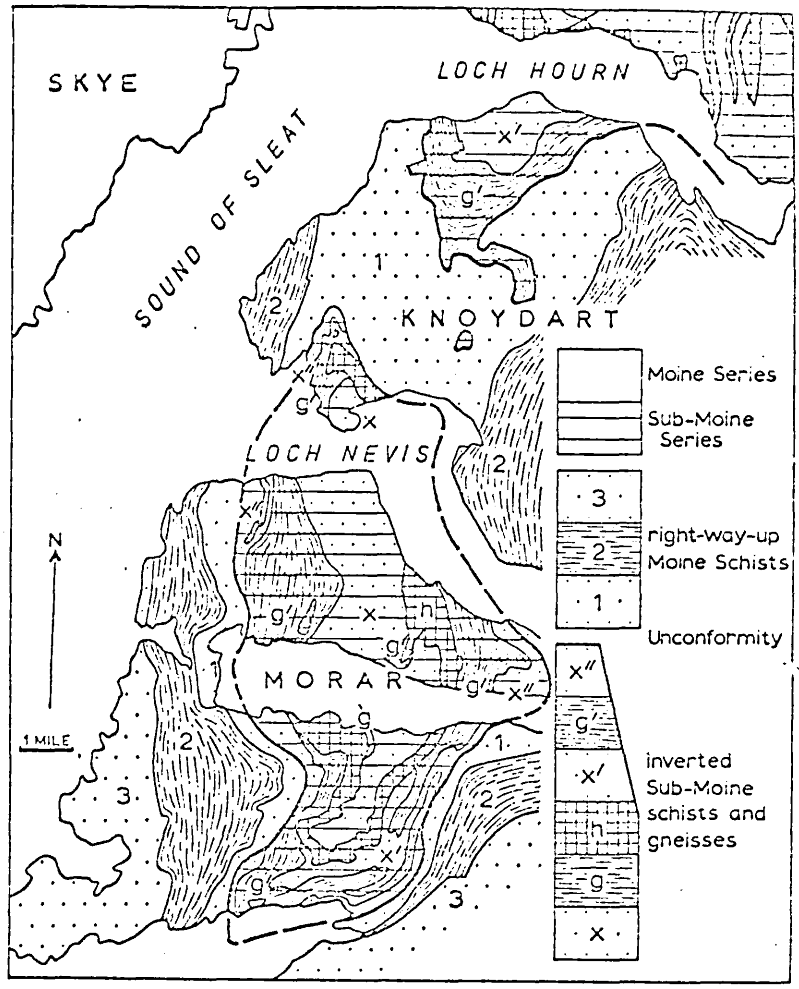
FIGURE 3b Structural Succession of the "Core" rocks (Sub-Moine) of Igneous and Sedimentary gneisses after Richey (1937).

(a) Psammitic gneiss with epidote-rich bands near the top.

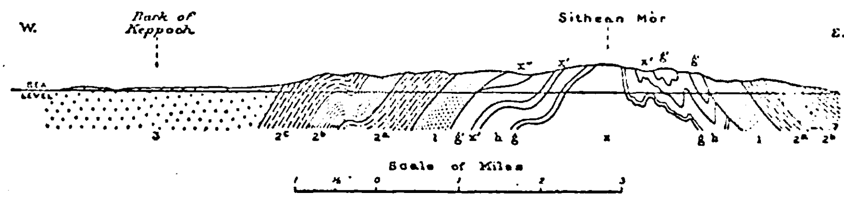
(b) Hornblendic and felspathic rocks, forming injection gneisses with sedimentary gneisses of groups (a) and (c) as host rocks.

(c) Striped and banded psammitic-pelitic gneisses.

(d) Psammitic gneisses, showing rodding, locally with thin band of hornblendic and felspathic gneiss.



The Moine/Sub-Moine interpretation of the stratigraphy of the Morar and Knoydart areas proposed by Richey & Kennedy (1939)



Horizontal Section across the Morar Anticline along an E.—W. line about 1½ mls. S. of Loch Morar.

Sub-Moine Series: x, Central Psammitic Group; g, Subsidiary Striped Group; x′, Intermediate Psammitic Group; g′, Main Striped Group; x″, Outer Psammitic Group; h, Hornblendic Gneisses.
Moine Series: 1, Lower Psammitic Group; 2a, Lower Striped Sub-group; 2b, Pelitic Sub-group; 2c, Upper Striped Sub-group; 3, Upper Psammitic Group.

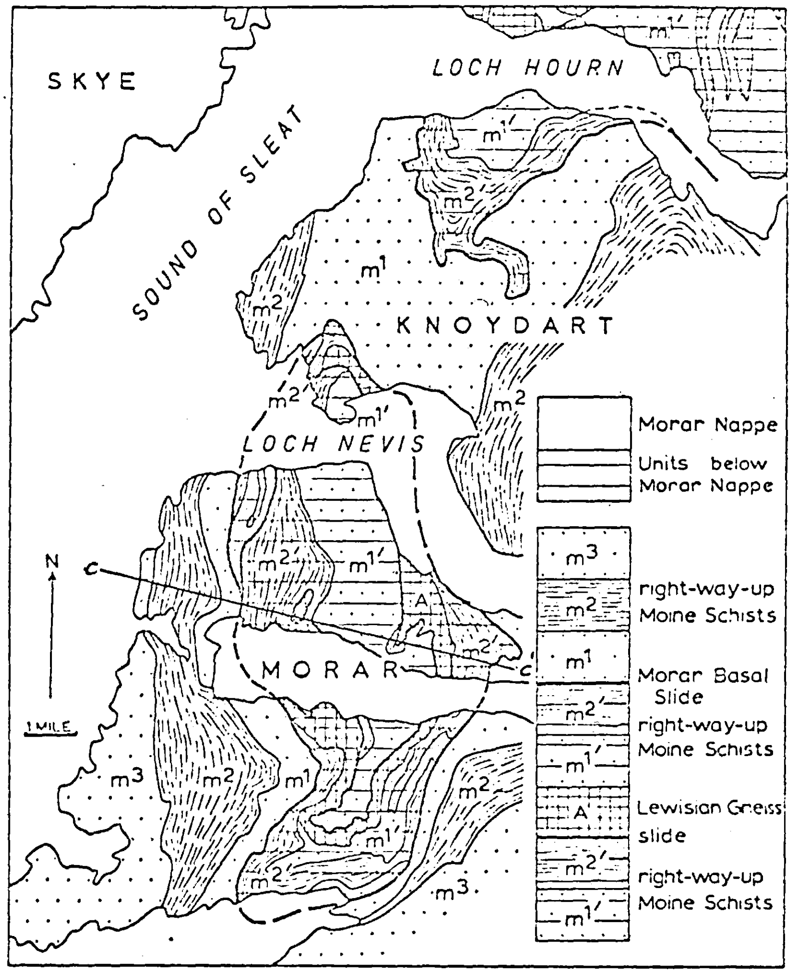
Fig. 4. The stratigraphy and structure of the Morar-Knoydart areas after Richey and Kennedy (Fig. 6, 1939; and Ramsay & Spring, Fig. 3, 1962).

probability an unconformity (Fig. 4). MacGregor later (1952a and b) put forward two major objections to the Richey and Kennedy interpretation. The first of these was the lack of significant differences between the granulites of the Moine and the sub-Moine series. MacGregor (ibid. 1952) remarks on the transitional nature of the junction between the Moine and sub-Moine series, suggesting an alternative proposal to explain the distribution of the Moine and sub-Moines. He postulated that by reduplication of the Moine schists of what was then called the Morar nappe in the core of the Morar anticline, there would be no further need for the proposed discordance between the Moines and sub-Moines.

In 1955, Kennedy revised his earlier views and suggested that the old sub-Moine series represented reduplicated parts of the lower Moine Succession with gneisses of Lewisian type occupying a window in the Upper Moine or Morar nappe. The Lewisian type gneisses he suggested had been tectonically incorporated into the Moine series during the formation of a tectonic slide (or discontinuity) which separates this group of rocks from the Moine series of the Morar nappe. The rocks below the slide, he referred to as the "core" rocks, and those above it as the "envelope" rocks (Fig. 5). Kennedy's interpretation was based on the hypothesis that the discontinuity between the complex "core" and the simply folded "envelope" Moine rocks, initiated as a slide in the lowest part of the original Moine succession, drove upwards and westwards thereby reduplicating the lower stratigraphic groups and incorporating Lewisian basement. Kennedy suggested that the interfolded Moine and Lewisian rocks of the Glenelg area further north represented an analogous structure, forming the core of the Loch Hourn-Glenelg anticline. Deformation during subsequent regional metamorphism and injection of the Moine schists, folded the slide and resulted in the formation of the Morar and Loch Hourn-Glenelg anticlines, thereby exposing the reduplicated "core" rocks.

Kennedy, however, still suggested differences in the metamorphic features of the "core" and "envelope", although MacGregor (1948 and 1952) had pointed out their transitional nature, and Read (1956) later argued strongly against the possibility of recognising continuity of metamorphic zones through rock formations which were geologically and petrologically dissimilar.

Later work by Lambert (1958 and 1959) supported MacGregors transition concept, and showed that the boundary represented a transition



Interpretation of the stratigraphy of the Morar and Knoydart regions after Kennedy (1955)

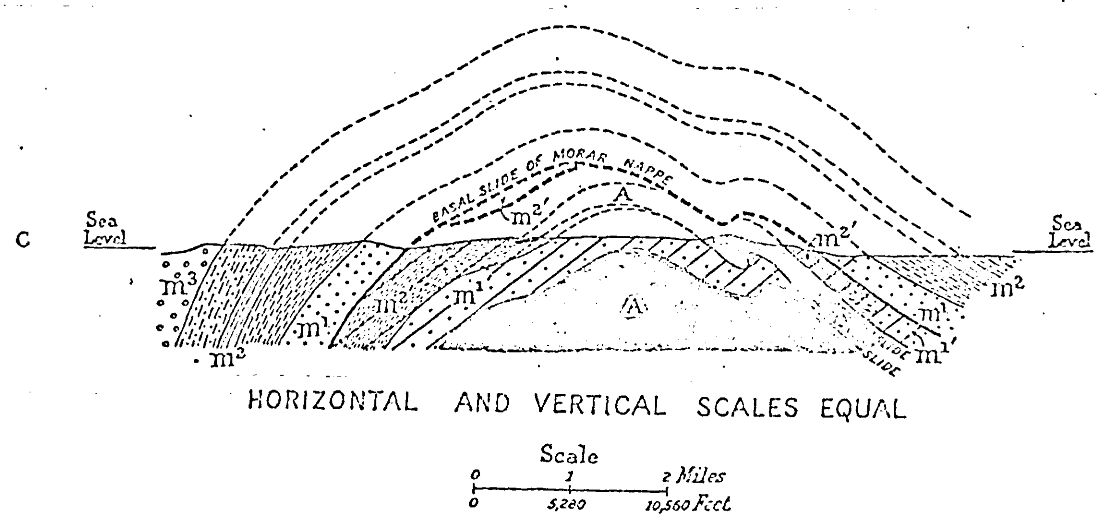


Fig. 5. Kennedy's revised stratigraphy and structure of the Morar-Knoydart areas (1955). (Fig. 4, Ramsay & Spring 1962; section from Kennedy 1955). C-C marks the line of section.

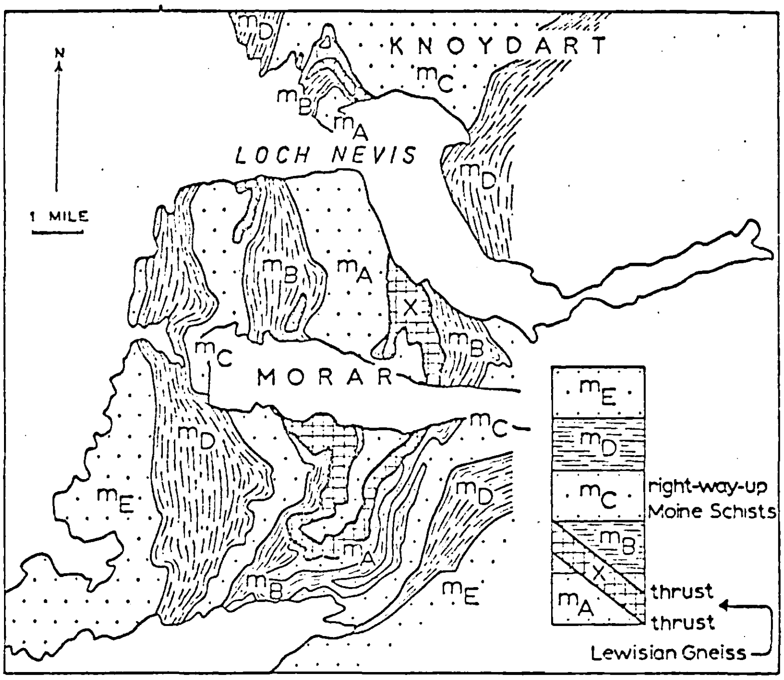
between two metamorphic states and that it transgressed the geological contacts. This "transition zone" included non-gneissose rocks of Lewisian mineralogy but devoid of hornblende (which on the one side was adjacent to massive Lewisian hornblende gneisses), followed by muscovite-biotite semipelite or pelite allied to Moine type but showing no sedimentary features. These "Moine type" rocks pass into Moine units where sedimentary structures are represented. Hence the metamorphic grade could range from high grade gneissic rocks to semipelitic low-grade rocks over a matter of 30 metres (Lambert 1963).

Lambert (1958 and 1959) implied that he did not accept the Morar Basal Slide or Kennedy's structural hypothesis. He proposed a further succession (Fig. 6), the base of which is not exposed. Lambert's map (see Fig. 6) differs from those published previously, the Moine-sub-Moine boundary being replaced by a metamorphic core-envelope boundary. This therefore supported the views of Wilson et al. (in discussion of Kennedy 1955); and slightly modified the positions of lithological contacts.

As well as the stratigraphic and structural problems in this area of the N.W. Highlands it is necessary to consider the implications of metamorphic events. MacGregor (1952) and Kennedy (1948 and 1949) generally accepted that the grade of metamorphism of the Moine schists increased from west to east towards the belt of injection metamorphism. Read (1934) however regarded the lower grade of the western Moines as a retrograde effect associated with the thrusts. Both Kennedy (1948 and 1949) and Read (1934a and 1940) believed the early Caledonian metamorphism of the Moines to be related to heat diffusing outwards from the intrusion of the "older granites".

MacGregor, on the other hand (1952), suggested that the dislocation metamorphism of the schists above the mylonites associated with the Moine thrust plane, was high (not less than garnet) grade, the thrust movements having taken place while the recrystallizing schists were still hot. According to this view, regional metamorphism, thermal zoning and migmatization were penecontemporaneous and of early Caledonian age, and the thrust dislocations occurred late in the same period.

Bailey (1950) citing evidence from Moine and Lewisian rocks in Skye, stated that the similarity in metamorphic condition of the two groups of rocks was due to recrystallization accompanying movement along the Moine thrust; thus enabling the crystallization of



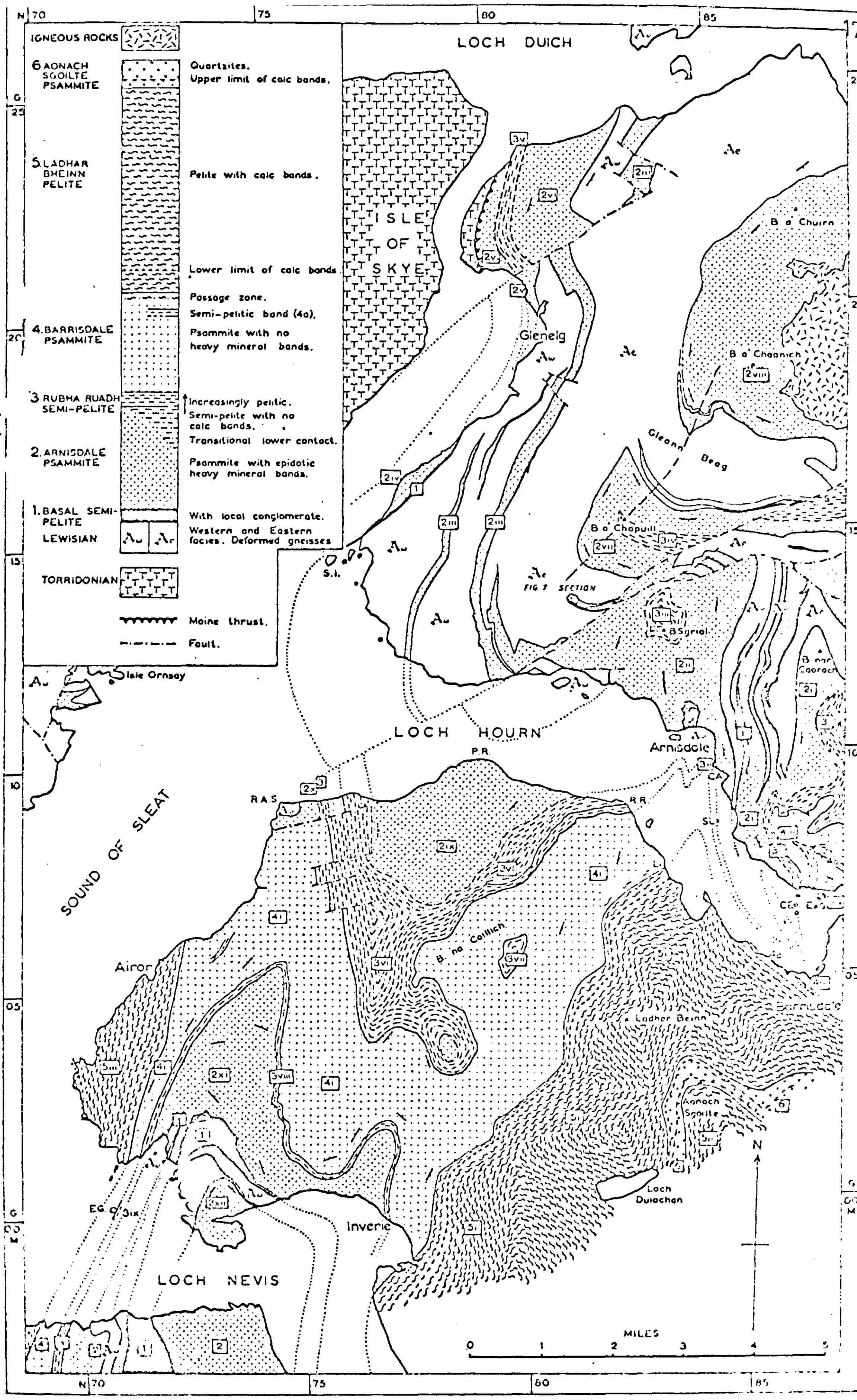
Interpretation of the stratigraphy of the Morar and S. Knoydart areas after Lambert (1958, 1959)

Fig. 6. Lambert's stratigraphy of the Morar-Knoydart areas (1958 & 1959). (Fig. 5, Ramsay & Spring, 1962).

garnet and albite in the Moines and simultaneous crystallization of hornblende and albite in the Lewisian. This implied that the Moine sediments were unmetamorphosed prior to thrusting, and that metamorphism of the Moine schists was consequently of late Caledonian age. Later, however, Bailey (1955) concluded that metamorphism of Moine sediments was of early Caledonian age and therefore prior to thrusting. The sudden increase of metamorphic grade above the Moine thrust, he stated, was due to both eastwardly increasing metamorphism within the Moine nappe as a result of pre-thrusting early Caledonian metamorphism, and substantial post-main crystallization transport of the Moine nappe. Consequently the narrow zone of dislocation metamorphism adjacent to the thrust itself was of later Caledonian age than the Caledonian metamorphism of the Moine nappe as a whole. Johnson (1957) also represented evidence that the thrust movements were distinct from, and later than, the movements which gave rise to the regional structures of the Moine schists.

The following years saw an influx of workers, not only those connected to the Geological Survey concerned with Moine-Lewisian problems of the Scottish Highlands. Various theories were proposed to account for the presence of Lewisian rocks in the cores of early (F_1) folds, incorporating both thrusting and infolding of Lewisian rocks. Ramsay (1958) proposed that during the initial phases of deformation affecting both cover and basement in the Glenelg district, the basement had been sliced up, the slices becoming involved in the folding and behaving like beds. Sutton and Watson (1959) suggested that thrust slices of Lewisian basement formed the cores of F_1 folds in the Moines. It is probable that both mechanisms occur.

By the 1960's the stratigraphic position of the succession within the Moine rocks was still confused, but work by Ramsay and Spring (1962) did much to establish a revised succession in the Glenelg, Loch Hourn and Knoydart regions. This succession (Fig. 7) consists of six members; three pelitic and three psammitic. Tentative correlations were made with groups in the Morar region to the south. In the discussion of the Ramsay and Spring paper (1962) and in a later publication (1964) Powell confirmed the correlation suggested by Ramsay and Spring for the south Morar area and compared his Lochailort stratigraphic succession with that suggested by Richey and Kennedy in 1939 (Fig. 8). Poole (1966) from work in the N.E. Morar region, extended the correlation of the Glenelg-Knoydart succession of Ramsay and Spring (1962) to this area



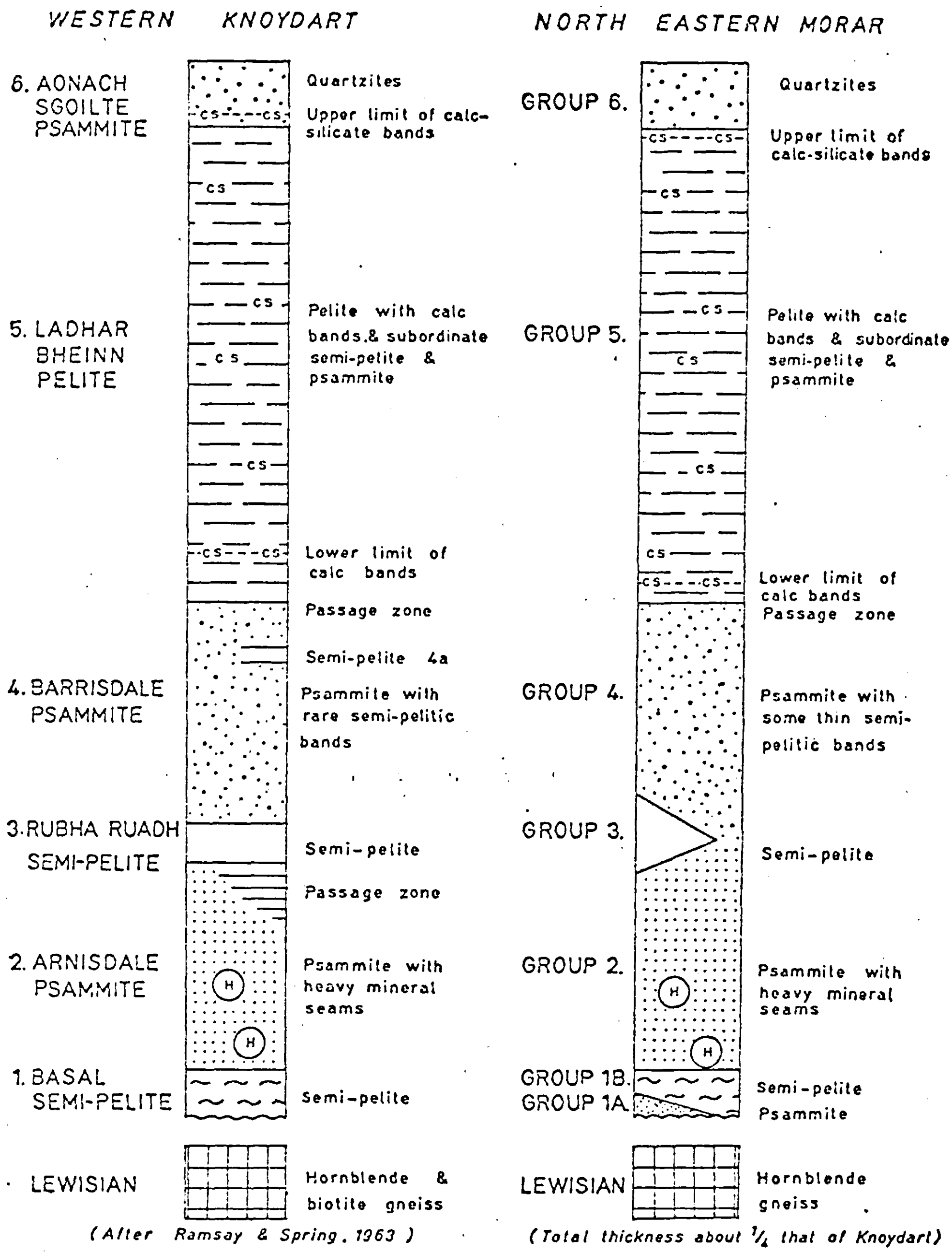
The new interpretation of the stratigraphy of the Glenelg and Knoydart areas. C.A.: Crudh 'Ard; C.E.: Cor Eileanan; E. a' G.: Eilean a' Garbh-lain; E.G.: Eilean Glas; P.R.: Priest's Rock; R.A.S.: Rubh 'Ard Slisneach; R.R.: Rubha Ruadh; S.: Strathcomair; S.I.: Sandaig Islands; S.L.: Sceir Leathan [To face p. 308

Fig. 7. The stratigraphy of the Glenelg and Knoydart areas after Ramsay and Spring (Fig. 6, 1962).

FIGURE 8 Correlation of Successions, after Ramsay & Spring 1962, Richey & Kennedy 1939, and Powell 1964

Younging direction

	Glenelg-Knoydart Succession	Morar Succession	W. Lochailort Succession
1.	Basal Semi-pelite	Subsidiary Striped Gp (g)	Beasdale Pelitic Gp.
		Main Striped Gp. (g_1)	
		?Intermediate Ps. Gp. (x)	
2.	Arnisdale Psammite with magnetite and epidote bands	Central Psammite Gp. (x) both with magnetite and epidote bands	
		Outer Psammite Gp. (x_{11})	
		Lower part of envelope	
		Lower Psammite Gp. (m_1)	Loch Nan Uamh Psammite Gp.
3.	Rubha Ruadh Semi-pelite Gp.	Semi-pelitic beds within the Lower Psammite Gp. (m_1)	
4.	Barrisdale Psammite	Upper part of Lower Psammite Gp. (m_1)	
5.	Ladhar Beinn Pelite	Striped and Pelitic Gp. (m_2)	Loch Mama Pelitic Gp.
6.	Aonach Sgiolte Psammite	Upper Psammite Gp. (m_3)	Ardnish Psammite Gp.
	Not represented	Not represented	Lochailort Pelite



A comparison of the stratigraphic successions of west Knoydart and north-eastern Morar (not drawn to scale).

Fig. 9. The stratigraphic correlation of Western Knoydart and North Eastern Morar. Suggested by Poole (Fig. 1, 1966).

(Fig. 9).

Johnstone et al. (1969) included the correlations suggested by Ramsay and Spring (1962) in a summary paper which correlated work by numerous authors (Richey & Kennedy 1939, Powell 1964, Tanner 1965, Clifford 1958, Dalziel 1966, Dalziel & Johnson 1963). Figures 10 and 11 show the extent of this correlation within the Morar, Loch Hourn, Lochailort, Ardgour and western Inverness-shire regions and also the tentative extrapolations into Ross-shire (Fig. 10). The Moine assemblage here has been subdivided into three major units. The Morar division, the units of which are considered to be the oldest Moine rocks, is confined to the west, adjacent to the foreland Lewisian rocks, and is succeeded by the Glenfinnan and Loch Eil divisions further east. Sedimentary structures in the Morar Division show younging directions in these rocks away from the Lewisian, towards the Glenfinnan division. The Glenfinnan division includes Powell's (1964) Lochailort Pelite and the Glenfinnan Striped schists (Dalziel 1963). Sedimentary structures are lacking in these rocks but the structural and stratigraphic evidence in the Lochailort region (Powell 1964) enables the stratigraphic position of this division to be placed as younger than the Morar Division on the basis of the stratigraphic position of the Lochailort Pelite. The apparently youngest, Loch Eil division, overlies the Glenfinnan division (Dalziel 1966).

According to Anderson (1948) the Loch Eil division Moine rocks pass conformably into the Lower Dalradian rocks of the West Grampians. If this is so, problems arise concerning the evolution of the Moine nappe where Pre-Cambrian orogenic activity and undisturbed sedimentation occurred apparently simultaneously. These problems will be discussed later (see p. 24).

Tanner (1970 and 1971) extended the stratigraphic correlation within the Moines to include the area around Kinloch Hourn (Fig. 1). He (ibid. 1970 and 1971) recognised two successions; the Kinloch Hourn and Runival successions, which are separated by a tectonic break, the Sgurr Beag Slide.

The Runival succession is equivalent at least in part to the Glenelg-Knoydart succession, with the occurrence of the Ladhar Beinn Pelite in both successions (Fig. 10). The lowest member, the Main Psammitic Group, has been equated with Clifford's (1956a) Siliceous

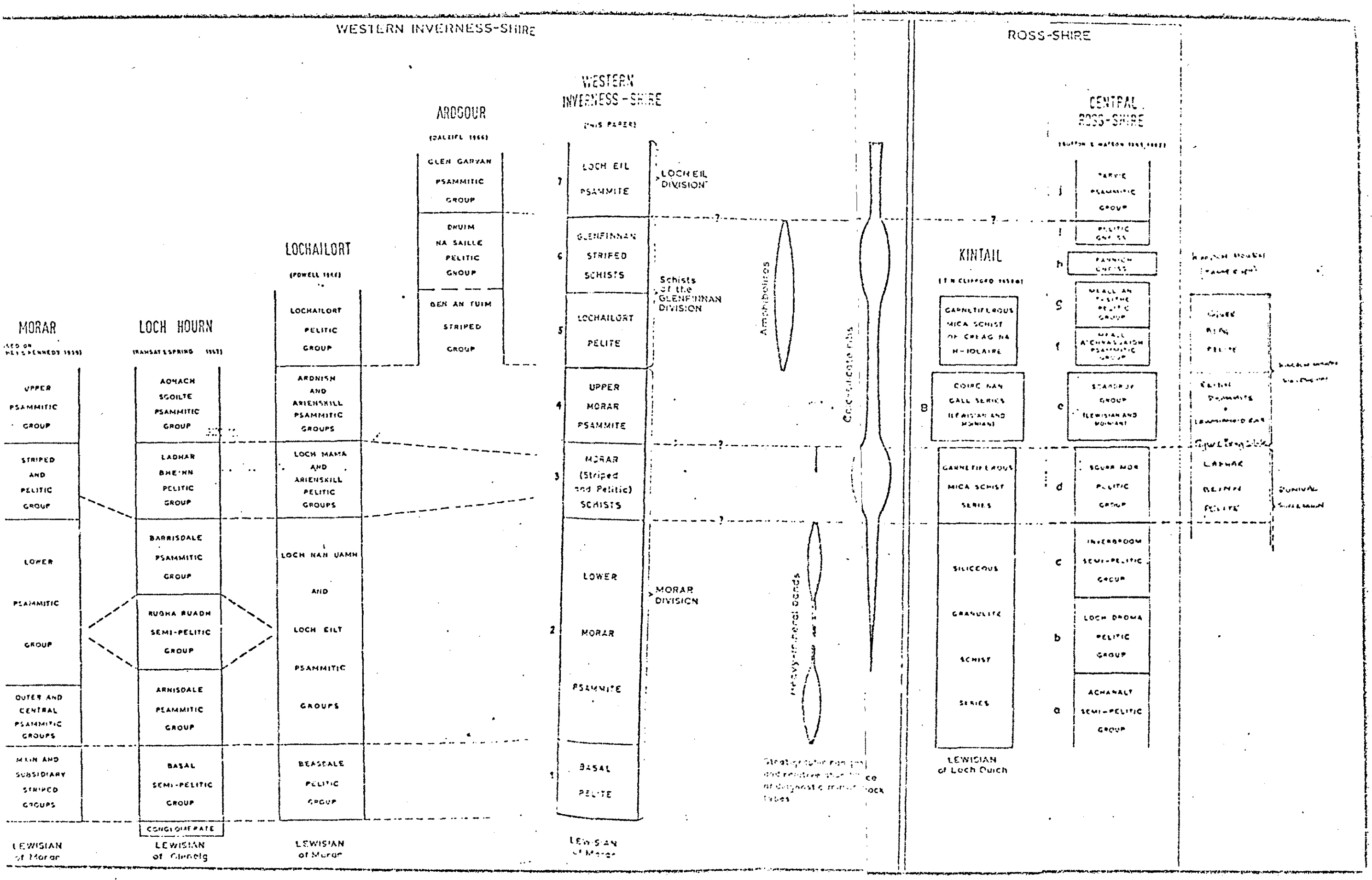
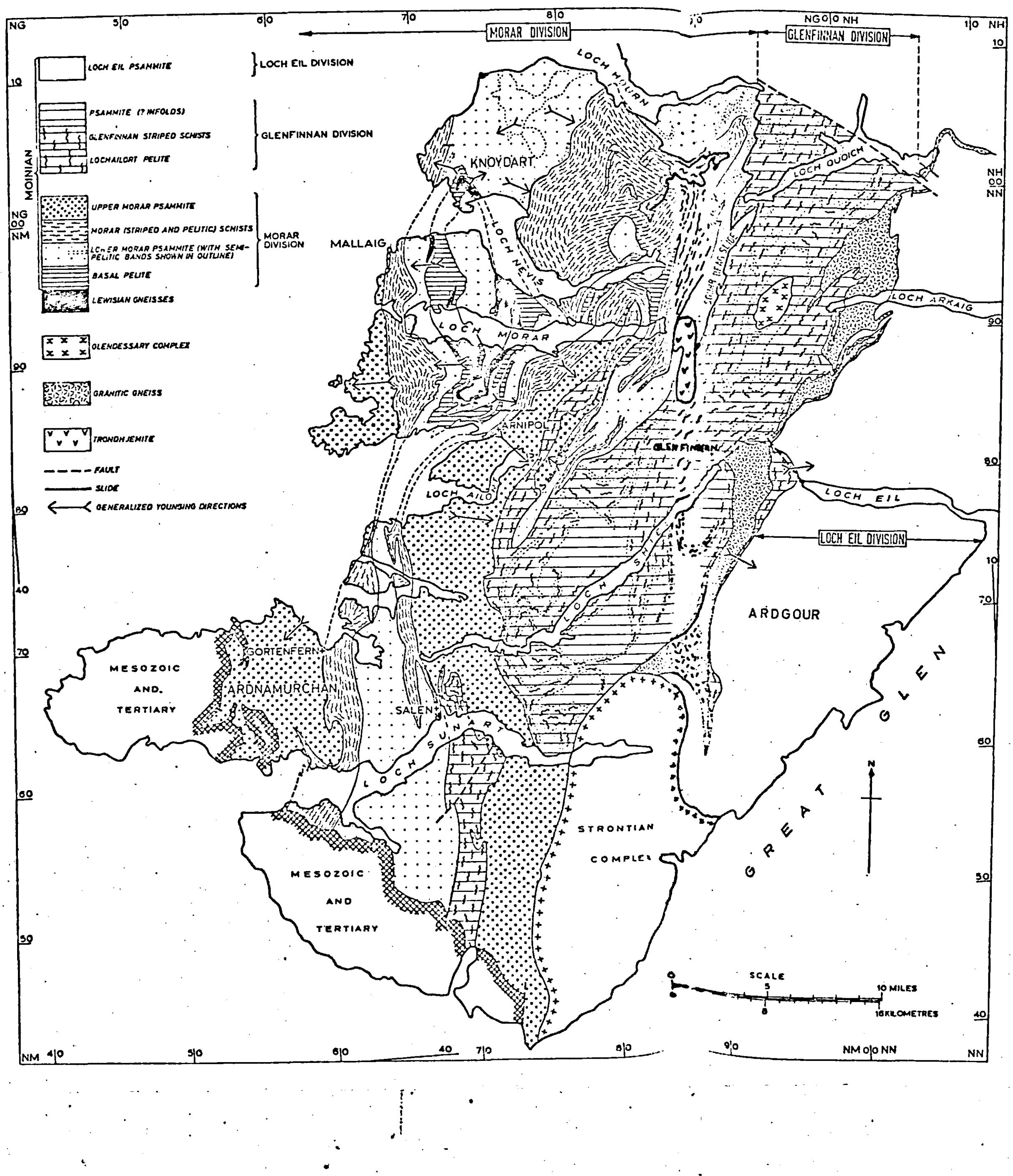


Fig 10: The stratigraphic successions in the Moinian Assemblage of Western Inverness-shire and Ross-shire (after Johnstone et al 1969).

FIGURE 11. Geological sketch map of Western Inverness-shire showing the distribution of Morar, Glenfinnan and Loch Eil Divisions of the Moinian. (Fig. 2 Johnstone et al. 1969)



Granulitic Schist Series in Kintail, which in turn is correlated with the lower part of the Glenelg-Knoydart succession by Johnstone et al. (1969) (Fig. 10).

The Kinloch Hourn succession outcrops east of the Sgurr Beag Slide and is thought to have been brought into its present position by movement on that slide (Tanner 1971). This succession is tentatively correlated with part of the Kintail succession (Clifford 1957, Tanner 1971, and Fig. 10), and "would appear to be a lateral equivalent of some part of the Glenelg-Knoydart succession" (Tanner 1971, p.460). This statement supports Johnstones et al's. (1969) correlation of the Kintail succession with part of the Glenelg-Knoydart succession.

Johnstone et al. (1969) also deal with the problems of metamorphism in the Moines, and the conflicting evidence between the radiometric age determinations obtained, and the maximum ages of tectonic and metamorphic events based on stratigraphic evidence. Their conclusions were that the Moine rocks had been affected by three major phases of deformation, and that metamorphism accompanying these tectonic events had been continuous from "late pre-Cambrian and continuing possibly until the early Devonian, at least in the central part of the orogenic belt".

The isotope studies of Gilletti et al. (1961) sought to settle the controversy of the age of the Caledonian metamorphism. They established that a widespread Caledonian (s.s.) metamorphism affected the Moine series at approximately 420 ± 15 Ma, and that the Caledonian orogeny occurred within the Silurian period. Older ages of 740 Ma and 665 Ma were obtained from pegmatites in the Knoydart-Morar area. Consequently it was suggested that Moine sedimentation in this area must be older than 740 Ma. Moorbath et al. (1968) also suggested that this area may have undergone an early metamorphism before this date.

The relationships of the Moines to the Torridonian were also considered by Gilletti et al. (1961). They concluded that the Torridonian sediments were younger than 1600 Ma, i.e. post-dating the Laxfordian metamorphism. If the Moines are the metamorphosed equivalent of the Torridonian, then the latter must be older than 740 Ma (the age of pegmatites within the Moines).

However, it is possible that the Upper Torridonian sediments were derived from the Moines (Dunning 1973). Torridonian sedimentation was thought to be younger than 1600 Ma (Gilletti et al. 1961) thereby suggesting an even older date of sedimentation for the Moines.

Isotope work continued to investigate the problem of the age of sedimentation of the Moine and Torridonian. Long and Lambert (1963) suggested from Rb-Sr isotopic evidence that the maximum possible age for Moine sedimentation would be about 1000 Ma. Moorbath (1969) suggested that the Upper Torridonian and Upper Moines might be partial stratigraphic equivalents. This proposal was based on the then (1969) current idea that the Upper Torridonian Rb-Sr isochrons were only 10-20 Ma older than the 740 Ma Rb-Sr age of the Knoydart pegmatite.

Revision of the age of the Torridonian (based on the $1.39 \times 10^{-11} y^{-1}$ decay constant (Moorbath 1973)) means that the Stoer Group is 995 ± 24 Ma and the Torridonian Group is 810 ± 17 Ma. The implication from these current ages is that if the Torridonian was derived from the Moine, sedimentation of at least part of the Moine assemblage took place prior to 995 ± 24Ma.

Prior to the revision of these dates, Lambert (1971) had proposed that Moine deposition took place before 810-820 Ma. He also proposed that if the 1200 Ma date for the Carn Chuinneag intrusion (Pidgeon & Johnson, 1971 and 1973) is correct, then Moine sedimentation must be older than 1200 Ma. The 1200 Ma date for the Carn Chuinneag intrusion has yet to be substantiated, however.

Because some of the pebbles within the Torridonian group are metamorphic, and if the Torridonian is derived from the Moine Series, it is necessary to invoke a thermal event affecting at least the lower part of the Moine series, prior to erosion to form the Torridonian Series.

It is possible that this early metamorphism took place prior to the deposition of the Upper Moine Series and the supposedly conformable Dalradian rocks (Anderson 1948, and see p. 20 of thesis). If this is the case then the unconformity between the lower Moine units which suffered an early (Pre-Cambrian?) metamorphic event, and the overlying unaffected upper Moine Series is yet to be found, but may now be represented by a tectonic junction. If, however, this course of evolution did occur, it would possibly account for the record of Pre-Cambrian orogenic activity in the Moine, and apparently uninterrupted sedimentation from the Upper Moine Series into the Dalradian (Anderson 1948).

A symposium held in Edinburgh in 1971 concerned with the dating of events in the Scottish Caledonides was summarised by Dunning (1973), and showed the stage reached thus far in research concerning the age of events in the Moines and Dalradians of the Scottish Caledonides. Dunning presented the "classical" four fold sequence of deformation of the Moine thrust belt based on the works of Soper and Wilkinson (1971), Johnson (1961 and 1965) and Barber (1965):-

D_1 - N.N.E. trending isoclinal folds and related mylonite belts

D_2 - E.S.E. plunging, sideways closing tight folds with intense penetrative, axial lineations affecting the mylonites, Torridonian, Moines and Cambrian

D_3 - N.N.E. trending asymmetrical folds

D_4 - conjugate folds and kink bands

Dunning (1973) stated that this sequence could not be readily identified in the Moine nappe.

As well as attempting to correlate structural events it is hoped, here, to substantiate the suggestions made by Gilletti et al. (1961), Tobisch et al. (1971) and Powell (1971) for two distinct phases of metamorphism, the earliest of which may represent a Pre-Cambrian event.

Recent isotopic work by van Breeman et al. (1974) lends support to the idea of two period of pegmatite intrusion, the earliest of which may be related to a Pre-Cambrian thermal event (see also Chapter 7).

Some of the most recent work on the Moines is to be found in unpublished Ph.D. theses, e.g. Howkins (1962), Poole (1963), Spring (1961), Dalziel (1963) Clark (1961) and Powell (1962).

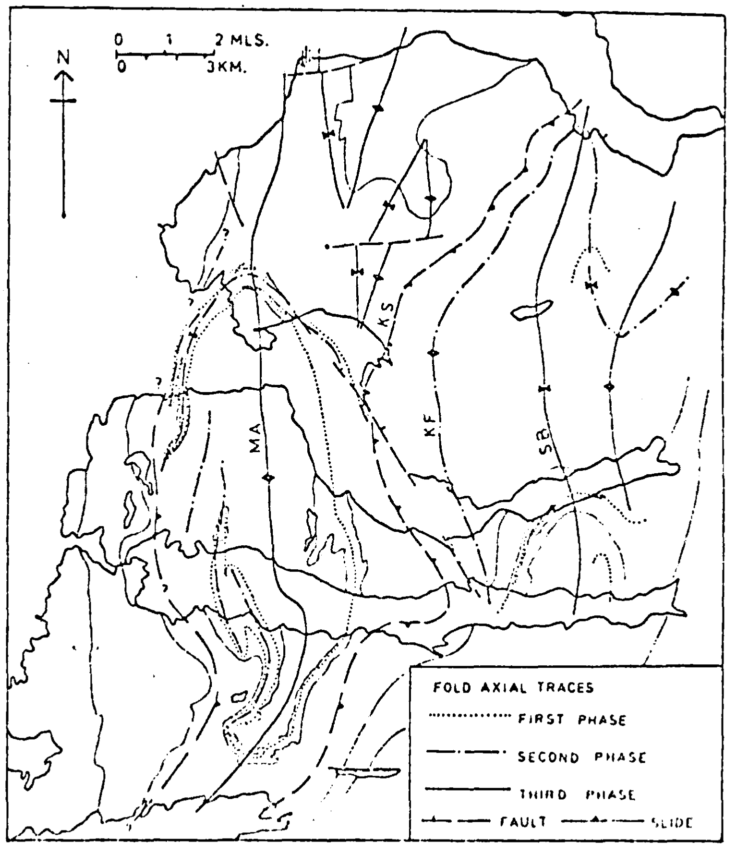
Poole and Spring (1974) and Powell (1974) have attempted to correlate major structures within the Morar-Knoydart area, but have arrived at different structural interpretations of the evidence available.

Both studies agree that an early phase of deformation was responsible for isoclinal infolding of the Lewisian basement rocks into the Moine cover. Differences arise, however, concerning interpretation of the subsequent deformational history. Poole and Spring (1974) advocate three episodes of deformation. They suggest that a second phase is responsible for a major, recumbent, westward closing antiform (the Knoydart fold) which refolds the earlier structural succession, and is associated with a coeval slide on the lower limb. This fold is itself refolded by third generation folds, resulting in the Morar Antiform in the west, and the Ben Sgriol Synform in the east (see Fig. 12).

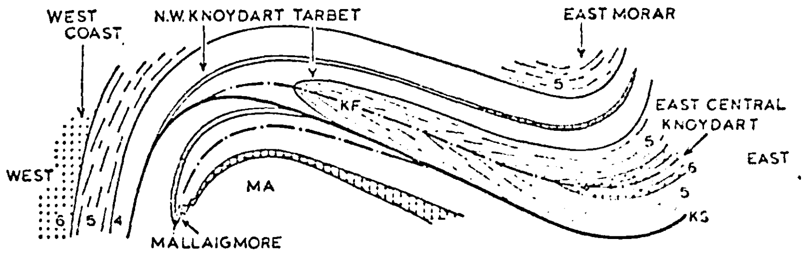
Powell (1974) proposed a four-fold deformation history incorporating two episodes of sliding which affected both basement and cover rocks. He (ibid, 1974)was able to identify this sequence of deformation from the Glenelg-Arnisdale area to the north southwards to Ardgour and Moidart (Fig. 13).

Powell's (1974) interpretation of the structure of the Morar-Knoydart-Glenelg-Ardgour-Moidart area was based partly on results obtained during the course of the present project, and presented later in this thesis (Powell 1974, pp.581, 586 and MacQueen & Powell in press - Appendix).

The problems associated with the correlation of events in this structurally and metamorphically complex area arise largely from the differences between sequences of events proposed previously for isolated areas within the orogenic belt. Ramsay (1963) proposes 3 major phases of deformation within the Caledonian mobile belt, and a fourth which is restricted to the Moine Thrust Zone. Cheeney and Matthews (1965) suggest that five phases of folding affected rocks of the Moine nappe on Skye; Johnstone et al. (1969) propose a three-fold division of structures affecting the Moines from Ardnamurchan to Carn Chuinneag; Tobisch et al. (1970) envisage a seven phase deformation sequence in the Strathconon-Glen Affric area; Brown et al. (1970) propose four phases of deformation in the Ardgour-Sunart-Moidart area; Johnson and Shepherd (1970) suggest four phases of deformation in the Carn Chuinneag area; Tanner (1970) presents evidence for three major phases of deformation in the Kinloch Hourn area, but referred to two separate pre-F_2 fold episodes; Soper (1971) refers to four phases of deformation in the Moine thrust zone at Eriboll, in the north and Barber (1965) also advocates structures related to four separate phases of deformation. Recently Powell (1974) and Poole and Spring (1974) presented syntheses for the Knoydart-Morar area with the former author suggesting a structural sequence of four main events, and the latter authors a 3-fold



The position of the axial traces of folds on the present land surface. KF, Knoydart Fold; MA, Morar Antiform; SB, Ben Sgriol Synform; KS, Knoydart Slide.



A diagrammatic east–west section across north Morar. MA, Morar Antiform; KS, Knoydart Slide; KF, Knoydart Fold. Numbers refer to the stratigraphical groups.

Fig. 12. The structural interpretation of the Knoydart and Morar area after Poole and Spring (Figs. 3 & 4, 1974).

Fig. 13. (after Powell, Table 2, 1974).

Summary of the deformation phases recognized in the Moine and their possible correlation.

MOINE THRUST ZONE - SOUTH (Barber 1965)	GLENELG-ARNISDALE (Ramsay 1960, 1963)	KINLOCH HOURN (Tanner 1971)	MORAR-LOCH EILT (This paper)	MOIDART-ARDGOUR (Brown et al. 1970)	STRATHCONNON-GLEN AFFRIC (Tobisch et al. 1970)	CARN CHUINNEAG (Shepherd 1973)	MOINE THRUST ZONE - ERIBOLL (Soper 1971)
	F1. Isoclinal major and minor folds; inter-leaving of Moine cover and Lewisian basement	F1[a] Referred to but not described	F1 Isoclinal major folds; rare minor folds; "bedding" schistosity	F1 Rare minor isoclinal folds	PRE-CANNICH Isoclinal minor folds; axial planar schistosity		
			Pegmatites 730 ± 20*			D1 Isoclinal folds: "bedding" schistosity	
	F2 Tight major and minor folds; penetrative axial planar schistosity	F1 Tight to isoclinal minor folds; axial planar schistosity and quartz veins.	F2 Tight to isoclinal major and minor folds with variable plunge; axial planes N-S; penetrative axial planar schistosity, quartz and pegmatite veins, gneissose foliation. Sliding	F2 Major and minor folds with strong axial planar schistosity.	CANNICH Isoclinal folds; axial planar schistosity. Sliding STRATHFARRAR Restricted occurrence. ORRIN Restricted occurrence		
			Pegmatites: 428 ± 6^Δ 450 ± 10*			Intrusion Carn Chuinneag Granite - 560 ± 10*	
Formation of Primary mylonites - - - - - - - Isoclinal minor folds & coaxial lineation plunging ESE.	F3 e.g. Ben Sgriol Synform Open to tight folds; co-axial crenulations; N-S axial planes; low plunge.	F2 Tight major and minor folds; axial planar schistosity and quartzo-feldspathic veins. Coeval Sliding.	F3 West: Open to tight minor folds; coaxial crenulations; axial planes N-S; low plunge; often dis-harmonic. East: Tight major & minor folds with co-axial crenulations & axial planar schistosity; N-S to NE-SW axial planes; variable plunge. Sliding.	F3** Open to tight major & minor folds; Coaxial crenulations.	MONAR Open to tight folds; axial planar schistosity; N-S to NE-SW axial planes.	D2 Reclined folds; axial planar schistosity; N-S, NW-SE axial planes.	D1 Formation of primary mylonites. - - - - - - - D2 Isoclinal folds; coaxial lineation; plunging ESE.
- - - - - - - Asymmetric folds; N-S hinges.	F3 e.g. Loch Hourn Anti-form north of Strath-connon Fault.	F3 Open minor folds with coaxial crenulations.	F4 Open to tight minor folds developed as a conjugate system; axial planes NE-SW & NW-SE, steep plunge to E and SE; coaxial crenulations.	F4 Rare open major and minor folds; coaxial crenulations.	AFFRIC Restricted to SE; open folds; coaxial crenulations.	D3 Major and minor folds; NW and NNE axial planes; co-axial crenulations; locally conjugate.	- - - - - - - D3 NNE trending folds, coaxial crenulations
Monoclinal minor folds & thrust movements.	F4 Conjugate minor folds adjacent to Moine Thrust.					D4 Open monoclinal folds.	D4 Box & kink folds; movements on Moine Thrust.

* van Breemen, Pidgeon & Johnson (1974). Johnson & Shepherd (1970). Δ Brook (pers. comm.). ** Some of Brown *et al's* F3 folds are considered here to be F4 in age.

deformational sequence.

Dunning (1973) has already stated that the generally accepted four-fold division of tectonic events affecting the Moine rocks within the Moine thrust zone could not be readily correlated with events in the Moine nappe. Powell (1974), however, suggested correlation of most, if not all, of the structural events affecting both the Moine thrust zone and the Moine nappe (Fig. 13). Evidence presented in this thesis will show that a four-fold structural and two-fold metamorphic sequence established in the Moine thrust zone, can in fact be carried eastwards through the Moine nappe, at least as far as eastern Knoydart. The lithostratigraphic succession summarised by Johnstone et al. (1969) is accepted, and Moine units with the Moine nappe on Skye are correlated with part of this succession (Chapter 3). Moine units in eastern Knoydart have previously been tentatively correlated with members of the Morar division of the Moinian assemblage (Ramsay & Spring 1962, Powell 1974) and these correlations are confirmed.

Whilst the content of the present thesis cannot conclusively answer the pre-Cambrian versus Caledonian controversy of the Moines, it is hoped to present evidence to support the concept of both pre-Cambrian and Caledonian (s.s.) events (both tectonic and thermal) being represented in the Moine rocks of western Inverness-shire.

CHAPTER 3 STRATIGRAPHY

3.1 Introduction

The rocks of the research area fall into the oldest, or Morar division of the Moine succession as proposed by Johnstone et al. (1969). Fig. 14 shows the stratigraphic units comprising this division and the local names used for different units in different areas. No generalised thicknesses are shown because structural complexities are responsible for marked variations in thickness over small areas.

3.2 Description of lithologies

3.2.1 The Lewisian

Lewisian rocks in the area range from high-grade gneisses to schists. Gneisses are present in Knoydart and south Morar within the mobile belt, and within the Moine thrust zone on the Sleat peninsula of Skye. These basement rocks show marked compositional banding resulting from metamorphic segregation of minerals and can be readily distinguished from the Moine metasediments whose compositional banding reflects the original lithological layering (i.e. bedding). The Moine and Lewisian groups also exhibit different metamorphic grades; the Lewisian usually being represented by high-grade gneisses, and the Moine by low to medium grade schists. The junction between the two groups is commonly obscured by faulting or sliding. In western Knoydart, the Lewisian rocks comprise banded hornblendic and feldspathic gneisses with occasional amphibolite pods, which outcrop in the core of the Morar anticline (Fig. 22). Banding in the Lewisian and the adjacent Basal Pelite on the western limb of the fold is discordant on a small scale (Figs. 15 and 22) and rocks at the junctions between the amphibolite pods and the adjacent Moine rocks show brecciation and retrogression to chlorite schists (Fig. 15). On the eastern limb of the Morar antiform, Lewisian rocks abut against various units within the Lower Morar Psammite and again exhibit discordant contacts.

High-grade Lewisian rocks in the Moine nappe on Skye range from "acidic" quartzo-feldspathic gneisses with some biotite or hornblende, to amphibolites with or without biotite and feldspar. The major minerals are quartz, k-feldspar, plagioclase, muscovite, epidote,

FIGURE 14 Shows Stratigraphic Succession of Morar Division of Moine Assemblage after Johnstone et al. (1969) Ramsay & Spring (1962) and Correlation of Skye and E. Knoydart Succession

Western Inverness-shire Johnstone et al. 1969	Sheet 61 Geological Survey (Publ. IGS. 1971)	Loch Hourn Ramsay & Spring, 1962	Skye (present thesis)	East Knoydart (present thesis and Ramsay & Spring, 1962)
4. UPPER PSAMMITE	QUM	Aonoch Sgiolte Psammitic Group		Upper Psammite Aonoch Sgoilte Psammitic Gp.
				Tectonic Junction (The Inverie Line - Richey 1937)
3. MORAR - Garnetiferous Gp. (Striped and Pelitic) SCHISTS	sSM	Ladhar Beinn Pelitic Group	(Top not seen)	
	PM		Armadale Pelitic Gp.	Ladhar Beinn Pelitic Group (Includes Garnetiferous Gp.)
	$s^{f}M$		Armadale Psammitic Gp. (Base not seen)	
				Tectonic Slide Junction
2. LOWER MORAR PSAMMITE	QLM	Barrisdale Psammitic Gp.		Lower Morar Psammite
	SR	Rubha Ruadh Semi-Pelitic Gp.		(Base not seen)
	$Q^{a}M$	Arnisdale Psammitic Gp.	(Top not seen) Tormore Psammitic Gp. (Base not seen)	
1. BASAL PELITE	QPM	Basal Semi-Pelitic Gp.		
		Conglomerate		
LEWISIAN	LEWISIAN	Lewisian		

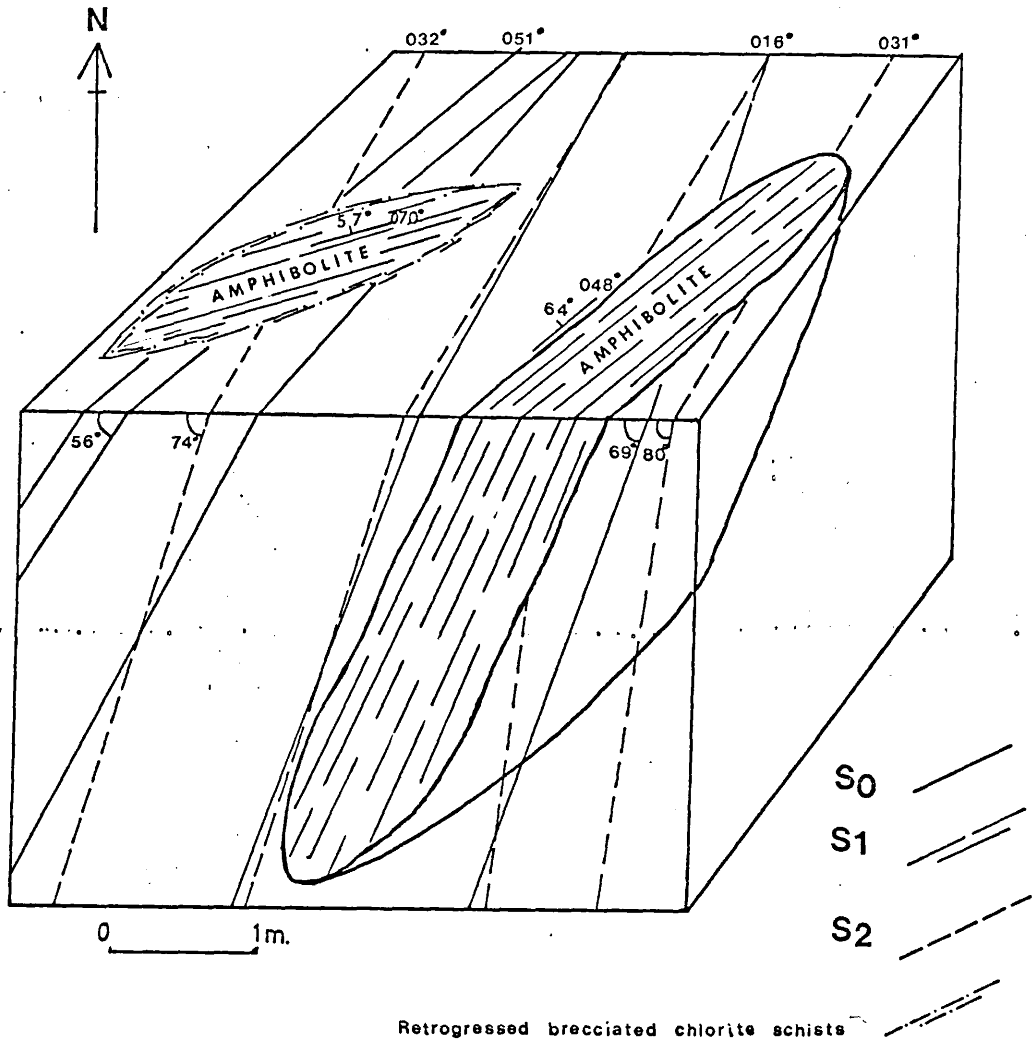


Fig. 15. Block diagram showing discordant Moine-Lewisian junctions on a small scale, east of Sandaig Bay, West Knoydart.

The fabric (S_1) within the (boudinaged?) amphibolite pods is oblique to the layering of the adjacent Moine psammites (S_0), and the earliest tectonic fabric within them (S_2). It is suggested that the attenuation of the amphibolites and the fabric preserved within them are the result of an early phase of deformation (D_1). The S_2 fabric forms oblique to the lithological layering (S_0) and the early (S_1) fabric in the amphibolite pods. It has a consistent strike (031°) and is steeper than the layering (S_0). It forms as the result of a later (D_2) phase of deformation.

biotite, hornblende and garnet. Pyroxene is not normally present, and chlorite and carbonate are common accessories. Isolated ultra-basic serpentinite bodies occur in the axial region of the Knock synform (Fig. 22). A common feature of the basic portions of the banded gneisses is the occurrence of large ($<$ 1 cm) actinolite needles which are randomly oriented with respect to the banding, suggesting post-tectonic crystallization.

Within 2 km. of the Moine thrust plane retrogressive effects are obvious, resulting in the production of phyllonitic chlorite schists with rarely preserved quartzo-feldspathic blebs, commonly strung out within the plane of schistosity. Otherwise little of the original banding is retained.

3.2.2 The Moines of Morar and Central Knoydart

(a) The Basal Pelite:- this is the lowest member of the Moine succession, lying in some places adjacent to Lewisian rocks. Nowhere, however, within the main research area, is a marked angular unconformity with the Lewisian visible. This may be due to intense flattening and/or movement at the Moine - Lewisian junction. The Basal Pelite is not always present at Moine-Lewisian contacts, notably on the eastern limb of the Morar Dome in Knoydart, and in Skye where Moine-Lewisian junctions are highly sheared or replaced by minor thrust planes, and are therefore tectonic.

Small-scale crumpling and folding is common within this group of interbanded psammitic, semi-pelitic and pelitic schists. Highly contorted veins and augen of quartz, occasionally with some feldspar, are an abundant and characteristic feature.

(b) The Lower Psammite Group:- consists of pink or grey quartzo-feldspathic, massive, psammitic schists with subordinate bands of semi-pelite and rare pelites. Cross-bedding, graded units and slump folding in the psammitic portions provide conclusive evidence for the way-up of the rock units. Relatively undeformed sedimentary structures from Knoydart are shown in Figure 16; diagrams 16a - 16d from rocks on the western limb of the Morar antiform show younging westwards, whilst 16e from the eastern limb shows younging to the east.

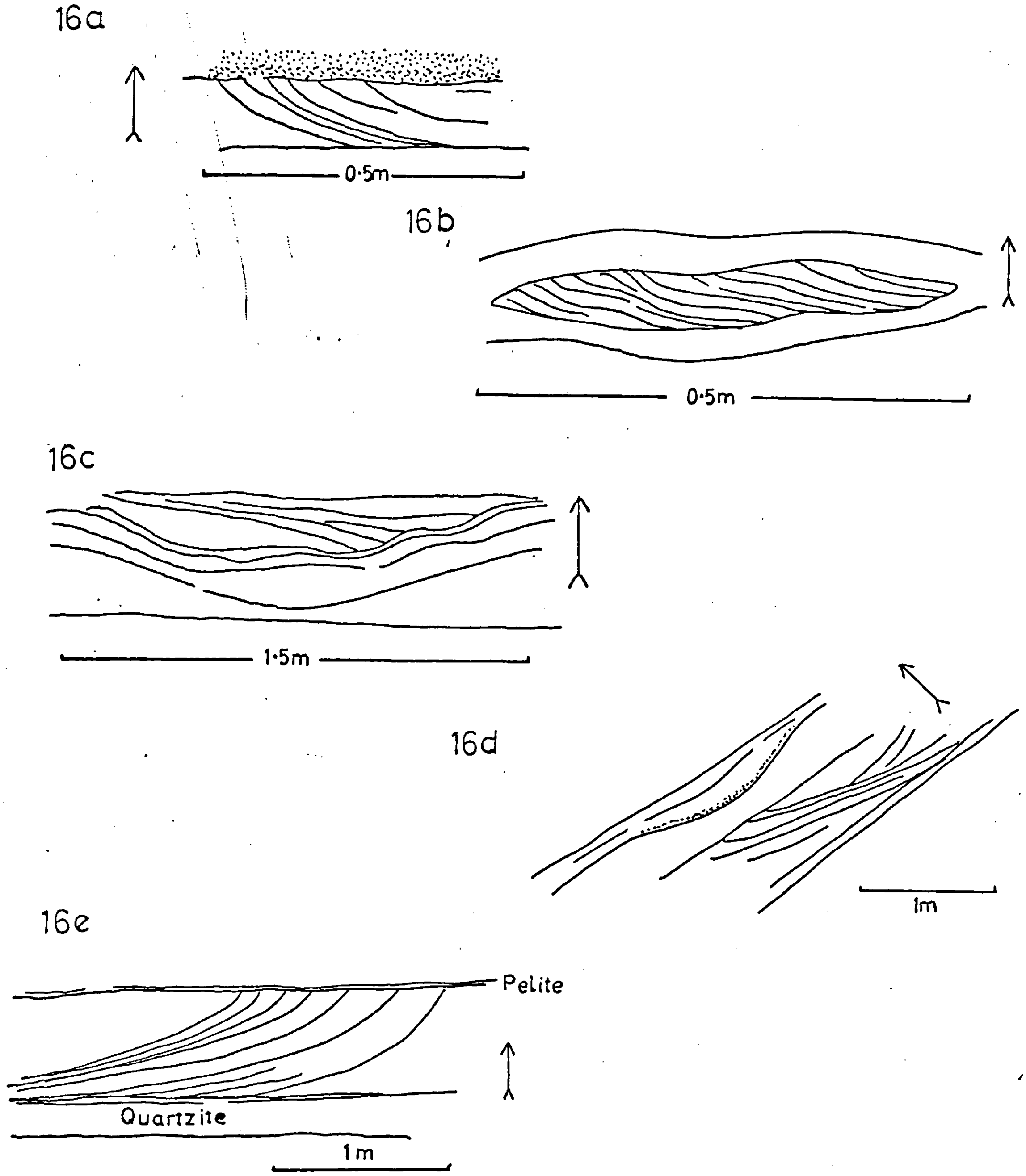


Fig. 16. Sedimentary structures in the Lower Psammite Group of West Knoydart; diagrams 16a-d are from rocks on the west limb of the Morar Dome and 16e from rocks on the eastern limb of the Morar Dome.

16a. Cross-bedded psammite truncated by coarser psammite with a basal grit layer with fragments <1cm. Location - north of Airor.

16b. Coarse grained cross-bedded lenses exhibiting careous weathering, in host rock of quartz-feldspar psammite. Location - north of Airor.

16c. Washout or channel infill in medium grained psammites. Location - Sandaig Bay.

16d. Cross-bedded psammites passing upwards into unit with a channel infill with a grit layer at the base. Location - Sandaig Bay.

16e. Large-scale cross-bedded units separated from quartzite layers by thin pelitic partings. Location - Scottas.

The arrow indicates the direction of younging.

Plates 1-3 and Fig. 17 show examples of cross-bedding, washouts, and slump folding from the Lower Psammite group in south Morar. These sedimentary structures young consistently to the west, and are on the western limb of the Morar Dome. Epidote, ilmenite and magnetite heavy mineral bands and lenses are characteristically developed in and restricted to, this group.

(c) The Striped and Pelitic Group (Richey & Kennedy, 1939) or Morar Schists (Johnstone et al., 1969) or Morar Pelite (Powell, 1974):- can be subdivided into three separate units, each having gradational contacts. The Striped and Pelitic Group also has gradational contacts with the Upper and Lower Psammite groups. The group occurs in west and east Knoydart, south Morar and Skye, but descriptions of the representatives in Skye will be dealt with in Section 3.3. The Ladhar Beinn Pelite of eastern Knoydart (Ramsay & Spring, 1962), forming the mountainous area of Ladhar Beinn (NG 824040), Stob a' Chearchail (NG 846029) and Sgurr Coire Choineachain (NG 791011), north of Glen Dubhlochain (Figs. 1 and 22), is equivalent to the Striped and Pelitic group of West Morar (Richey & Kennedy, 1939).

The Lower Striped schists are laminated psammites, semi-pelites and pelites, occasionally with ribs of coarse psammitic schist. The psammitic proportion increases towards the junction with the Lower Psammite group. Calc-silicate bands are notably absent.

Garnetiferous Pelitic schists form the central subdivision of this group commonly developing garnet porphyroblasts, which may be up to 1 cm. in diameter in the east. Calc-silicate bands are a characteristic feature of this group, usually about 3-5 cm. wide (although this may be a tectonic modification of the original thickness). They occur between semi-pelitic bands within the main pelitic schists.

The thickness of this group is variable, e.g. on the eastern flank of the Meall Bhasiter Dome, but this may also reflect tectonic thinning (see Fig. 22, and Section 3.4.4).

The Upper Striped schists are a series of finely laminated semi-pelites with subordinate psammitic and pelitic layers. Lenticles and thin layers (maximum thickness, $<$ 10 cm.) of pinkish-white, garnetiferous calc-silicate occur, usually within semi-pelitic horizons.

Plate 1

Plate 2

Plate 3

Plates 1-3: Sedimentary structures from the Lower Psammite Group, Arisaig.

Plate 1: Slump folds.

Plate 2: Slump folds and cross-bedding.

Plate 3: Cross-bedding.

Fig 17

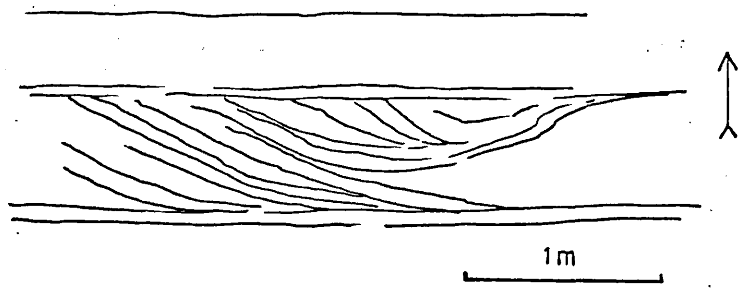


Fig. 17. Sedimentary structures from the west limb of the Morar Dome in South Morar. Diagram shows cross-bedding and washout in Lower Psammite. Arrow indicates direction of younging.

Fig18

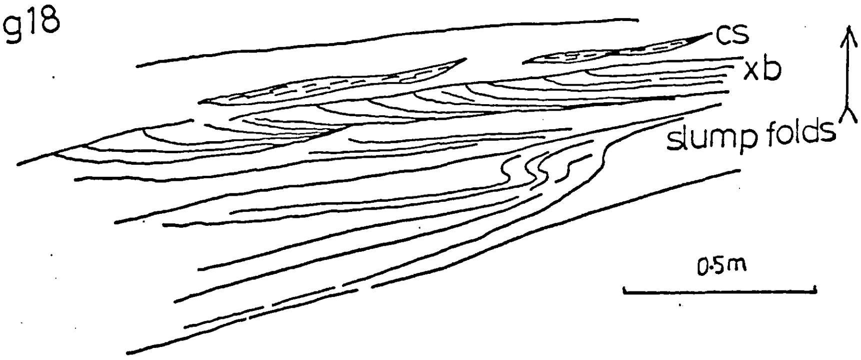


Fig. 18. Sedimentary structures from the Upper Psammite in South Morar. Diagram shows calc-silicate lenses (c.s.), cross-bedded psammites (x.b) and slump folds.
Arrow indicates direction of younging.

Rarely, microscopic bands of magnetite and graphite are also visible.

(d) The Upper Psammite group:- outcrops on the extreme western flank of the Morar Dome in south Morar, and forms isolated areas in eastern Knoydart (Fig. 22). The rocks are massive, bedded quartzo-feldspathic granulites, often with quartzite layers and frequent semi-pelitic horizons. The proportion of semi-pelitic material increases towards the junction with the Striped and Pelitic group. Calc-silicates are found only within the lower part of this group in association with semi-pelitic layers; heavy mineral bands are absent. Sedimentary structures are abundant; Figure 18 shows cross-bedding and slump folds from the lower part of the Upper Psammite in south Morar.

3.3 The Moines of Skye

3.3.1 Introduction

Two distinct lithostratigraphic units are present within the Moine rocks of Skye, forming an essentially psammitic unit, and a distinct pelitic unit.

The psammitic unit is best exposed on the coast section running northeast from Tormore, and the essentially pelitic assemblage on the headland at Armadale. The two units have been designated the Tormore Psammite and Armadale sequence respectively.

3.3.2 The Tormore Psammite

This consists of massive quartzo-feldspathic units, often less than one metre thick, interbedded with gritty, possibly graded, quartzites which exhibit "careous" weathering (Plate 4). Heavy mineral bands are prominent (Plate 5) and calc-silicates are totally absent. Graphite trails occur parallel to the layering on a microscopic scale (Plate 6) and are most frequent within interbedded semi-pelitic horizons. The junctions between the main quartzo-feldspathic units and the interbedded gritty quartzite layers are sharp, but concordant. The semi-pelitic units grade into the quartzo-feldspathic units, becoming gradually increasingly psammitic with an increase in the amount of quartz and feldspar. Mineralogically, the massive psammite units are composed of quartz, plagioclase, feldspar, minor amounts of muscovite, occasional microcline and rare small crystals of garnet

Plate 4: Tormore Psammites: grey quartzo-feldspathic units with interbedded gritty, quartzites. Quartzite unit 1 metre thick.

Plate 5: Tormore Psammite: photomicrograph of a heavy mineral band. (x10,P.P.L.)

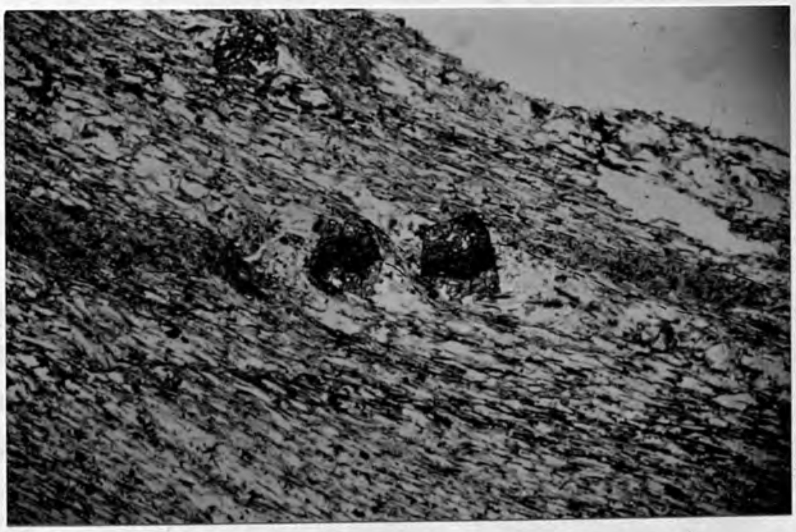


Plate 6: Tormore Psammite: graphite layer parallel to S_0 forms part of inclusion fabric Si in rotated garnet crystals.(x50,P.P.L.)

and epidote. The gritty layers have $<75\%$ quartz which is strained suggesting incomplete post-tectonic recrystallisation. Calcite is common in the gritty horizons, and may be responsible for the "careous" weathering effect (Plate 4). Semi-pelitic layers are composed of quartz, k-feldspar, muscovite, green (usually) biotite, epidote and garnet. Occasionally, magnetite grains or patches occur with the semi-pelitic units.

The heavy mineral bands are composed of epidote, magnetite and ilmenite (Plate 5). Graphite layers appear to be formed by minute grains dispersed between crystals and possibly relict detrital grains of other minerals, but are restricted to fine layers or trails within semi-pelitic hosts (Plate 6).

The units strike approximately E.N.E.-W.S.W., and dip steeply to the S.S.E. The junction with the underlying Lewisian chlorite schists is a thrust plane which is marked, where unexposed, by a strong topographic depression. Locally brecciated and sheared psammites outcrop where the thrust plane reaches the coastline, and late stage kink folds are common. Cross-cutting, closely spaced Tertiary dykes further obliterate psammite-Lewisian contacts.

The lack of calc-silicate horizons and in particular the abundance of heavy mineral bands, is taken as evidence for the correlation of the Tormore psammite with the Lower Psammite group. The exact position of this unit of rocks within that group is difficult to ascertain because of limited exposure and the tectonic nature of the contact with the Lewisian. The moderately high proportion of semi-pelitic material, and lack of noticeably marked quartz veining, would however suggest closer proximity to the Striped and Pelitic group than to the Basal Pelite.

3.3.3 The Armadale sequence

The rocks forming the headlands of Rubha Phoil and Rubha Dubh, northeast of Tormore (Fig. 1), dip moderately towards the southeast and although there are no sedimentary structures preserved, the structural evidence (Chapters 4 and 5) suggests that the rocks represent a right way up stratigraphic sequence. Consequently the oldest group represented is predominantly a series of micaceous psammites (usually less than 15 cm. thick) interbedded with massive quartzo-feldspathic units, rarely thicker than 0.5 m., with occasional semi-pelitic units $<$ 10 cm. thick. Calc-silicates bands are absent. This group passes conformably upwards into a highly garnetiferous pelite, interbedded, occasionally, with thin ($<$ 5 cm.) semi-pelitic bands (Plate 7).

Mineralogically the psammitic rocks consist of quartz, plagioclase feldspar, occasional muscovite and rare calcite. Epidote occurs infrequently as small crystals throughout the rocks. The pelitic group has less quartz and feldspar and more muscovite and biotite (usually brown). The amount of epidote and clino-zoisite increases, and garnet is common. Large quartz crystals in both the Armadale Psammite and Pelite show strain shadows indicative of incomplete post-tectonic recrystallisation. In the psammites these large quartz crystals may be rimmed by smaller, recrystallised quartz grains (mortar texture).

It is proposed to name the predominantly psammitic group the Armadale Psammite, and the garnetiferous group the Armadale Pelite. The distinctive nature of the garnetiferous Armadale Pelite (with garnet porphyroblasts commonly up to 5 mm. diameter, the total lack of calc-silicates and the nature of the interbanding of pelitic and semi-pelitic units (Plate 7)), suggests that it is equivalent to the lower part of the Garnetiferous Pelite of the Striped and Pelitic group. The underlying Armadale Psammite, which is lacking in calc-silicates and is conformable with the Armadale pelite is thought to be equivalent to the upper part of the Lower Striped group.

The junction between the Armadale psammite and the adjacent Lewisian is marked by brecciation and shearing of both the psammites and the adjacent chlorite schists, and by the development of angular kink folds, suggesting that this junction is also tectonic.

3.3.4 Discussion of relations between the different groups of Moine - the Lewisian, and their positions within the Moine nappe.

Whilst exposure along the coast of Sleat is relatively good, inland it is very poor. Consequently it is difficult to ascertain

Plate 7: Armadale Pelite: garnetiferous pelite interbedded with semi-pelitic ribs (<5 cm).

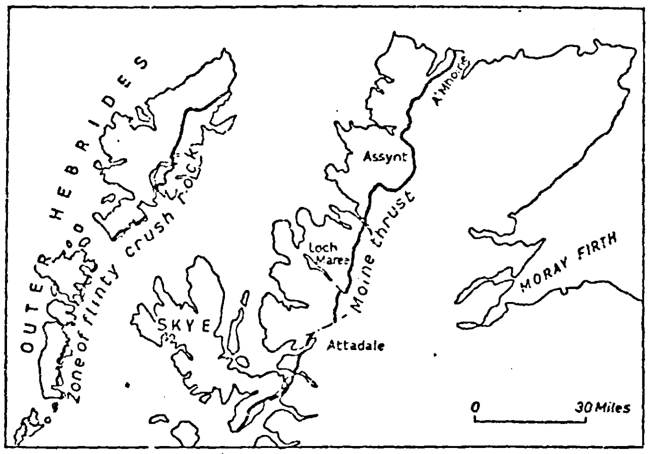
Plate 8: Small scale thrust plane, infilled with quartz, in the Armadale Pelite, Skye.

with any certainty either the full range of lithology of the Moine units present, or the nature of their contacts with the Lewisian chlorite schists. The majority of the Moine rocks located inland, above the Moine thrust, tend to be semi-pelitic in composition, rarely garnetiferous, and occasionally quartz-veined and distorted in a manner similar to that seen elsewhere in the Basal Pelite. If the correlations proposed for the Tormore Psammite, and the Armadale sequence are correct, the implication is that part of the Basal Pelite, and part, at least, of the Lower Psammite group are not present in this area. The upper (?) part of the Lower Psammite is represented at Tormore but neither the upper nor lower junction of this unit is seen. It is possible that these groups were either never deposited, or deposited and then removed by either some tectonic or erosional means. The evidence for thrusting in this area is abundant; major thrusting being represented by the Moine thrust and thrusting on a smaller scale being seen at Tormore and Armadale (Fig. 22 and Plate 8). Because of this and the general abundance of brittle deformation structures (kink folds, shear planes and fractures) it is suggested that the Moine-Lewisian sequence here has been entirely tectonically emplaced as a series of "stacked" thrust sheets.

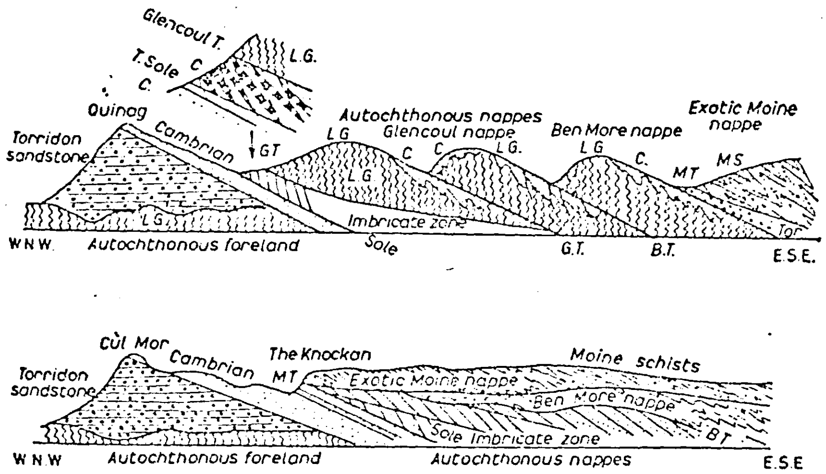
It is this emplacement along thrusts which is thought to be responsible for the disposition of the Tormore Psammite, structurally below the Armadale Psammite and Pelite. The Tormore Psammite occurs in a lower thrust sheet than the Armadale sequence (Fig. 20).

Wherever thrust planes are exposed, e.g. at Tormore, Rubha Phoil and Rubha Dubh (Figs. 1 and 22), the sense of movement as shown by the attitude of the layering above and below the thrust plane suggests a general translation towards the northwest. This coincides with the direction of movement of the Moine nappe as a whole on the Moine thrust. Imbricate structures on a larger scale are well documented from other parts of the Moine thrust zone (Fig. 19A), and are characteristic features associated with the margins of other orogenic belts, e.g. the Valley and Ridge Province of the Appalachians (Fig. 19B) and also in the Alps. Similar structures to these are proposed to account for the disposition of the various rock groups within this area (Fig. 20).

FIG 19A



THE MOINE THRUST AND RELATED MAJOR STRUCTURES. (*After McIntyre*)



(*After Wills, Physiographical Evolution of Britain.*) *M.S.*, Moine Schists; *C.*, Cambrian; *TOR.*, Torridonian; *L.G.*, Lewisham Gneiss; *G.T.*, Glencoul Thrust; *B.T.*, Ben More Thrust; *M.A.*, Moine Thrust. Inset details of the imbricate structure.

FIG 19B

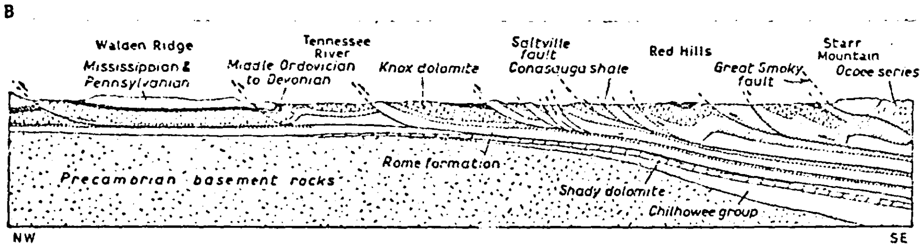


Fig.19a. Imbricate structures developed in the Moine Thrust. Zone of Sutherland and Ross-Shire (Sherbon Hills 1966 - Figs. V11-45 & 46).

Fig.19b. Reverse faults in the Appalachian Valley and Ridge Province causing the "stacking" of thrust sheets. (Sherbon Hills 1966 - Fig.V11-38).

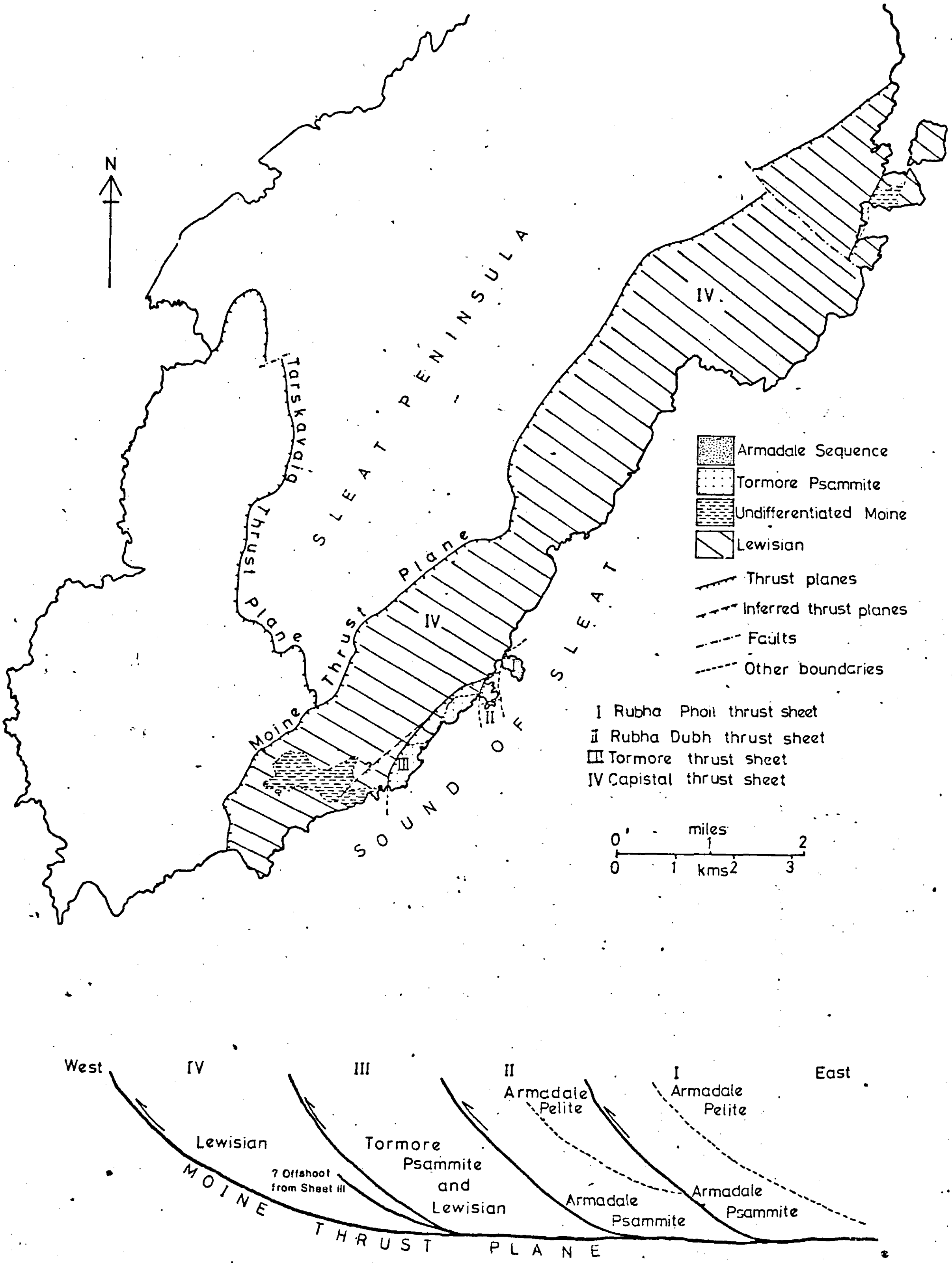


FIGURE 20. Imbricate structure in the Moine nappe in Skye. The map shows the geographical distribution of the thrust sheets on the Sleat Peninsula. The section is diagrammatic, drawn approximately from East to West, showing the relation of the imbricate thrust slices to the Moine thrust plane.

It follows from this discussion that the Moine rocks of Skye, above the Moine thrust plane, contain features characteristic of the margins of orogenic areas, which can be directly related to a major, gently inclined dislocation. Thus an imbricate structure of a series of small-scale thrust nappes occurs on the southeastern seaboard of the Sleat peninsula, above the main Moine Thrust Zone.

3.4 The Eastern Knoydart, Moine rock groups

3.4.1 Introduction

The ground east of Inverie (Fig. 1 and 22) is largely dominated by the Ladhar Bheinn Pelite, a laminated semi-pelitic and pelitic assemblage with intercalated psammite bands. A characteristic garnetiferous pelite horizon can be distinguished and calc-silicate lenses and bands are present in all but the lowest part of the unit. Psammitic rocks occur in the region of Meall Bhasiter (Fig. 22) but are given no named or definite stratigraphic affinity on Sheet 61 of the Geological Survey (1971), although Ramsay and Spring (1962) suggest a correlation of this unit with the Striped and Pelitic Group of Morar (Richey & Kennedy, 1939).

An attempt will be made here to confirm the correlation of the semi-pelitic rocks with the Striped and Pelitic group, and the psammitic rocks with the Lower Psammitic group of the Morar Division of the Moinian assemblage.

3.4.2 The Ladhar Bheinn Pelite

East of the tectonic junction between the Lower Psammite and the Ladhar Bheinn Pelite at Inverie (Johnstone et al., 1969), the texture of the rocks rapidly becomes more coarsely crystalline, corresponding to a marked increase in metamorphic grade. The compositional layering within the rocks represents modified bedding planes as is exemplified by occasionally preserved sedimentary features. Certain diagnostic features, such as the presence of calc-silicate bands and the garnetiferous pelite, allow these rocks to be correlated with less deformed and metamorphosed equivalents on the western flanks of the Morar Anticline.

Excellent exposures in Gleann Meadail, and south of the Inverie river, have enabled a detailed structural geometry and history to be established in this region (Chapters 4 and 5). The psammites exposed in the core of the Meall Bhasiter Dome (Fig. 22), pass westwards and eastwards through a narrow band of striped schists with no calc-silicate bands and similar in appearance to the Lower Striped group, and/or a garnetiferous pelite. Sedimentary structures in the more psammitic rocks suggest that the sequence outwards from the Meall Bhasiter Dome is essentially a stratigraphic sequence. The present disposition of the rock units is due to complex refolding (Chapters 4 and 5). Consequently, the Ladhar Bheinn Pelite in its entirety, is equivalent to the Striped and Pelitic schists of the Morar division, and the pelitic garnet bearing horizon is equivalent to the Garnetiferous (or Morar) Pelite, within this group.

3.4.3 The Meall Bhasiter Psammite

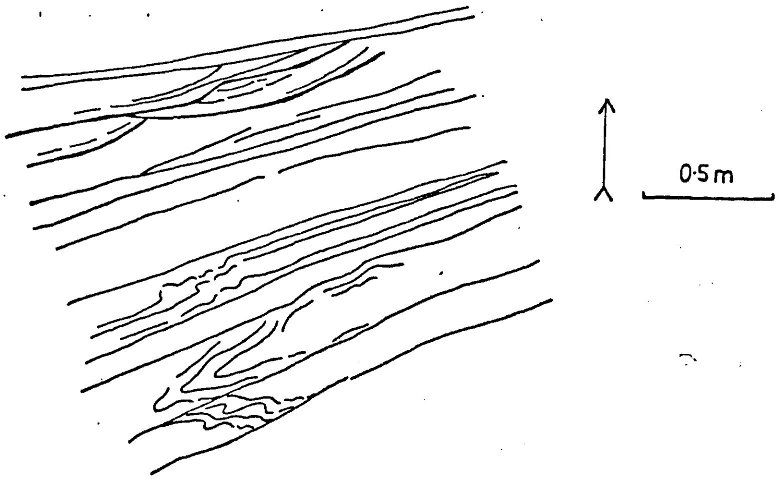
The rocks exposed in the core of the Meall Bhasiter Dome (Figs. 1, 22 and 60) consist of evenly banded psammitic schists. Neither calc-silicate horizons nor heavy mineral bands were found. Because of structural "facing" directions (Chapter 5; Fig. 22) and sedimentary younging directions (Fig. 21) from the psammite consistently towards the Ladhar Bheinn Pelite ≡ Striped and Pelitic group, the siliceous rocks are considered to represent the Lower Psammite group of the Morar division. Although the region is structurally complex the Meall Bhasiter Dome forms a relatively simple antiformal structure whereby older rocks forming the core are flanked by younger units on the limbs.

3.4.4 Modifications of the Eastern Knoydart stratigraphy; correlations of the Ladhar Bheinn Pelite and Meall Bhasiter Psammite

Accepting the correlations suggested above, the eastern flank of the Meall Bhasiter Dome shows a succession from the Lower Psammite into the Garnetiferous Pelite, whilst on the western flank the Lower Striped Group is present, but much attenuated. The junction between the two main units, i.e. the Lower Psammite group and the Striped and Pelitic schists, whilst being conformable stratigraphically,

Fig 21

Cross-bedding and slump folds



Washouts and slump folds

Fig.21. Sedimentary structures in the Meall Bhasiter Psammite, East Knoydart. Structures include cross-bedding, washouts and slump folds. Arrows indicate younging direction.

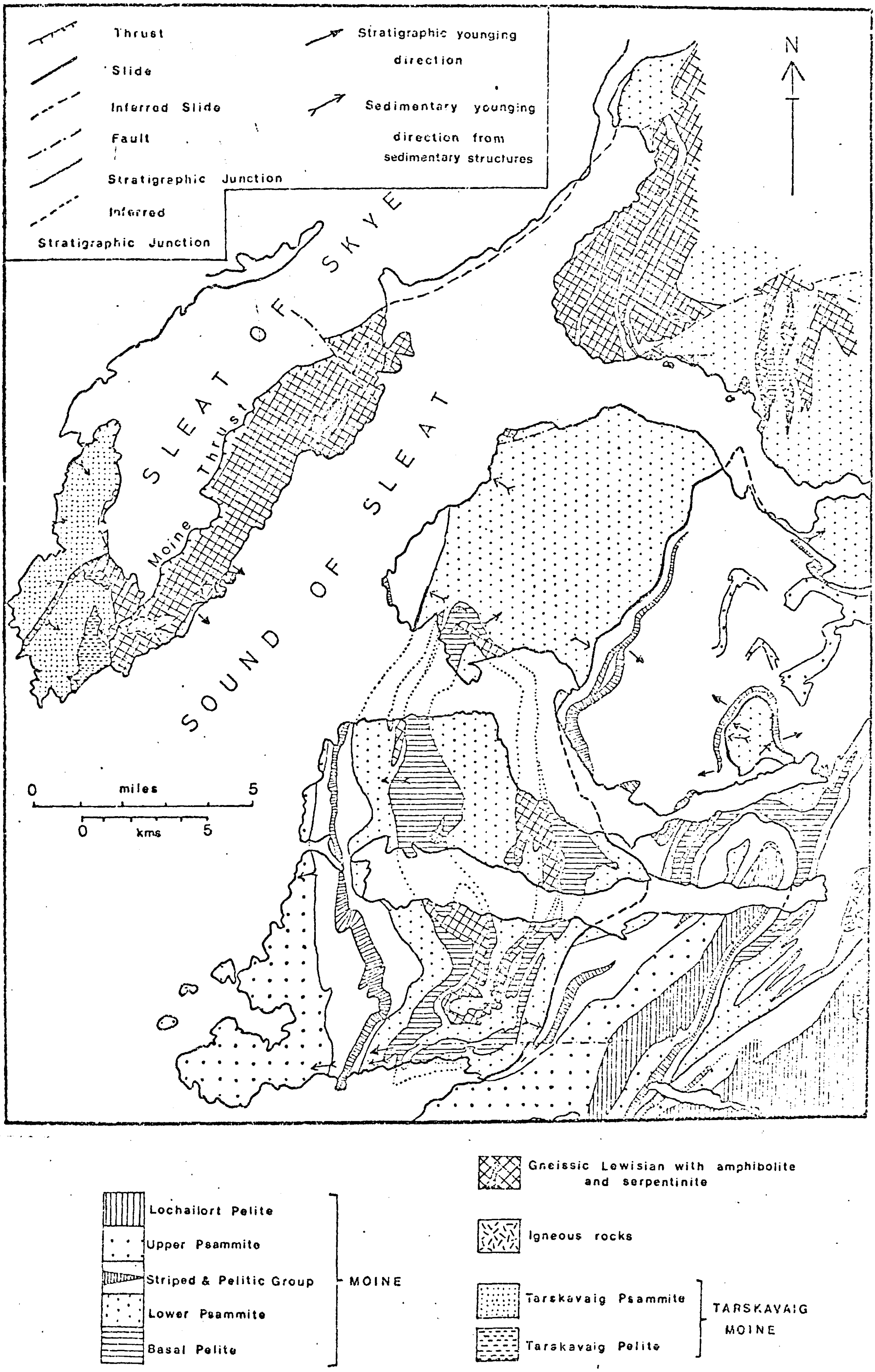


Fig.22. Stratigraphic map of the Skye-Knoydart-Morar area. Based partly on Geological Survey Sheet 61(1971) and Powell (1974).

has been modified structurally. It is suggested that this junction on the eastern flank of the Meall Bhasiter Dome is a slide, and has thus been termed the " Meall Bhasiter Slide" (= Powell's 1974 Slide E). The evidence for the slide junction stems partly from the progressive cutting out of the lower part of the Striped and Pelitic group such that the Lower Psammite and Garnetiferous Pelite are juxtaposed on the eastern limb, and partly from the flaggy nature of the lithologies in this region; whilst a similar fabric is not present on the western limb of the Dome (Figs. 22 and 60).

3.5 Summary

Figure 22 shows a lithostratigraphical interpretation of the region. It is compiled from the work of numerous authors (Johnstone et al., 1969; Ramsay & Spring, 1962; Poole & Spring, 1974; Powell, 1974; and Geological Survey reports of 1963 and 1971), with slight modifications by the present author. It is hoped that by establishing the overall stratigraphic succession within the research area, in respect of Moine/Moine junctions as well as Moine/Lewisian contacts, the structural and metamorphic complexities will be better understood.

CHAPTER 4. EARLY DEFORMATION (D_1 AND D_2) AND METAMORPHISM (M_1)

4.1 Introduction

The aim of this chapter is to outline the evidence for the earliest phases of deformation represented in the Moine thrust zone on Skye, and the mobile belt areas of Morar and Knoydart, and to show their relationships to the first metamorphic event. There are two major phases of deformation termed D_1 (first phase) and D_2 (second phase) respectively; the early phase of regional metamorphism in this region will be referred to as M_1. The terms D_1, D_2 and M_1 are initially local labels applied to the features related to the earliest phases of deformation and metamorphism recognised in each area. D_1 structures include F_1 folds, S_1 schistosity and an L_1 mineral elongation lineation. D_2 structures include F_2 folds, S_2 schistosity, L_2 intersection lineation of S_2 with either S_o or S_1 and L_2' a mineral elongation lineation. S_o represents the lithological layering.

4.2 Structures associated with the first phase of deformation D_1

4.2.1 D_1 structures in the Moine rocks of the thrust zone (Fig. 23)

Within the thrust zone of the Moine nappe, structures related to D_1 are largely restricted to isolated minor fold closures (F_2), L_1 and S_1; L_1 and F_1 are coaxial (Fig. 23). The lineation L_1 is formed by an elongation of quartz and feldspar in psammitic rocks, forming a characteristic "rodding" lineation (Fig. 23, Projection A). This is best developed at Tormore where it is commonly seen to be refolded by F_2 isoclinal folds. In pelitic rocks, L_1 takes the form of a crystallographic and shape orientation of biotite crystals. The biotite forms elongated (< 2 mm.) black, needle-like crystals which are deformed and recrystallised during subsequent tectonothermal events. Examples of this lineation have been observed on Rubha Phoil and Rubha Dubh (Fig. 23, Projection B). In thin section, S_1 can be distinguished from the lithological layering (S_o) as an oblique muscovite "felt" (Fig. 24) and the later schistosities S_2 and S_3. Recognition of this early fabric at Armadale has greatly facilitated

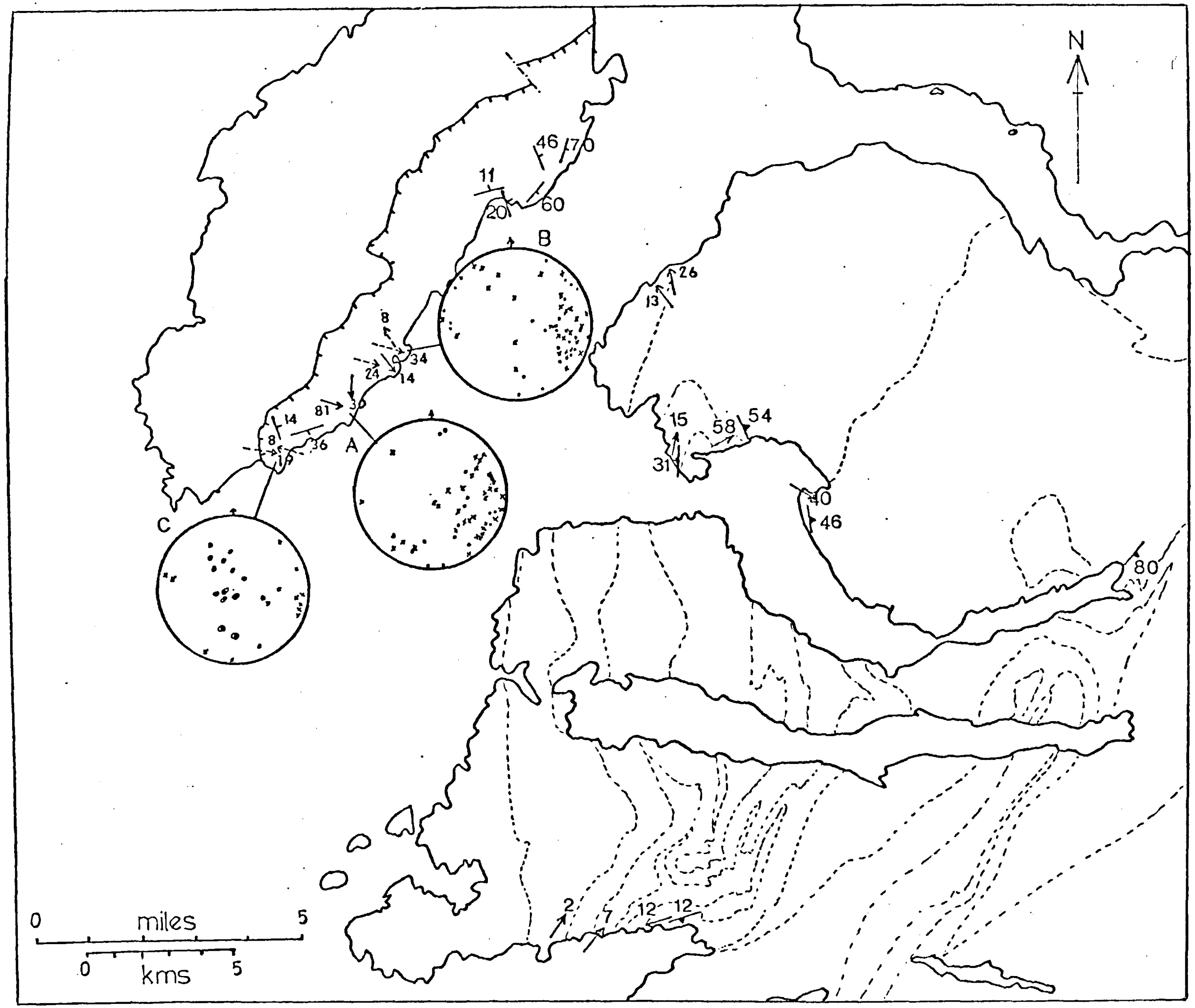


Fig. 23 D_1 structures of the Moine nappe.

PROJECTIONS

A Tormore

B Rubha Phoil } Armadale section
Rubha Dubh }

C Aird

KEY TO PROJECTIONS

• F_1 fold hinges

× L_1 mineral elongation lineation

∘ Poles to S_1 or banding

KEY TO MAP

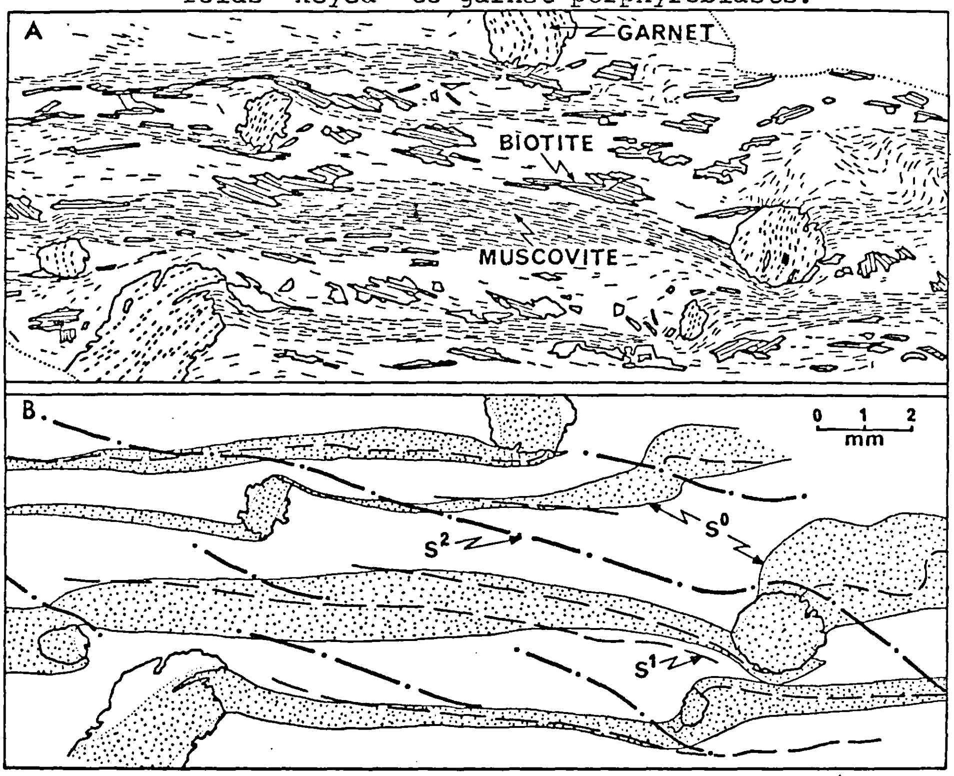
F_1 fold hinges

S_1 or banding

L_1 mineral elongation lineation

F_1 axial planes

FIGURE 24. Diagram (B) of thin section (A) from Skye, illustrating the relationships between inclusion fabrics in garnet crystals and matrix elements. S_o-bedding; S_1-first schistosity; S_2-second schistosity. S_o and S_1 are overgrown by garnet, and S_2 is axial planar to microfolds "keyed" to garnet porphyroblasts.



a. b.

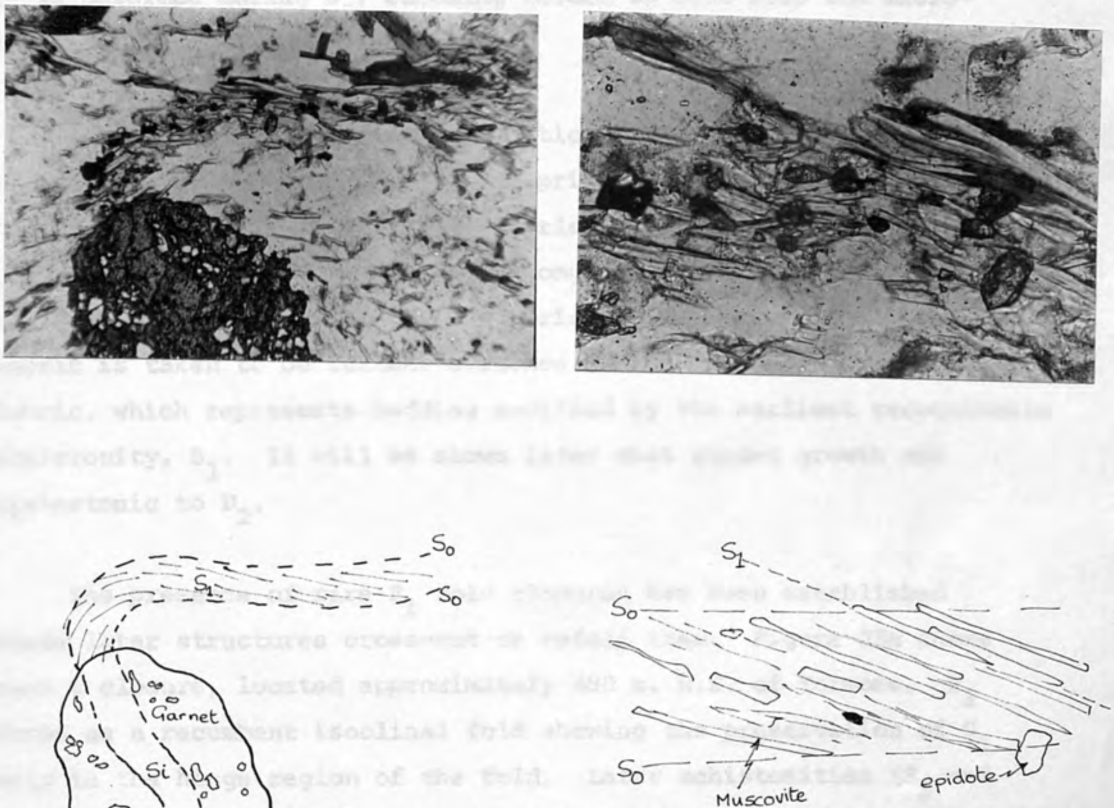


Plate 9: Photomicrographs (P.P.L.) showing the layering (S_0) and the oblique early fabric (Si) outined by muscovite crystals. Samples taken from the Armadale Pelite. (a)x10, (b)x50).

the interpretation of the sequence of structural and metamorphic events in the thrust zone. Figure 24 shows the relationship between S_o and S_1 and S_2, and Plate 9 shows the layering (S_o) and the oblique early fabric (S_1). The muscovite "felt" which constitutes S_1 is deformed during D_2, becoming folded on both meso and microscopic scales.

Garnet crystals within the pelitic rocks at Armadale show an inclusion fabric (S_i). Minerals comprising this inclusion fabric (S_i) often show preferential shape orientation of individual grains (quartz and magnetite) as well as elongated groups (trails) of crystal aggregates. The preferred orientation of the inclusion fabric is taken to be further evidence for a pre-garnet, planar fabric, which represents bedding modified by the earliest recognisable schistosity, S_1. It will be shown later that garnet growth was syntectonic to D_2.

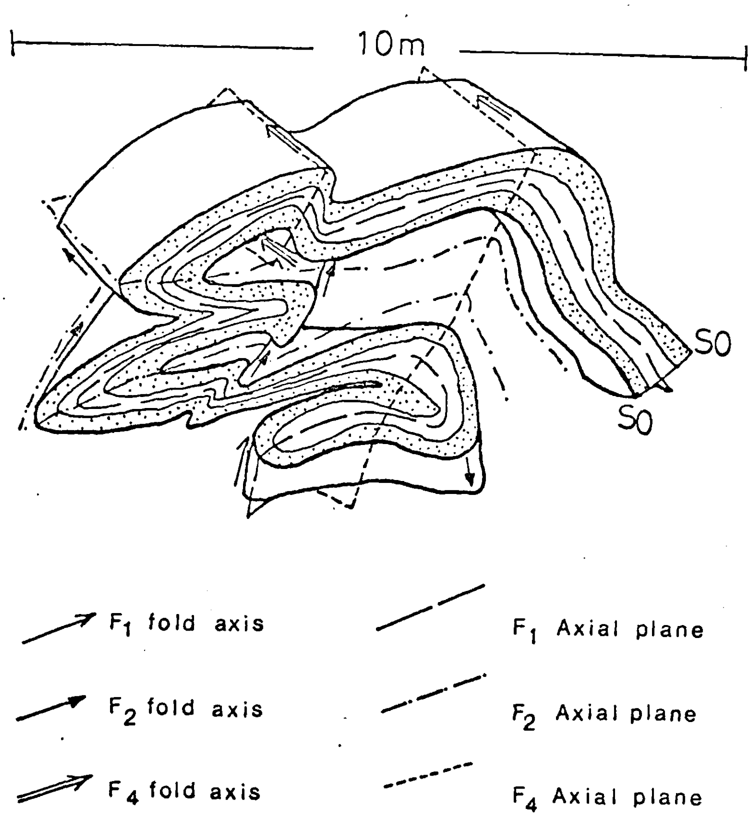
The presence of rare F_1 fold closures has been established where later structures cross-cut or refold them. Figure 25a shows such a closure, located approximately 400 m. N.E. of Tormore. F_1 forms as a recumbent isoclinal fold showing the preservation of S_1 only in the hinge region of the fold. Later schistosities (S_2 and S_4) obliterate the earlier planar fabric (Fig. 25b). Other isolated early fold closures occur, but no regional trend or orientation pattern can be established (Fig. 23, Projections A and B) due to later phases of deformation.

Early structures in the Lewisian rocks of the thrust zone are not readily distinguishable because of chloritisation and retrogression of the rocks, brecciation and intense kink banding related to the dislocation of the Moine nappe during thrusting. Projection C of Figure 23 shows the lack of systematic preferred orientation of the large scale S_1 schistosity and associated L_1 lineations.

4.2.2 First phase deformation (D_1) structures within the mobile belt

Evidence for the earliest phase of deformation within the mobile belt is similarly limited on a small-scale to isolated F_1 fold closures and lineations, L_1. Figures 26a-c and Plates 10a-c show

25a



25b

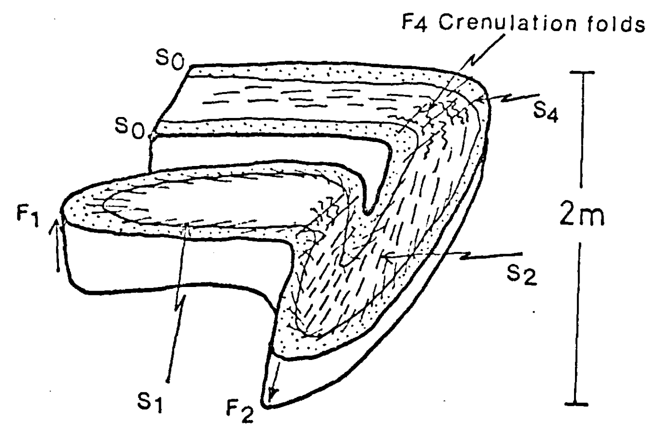
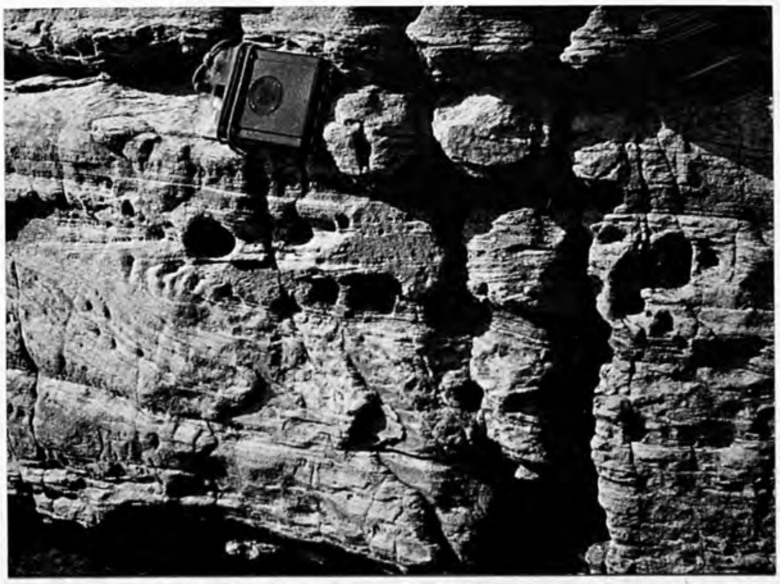


Fig. 25. Evidence of 3 phases of superimposed deformation, Tormore, Skye.
Fig.25a is drawn from a field locality and shows an F_1 isoclinal fold refolded by F_2 isoclines and F_4 open profile folds.
Fig.25b is an enlargement of the F_1 closure to show the deformation and obliteration of the early S_1 schistosity (axial planar to the F_1 fold) by later folds.

a.

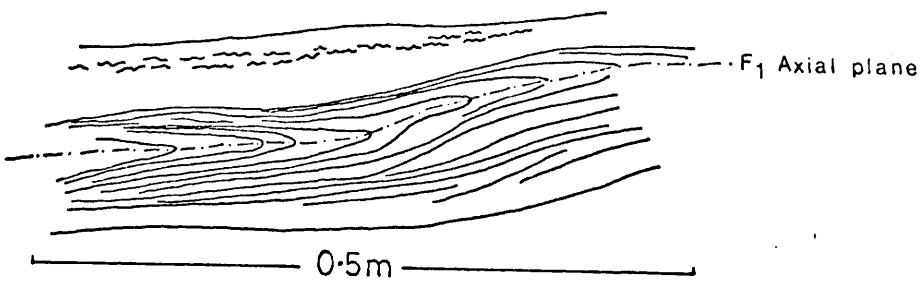


b.

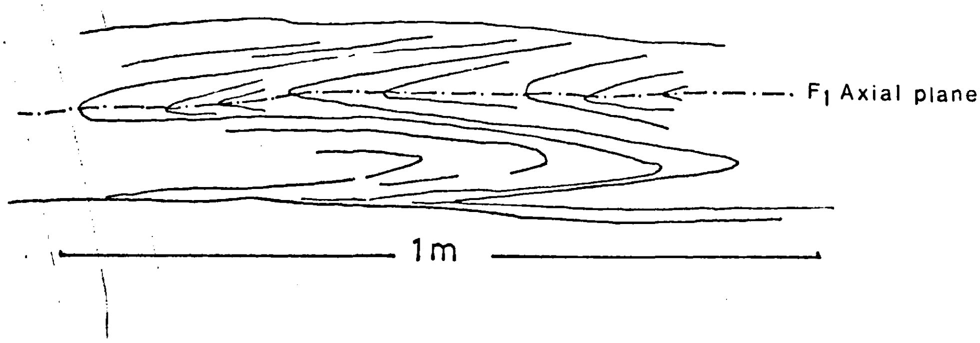
c.

Plate 10: Intrafolial F_1 folds. Examples 10a and 10b from Arisaig, example 10c from Knoydart.

26a



26b



26c

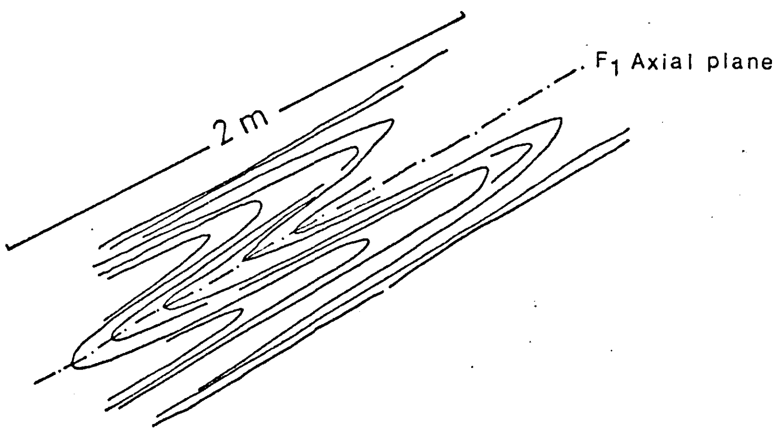


Fig.26. Intrafolial F_1 folds. Figs. 26a and b are examples from the Druimindarroch section in South Morar, and Fig. 26c is from east of Sandaig Bay in West Knoydart.

examples of F_1 intrafolial folds, and Figure 27 and Plate 11 show examples of F_1 folds deformed by later structures. Because of modification by later phases of deformation the original fold profiles cannot be accurately determined, but F_1 folds now range between either class 2 or class 3 of Ramsay (1967).

D_1 structures on a large scale have been established in the Glenelg region by the recognition of Lewisian rocks occupying the cores of large scale isoclinal folds, which are the earliest structures to be recognised in this area (Ramsay, 1958 and 1962). The occurrence of Lewisian gneisses, closely associated with basal members of the Moine assemblage coupled with way-up criteria has been used to establish a large scale isoclinal fold closure in Knoydart on the western limb of the Morar Dome. Figure 28 shows a schematic cross-section from Sandaig Bay to Rubha Raonuill demonstrating the presence and age of this early fold. However, the direction of closure is arbitrarily drawn as there is no evidence to indicate whether the fold closes to the east or west.

Little indication of an oblique early schistose fabric is found in the Knoydart area. However, the alignment of micas and elongate grains of quartz and feldspar parallel to bedding, producing a bedding schistosity, may well in part, or wholly, be due to D_1 deformation since most of the rocks exposed constitute the limbs of D_1 isoclinal folds. In the extreme east where gneissose textures are particularly common in the pelitic rocks the banding is partially assumed to be the result of a modification of S_o by S_1, during D_1/M_1. This early (S_1) fabric may well however be obliterated by recrystallisation during later metamorphic events, although the elongation of individual grains and trails of crystal aggregates forming the inclusion fabric (S_i) within the innermost zones of garnet porphyroblasts, is thought to reflect the earliest modifications of S_o by S_1 (see Section 4.5 on metamorphism, M_1).

4.3 Structures associated with the second phase of deformation (D_2)

4.3.1 D_2 structures of the Moine thrust zone

The Moine thrust zone of Skye can be considered as three main

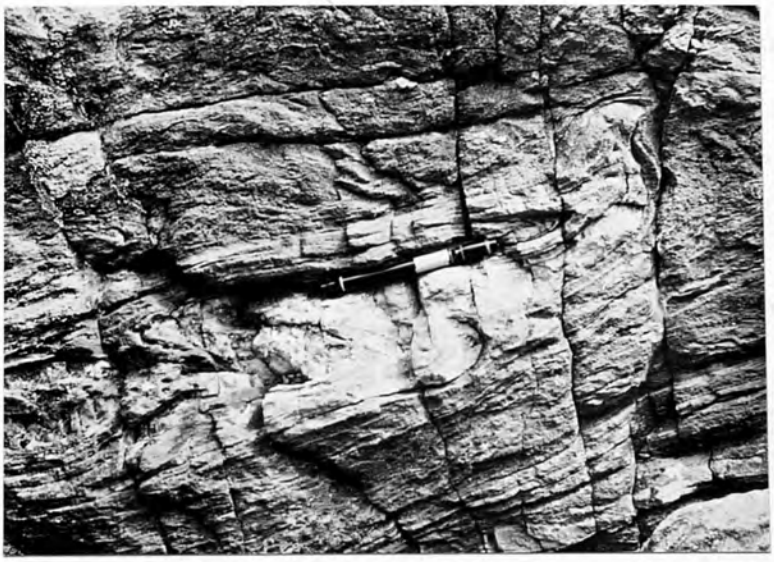


Plate 11: Small scale F_1 isoclinal fold refolded by F_2 folds. Pen is parallel to F_1 axial plane (see also Fig. 27a).

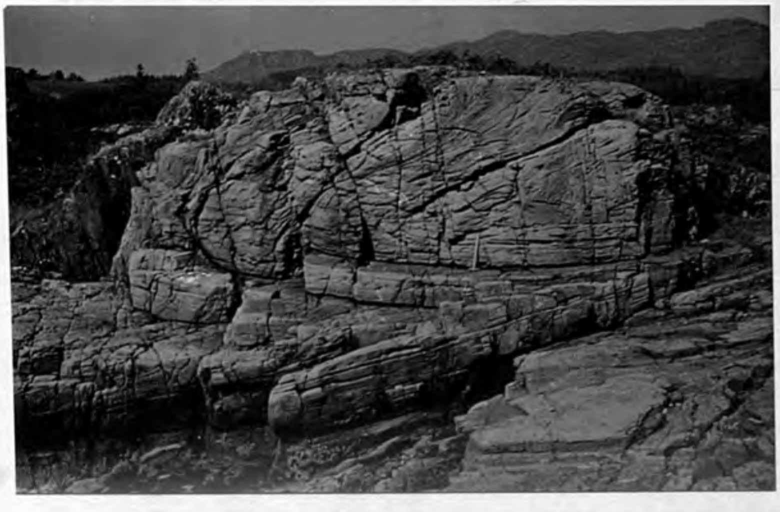
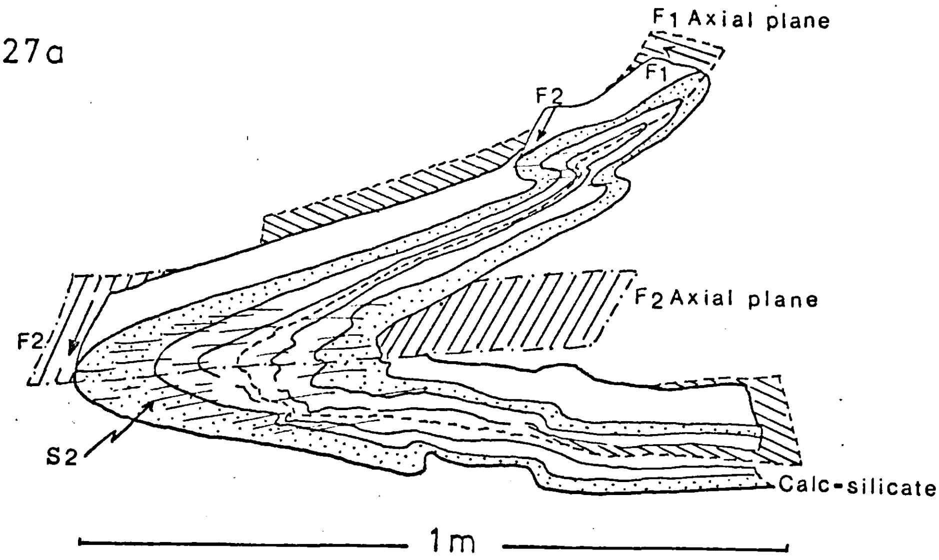


Plate 12: Mesoscopic recumbent, F_2 isoclinal fold, Druimindarroch. (See also Fig. 29c).

27a



(See plate 11.)

27b

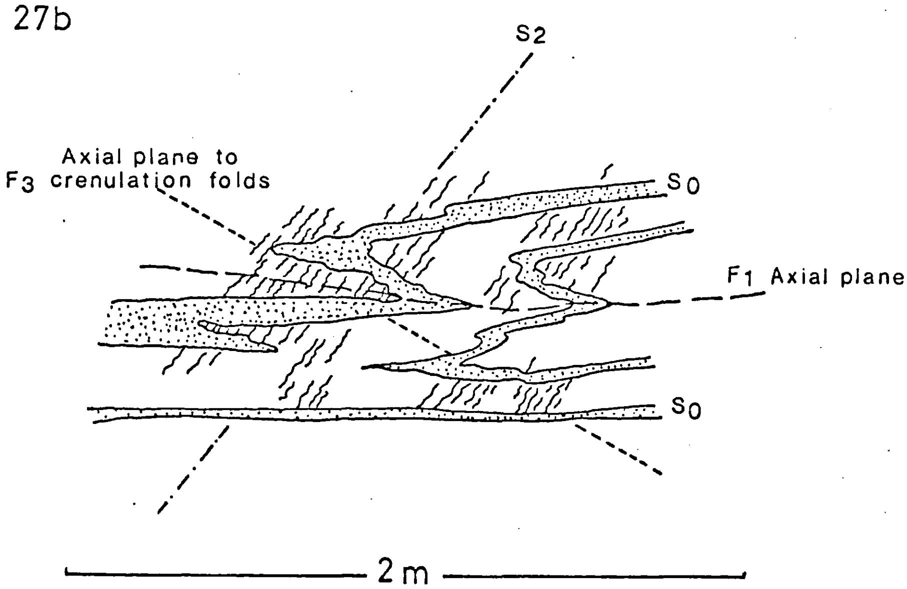
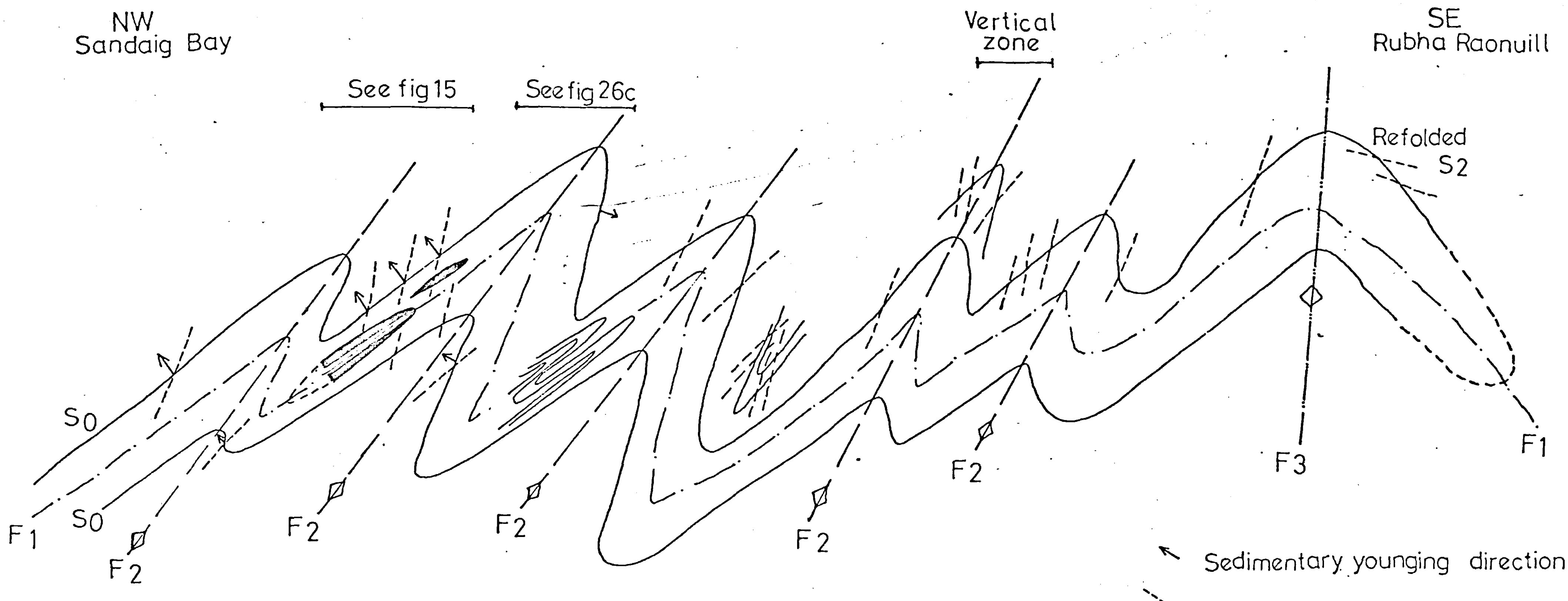


Fig.27. F_1 folds deformed by later structures.

27a. F_1 isocline in calc-silicate band refolded by F_2 folds (see also Plate 11). Location, Druimindarroch, South Morar.

27b. Small scale F_1 isoclinal folds cross-cut by S_2 schistosity which is crenulated by F3 folds. Location north of Airor, West Knoydart.



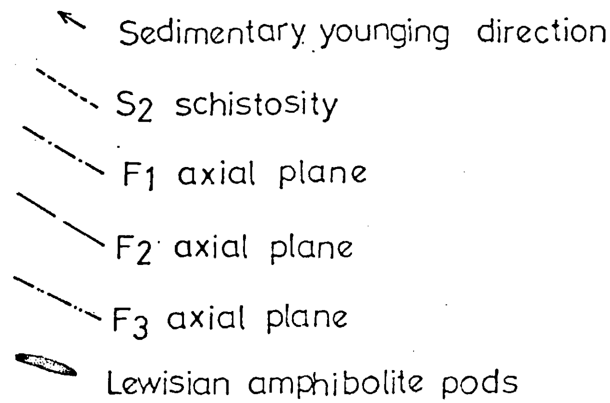


Fig. 28. Diagrammatic cross-section from Sandaig Bay to Rubha Raonuill in West Knoydart. The diagram shows a large scale F_1 fold, based on sedimentary structures (see Fig.16) and bedding-cleavage (S_2) intersections, plus isolated Lewisian amphibolite pods (Fig.15) and rare minor F_1 fold closures (Fig.26c). The section is not drawn to scale.

sub-areas, (a) the Armadale section, (b) the Tormore section, and (c) the Aird section.

(a) The Armadale section. Locally, isoclinal folds (class 1C-2, Ramsay 1967) with sub-horizontal axes, refold L_1 lineations (Fig. 29a). The fold axes form a scatter between south and northeast (Projection A, Fig. 30) with an intersection lineation (L_2) of S_2 on S_o parallel to the fold hinges. The cleavage and axial planes dip at shallow to moderate angles between northeast and southeast (Projection A, Fig. 31). In many instances S_2 and S_3 are coplanar (see also Chapter 5) and therefore indistinguishable in hand specimen.

(b) The Tormore section contains large scale upright isoclinal folds (class 1C-2 Ramsay 1967) which develop with parasitic minor folds on the limbs. L_1 is refolded by F_2 isoclines, and this is best seen on the parasitic minor folds (Fig. 29b). Figure 32 illustrates the geometry of small F_2 folds which are used to determine the presence of large scale isoclinal closures. An axial plane schistosity is strongly developed, particularly in pelitic horizons. It is usually represented by the parallel crystallographic alignment of micas and general elongation of minerals (quartz and feldspar) and mineral aggregates. Projection B, Figure 30 shows the distribution of F_2 fold hinges and associated intersection lineations L_2 of S_2 on S_o, which trend approximately east-west and plunge at varying angles. Plot B, Figure 31 shows D_2 planar structures from this area. The F_2 axial planes and S_2 cleavage planes dip moderately southeast, with a certain amount of scatter towards the east and south. The enveloping surface of the layering (Plot C, Fig. 31) emphasises the resulting southeasterly dip.

(c) Within the Aird section, D_2 structures in both the Moine and the Lewisian are poorly developed. Rare isoclinal fold closures which deform the layering, together with localised intersection lineations, are thought to be of D_2 age (Projection C, Fig. 30). This correlation is based on similarities of fold style, deformation of pre-existing linear (L_1) and planar (S_1) fabrics thought to represent the earliest structural features in this area. Later structures deform these F_2(?) isoclinal folds.

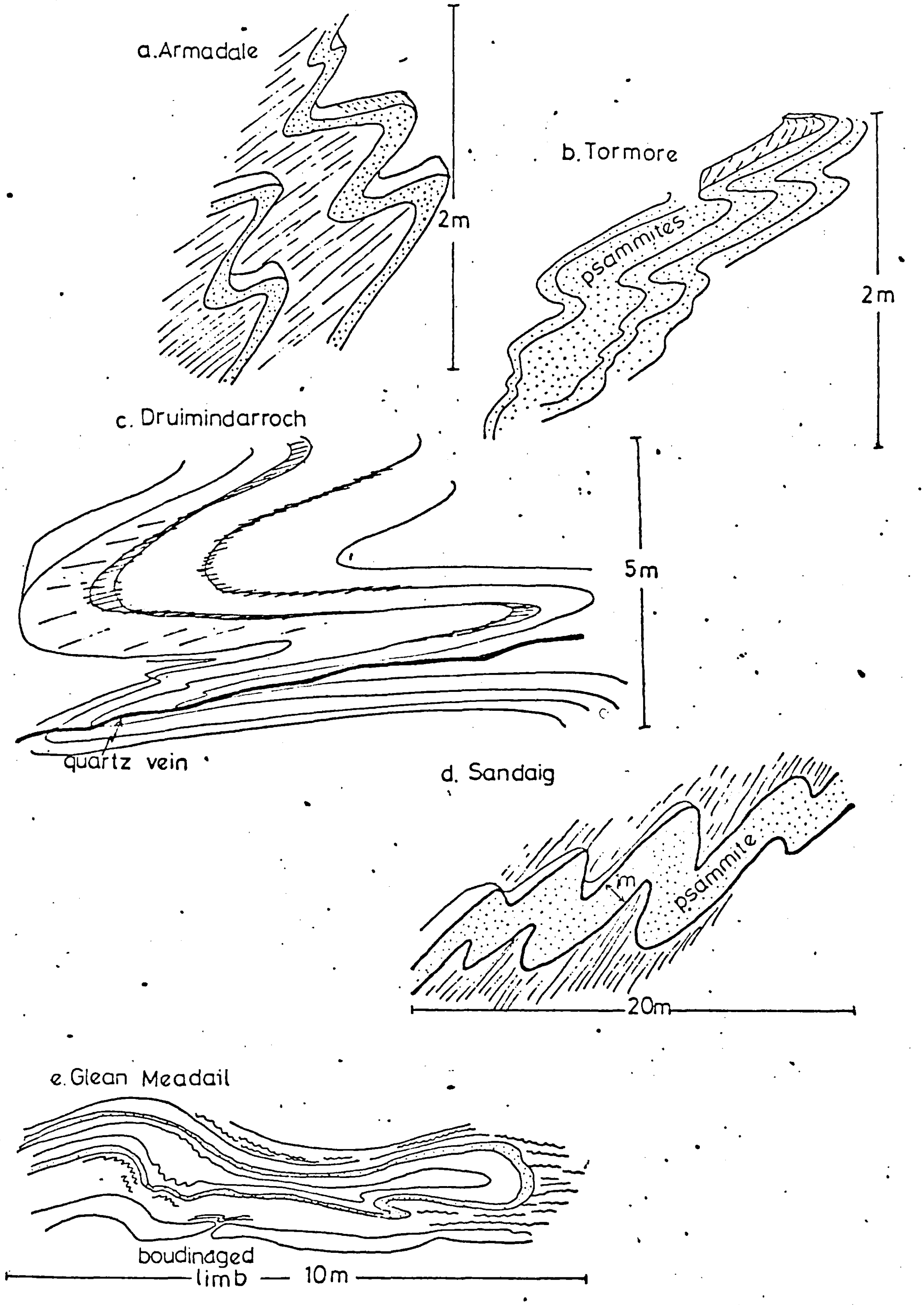


FIGURE 29. F_2 fold styles

Figs. 29a and b from Skye show F_2 folds refolding an earlier (L_1) lineation. S_2 restricted to semipelitic units.
Fig. 29c Druimindarroch. Large recumbent isoclinal folds, S_2 axial planar schistosity restricted to pelitic layers between massive psammite units. (See also Plate 12)
Fig. 29d. Sandaig. Large scale assymmetric F_2 folds on western limb of Morar Dome. Schistosity restricted to semipelitic horizons.
Fig. 29e. Gleann Meadail. Large recumbent F_2 isocline with boudinaged fold limb refolded by F_3 open profile and coaxial crenulation folds. (See also Plate 18)

PROJECTIONS

A Armadale
B Tormore
C Aird
D Arisaig (South Morar)
E Doune-Inverie (west Knoydart)
F Inverie-Gleann Dubhlochain
G Inverie-Kylesknoydart
H Gleann Meadail - Carnoch
I Kylesknoydart-Camusrory

KEY TO PROJECTIONS

• F_2 fold hinges
× L_2' mineral elongation lineation

KEY TO MAP

F_2 fold hinges
L_2 intersection lineation
L_2' mineral elongation lineation

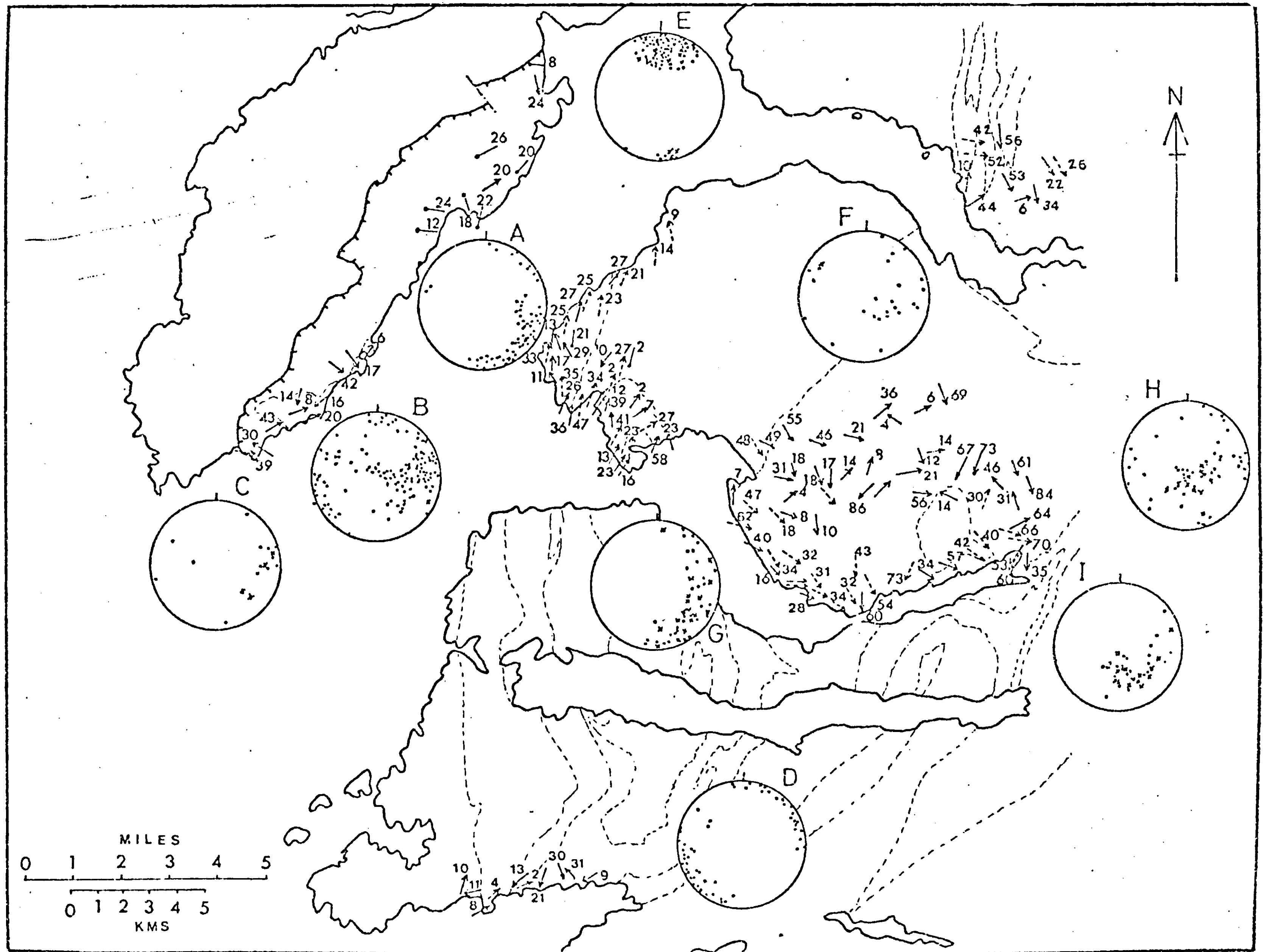


Fig. 30. D2 Linear structures in the Moine nappe.

PROJECTIONS

A Armadale

B Tormore

C Tormore - Poles to S_0

D Arisaig (South Morar)

E Doune-Inverie (West Knoydart)

F Inverie-Gleann Dubhlochain

G Inverie-Kylesknoydart

H Gleann Meadail-Carnoch

I Kylesknoydart-Camusrory

KEY TO PROJECTIONS

• Poles to S_2

× Poles to F_2 axial planes

KEY TO MAP

S_2 schistosity

F_2 axial planes

quartz veins parallel to F_2 axial plane.

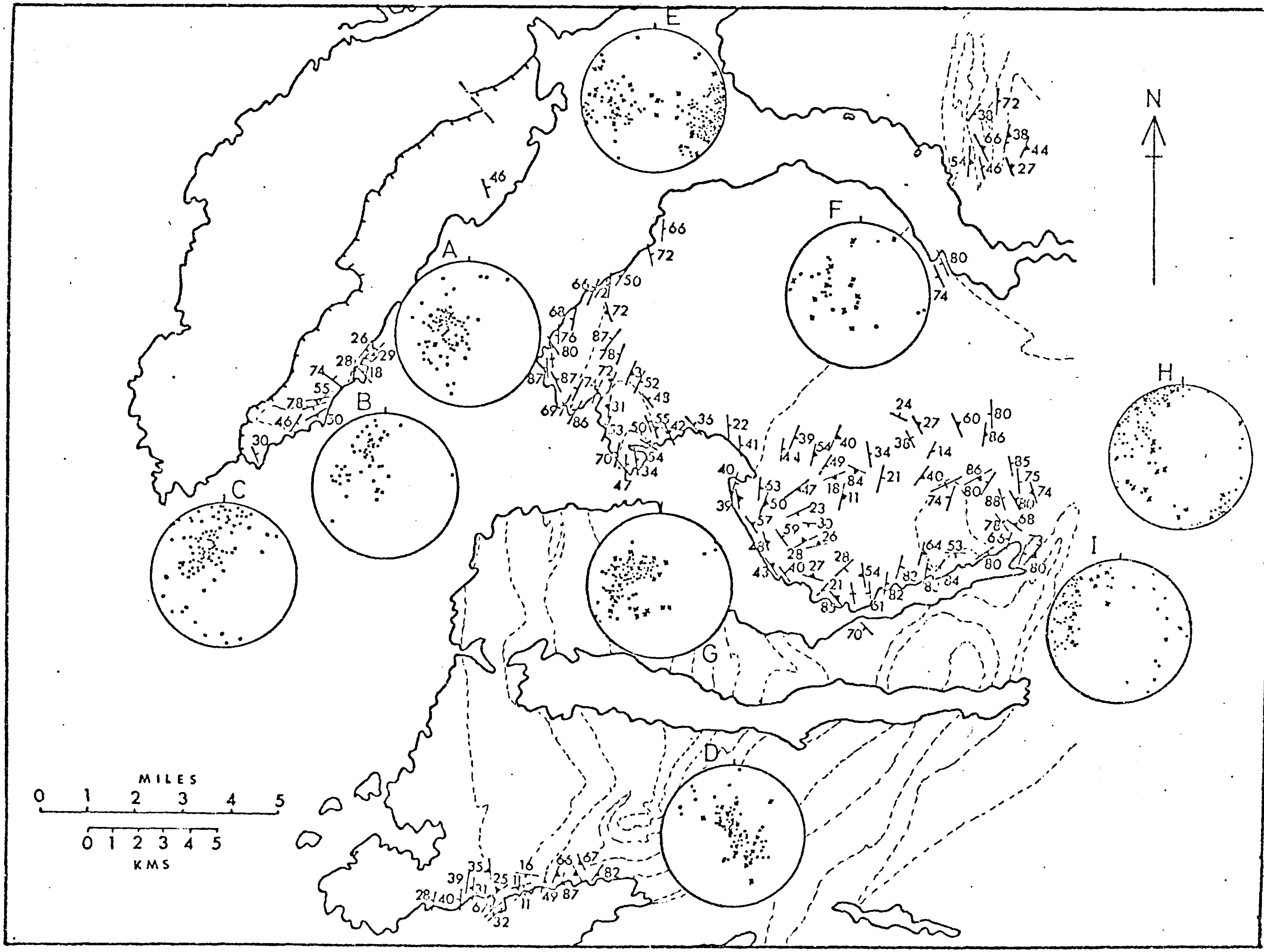
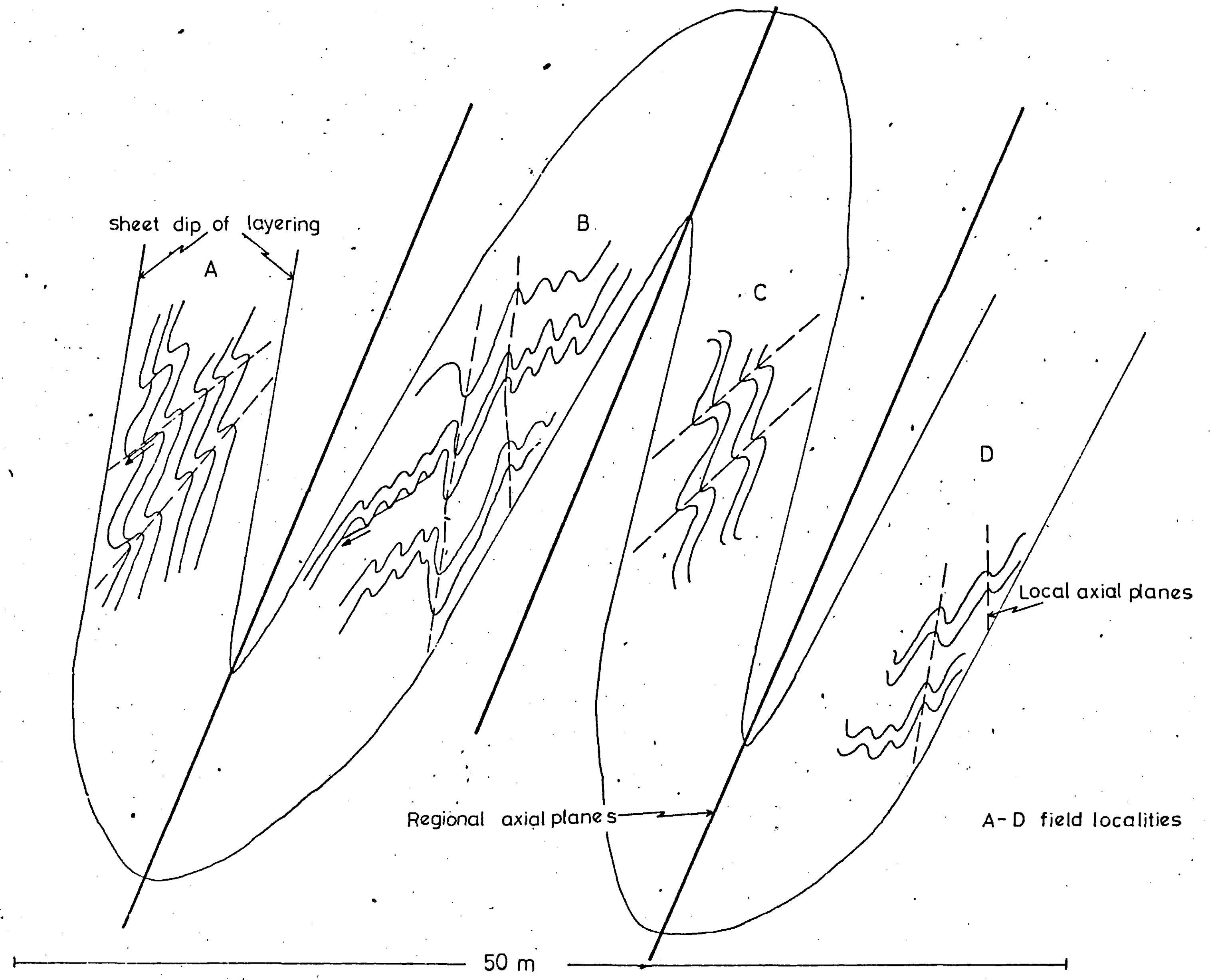


Fig. 31. D_2 planar structures in the Moine nappe.

FIGURE 32. Small scale F_2 folds showing a parasitic relationship to macroscopic isoclines at Tormore, Skye. Local axial planes fan about the major fold closures. The axial planes of the regional F_2 folds dip consistently southeast at steep angles. Viewed looking southwest.



4.3.2 D_2 structures in the mobile belt

The second phase deformation in south Morar (Arisaig) has produced recumbent, isoclinal F_2 folds (Plate 12, Fig. 29c) which plunge between northeast and southwest at shallow angles (Projection D, Fig. 30); whilst planar elements (Projection D, Fig. 31) show an approximate great circle distribution between northwest and southeast, reflecting moderate to steeply dipping axial planes and S_2 schistosity.

In Knoydart the second phase of deformation is similarly represented by isoclinal folds which develop an axial plane schistosity (S_2) and which in many areas show marked limb attenuation and associated boudinage (Plates 13 and 14, Fig. 29e).

In west Knoydart, structural traverses across the Morar antiform suggest that this fold is D_2 in age, and not D_3 as previously proposed (Bailey, 1955; Ramsay, 1963 and Poole & Spring, 1974). Parasitic F_2 fold closures on the western limb of the fold give antiformal vergence eastwards (Plate 15, Fig. 29d) and S_2 is less steep than bedding (Plate 16); whereas on the eastern limb parasitic F_2 folds show antiformal vergence towards the west and S_2 is steeper than bedding. Figure 33 shows a schematic section across the Morar antiform illustrating these relationships.

Figure 30, Projection E, shows F_2 fold hinges, L_2' mineral elongation lineations and coaxial quartz rodding (L_2') plus associated quartz vein folds plunging due north at shallow to moderate angles. There is a restricted amount of scatter in a northerly direction and occasional shallow plunges to the south. The trend of F_2 folds becomes more northeasterly towards the core of the Morar antiform. Figure 31, Projection E, shows D_2 planar structures; S_2 and F_2 axial planes strike approximately north-south, dipping moderate to steeply east and west. D_2 mesoscopic isoclinal folds are commonly upright structures, except where refolded, and as a consequence the axial planes and cleavage tend to be near vertical.

Eastwards, structures developed during the second phase of deformation become progressively less recognisable because of later refolding during the third and fourth phases of deformation (Chapter 5). As a

a.

b.

Plate 13a & b: Boudinaged psammite layers in Gleann Meadail. Boudinage axes are coaxial with F_2 fold axes. Note F_2 fold closure in Plate 13a.

Plate 14: Detached F_2, isoclinal fold nose, Gleann Meadail.

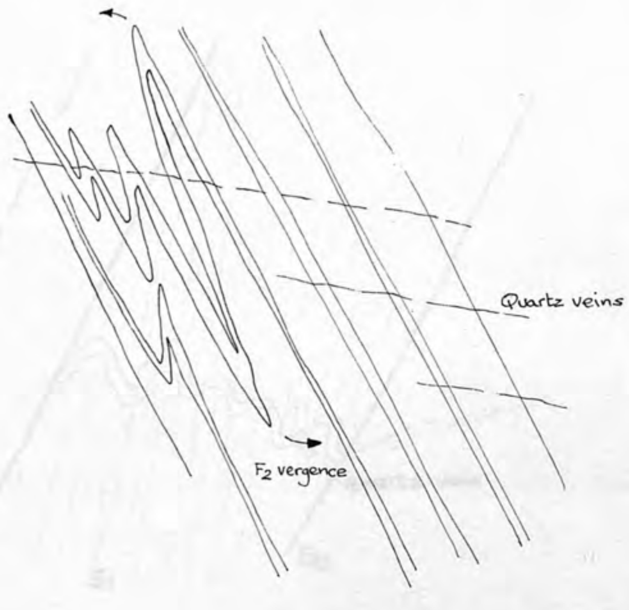


Plate 15: F_2 parasitic folds on the western limb of the Morar Antiform, give antiformal vergence to the east. (Viewed looking south and down the plunge of the folds). Cross-cutting quartz-veins are parallel to S_3. Location - Airor, West Knoydart.

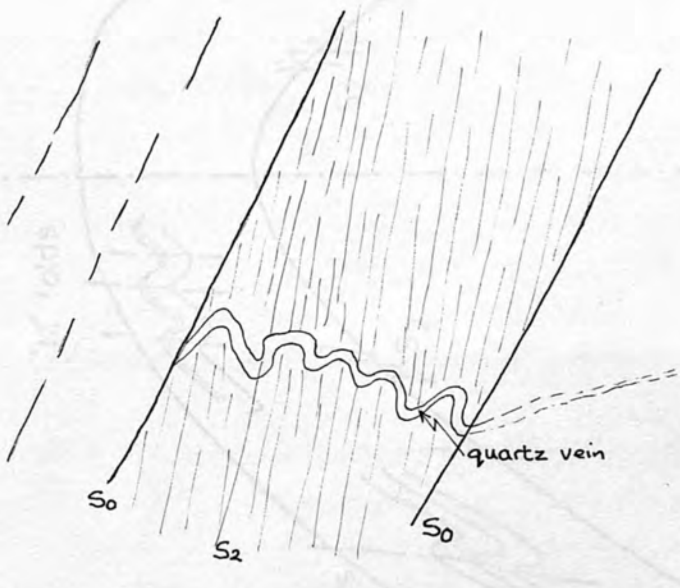


Plate 16: Bedded psammites and semi-pelites which show that the S_2 schistosity is steeper than bedding (S_0), on the western limb of the Morar Antiform. (Facing north).

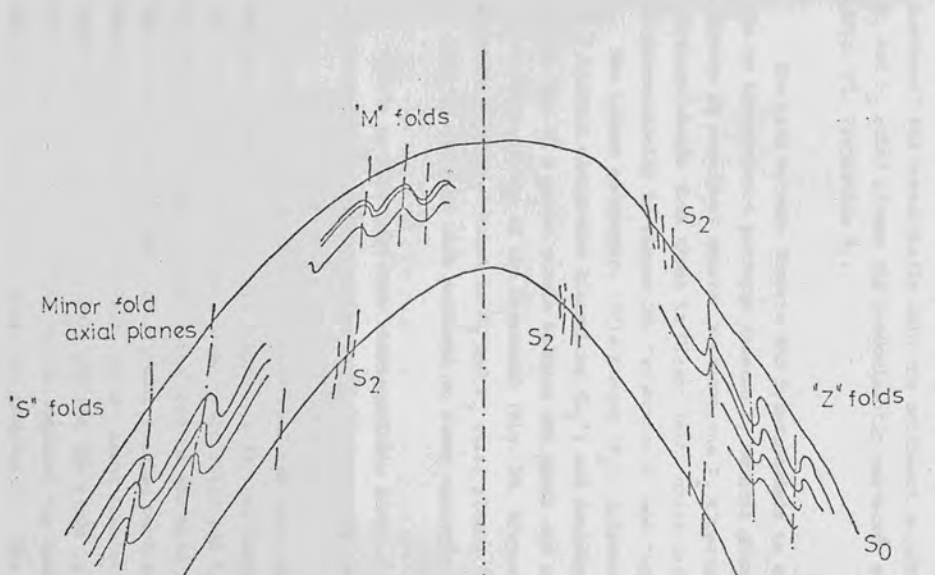


FIGURE 33. Diagrammatic cross-section of the Morar Antiform. Parasitic folds and schistosity (S_2) - bedding (S_o) intersections are taken from field examples. Note that minor F_2 fold axial planes and S_2 schistosity are parallel to the major axial plane, F_3 axial planes and S_3 schistosity fan about the major fold closure (see fig. 46)
(Not to scale)

result of this the linear and planar elements of D_2, where present, show a marked variation in attitude and orientation (Figs.30 Projections F and I, 31 Projections F and I, and Plates 17-20 and 14).

From Inverie to Gleann Dubhlochain isoclinal closures are rare and fold hinges show a scatter (Fig. 30, Projection F) throughout the northeast and occasionally into the northwest sector of the stereonet. S_2 and F_2 axial planes dip predominantly eastwards at varying angles (Fig. 31, Projection F).

The area between Inverie and Kylesknoydart is structurally complex due to interference patterns created by several phases of deformation. Because of excellent coastal exposure, the D_2 structures are more readily distinguishable than those in Gleann Dubhlochain and are represented diagrammatically in Figure 30, Projection G, and Figure 31, Projection G. The linear elements:- fold hinges (F_1), intersection lineations (L_2) mineral elongation lineations (L_2') and associated quartz vein folds, lie on a great circle between the north and south poles in the eastern sector of the stereonet (Fig. 30, Projection G) all showing moderate plunges. Poles to S_2 and F_2 axial planes (Fig. 31, Projection G) plot in the west with moderate to steep easterly dips.

Folds in this area show characteristic hinge thickening and limb attenuation and belong to classes 2 and 3 (Ramsay 1967), (Plate 17).

A major F_2, recumbent, isoclinal fold has been recognised in central Knoydart (Spring, 1961; Poole & Spring, 1974, and Powell, 1974), termed the Knoydart fold. Mesoscopic parasitic folds and S_2 schistosity-bedding intersection relationships confirm the main fold closure within the Ladhar Beinn Pelite. Syntectonic sliding occurred during the formation of the Knoydart fold, on the lower limb of the recumbent fold (see Fig. 12, Chapter 2). Evidence for the slide is based on the thinning of the Ladhar Beinn Pelite (against the Lower Psammite) around the Knoydart fold, (Fig. 22, Chapter 3). The slide is refolded during subsequent phases of deformation such that it is exposed to the east of Inverie in central Knoydart, and in eastern Knoydart in the region of the Meall Bhasiter Dome (Chapter 5.2.3).

Plate 17: Class 3, (Ramsay, 1967). F_2 fold from the Inverie-Kylesknoydart section, showing a folded calc-silicate in a semi-pelite. S_2 is axial planar to the fold.

Plate 18: Recumbent F_2 isocline. S_2 axial plane schistosity, which is parallel to the limbs of the fold, is crenulated by F_3 folds. Hammer is parallel to F_2 axial plane. Location - Gleann Meadail.

19

20

Plate 19 & 20: F_2 isoclinal folds (Class 2-3, Ramsay, 1967) from eastern Knoydart. S_2 axial plane schistosity is well developed in Plate 19, and crenulated by F_3 folds (see to the left of camera lens).

The section from Glen Inverie along Gleann Meadail to the Carnoch ruins shows mesoscopic, often recumbent, isoclinal folds with an axial plane schistosity which becomes strongly crenulated during subsequent deformations (Plate 18, Fig. 29e). S_2 is similarly preserved in the thickened axial regions of the folds, but elsewhere tends to emphasise the layering as it is commonly parallel or sub-parallel, to the limbs of the folds.

Figure 30, Projection H shows the scatter of linear structures due to refolding and Figure 31, Projection H the variability in attitude of axial planes and schistosity. The planar elements show a certain amount of consistency of northeasterly-southwesterly strike and moderately steep dips to the southeast or northwest, which in part also reflects the attitude of the layering (S_o/S_1).

The section from Kylesknoydart, east along the northern shore of Loch Nevis to Camusrory, exposes F_2 folds of similar styles, trends and orientations as those of the Gleann Meadail-Carnoch section (Plates 19 and 20). The linear elements are slightly more preferentially oriented into the southeast sector of the plot (Fig. 30, Projection I) with moderate to steep south to easterly plunges. S_2 and F_2 axial planes strike predominantly northeast-southwest, and dip steeply to the southeast or northwest (Fig. 31, Projection I). These planar elements parallel the layering, which in these eastern regions is a gneissose banding rather than a bedding schistosity, and becomes strongly crenulated during later deformations.

4.4 Correlations of D_1 and D_2 throughout the area

Evidence presented in section 4.2 showed that the earliest structures found in the research area include large and small scale isoclinal folds (F_1); an axial planar schistosity - S_1 - preserved in the hinge zones of F_1 folds or observed in thin sections as a muscovite "felt" oblique to the lithological layering; and a mineral elongation lineation (L_1) formed by the alignment of mica, quartz or feldspar crystals or aggregates coaxial to F_1. The planar inclusion fabrics preserved in porphyroblastic metamorphic minerals which grew during M_1 (see following Section 4.5) is also thought to have been formed during D_1.

The regional correlation of D_1 structures within the thrust zone in Skye with those of mobile belt areas of Morar and Knoydart is based on several factors:-

(i) The similarity of the relations between the S_1 muscovite "felt" and the lithological layering (in thin section), in areas within the thrust zone (i.e. the Tormore and Armadale sections), and from the thrust zone to the mobile belt. The same S_1 fabric, oblique to S_o, may be observed in pelitic rocks in west Knoydart and south Morar. Further east in Knoydart this fabric is not preserved so a similar correlation may not be conclusively made;

(ii) Lewisian rocks in west Knoydart form the core of a large scale isoclinal F_1 fold, whose presence is confirmed by sedimentary structures. Similar F_1 fold closures are described from Glenelg (Ramsay 1958, Sutton & Watson 1959) and these large scale, recumbent isoclinal folds, with Lewisian cores, are thought to be analagous to that in west Knoydart.

(iii) The mineral elongation lineation L_1 which is coaxial with F_1 folds, becomes deformed (refolded) by subsequent phases of deformation whose structural affinity can be more readily correlated.

Because of the complex polyphase nature of the deformation in the research area, the correlation of these earliest recognised structures is conjectural.

The regional correlation of D_2 structures is based on a combination of structural and metamorphic evidence. The former will be outlined here, and the latter in Section 4.6 following the description of the early metamorphic event (M_1), where correlations of D_1, D_2 and M_1 will be summarised.

D_2 structures throughout the area include folds, an axial plane schistosity and intersection and mineral elongation lineations. Characteristic fold styles are developed (Fig. 29) and in areas where subsequent deformation is either minimal or of a markedly different character, this serves as a tentative basis for initial correlation. Axial trends and the attitude of schistosities and axial planes are fairly consistent in the west (Figs. 30 and 31), but vary greatly in the east. This is due to major refolding and therefore re-orientation of pre-existing structures during later phases of deformation. In this easterly part of the area the recognition of D_2 structures was based partly on the unravelling of later structures, working back through the structural sequence.

Continuous across-strike traverses from west to east Knoydart, made it possible to trace D_2 structures from relatively less complex areas into more complex areas, thereby enabling the correlation.

Evidence has been outlined in support of a D_2 age for the Morar Antiform in west Knoydart. This evidence includes the vergence of parasitic folds and S_2 schistosity - bedding intersection relationships. In south Morar mesoscopic F_2 folds are frequently recumbent and their possible parasitic relationship to the Morar Antiform is difficult to determine. Similarly S_2 schistosity-bedding intersection relationships are also inconclusive. Because of this it is not possible to prove that the Morar Antiform in south Morar is D_2 in age.

In both the thrust zone and the mobile belt, F_2 folds are often characterised by quartz veins or pegmatites, parallel to the axial planes. In eastern parts of Knoydart, boudinaged quartz veins and pegmatites occur, and the attitudes of these is such that they parallel the layering. The boudin axes are commonly coaxial with F_2 folds (Plate 13a and b). As later phases of deformation tend to produce open profile and associated crenulation folds (Plate 18, and Chapter 5), with no marked limb attentuation, it is suggested that the boudinage was the result of deformation and flattening pre-D_3 and probably syn-D_2. The evidence for flattening of quartzite layers producing boudinage of F_2 fold limbs and detatchment of F_2 fold noses is seen in Gleann Meadail (Plates 13a and b, and 14), and the resulting recumbent S_2 axial plane cleavage becomes strongly crenulated by D_3. Consequently, boudinaging of fold limbs and coplanar quartz veins and pegmatites is attributed to flattening during D_2 rather than D_1. Flattening during D_2 is also thought to be responsible for the near detachment of F_2 isoclinal fold noses in areas where occasional competent layers (psammites) are interbanded in largely incompetent strata (pelites) (Plate 14). Elsewhere F_2 hinges often appear curved but it is difficult to ascertain whether this is a reflection of original deformation during D_2 or if it is the result of later refolding. Only in isolated cases can later folds be seen refolding the earlier hinges, e.g. Airor and Tormore (see Fig. 32).

4.5 The "Early" Metamorphism - M_1

4.5.1 Introduction

Two distinct phases of regional metamorphism in the research area have been proposed by several workers - Long and Lambert, (1963); van Breeman et al, (1974); Powell, (1974) and Winchester, (1974); each with its related metamorphic facies sequence. Both metamorphic episodes show an increase in grade from west to east. Consequently a map showing the distribution of the metamorphic facies for a single metamorphic event cannot be easily established. Winchester (1974) has published a zonal map of the Scottish Highlands showing metamorphic zones based on the mineralogy of calc-silicates (Fig. 34). He attributes the complexity of the zonal pattern to the interaction of different metamorphic events, widespread retrogression, apparent metamorphic inversion, and post-metamorphism deformation of isograds.

The initial regional migmatisation and the earliest phases of deformation suggested by Dalziel, (1966); Dalziel and Brown, (1965); Shepherd, (1973) and Tobisch et al., (1970) are attributed to a "Morarian" event (Lambert 1963). It is this "Morarian" event (with the inference that it is Precambrian) that is referred to in this thesis as M_1. The following Section (4.6) will endeavour to establish that this early metamorphic event overlapped the first two phases of deformation, D_1 and D_2, and not just the D_1 events as suggested by van Breeman et al., (1974).

4.5.2 Evidence for M_1 in the Research area

The highest metamorphic grade attained during M_1 in the west was garnet grade, with porphyroblasts occurring frequently in pelitic rocks. Winchester's (1974) zonal map (Fig. 34) needs some modification in that the Moine rocks of the Moine nappe on Skye lie within the Almandine (garnet) zone, and not within the biotite zone as shown; garnet as well as biotite is found in the Armadale Pelite, and in semi-pelitic and pelitic horizons of the Tormore psammite (Chapter 3).

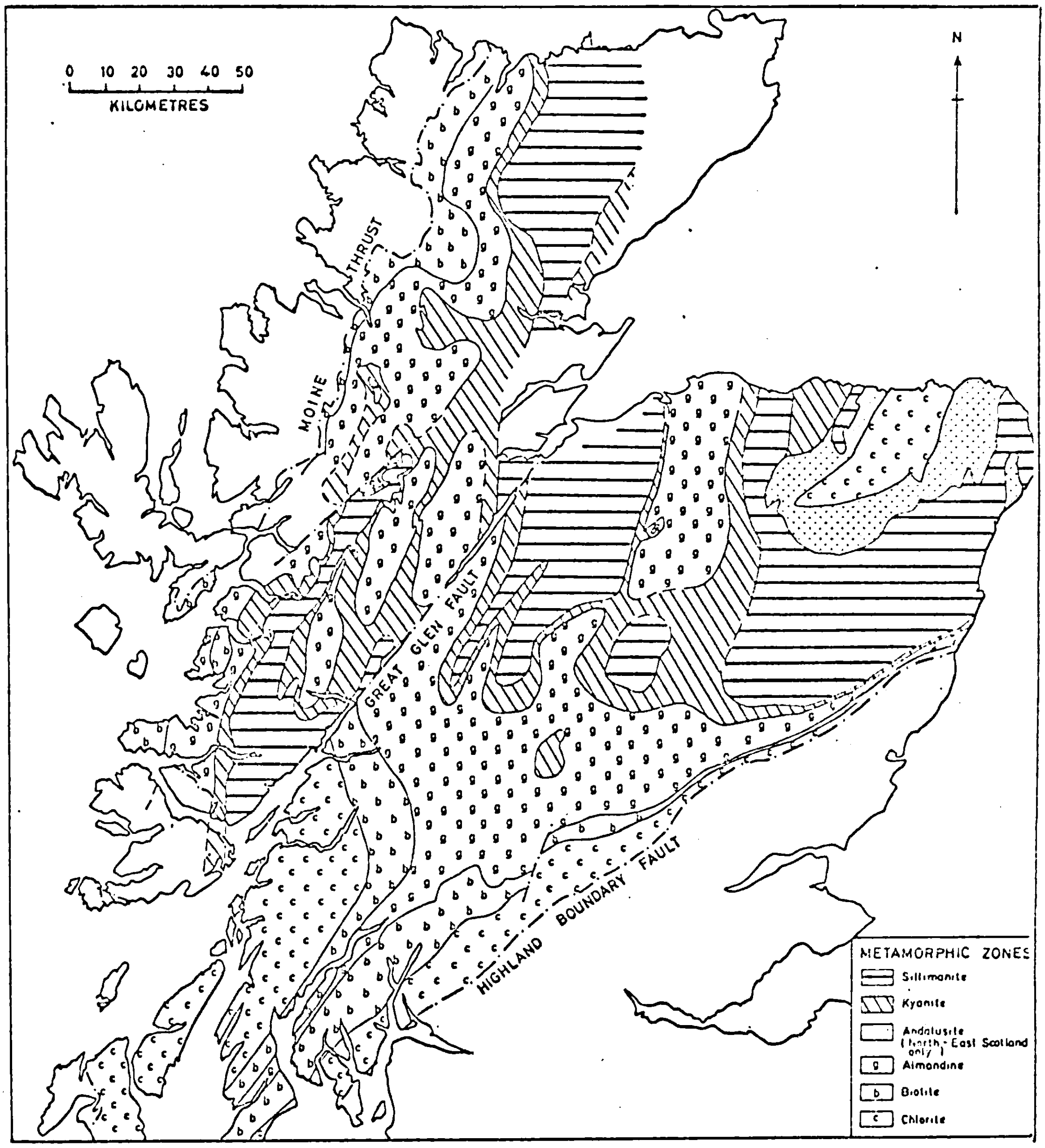


Fig.34. Metamorphic zonal map of the Scottish Caledonides, based on the mineralogy of calc-silicates. (After Winchester 1974, Fig.3).

Characteristic mineral assemblages for pelites in the west (e.g. Skye, West Morar) are quartz-plagioclase (An_{18})-muscovite-biotite-garnet-epidote. Further east in central South Morar, and west and central Knoydart pelitic mineral assemblages are of quartz-plagioclase (An_{30})-muscovite-biotite-epidote-microcline$\pm$garnet. An increase in quartz in either of these assemblages produces more semi-pelitic rocks. Calc-silicate rocks are absent from the Sleat Peninsula of Skye, but elsewhere mineral assemblages include quartz-epidote-amphibole-garnet-andesine.

It is difficult to ascertain what the mineral assemblages in the east were during M_1 because of overprinting and recrystallisation during the later (M_2) metamorphic event. The M_1 metamorphic grade attained was, however, at least garnet grade as inclusion fabrics within the garnets are similar to those further west, which, it will be shown, crystallised during the early M_1 event.

In the west of the area a lithological layering (S_o) is clearly distinguishable within the rocks. Oblique to this an early schistosity (S_1) may be seen composed of a muscovite "felt" of parallel muscovite crystals (see Plate 9, and Fig. 35). Garnet porphyroblasts developed within the pelitic rocks post-date this oblique S_1 fabric, as the layering (S_o) and S_1 schistosity are included by the garnet crystals and deformed by the rotation of the garnet porphyroblasts (Fig. 35 and Section 4.6).

A planar inclusion fabric is preserved within the garnet crystals and consists of individual elongate grains of quartz and feldspar, zoisite, opaque ore grains (possibly iron) and dust trails. Where individual quartz or feldspar grains occur they exhibit a preferred shape orientation. Trails of elongate quartz grains also occur. All of these elements are coplanar. The preferred parallel orientation of the inclusion fabrics plus the evidence of an early schistosity oblique to the layering in the rock matrix, implies an earlier period of deformation and crystallisation to produce such a fabric. This evidence of planar inclusion fabrics and an early oblique schistosity are the earliest features recognised in these rocks, and are referred to as D_1 features. These fabrics, indicative of an earlier event, are deformed by all later structures.

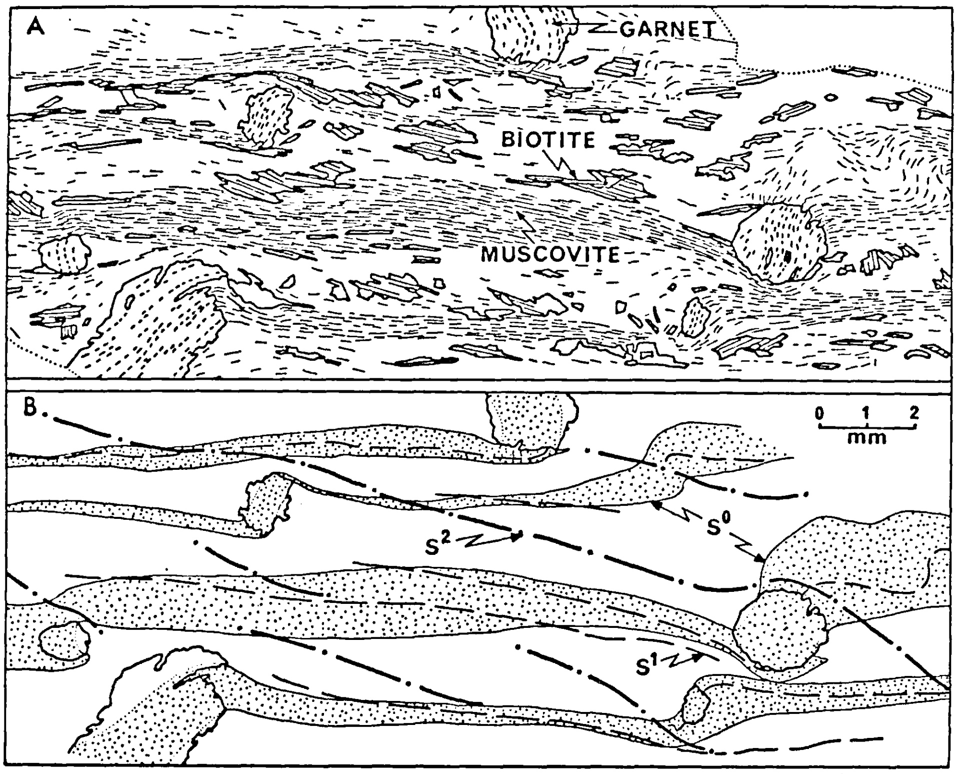


Fig.35. Diagram (B) of thin section (A) from Skye (Sample station A9) illustrating the relationships between inclusion fabrics in garnet crystals and matrix elements. S_0- bedding, S_1- first schistosity, S_2- second schistosity. Note that both S_0 and S_1 are overgrown by garnet whereas S_2 is axial planar to microfolds "keyed" to the porphyroblasts.

Garnet porphyroblasts from Skye and west Knoydart show rotational "S" inclusion trails (Powell and Treagus 1970), indicating syntectonic crystallisation (Fig. 36). The inclusion fabric (referred to as S_i) is continuous with the S_o/S_1 fabric of the rock matrix (Fig. 35 and 36 and Plate 9).

Textures in the garnet crystals from the central and eastern parts of the research area show various differences to those seen in the west. These garnets exhibit distinct optical, textural and chemical zones (see Figs. 36, 37, 38, 39 and 40 and Table 1). Up to three distinct zones may be distinguished, but not necessarily occurring in every crystal (Fig. 41). The zones are distinguished partly by a variation in colour from the centre of the crystal to the outside (Plate 21). Colour zoning is particularly well seen in thick sections and is related to an apparent greater or lesser degree of visible surface relief. The degree of surface relief tends to increase from the centre of the crystal outwards.

Different zones may also be distinguished by the nature and concentration of the inclusions making up the internal fabric. In crystals where the maximum number of zones are developed, the concentration of inclusions tends to be highest near the junctions between the different zones. Frequently a single zone may be subdivided into a portion relatively free of inclusions and a portion where the inclusions are concentrated. The portion of the zone with a high concentration of inclusions is usually the innermost part of that zone (see Plate 21, and Table 1). Table 1 summarizes the main characteristics of the optical and textural zones as they are seen in crystals from Morar and Knoydart.

Chemical zoning was established by probe analyses (undertaken by ~~Atherton~~ Anderson and Olympio, University of Illinois, and Atherton, University of Liverpool) - Fig. 40. The patterns of distribution of FeO, MnO and CaO vary across individual garnet crystals (Fig. 40 and Section 4.6). The patterns established are very similar to those previously published by various authors (Atherton and Edmunds, 1966; Harte and Henley, 1966; Holister, 1966, 1969; Leake, 1968 and Anderson and Buckley, 1973), for whole crystals. The implication of this is that growth in the Moine garnets would appear to be continuous from nucleation at

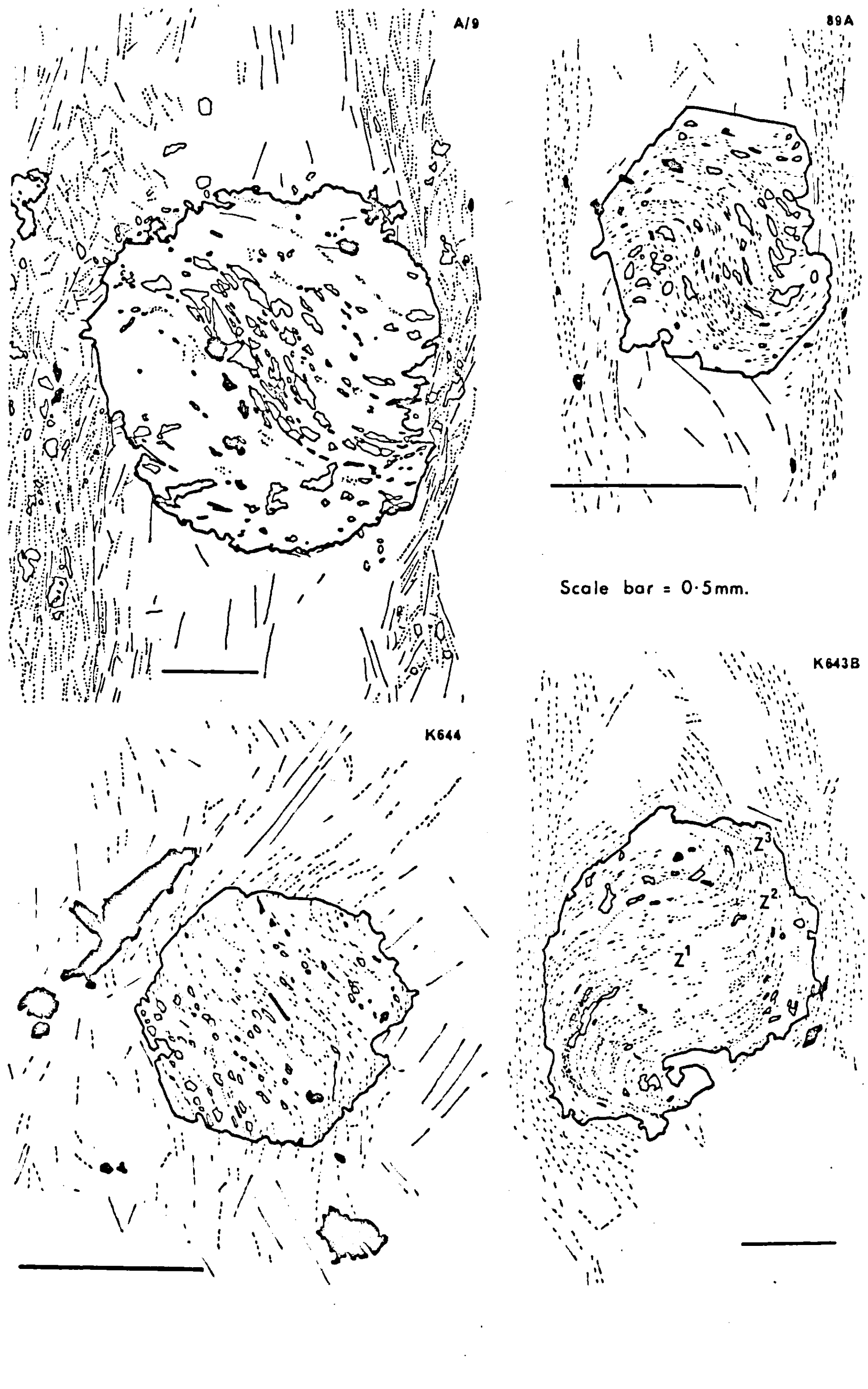
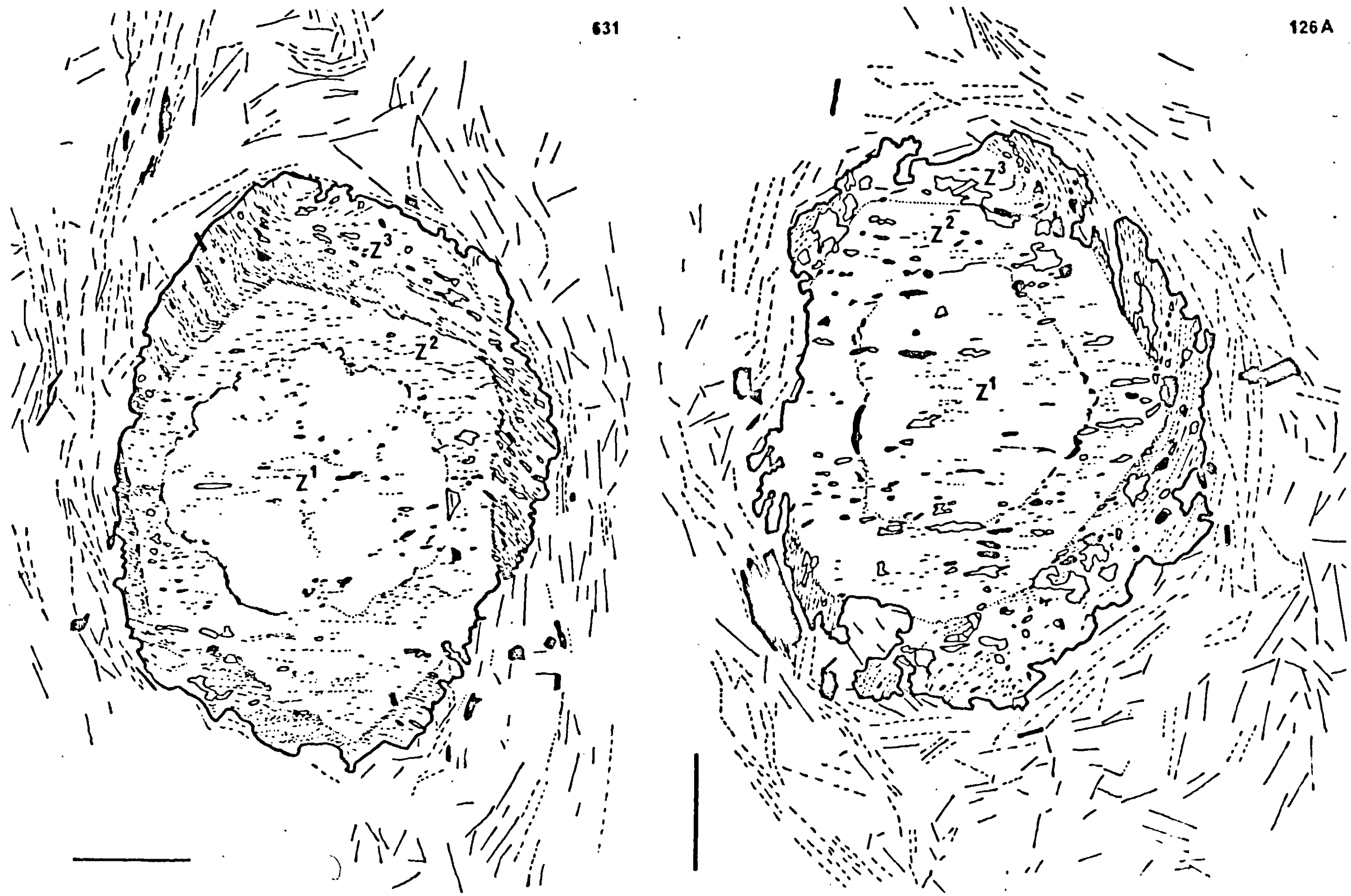


Fig.36. Textural zoning in garnet crystals from Skye and West Knoydart. Within the garnets: black-opaques, dots and fine dashes-opaque dust, white-quartz (single crystals and crystal groups).
In the matrix: black-opaques, long lines - trend of schistosity in individual biotite crystals, broken lines - schistosity in individual muscovite crystals.
Z1-2-3 - Zones 1, 2 and 3 referred to in text.



Scale bar = 0·5mm.

Fig.37. Textural zoning in garnet from South Morar and Moidart. Ornament as in Fig.36. Note particularly changes in the concentration of inclusions with respect to the three zones; the concentration of opaques at the Z1/2 boundary; and the idiomorphic nature of the Z2/3 boundary which is further characterised by the sudden increase in concentration of fine opaque inclusions.

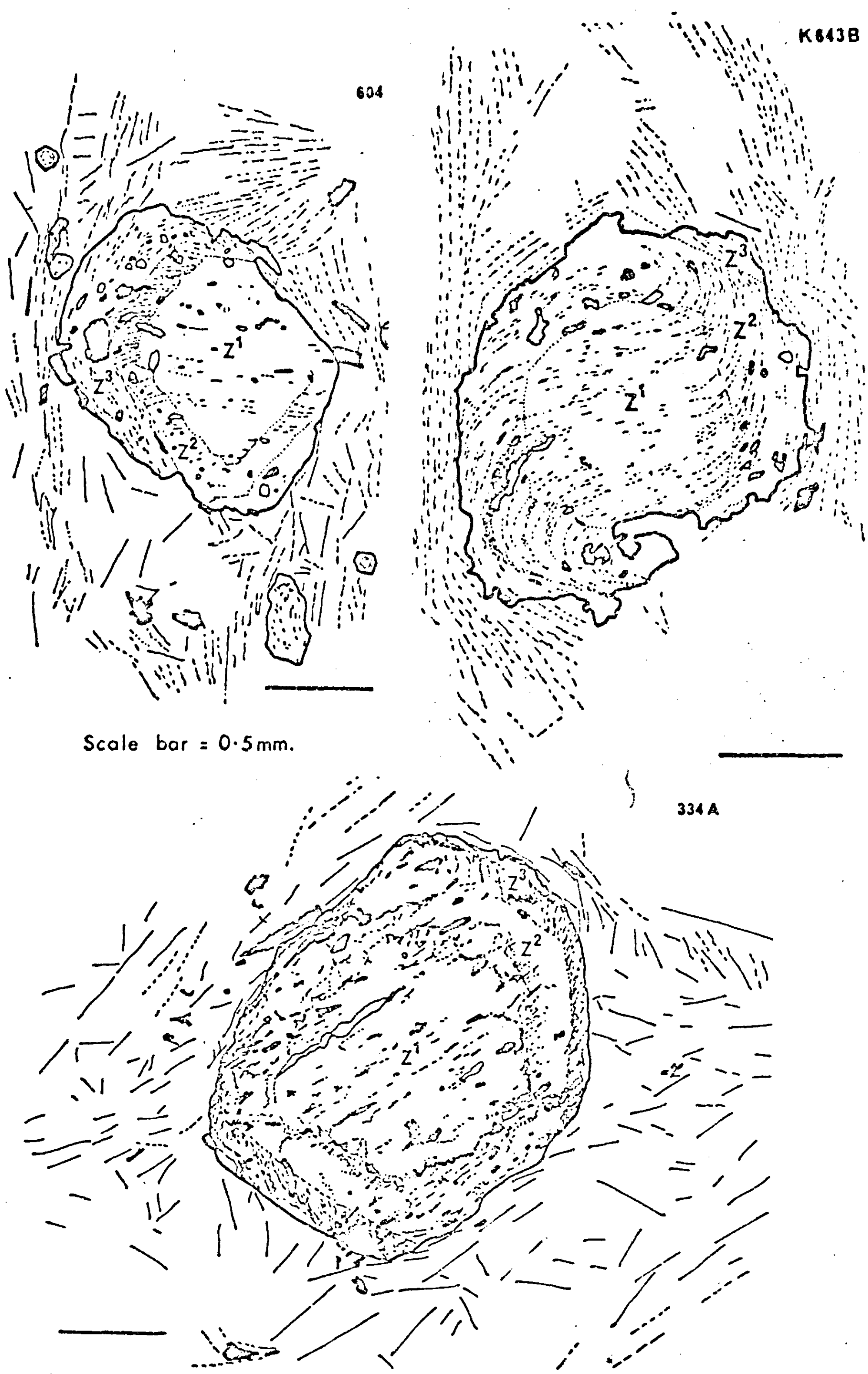


FIGURE 38. Textural zoning in garnet crystals from South Morar, North Morar and South Knoydart. Ornament as in Fig. 36. Each of the crystals exhibits features diagnostic of the three zones. Note the continuous curvature of the inclusion fabric across zone boundaries in 604 and K643, indicating continuity of growth.

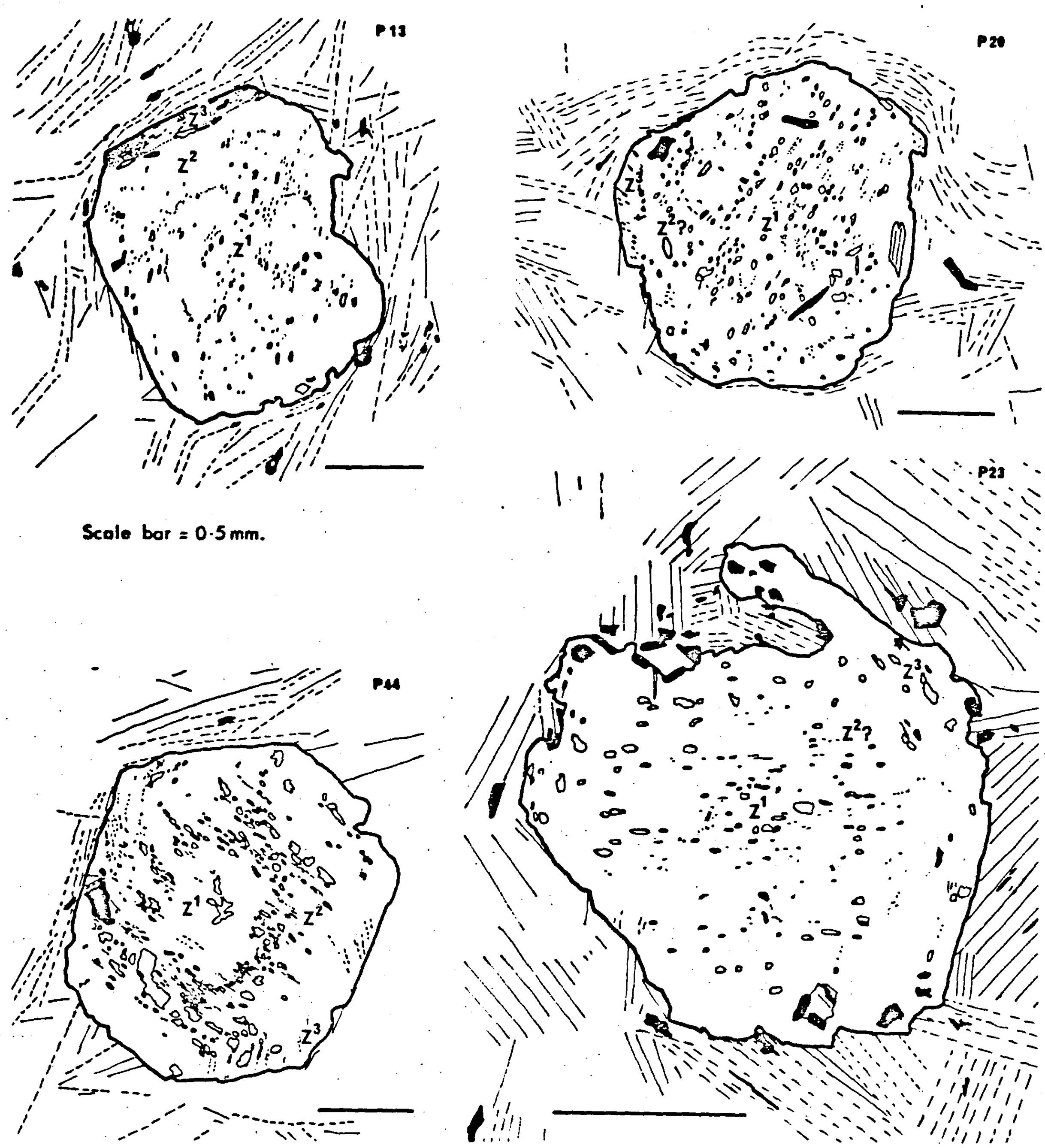


FIGURE 39. Textural zoning in garnets from Central and East Knoydart. Ornament as in Fig. 36 plus indication of cleavage in mica inclusions in garnet crystals. In P13 three zones can be distinguished on changes in abundance of inclusions and the preservation of zone boundaries. The microprobe trace P20 in Fig. 40 is across a crystal from the same specimen as the P20 illustrated here indicating how the chemical data can be used to supplement inconclusive textural data.

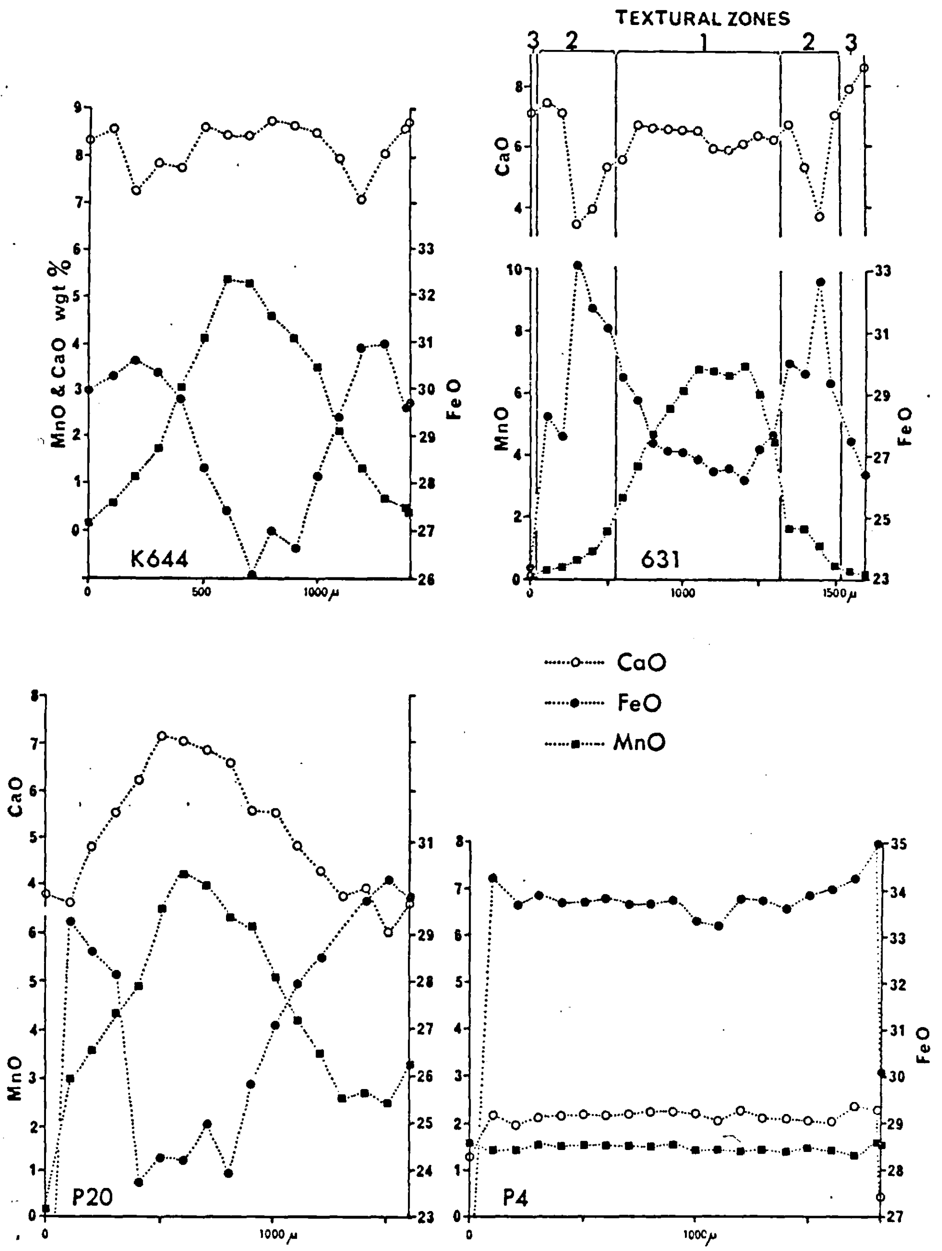


Fig.40. Chemical zoning in garnets. Analyses by D.E.Anderson and J. Olympio, University of Illinois. 631-textural zones 1, 2 and 3 are present and are reflected by chemical changes. K644-exhibits no textural zoning but by comparison with 631 it appears that Zones 1 and 2 are present. P20 - no textural zones are visible but chemical variations indicate zones 1 and 2 at least are present. P4 - no textural or chemical zones indicated. The microprobe traces are for crystals from the same hand specimen as those illustrated.

TABLE I

ZONE	MINERAL	SIZE RANGE mm	SHAPE	ORIENTATION	CONCENTRATION AND GARNET SHAPE
1 Colour: Yellowish-buff "light"	Quartz: crystals sub-euhedral QUARTZ AGGREGATES	0.05-0.06 0.15x0.04-0.24x0.06	Equidimensional Elongate aggregates <0.03 mm individual grains	Random, or aligned parallel to planar element in garnet crystal, usually parallel to one of garnet crystal faces at junction Z_1/Z_2.	Inclusions are equally distributed throughout Zone 1, unless Si is markedly developed where preferential alignment of minerals occurs.
	OPAQUE ORES	0.1-0.15	Equidimensional or elongate	When aligned, parallel to quartz and zoisite crystals as planar Si in garnet.	
	CLINOZOISITE	0.02^2	Equidimensional	Random	
	DUST PATCHES	irregular			Euhedral boundary with Zone 2
2 Colour: pink-brown, cloudy but "light" High relief	QUARTZ GRAINS subhedral	0.05-0.1	Rarely elongate	Aligned parallel to Si which may be straight or rotated according to tectonic history of crystal..	Concentration of inclusions varies, it is high near the junction between Z_1 and Z_2, but is markedly decreased at Z_2/Z_3 junction.
	OPAQUE ORE	0.1-0.06	Elongate grains	Shape orientated parallel to garnet crystal boundary which is controlled by garnet crystal lattice structure.	
			Equidimensional	Random	Garnet zone outline is commonly euhedral if Z_3 is not developed, or boundary between Z_2/Z_3 is well formed - i.e. crystal faces developed.
	ZOISITE-subhedral	0.02-0.025	Equidimensional	Random	
	MICA FLAKES - BIOTITE commonly	0.35-x0.05	Elongate parallel to cleavage ('C')	Aligned parallel to margins of Z_2/Z_3, or parallel to Si fabric.	
	DUST TRAILS			Aligned parallel to inclusion fabric Si	
3 Colour: Pale buff-neutral. Apparently pitted surface relief.	QUARTZ CRYSTALS	0.1x0.05	Elongate parallel 'C'	Aligned parallel to the plane forming Si in garnet crystals.	
	QUARTZ CRYSTAL	0.3x0.1	Individual crystals are equidimensional	ditto	Concentration of inclusions is high at inner edge of zone, and tends to decrease outwards although this may be as a result of the ragged or skeletal outline of the garnet crystal as a whole.
	Fe (opaque) ORES	0.1x0.1 0.15x0.1	Equidimensional, rarely elongate	When elongate parallel to Si; also commonly occur at junction Z_2/Z_3 in association with zoisite.	
	ZOISITE	0.02	Equidimensional	Random	
	BIOTITE CRYSTALS	0.7x0.1	Elongate parallel 'C'	As penetration crystals from groundmass, or aligned parallel to junction between Z_2 and Z_3	
	GRAPHITE DUST			As patches or trails parallel to Si.	

GENERAL: All zones are non-pleiochroic; anomalous anisotropism occasionally reflects zoning seen in P.P.L. Increae in Fe ore concentration outwards (i.e. Z_1Z_2) is a possible reflection of less Fe present in garnet crystal composition or structure (Probe analyses).

Table 1 Zone characteristics in garnet crystals.

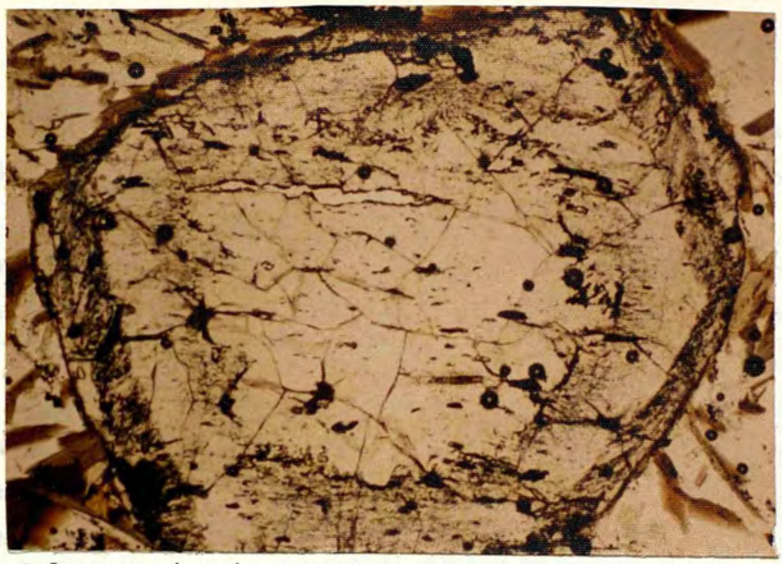


Plate 21: Colour zoning in garnet porphyroblast, Druimindarroch (x40, P.P.L.).

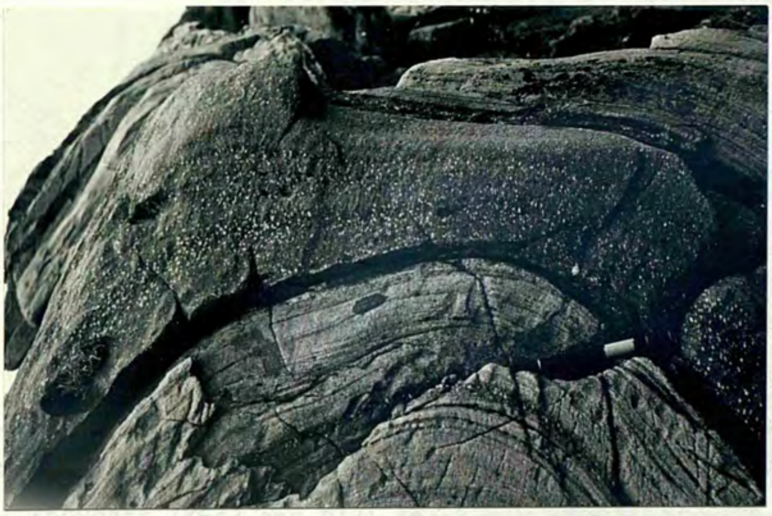


Plate 22: Microcline porphyroblasts aligned parallel to, and lying within, the S_2 schistosity, in the nose of an F_2 isocline, Druimindarroch.

Plate 23: Photomicrograph of microcline (grey) partially enclosing a garnet porphyroblast (grey-black) (x25, X-nicols). Location - Arisaig.

least as far as zone 2a. (Zone 1 here refers to the innermost zone, zone 2, to the intermediate zone, and zone 3 to the outermost zone.)

If, however, all the chemical, optical and textural evidence is considered certain features suggest that growth of garnet was continuous from nucleation to their present form (i.e. through all 3 zones). The evidence for this is based on several features. The inclusion fabrics pass from one zone into the next with no abrupt change in grain size which would be indicative of recrystallisation of the inclusion fabric. In many instances there is no sudden change in the angle of curvature of the inclusion fabric (Figs. 36 and 38). From Fig. 40 it will be seen from specimen 631 that the junctions of the textural zones do not necessarily correspond to marked changes in the chemical composition of the garnets.

As previously mentioned a maximum of 3 zones can be recognised in the garnet crystals within the research area (Fig. 41). Not all crystals develop 3 zones, some may consist of zone 1 only, others of zones 1 and 2, whilst others show the development of all 3 zones. All types may be found in a single thin section.

The majority of the samples* collected throughout the Morar-Knoydart area showed a varying development of zones. Strong textural and chemical similarities for specimens from South Morar (Spec. 334), west and central Knoydart (K643 and P13) enables confident correlation of the 3 zones developed in these crystals. Garnets from Skye (89A and A9) and some west Knoydart samples (K644, Figs. 36 and 41) do not exhibit textural zoning which can be directly related to the Morar and central Knoydart types. Occasionally west Knoydart specimens (K34) do show some colour zoning. Chemical analyses, however, from these western localities show that the patterns of distribution of FeO and MnO closely resemble those within zones 1 and 2 of the South Morar material. Compare analyses for specimen K644 (west Knoydart) and specimen 631 (South Morar) in Figure 40.

*Numbered samples refer to those chosen to illustrate this study (see also Appendix I) but numerous specimens were collected from each locality. All garnets from a single locality were consistent as regards textures, zoning, etc.

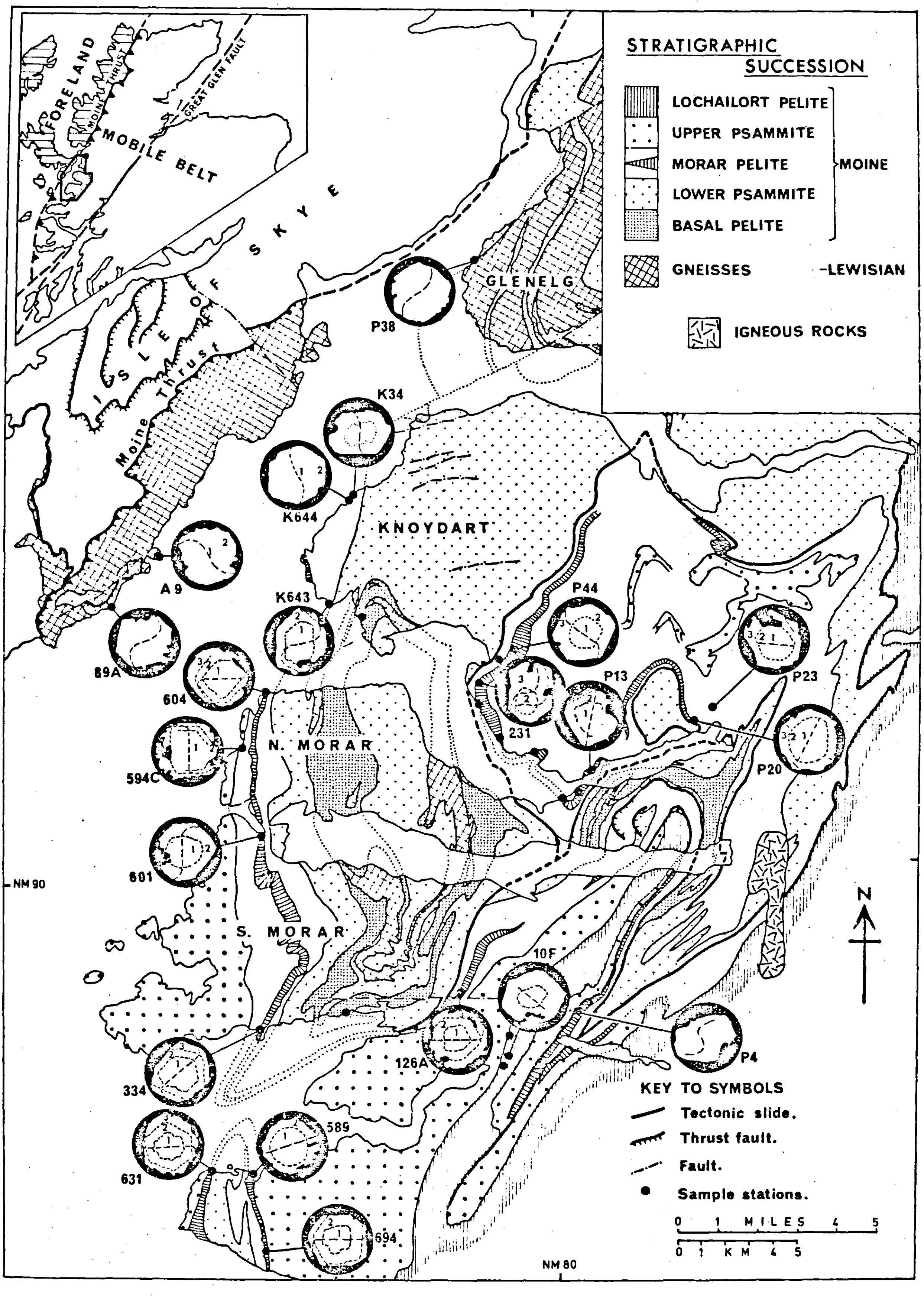


FIGURE 41. Geological map of the Morar-Glenelg region.
Circles enclose sketches of garnet crystals drawn to show zoning and attitude of inclusion fabrics.

Garnets from east Knoydart (231, P20, P23 and P44) (Figs. 39 and 41) show ill-defined textural boundaries and little or no colour variation. There is, however, some variation in the distribution and composition of the inclusions. In most instances an inner zone showing shape orientated inclusions (usually quartz or dust trails) lying parallel to flat planes, is surrounded by a thin, often discontinuous area with few or no inclusions (Figs. 39 and 41). Occasionally inclusions in the outer part of the crystal exhibit shape orientation parallel to planes at an angle to those of the inner part of the crystal (Fig. 39, Sample P20). Rarely the crystals from this region exhibit more distinct zones with pre- and syntectonic inclusion fabrics (Fig. 39, Samples P44 and P13).

One feature common to garnets from the eastern localities and not found in samples from the west, is the presence of relatively large inclusions and semi-inclusions of biotite, muscovite, plagioclase and quartz (Figs. 39 and 42). These would appear to be penetration inclusions (Rast, 1965) resulting from substantial recrystallisation of the matrix and limited recrystallisation of garnet. That garnet has suffered recrystallisation, or at least chemical exchange with the matrix, is indicated by the lack of distinct chemical zoning (Fig. 40 Spec. P.4), the increase in roundness of inclusions, and the development of irregular garnet outlines.

The textural and chemical zoning exhibited by some of the garnets from east Knoydart seem to represent relic features which have survived the recrystallisation during a later metamorphic event M_2., that has given rise to the gneissose fabrics of the host semi-pelitic rocks. Throughout the region further evidence exists for the recrystallisation of matrix minerals after the crystallisation of garnet. In the majority of cases the inclusions have a very much smaller grain size than the same minerals in the matrix, which is indicative of substantial matrix recrystallisation. Further, the grain size of inclusions does not increase or decrease from the centres of garnet crystals to their margins indicating that the matrix grain enlargement took place after the growth of garnet.

The substantial recrystallisation of matrix minerals and the partial recrystallisation of garnet in eastern Knoydart is attributed

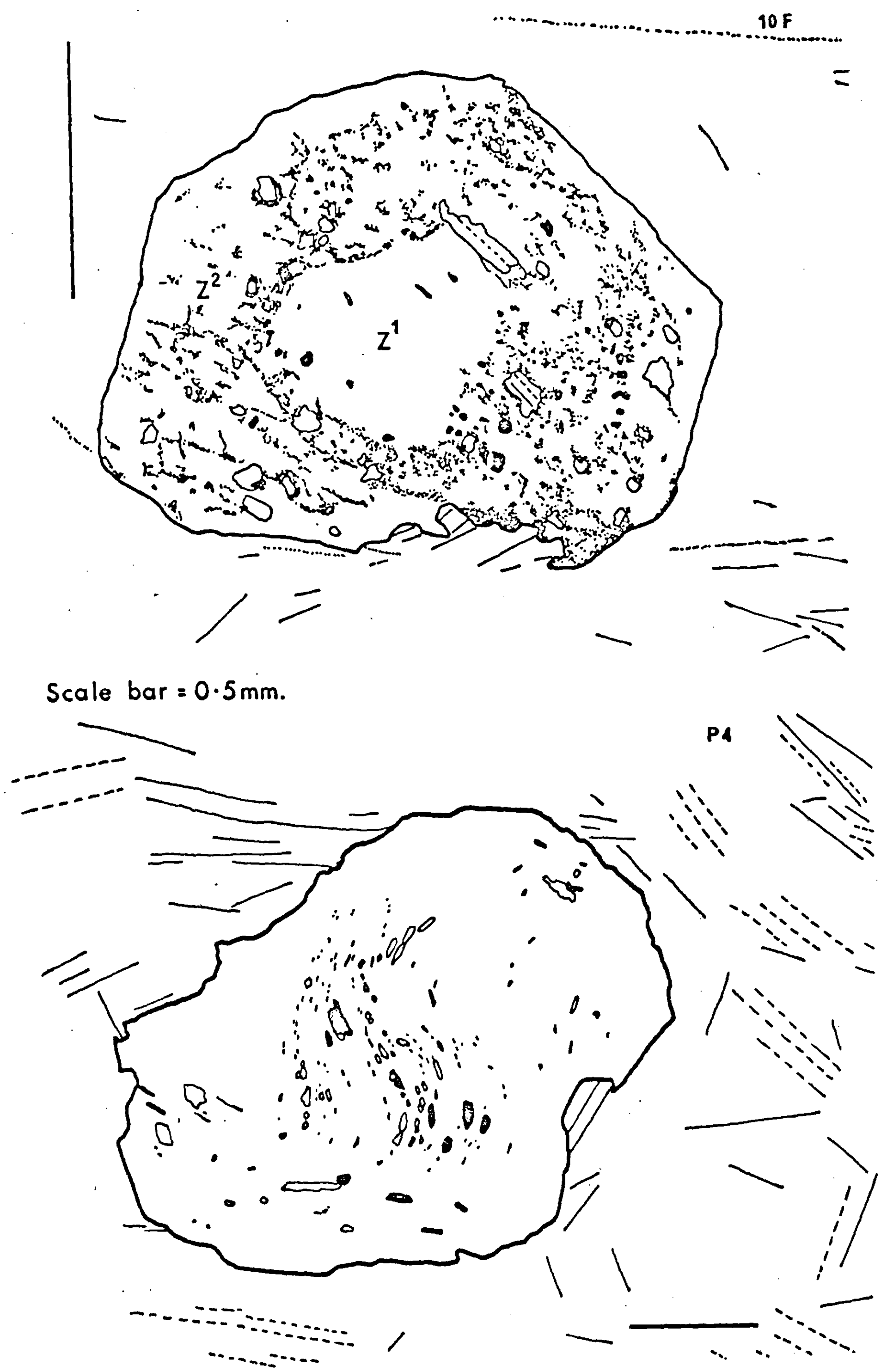


Fig.42. Textural zoning in garnets from Southeast Morar. Ornament as in Fig.36. P4 is difficult to interpret because the textural zoning is not readily related to that shown in the west, nor does the chemical data, Fig. 40, provide alternative evidence.

to the second phase of metamorphism (M_2) which was effective during the later phases of deformation D_3 and D_4 (Chapter 5).

In central Morar and west and central Knoydart, microcline as well as garnet crystallised during M_1. Microcline porphyroblasts, often up to 5 mm. in size, lie within the S_2 axial planar schistosity of F_2 folds (Plate 22) suggesting crystallisation of microcline during D_2. Garnet evidently pre-dates the microcline growth and because garnet crystals outside the microcline porphyroblasts exhibit the same inclusion fabrics, amount of growth (as represented by the number of zones) and physical features as those enclosed by the microcline crystals (Plate 33) it may be concluded that no post-microcline crystallisation or recrystallisation of garnet has occurred.

Clough (in Peach et al., 1910, p.52) noted several occurrences of "secondary micropoikilitic potash feldspar, sometimes showing the structure of microcline" in Knoydart. Further recordings of microcline have been made by Lambert (1959, and in discussion of Ramsay & Spring, 1962) in the Morar and Mallaig areas, Lewry (unpubl., 1964) in South Morar, Butler (1965) in Ardnamurchan and Smith & Harris (1972) in the Knoydart-Morar-Moidart area. Microcline commonly occurs as porphyroblastic crystals in most of the metamorphic rocks present, but reaches its maximum development in terms of size and frequency in pelitic and semi-pelitic schists.

Smith and Harris (1972) noted the absence of microcline porphyroblasts east of the western limit of regional migmatisation in eastern Knoydart. The present study confirms their observation.

In their study Smith and Harris (1972) concluded that certain sedimentary rocks contain K_2O, in excess of that required to form biotite (Mather 1970), and that such a chemical composition would enable microcline to exist as a stable phase in equilibrium with quartz, plagioclase, muscovite, biotite, epidote $\pm$ garnet.

According to Butler (1965) and Stevenson (1971), there is no apparent significant variation in K_2O between the migmatitic and non-migmatitic pelitic rocks.

Smith and Harris (1972) suggest that the possible greater mobility of material in the migmatised rocks either inhibited nucleation of microcline initially or accelerated their dispersal with the formation of numerous small microcline crystals distributed throughout the matrix of the rock. In the pelitic rocks east of the western limit of migmatisation in Knoydart, microcline crystals do occur within the matrix of the rock, but not as porphyroblasts. This would appear to support Smith and Harris' (1972) proposal of increased mobility of material within migmatised rocks.

4.5.3 Structural setting of the Knoydart pegmatite

Work by Gilletti et al. (1961) suggested an age of 740 ± 10 Ma for the Knoydart pegmatite, which was subsequently revised to 720 ± 15 Ma by Long and Lambert (1963) and redated by Fitch F.J. (Edinburgh 1971) as approximately 744 Ma. Various other radiometric results produced by Long and Lambert (1963) for the Carn Gorm and Sgurr Breac pegmatites show similar ages for "old" pegmatite intrusions (745 ± 25, 720 ± 10 and 780 ± 15 Ma respectively).

The implication of these isotopic dates is that a Precambrian event is recorded in the east Knoydart area. None of the previous authors however managed to establish the relationships of the "old" pegmatites to the structural sequence in the Moines; and evidence is yet to be offered to support Dunning's statement (1972) that the Knoydart pegmatite is post-D_3.

The pegmatite, composed of beryl, muscovite, plagioclase, garnet and quartz, occurs as lens-shaped bodies which are aligned parallel to the foliation of the host garnet-mica schists. The long axes of the pegmatite lenses are parallel to small scale isoclinal fold axes which plunge at approximately 40° to the south-east. The axial planes of these folds dip at moderate degrees to the south-east, sub-parallel to the foliation in the Moine schists (Fig. 43). These small scale folds are second generation structures (see Fig. 30, Projection G), parasitic to the Knoydart fold. The parallelism of these elements suggests that the pegmatite was deformed during D_2.

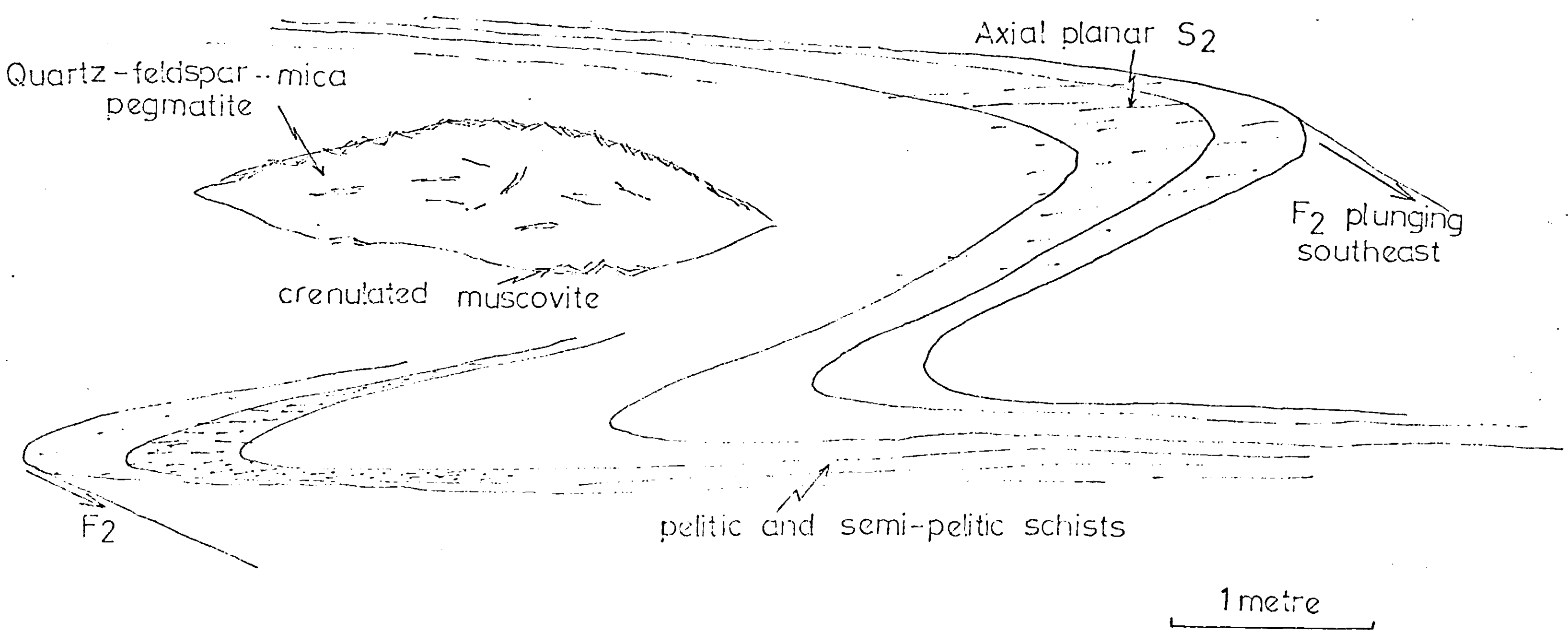


FIGURE 43. The Knoydart pegmatite. Located 1 km. northeast of Port Longaig in the Ladhar Bheinn Pelite. Viewed looking east. F_2 fold hinges and the axes of the boudinaged pegmatite lens plunge to the southeast at approximately 45^{o}. Muscovite books are randomly orientated in the centre of the pegmatite lens, and are crenulated at the margin of the lens.

The dominant foliation in the area reflects bedding modified by both D_1 and D_2. The pegmatite lenses are invariably parallel to this layering and the junction between pegmatite and host rock is generally distinct. Within the pegmatite the muscovite "books" show random orientation becoming more preferentially aligned (parallel) towards the margin of the lens. Muscovite at the margins is crenulated by D_3 crenulation folds, thereby establishing its pre-D_3 age.

From the field evidence presented above the following conclusions can be drawn:

(a) The pegmatite is pre-D_3 because it is deformed by small scale F_3 folds (Fig. 43).

(b) The parallel alignment of the long axis of the pegmatite and minor F_2 fold axes is the result of D_2 deformation.

(c) The relatively distinct margins between the pegmatites and the host rock and the limited parallel alignment of muscovite within the pegmatite near its contact appears to be the result of only limited flattening deformation subsequent to the pegmatite formation, probably during the late stages of D_2. It is thought that if the pegmatite was intruded prior to D_1 the effects of deformation of 2 phases of deformation (D_1 and D_2), each producing strongly developed structures, would be more apparent within the pegmatite lenses. Whereas the internal fabric of the pegmatite is randomly orientated, becoming only partially preferentially aligned towards the margins.

Following from this it is suggested that the Knoydart pegmatite is post-D_1, and either pre- or syn-D_2 in age, thereby establishing at least D_1 and possibly the early stages of D_2 as Precambrian events.

Dalziel and Johnson (1963) suggest that the regional migmatisation was coeval with D_2 which van Breeman et al. (1974) consider to be Caledonian. The inference being that the "early" pegmatites of van Breeman et al. (1974) are not connected with the regional migmatisation. On the other hand Long and Lambert(1963) and Powell (1974) argued that the pegmatites were the result of regional metamorphism which could reasonably be connected with migmatisation. Thus implying that the pegmatites, migmatites and hence D_2 are the result of a Precambrian tectono-thermal event.

4.6 Relationships between D_1, D_2 and M_1

This chapter has outlined the structural evidence for two early phases of deformation D_1 and D_2, and has presented evidence of an early metamorphic event M_1. Tentative structural correlations for D_1 and D_2 were outlined in Section 4.4; these correlations are supported by the relationships between D_1 and D_2 structures and minerals and fabrics that developed during M_1.

The earliest distinguishable fabric developed during M_1 was the muscovite "felt" forming S_1 which has crystallised oblique to the lithological layering S_o (Plate 9). This in turn is overgrown and deformed by garnet porphyroblasts (Fig. 35) which have developed post-D_1.

Garnet porphyroblasts from F_2 fold closures in Skye show rotational "S" inclusion trails (Powell & Treagus, 1970) which are symmetrically disposed relative to F_2 axial planes (see Fig. 44). This indicates that garnet crystallisation in this area occurred syn-tectonically during D_2 deformation. Further evidence for D_2 syntectonic crystallisation of garnet is seen at Tormore (Skye), Airor (northwest Knoydart) and the Sandaig Islands (southwest Glenelg - see also Section 7. d) and is shown in Figs. 36 and 41.

The attitude of the inclusion fabrics within the garnet crystals relative to the third folds is also shown in Fig. 44, and will be further discussed in Chapter 5. The rotational "S" inclusion trails are assymmetric about the F_3 axial planes, suggesting refolding post-garnet crystallisation.

From the evidence cited above it can be seen that garnet crystallisation occurred post-D_1, syn-D_2 and pre-D_3 in the west of the mobile belt (Skye and west Knoydart).

Similar relationships in other parts of the region indicate that garnet crystallisation is earlier than the third phase of deformation (D_3) and at least partly syntectonic with the second phase D_2. "S" internal rotational fabrics are commonly preserved in the outer zones of the garnet crystals in Morar, west and central Knoydart and infrequently in samples from eastern Knoydart. Where possible the samples were

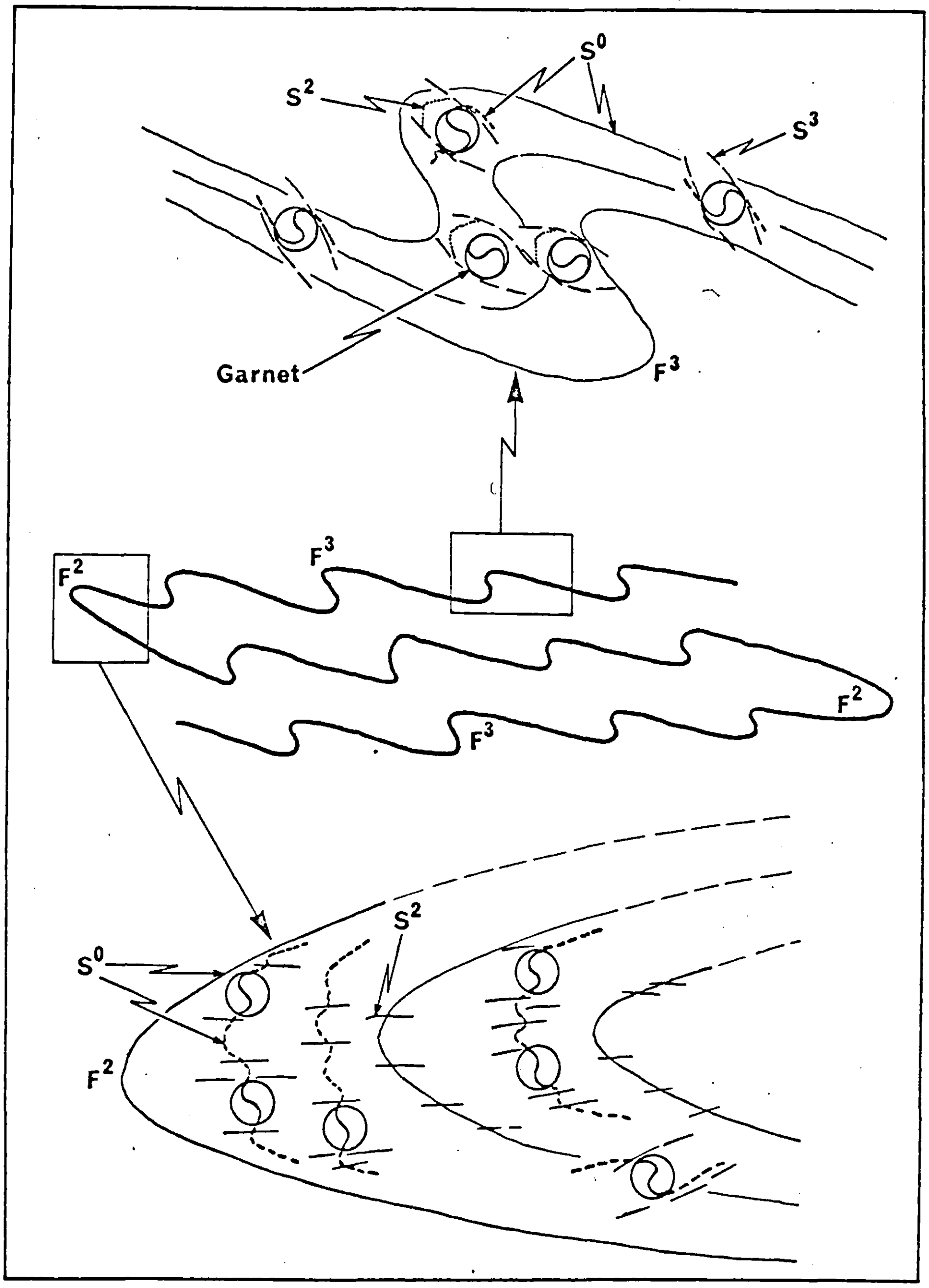


Fig.44. Relationships between rotational fabrics within garnet crystals, second (S_2, F_2) and third (S_3, F_3) phase deformation structures; based on field exposures and samples (see figs.29 and 47). Note the rotational fabrics are symmetrical about the F_2 axial plane, but assymmetric in relation to the F_3 axial planes.

collected from F_2 or F_3 fold closures. In all cases the rotational "S" inclusion trails are symmetrically disposed relative to F_2 axial planes in a manner similar to that in Skye (Fig. 44). The rotational fabrics are assymmetric in relation to F_3 axial planes.

In areas where collection of specimens relative to F_2 and F_3 fold closures was not possible, other lines of evidence were employed to determine the garnets relative structural age. This included the use of tectonic fabrics and the crystallisation of minerals post-dating the crystallisation of garnet. Consequently, in areas where garnets have both pretectonic (inclusions lying parallel to flat planes) and syntectonic (inclusions lying parallel to curved planes) internal fabrics it has been possible to establish their relative age of crystallisation. That is, growth postdated the formation of an earlier planar fabric (S_1), which is preserved as shape orientated inclusions within the garnets; and pre-dates the formation of F_3 folds; and in many instances can be shown to be at least partly syntectonic with respect to D_2.

In the area under study, examination of the relationships between garnet zones and the type of included fabric, pre or syntectonic relative to D_2, reveals that these differ systematically from northwest to south-east (Fig. 41). In Skye and west Knoydart, growth of zones one and two was entirely syntectonic with respect to at least part of D_2. In north and central Morar and central Knoydart zone 1 was pre-tectonic and zones 2 and 3 were syntectonic with respect to the same deformation.

In South Morar/Moidart and east Knoydart, zones 1 and 2 were pre-tectonic, and only zone 3 syntectonic. The only exception to this pattern occurs at station P4 where syntectonic fabrics are preserved throughout garnet crystals. In this case, however, it is not clear from the nature of the inclusions or the chemistry of the garnets which zones are represented.

Chemical analyses undertaken by Anderson and Olympio (University of Illinois) and Atherton (University of Liverpool) have enabled the recognition of chemical zones within the garnet crystals. Evidence of chemical zoning has previously been published by various authors (Atherton & Edmunds, 1966; Harte & Henley, 1966; Holister, 1966, 1969; Leake, 1968 and Anderson & Buckley, 1973). Most authors agree that chemical zoning is a result of diffusion during growth, implying that this occurs during pro-grade metamorphism.

Thus it is possible to suggest that the garnet growth during D_2 was the result of pro-grade metamorphism related to the M_1 event. However, M_1 and D_2 did not occur simultaneously throughout the area. In the west (Skye and west Knoydart) M_1 and D_2 were synchronous with syntectonic garnet growth. Evidence for the onset of M_1 prior to D_2 exists further east, as characterised by the development of pretectonic garnet growth, forming the inner zones of garnet porphyroblasts. The outer parts of these same garnet crystals exhibit syntectonic characteristics of rotational "S" inclusion fabrics. This period of rotational garnet growth in the east may also be directly related to D_2. Partial recrystallisation of garnet and the development of penetration inclusions has occurred in the extreme east, which may be related to a later metamorphic event (M_2).

Since the garnet textures may be matched across the region, the fold phase to which garnet is all or partly syntectonic is probably the same. Therefore, F_2 folds in Skye are equivalent to F_2 in Morar and west and central Knoydart. This evidence supports the structural evidence presented in Section 4.4.

The terms D_1 and D_2 were employed initially as local terms only, to describe the earliest recognised structures within individual areas. It has been shown, however, that these early phases of deformation D_1 and D_2 may be correlated throughout the area on the basis of structural features and relationships to the metamorphic event M_1.

CHAPTER 5. LATE DEFORMATION (D_3, D_4 and D_5) AND METAMORPHISM (M_2)

5.1 Introduction

There are two distinct tectonic episodes which have a regional effect on the area, post-dating both D_1 and D_2, and in part the early metamorphic peak, M_1. The earliest of these two phases, D_3 affects the entire area, whilst the later D_4 phase is developed in restricted areas only. D_5 structures associated with thrust movements are restricted to the Moine Thrust Zone.

D_3 structures include large and small scale folds - F_3, a crenulation schistosity - S_3, a crenulation intersection lineation on earlier planar structures - L_3 and a mineral elongation lineation - L_3'.

D_4 structures include large and small scale folds - F_4, a crenulation schistosity - S_4, and a crenulation intersection lineation on earlier planar fabrics - L_4.

D_5 structures are represented by sharp, angular folds - F_5.

The late regional metamorphic event (M_2) has resulted in a range in metamorphic grade across this region. In the west, Skye and west Morar, the Moine pelitic mineral assemblages include biotite and muscovite, and calc-silicate rocks develop calcite and zoisite. These minerals have recrystallised during M_2, showing this event to be low-grade in the west. Towards the east pelitic rocks contain biotite, muscovite, garnet, sillimanite $\pm$ staurolite ($\pm$ kyanite ?); calc-silicate rocks contain bytownite, hornblende and garnet. (Kennedy, 1949; Winchester, 1974; Powell, 1974; and MacQueen & Powell, in press). These minerals have recrystallised during M_2, indicating a higher grade of metamorphism was attained in the east than in the west. Generally, this increase in grade of metamorphism is progressive from west to east across the mobile belt.

5.2 Structures associated with the third phase of deformation (D_3)

5.2.1 Introduction

Throughout the area the third phase of deformation produces both small and large scale F_3 folds. The trends of fold axes (F_3), intersection lineations (L_3), and the orientation and attitude of axial planes and S_3, in areas little affected by D_4 deformation, form a relatively consistent pattern (Figs. 45 and 46). Third generation folds trend NE-SW with varying plunges (Fig. 45) and axial planes dip NW or SE usually at moderate angles (Fig. 46). Mesoscopic folds are usually open in profile, and are occasionally overturned with coaxial small scale crenulation folds typically developed. Fig. 47 shows F_3 fold styles from Skye (Fig. 47a), Arisaig (Fig. 47b) and Knoydart (Fig. 47c-e).

5.2.2 D_3 structures of the Moine Thrust Zone

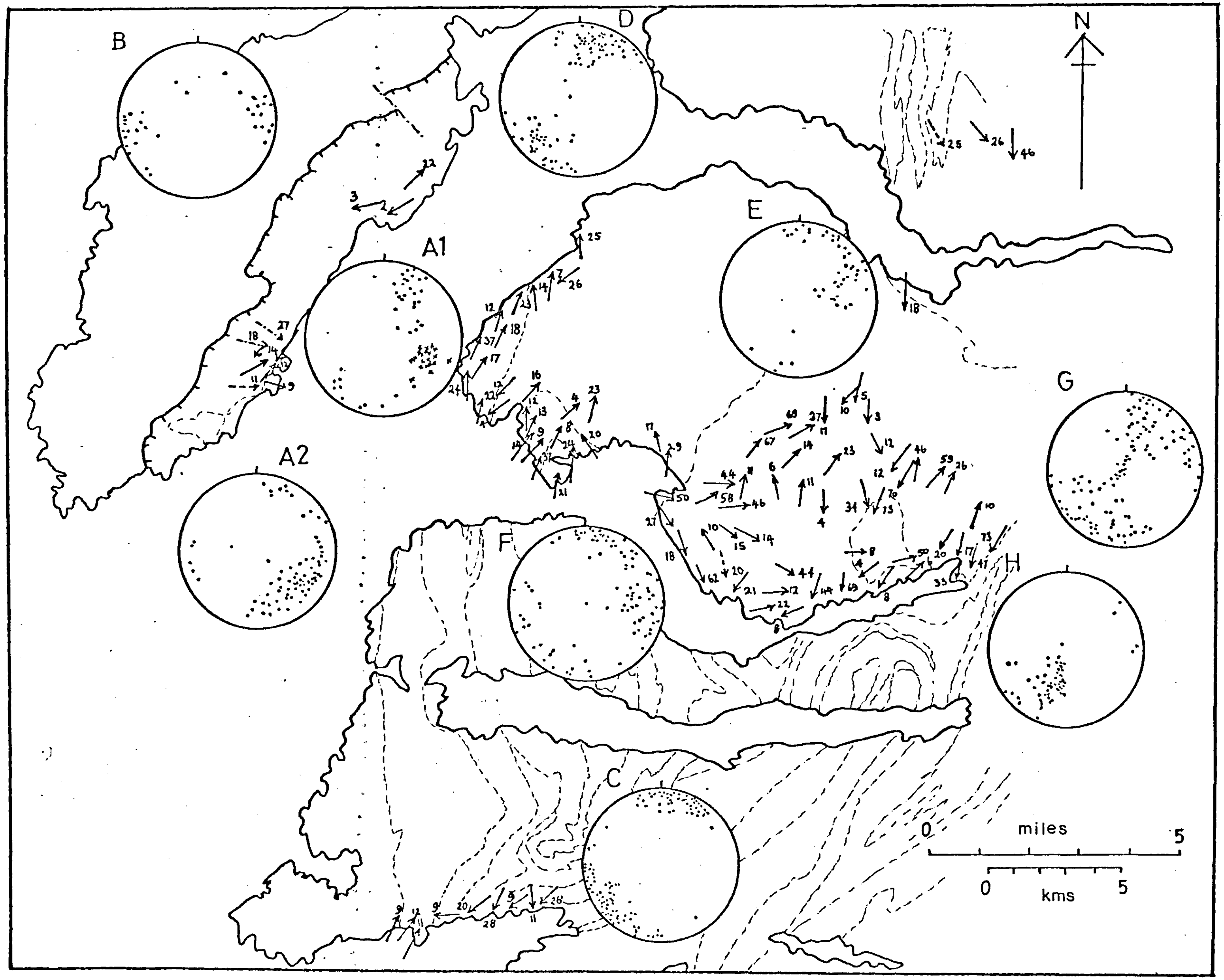
Third generation structures in the Moine Thrust Zone are not always recognisable throughout the entire outcrop of Moine and Lewisian rocks of the Moine nappe, but can be distinguished in restricted areas. They are best seen in the well exposed regions of the southeastern seaboard of the Sleat Peninsula. D_3 structures considered here occur in

(a) the Armadale section which includes the uppermost Thrust sheets I and II (Fig. 48)

(b) the lowest Thrust sheet IV whose base is the Moine Thrust plane.

In this lowest part of the Moine nappe, D_3 structures occur at Aird and Knock (Figs. 45 and 46). The latter two areas are composed essentially of Lewisian rocks, and the former of Moine metasediments.

(a) The Armadale Section (Sheets I and II) D_3 structures in this region include mesoscopic, open, overturned folds with coaxial micro-crenulation folds (F_3), S_3, which is axial planar to the folds, an intersection crenulation lineation (L_3) and a mineral elongation lineation (L_3') contained by S_3. These structures are shown graphically on projections A1 and A2 in Figures 45 and 46 along with the geographical distribution of structures. The linear elements (Fig. 45, Projections A1 and A2) comprising hinges of folds deforming earlier planar fabrics, deformed quartz veins and intersection lineations - show two distinct patterns. The linear structures in Sheet I (Projection A1, Fig. 45)



PROJECTIONS

A1 Rubha Phoil) Armadale section
A2 Rubha Dubh)

B. Knock Peninsula

C Arisaig (South Morar)

D Doune-Inverie (West Knoydart)

E Inverie-Gleann Dubhlochain

F Inverie-Kylesknoydart

G Gleann Meadail-Carnoch

H Kylesknoydart-Camusrory

KEY TO PROJECTIONS

• F_3 fold hinges and L_3 intersection lineation

× L_3' mineral elongation lineation contained by S_3

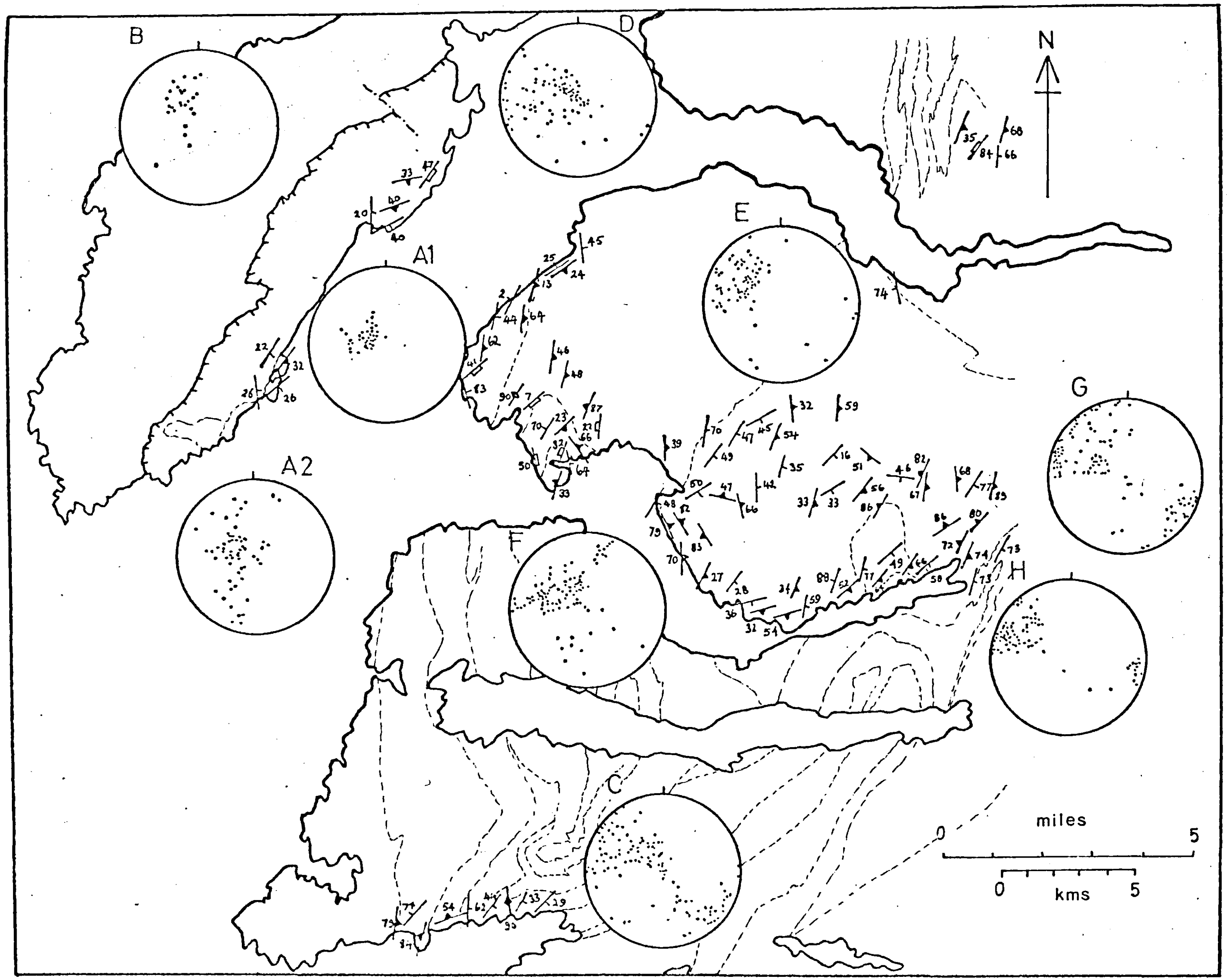
KEY TO MAP

F_3 fold hinges

L_3 intersection lineation

L_3' mineral elongation lineation contained by S_3.

Fig.45. D_3 Linear Structures in the Moine nappe.



PROJECTIONS

A_1 Rubha Phoil } Armadale section
A_2 Rubha Dubh }

B Knock Peninsula

C Arisaig (South Morar)

D Doune-Inverie (West Knoydart)

E Inverie-Gleann Dubhlochain

F Inverie-Kylesknoydart

G Gleann Meadail-Carnoch

H Kylesknoydart-Camusrory

KEY TO PROJECTIONS

• Poles to S_3 and F_3 axial planes

KEY TO MAP

S_3 schistosity

F_3 axial planes

Quartz veins parallel to F_3 axial planes

Fig.46. D_3 Planar Structures in the Moine nappe.

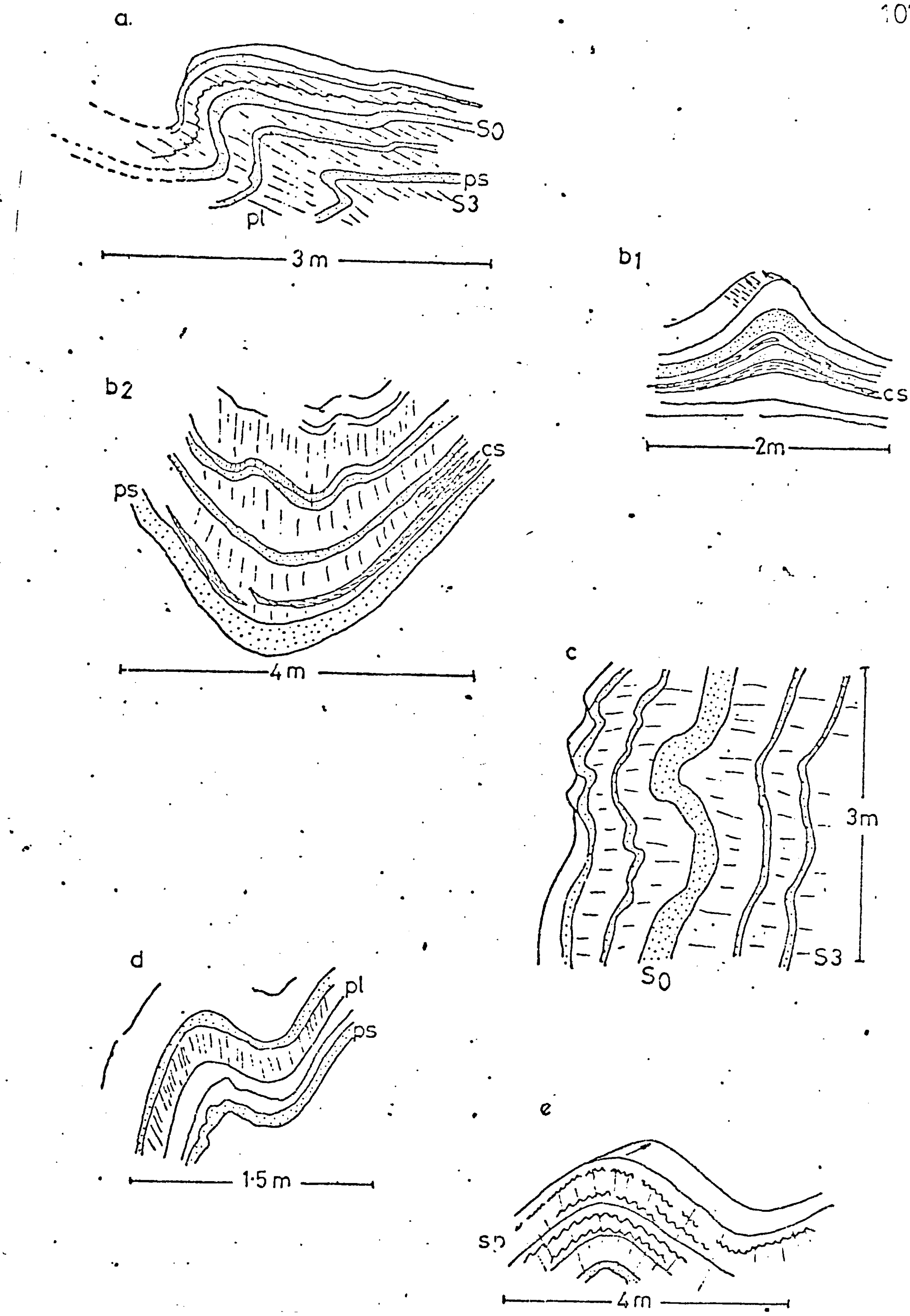


FIGURE 47. F_3 fold styles

(a) Armadale, Skye. S_3 crenulation schistosity is axial planar to F_3 folds.

(b) Arisaig, South Morar. (b1) shows the refolding of S_2 schistosity in a calc-silicate layer by the F_3 fold. The S_3 schistosity developed in the pelitic layers is axial planar to F_3 folds. (b2) shows similar refolding of S_2 in a calc-silicate and a crenulation lineation on the upper surface of the fold parallel to the major fold hinge.

(c)-(e) show examples from Knoydart where large F_3 folds are typically open in profile with coaxial crenulation folds.

S_o=layering: S_3=crenulation schistosity: ps=psammite; pl=pelite: sp=semipelite -F_3 fold hinge

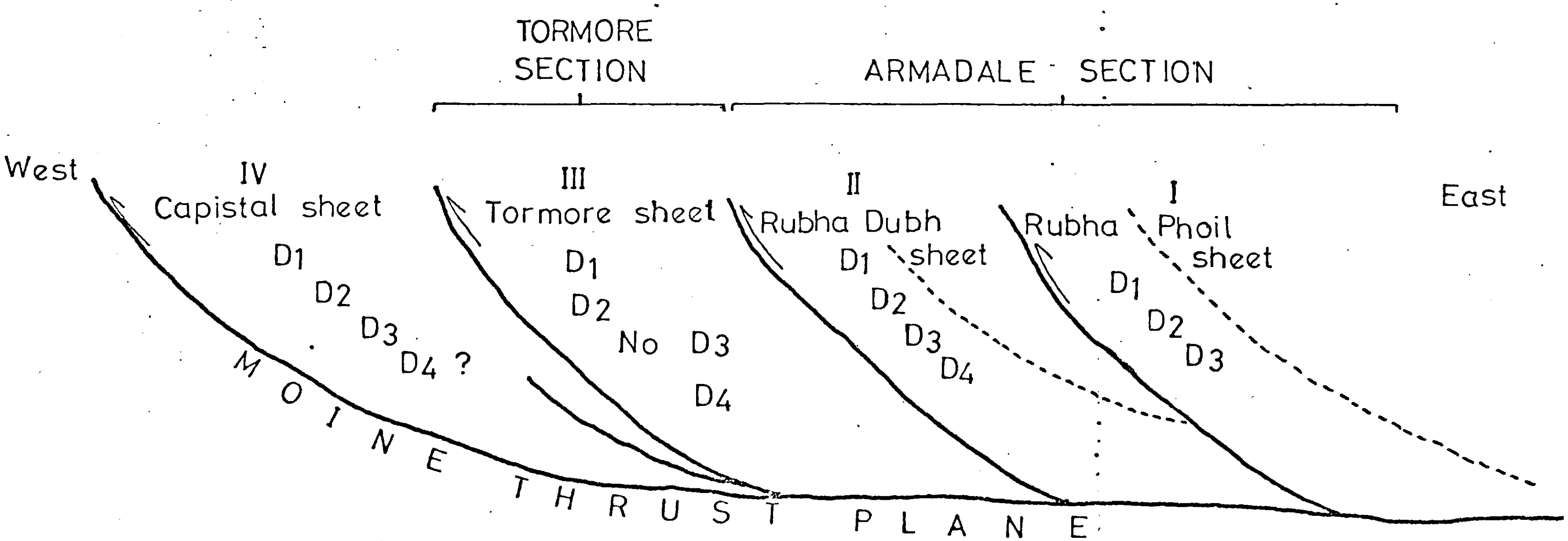


Fig.48. Imbricate zone of the Moine nappe in Skye. The diagram shows the phases of deformation contained by each thrust sheet (not to scale). See map in Fig.20 for geographic location of the thrust sheets on the Sleat Peninsula.

plunge consistently to the northeast at shallow to moderate angles, whilst those of Sheet II (Projection A2, Fig. 45) show a great circle distribution between north and south, with shallow to moderate plunges. The mineral elongation lineation (L_3') in Sheet I shows an invariable moderate plunge to the ESE (Fig. 45A1 and Plate 24). These two thrust sheets form the two uppermost thrust sheets in the imbricate structure above the Moine thrust plane described in Chapter 3. The uppermost sheet - I Rubha Phoil (see Fig. 48) shows well developed structures belonging to fold phases D_1 to D_3 (Figs. 23, 30, 31, 45 and 46) and no D_4 structures (Figs. 55 and 56). Whereas the underlying sheet - II Rubha Dubh (Fig. 48) - shows well developed structures belonging to all four episodes of deformation. Consequently the scatter observed for D_3 structures on Projection A2 on Figs. 45 and 46 is the result of later deformation during D_4 on Rubha Dubh (Sheet II) and the more consistent trends and attitudes of D_3 structures on Rubha Phoil (Sheet I) (Projection A1 on Figs. 45 and 46) are because of no subsequent refolding during D_4 and D_5 episodes, prior to thrust movements.

F_3 and L_3 linear elements in Sheet I (Rubha Phoil) Figure 45A1 show a consistent trend NE/SW, plunging at shallow to moderate angles. Plate 24 shows characteristic D_3 structures: F_3 open profile folds overturned westwards, S_3 strongly developed as an axial plane schistosity and associated L_3' extension lineation, and L_3 intersection lineation. F_3 folds deform earlier planar fabrics (in this case S_o, S_1 and S_2 - see Fig. 49 and Fig. 44, Chapter 4) and pre-F_3 quartz veins, and refold F_2 parasitic folds preserved in garnet porphyroblasts. Plate 25 shows that the attitudes of the pre-existing quartz veins has determined the nature of their deformation during D_3, producing either buckled (compressed) or boudinaged (extended) structures. The hinges of the buckled quartz veins and the boudinage axes of the extended/flattened quartz veins are coaxial with axes of F_3 folds which have deformed the layering. This suggests that the quartz veins were injected along planes which contained the F_3 hinge direction, so that their orientation was determined by the F_3 stress field.

The distribution of planar fabrics developed during D_3 in the Armadale section is shown on Figure 46 and graphically on Projections 46A1 and A2. Axial planes and S_3 generally dip to the SE at moderate angles (Plate 24). The bulk of the exposure comprises long limbs of

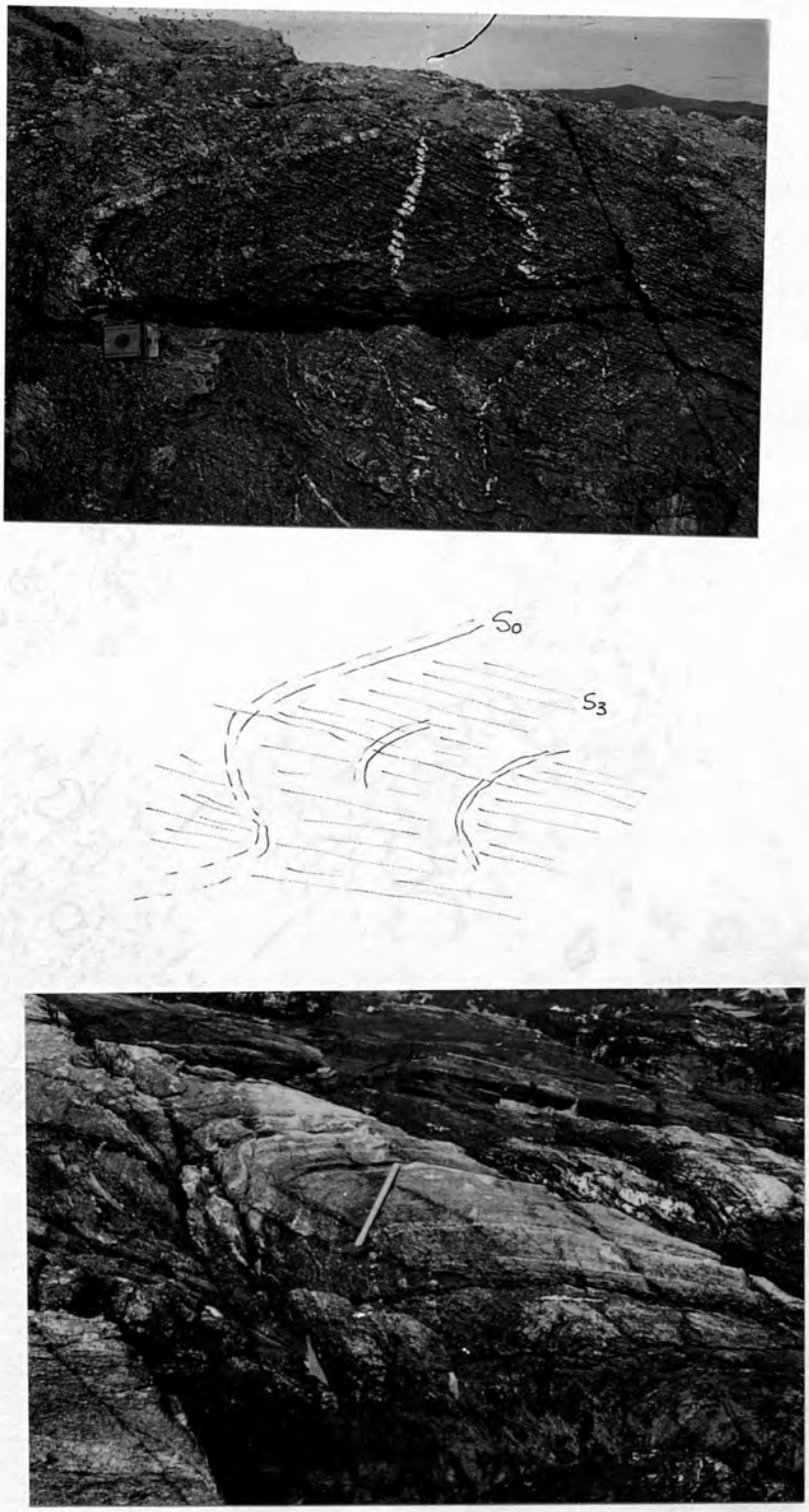


Plate 24: Open profile F_3 folds with axial planar schistosity.
Location - Armadale, Skye.

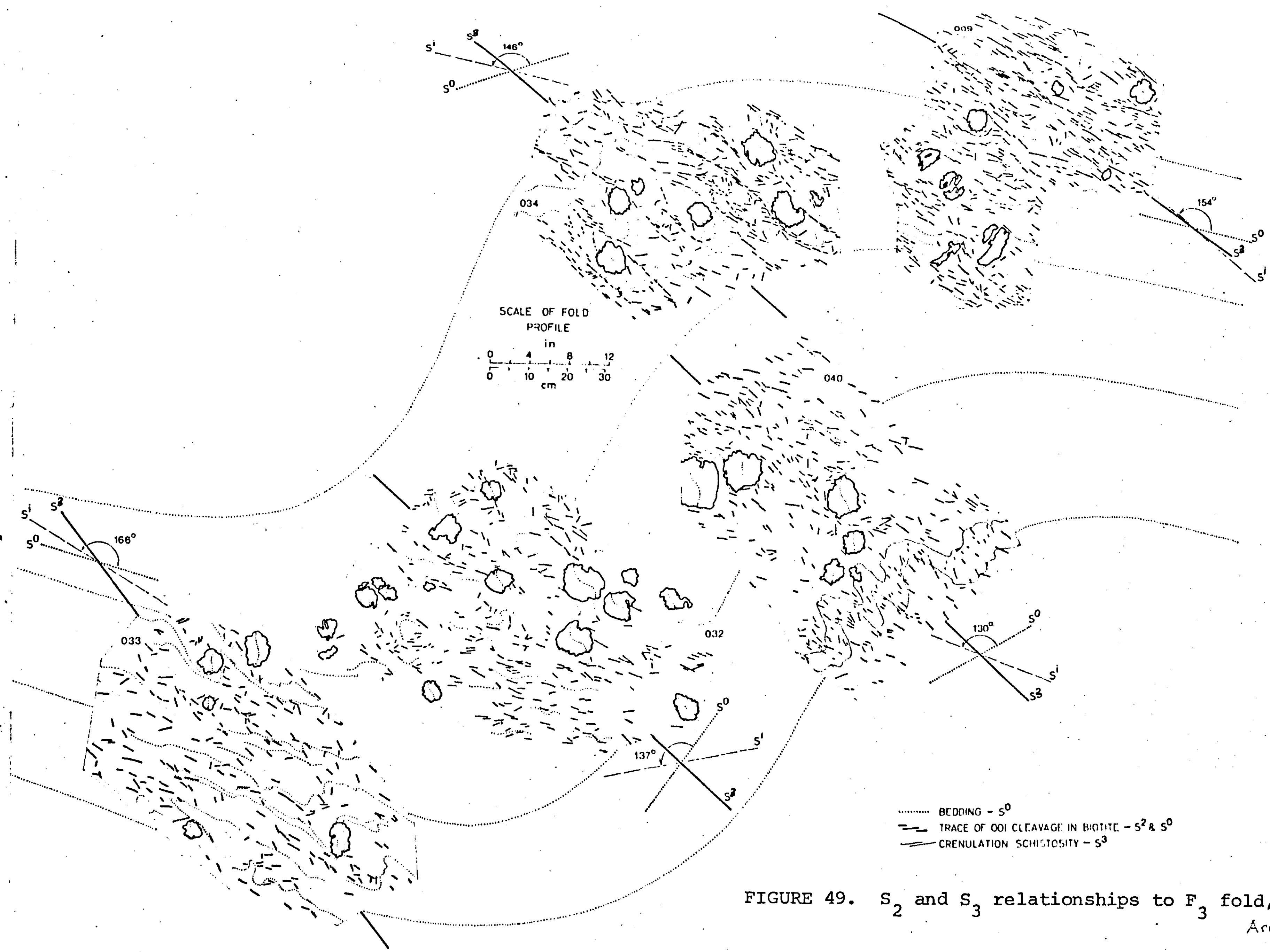


FIGURE 49. S_2 and S_3 relationships to F_3 fold, Skye

Armadale

F_2 folds, which are sub-parallel to the long limbs of mesoscopic F_3 folds. Consequently S_3 is parallel to and often indistinguishable from S_2 except in thin section (Fig. 49). On the short limbs of F_3 folds microfolding of the layering S_o/S_1 and S_2 schistosity has resulted in a crenulation schistosity (S_3) which is parallel to the short limbs of crenulation folds (Fig. 49 and Plate 26). Figure 49 also shows that the vergence represented by the inclusion trails within the garnet porphyroblasts is incorrect for F_3 fold closures, and has been refolded by F_3 folds.

Axial planar quartz veins or quartz-feldspar pegmatites are sometimes associated with third generation folds from Thrust Sheet II - Rubha Dubh. These segregations usually occupy the axial regions of folds but may also be more pervasive occurring parallel to S_3 schistosity planes.

(b) The Lewisian rocks which make up the lowest unit in the imbricate pile of Thrust Sheets - Sheet IV - provide evidence of later deformation attributable to D_3. Mesoscopic folds, small scale crenulation folds (F_3) an axial planar crenulation schistosity S_3 and an S_3/S_o intersection lineation (L_3) are developed. The mineral elongation lineation L_3' is not, however, present.

In the region of Knock Bay (Figs. 45 and 46), open profile folds with coaxial crenulation folds deform an earlier mineral elongation lineation. This lineation in the acidic gneisses is a parallel alignment of quartz and feldspar crystals, and in the basic layers takes the form of aligned amphibole crystals. The penetrative crenulation schistosity associated with the open profile "late" folds cross-cuts occasional isolated isoclinal fold closures of uncertain age. Rarely, the quartz-feldspar elongation lineation is seen to be parallel to these isoclinal hinges suggesting they are D_2 in age. Refolding of boudinage pods within the gneisses is also indicative of an earlier period of deformation and may be equivalent to D_2 boudinage in Knoydart (see Chapter 4.3.2).

Figure 45 Projection B shows the linear structures developed in the Knock area, and Figure 46 Projection B shows the planar structures. Linear structures trend ENE-WSW and plunge at shallow angles, whilst

Plate 25: Boudinaged and folded quartz veins; schistosity is S_3. Location - Armadale, Skye.

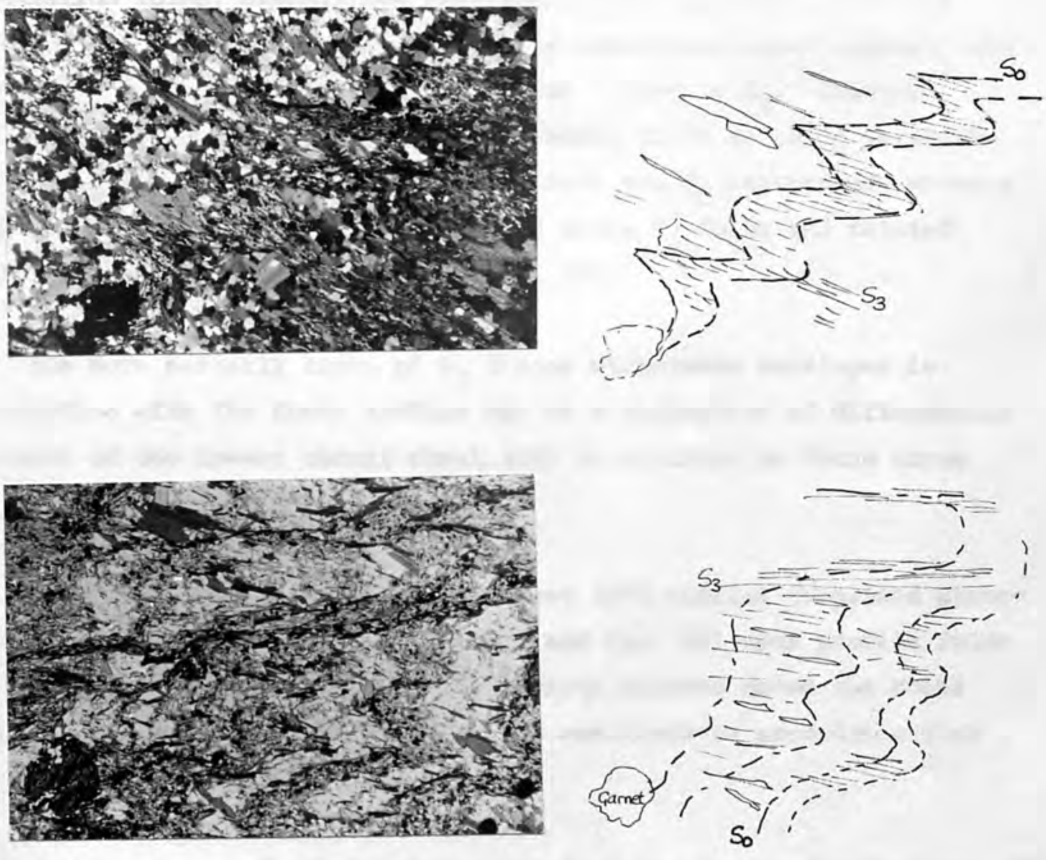


Plate 26: Photomicrograph of S_3 crenulation schistosity, and F_3 microfolds from the short, overturned limbs of F_3 folds, Armadale, Skye. (x5, a-X-nicols, b-P.P.L.).

planar structures dip south to southeasterly at moderate angles.

Axial planar quartz veins and/or quartz feldspar pegmatites are characteristically developed in association with the F_3 folds on the Knock Peninsula.

The vergence of mesoscopic parasitic folds indicates that there is a large scale synformal fold, whose axis trends approximately NE-SW, across the Knock Peninsula (Fig. 50). The earlier mineral elongation lineation (taken to be L_2) is refolded by it, whilst a coaxial intersection crenulation lineation and small scale parasitic folds are developed. Both large and small scale folds are overturned westwards in a manner similar to the folds present in the Armadale Section. Similarities in trends and attitudes of axial planes, coaxial crenulation folds, crenulation schistosity and lineation, and fold styles between the Knock synform and the Armadale Section suggest that these folds belong to the same generation - that is D_3. Cheeney and Matthews (1965) refer to the Rubha Phoil folds as being parasitic to the Knock Synform, but suggest that both are D_2 structures, whereas here they are assigned to D_3. (Fig. 50 shows F_3 folds and related structures from Thrust Sheets I, II and IV).

The more easterly trend of D_3 linear structures developed in association with the Knock synform may be a reflection of differential movement of the lowest thrust sheet (IV) in relation to those above it (Sheets I and II).

Elsewhere in the lowest thrust sheet (IV) similar localised structures are developed. At Aird (Fig. 45 and Fig. 46) open profile folds with coaxial crenulations occur in chlorite schists above the Moine thrust plane, giving synformal vergence eastwards in accordance with the Knock synform.

The attitudes of all D_3 structures from the lowest thrust sheet (IV) are given in Projection B, Figs. 45 and 46.

Various profiles have been suggested for the Knock Synform, each depicting the structure as an overturned (westward) syncline usually with an attenuated lower limb (Figs. 51A and 52). Cheeney and Matthews

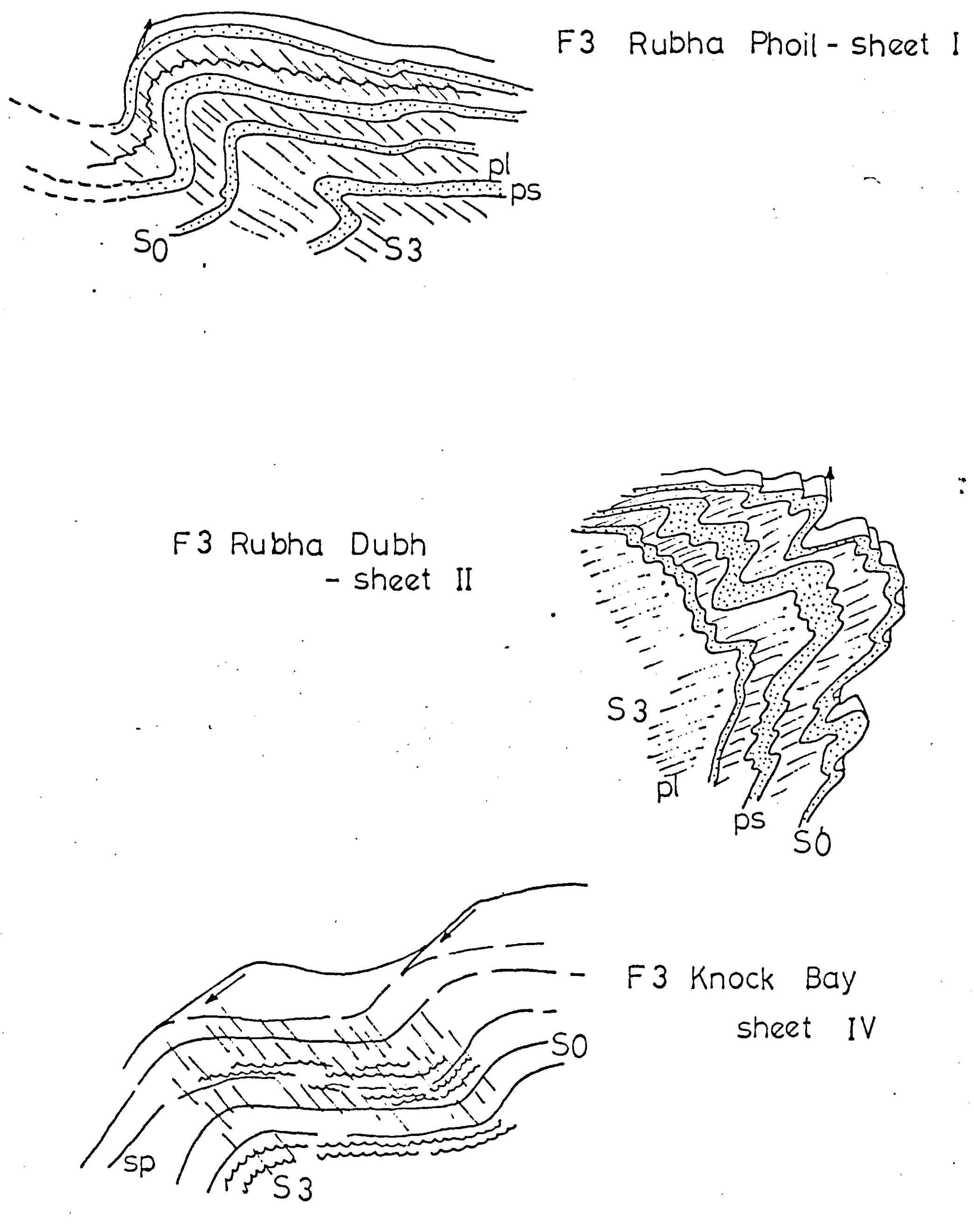


Fig.50. F_3 fold styles from the imbricate thrust zone in the Moine nappe on Skye.

ps = psammite; pl = pelite; sp = semi-pelite; S_0 = layering; S_3 = crenulation schistosity; F_3 fold hinge.

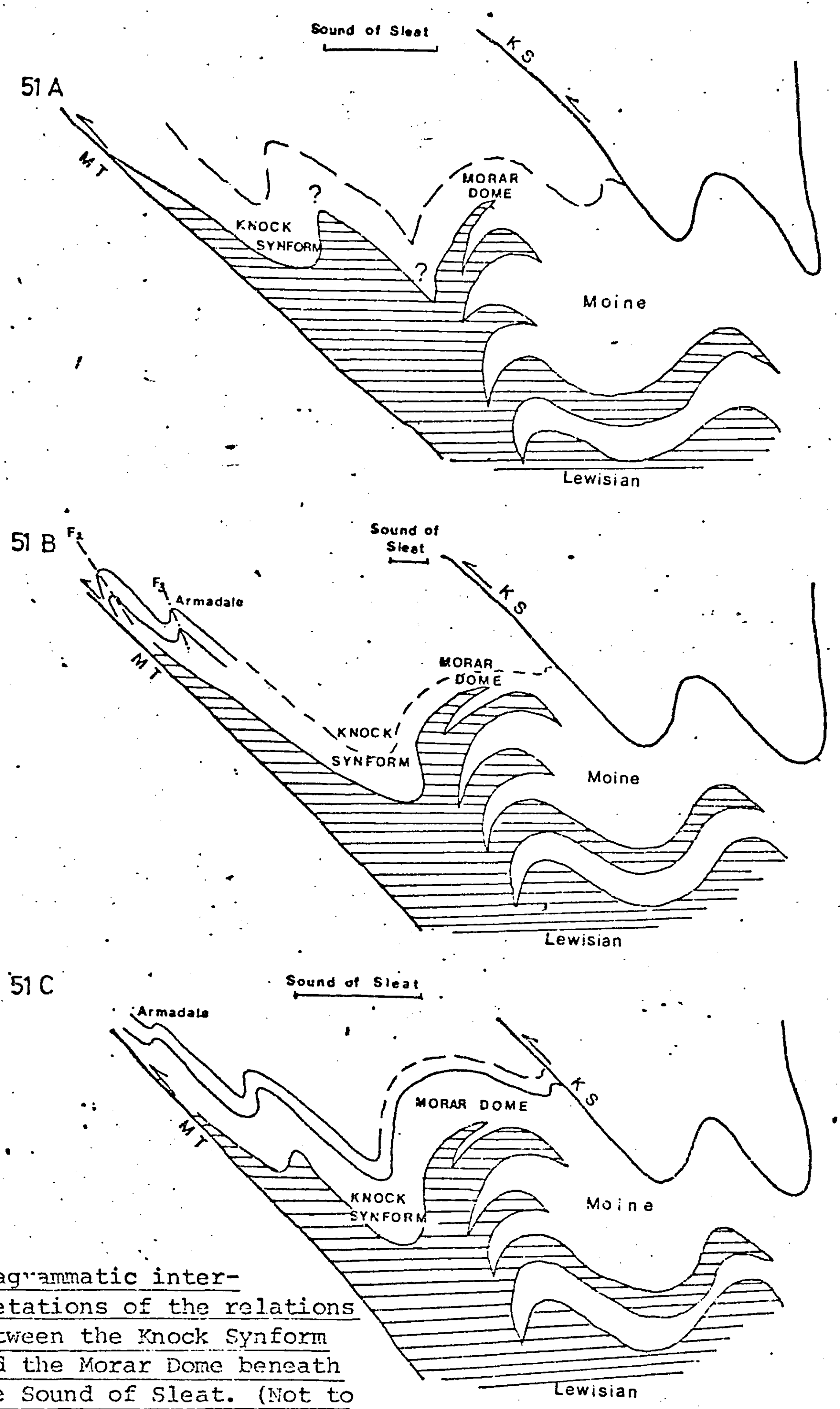


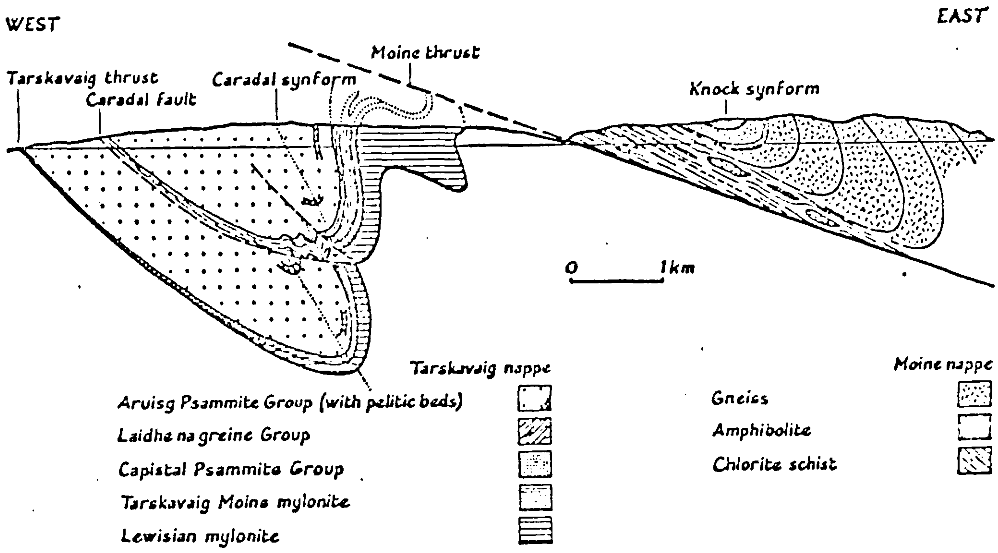
FIGURE 51. Diagrammatic interpretations of the relations between the Knock Synform and the Morar Dome beneath the Sound of Sleat. (Not to scale).

FIGURE 51A. From Powell 1974 (Fig. 5)

FIGURE 51B. The Knock Synform and Morar Dome share a mutual limb which is partly beneath the Sound of Sleat. F_3 folds at Armadale, Skye are parasitic to the Knock Synform on the western limb.

FIGURE 51C. A large scale overturned synformal third generation fold exists beneath the Sound of Sleat. The Knock Synform and F_3 folds at Armadale are parasitic folds on the western limb of this Synform.

(M.T.=Moine Thrust: K.S.=Knoydart Slide)



A simplified composite cross-section through the southern part of the Sleat peninsula.
T = Torridonian Epidotic Grit.

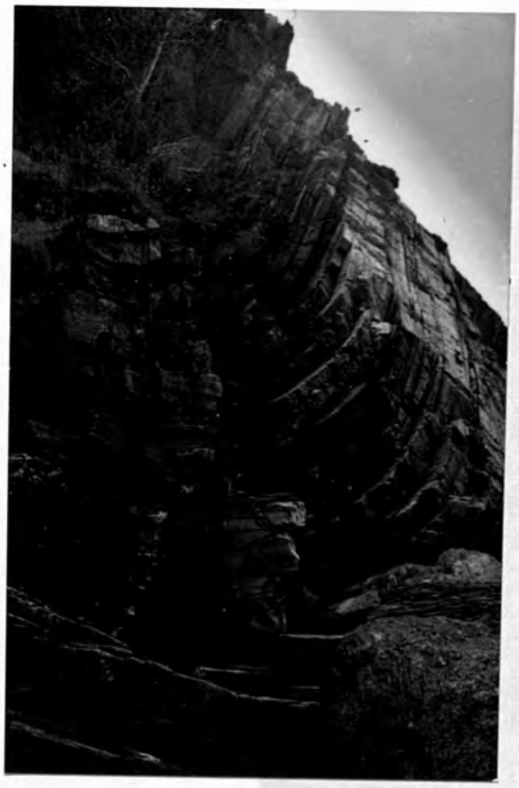
Fig.52. Profile of the Knock synform after Cheeney and Matthews (Fig.2, 1965).

(1965) provided evidence for retrogression of this NW limb of the Knock Synform. The rocks in the northwest are fine grained,fissile chlorite schists with remnant lenses and pods of the coarser grained massive gneisses, which make up the hinge region and southeast limb of the synform into which they transitionally pass. There is also evidence in the Ornsay-Camus Crosse area (Figs. 1 and 22) of contemporaneous thrusting of the southeast limb, with the development of a narrow zone of mylonite, and streaking and recrystallisation in psammites in the region of Ard Chunel (Figs. 1 and 22). These psammites have a tectonic junction with the Lewisian but cannot readily be correlated within the Moinian assemblage. Cheeney and Matthews (1965) refer to these psammites as "undifferentiated Moines" and this description is provisionally accepted here. Re-mapping of the Knock Peninsula has established that whilst both limbs of the Knock Synform generally dip to the southeast, the southeast limb of the fold becomes progessively less overturned eastwards, until in the extreme southeast the foliation varies between vertical and northwesterly dipping (Fig. 23). The axial plane of the Knock Synform dips to the southeast at between 40^{o}-50^{o} (Figs. 46B and 52), whereas the axial plane of the Morar Antiform varies between 50^{o}-70^{o} to the ESE Fig. 46 Plot D). Both are thus overturned folds. If the Knock Synform is a megascopic parasitic fold on the western limb of a larger synform present beneath the Sound of Sleat, then it is probable that this would be overturned westwards also. Powell 1974 (Fig. 51A) shows the synformal closure between Skye and the Morar Dome to be a pinched, angular synform, this would seem to be unnecessary as there is no reason why it should not be an overturned tight synform (Fig. 51C).

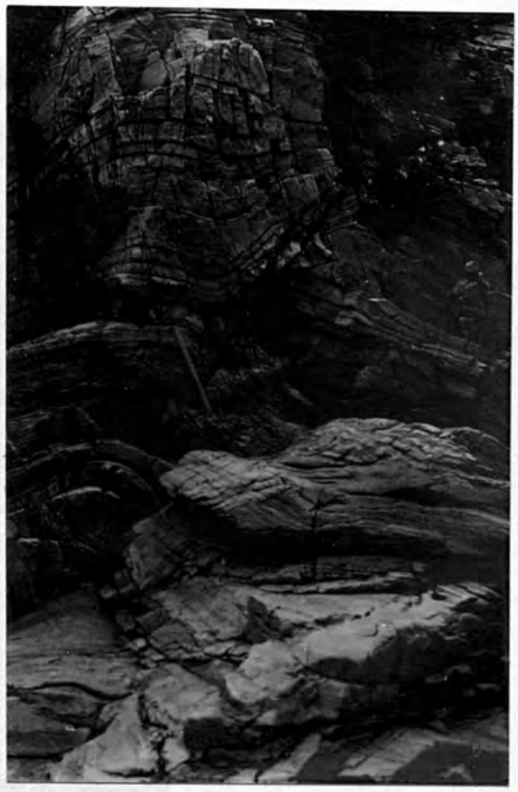
5.2.3 D_3 structures of the Mobile Belt

Third phase deformation structures are well developed in South Morar (Arisaig) on the western limb of the Morar Dome. Large scale open profile folds (wavelengths up to 10 metres) (Plate 27a) deform all earlier structures, crenulating S_2 to produce crenulation lineations L_3 and a pronounced crenulation schistosity S_3. The linear elements - folds, deformed quartz veins and intersection lineations - shown on Projection C, Figure 45 trend NE-SW with sub-horizontal axes; whilst the planar structures (Fig. 46 Projection C) dip southeast or northwest,

a.



b.



c.

Plate 27: F_3 folds, South Morar.

(a) Mesoscopic, open profile F_3 syncline.

(b) Limb of F_3 fold sheared out and partly infilled with quartz-feldspar, pegmatite.

(c) Small scale F_3 folds with crenulations on the short limbs.

Location Camus Ghaoideil, South Morar.

d.

e.

Plate 27: (cont'd)

F_3 folds, South Morar.

(d) Mesoscopic F_3 fold with restricted amplitude (<1 metre) and lamprophyre sill (black) forming plane of décollment.

(e) S_3 schistosity cuts lamprophyre sill. Chisel is parallel to S_3.

Location - Camus Ghaoideil, South Morar.

usually at moderate to steep angles. Third generation folds in this region are commonly upright structures with occasionally curved hinges varying about the horizontal. Quartz veins or quartz-feldspar pegmatites commonly occupy axial planes, or regions where one limb of an overturned fold has become sheared out (Plate 27b). Overturned mesoscopic folds (Plate 27c) show parasitic antiformal vergence to the east in accordance with the Morar Dome closure.

Mesoscopic third generation folds developed in the Lower Psammite group and psammitic portions of the Striped and Pelitic group (Chapter 3) commonly have shallow fold amplitudes (Plates 27d and e); folds with a wavelength of 2-3 metres may have an amplitude of less than 1 metre (Plate 27d). Excellent exposures of D_3 structures east of Camus Ghaoideil (Fig. 1) show how an earlier lamprophyre sill, intruded parallel to the layering, has acted as a plane of decollement during the formation of an open profile F_3 upright anticline above it (Plate 27d). S_3 which is axial planar to the F_3 fold also cuts the lamprophyre sill (Plate 27e and Plates 28a and b) which indicates a period of igneous intrusion prior to D_3.

Johnson and Dalziel (1966) record that metamorphosed lamprophyre sheets occur in Moidart but that "The deformation episodes recognised in the lamprophyre sheets post-date the main episodes of major and minor folding (F_1-F_3) that affected the surrounding Moine gneisses." If the notation of the structural sequence in Moidart is equivalent to that established in the South Morar region, viz. F_1-F_3 of Johnson and Dalziel (1966) being equivalent to D_1-D_3 established during the present work, then the implication is that the lamprophyre sheets of South Morar belong to an earlier episode of intrusion. More recent work by Johnson (van Breeman et al. 1974) again makes reference to "the post-F_3 lamprophyres" and "their intrusion at about 445 Ma". However, Smith (in discussion of van Breeman et al. 1974) has suggested that the "period of lamprophyre intrusion extended through the period of (younger) pegmatite formation" - that is 450 ± 10 Ma. Smith also refers to the presence of two distinct types of "lamprophyre" sheets, one of which pre-dates, and is therefore older than, the younger 450 ± 10 Ma pegmatites.

Third generation folds in this area refold "early" pegmatites. Plate 29 shows a boudinaged quartz-feldspar-mica pegmatite which is refolded by F_3 folds, and it is clear that the boudinage structures

a.

b.

Plate 28a & b: Photomicrographs of S_3 schistosity in lamprophyre sill (P.P.L. x5).

(a) Sample from margin of sill where minerals are aligned parallel to S_3.

(b) Sample from central portion of sill where minerals show less preferred orientation.

Location - Camus Ghaoideil, South Morar.

Plate 29: F_3 fold refolding a boudinaged "early" pegmatite.
Location - east of Druimindarroch, South Morar.

were produced by an earlier phase of deformation, either D_2 or D_1. Unfortunately no localities with cross-cutting relationships between the early pegmatites and the pre-F_3 lamprophyre sills were found. (See Table 2 and Tables 5 and 6 in Chapter 7 for a summary of structural, pegmatitic and igneous intrusive events).

D_3 structures are equally well developed in the northern part of the research area in Knoydart. The trend of fold axes (F_3), intersection lineations (L_3) and folds of deformed quartz veins is NE-SW, usually with shallow to moderate plunges (Projections D-H, Fig. 45). Folds are commonly upright or overturned westwards, open profile structures with coaxial crenulation folds, which produce the characteristic crenulation schistosity (S_3). Projections D-H on Figure 46 show the moderate to steep southeasterly dip of the axial planes and S_3. All previous structures and early pegmatites and quartz veins are deformed by this episode of deformation. Plates 30a and b and Plates 33a-h show the styles of F_3 folds developed in Knoydart. The mesoscopic folds usually fall into class 1C or 2 (Ramsay 1967) with hinge regions being particularly thickened in more competent strata.

Several important features must be noted in relation to the third episode of deformation in Knoydart. Firstly, in west Knoydart, mesoscopic F_3 parasitic folds are congruent with the Morar antiform, and S_3/S_o intersection relations support its antiformal closure; secondly, F_3 folds have deformed F_2 folds, the latter also show the same vergence. In effect, the D_3 deformation has tightened the pre-existing antiform into the domal structure now evident. S_3 develops parallel to either the limbs or axial planes of small scale crenulation folds which deformed S_2 (Plates 31 and 43d). This crenulation cleavage S_3 fans round the dome closure, dipping at shallow angles on the limbs and becoming increasingly steep towards the axis (see Fig. 46).

Parasitic folds on the western limb of the Morar Dome suggest a synformal closure to the west, beneath the Sound of Sleat. F_3 folds on the Sleat Peninsula of Skye in the Armadale section also support the existence of a synformal structure of F_3 age beneath the Sound of Sleat. Powell (1974, Fig. 5) suggests that a large scale anticline and syncline exist between the Morar Antiform and the Knock Synform (F_3), with wavelengths of less than 10 km., and amplitude greater than

Plate 30: F_3 folds, Airor, West Knoydart.

(a) Mesoscopic open profile folds, viewed up plunge, looking north.

(b) Small scale crenulation folds, quartz veins parallel to S_3 schistosity. Viewed looking north.

a.

b.

Plate 31: Photomicrograph of F_3 microcrenulation folds deforming S_2 to produce S_3 crenulation schistosity. (x4, P.P.L.). Location - Airor, West Knoydart.

1,000 m. (Fig. 51A). This interpretation, however, could be modified in the light of available evidence, and other explanations appear to be possible. Firstly, that the Knock Synform is the complementary fold to the Morar Dome with the common limb partially obscured by the Sound of Sleat (Fig. 51B). Secondly, it is possible that the Knock Synform is a megascopic parasitic fold on the western limb of a synformal closure beneath the Sound of Sleat, which is the complementary fold to the Morar Dome (Fig. 51C). In both instances the overturned folds at Armadale show correct vergence for the western limb of the synform. There are, however, several other factors to be considered:

(a) The rock units present on either side of the Sound of Sleat do not match up directly

(b) Several major fault systems extend from Glenelg further north southwestwards beneath the Sound of Sleat. These include the Strathconan fault which is thought to have at least a 1 mile vertical and 1 mile horizontal (sinistral) displacement (Ramsay pers. comm., and from tectonic considerations in the Loch Duich area).

(c) Late phase brittle deformation structures developed in the extreme west of Knoydart at Doune (Fig. 1) are typical of those developed elsewhere in association with thrust planes. Characteristic of these are conjugate sets of kink folds (Plate 32) and associated brecciation and retrogression of the rocks. Coupled with this is the existence of the same structures on the extreme end of the Rubha Dubh headland on Skye, which may directly correlate with those at Doune, West Knoydart. As this type of fold is invariably developed in association with thrust planes elsewhere it is tempting to suggest that such a tectonic break exists to the west of the Knoydart coastline. If Skye is returned to its original position (assuming that the displacement values quoted on the Strathconan fault are correct) these two areas of characteristic thrust plane structures are opposite to each other, but separated by the 4 km. of the Sound of Sleat.

A thrust plane separating the rocks of western Knoydart from those of Skye is therefore postulated so that the west Knoydart area structurally overlies the Armadale and Rubha Dubh rocks, forming the highest sheet in the imbricate pile of thrust slices above the Moine

Plate 32: Late stage conjugate kink fold which deforms earlier structures. Location - Doune, West Knoydart.

Thrust (Fig. 53). The movement on any of these minor thrust planes is almost impossible to measure but need not necessarily be of any very great distance.

Further east in Knoydart minor structures produced during the third phase of deformation indicate the presence of other large scale F_3 fold closures (Fig. 54). Progressively from west to east these include the Ladhar Bheinn Synform (defined by Spring 1961, and Powell 1974), which is possibly the southerly extension of the Ben Sgriol Synform (of Ramsay 1960); and the Meall Bhasiter Dome. In south central Knoydart, a further large scale antiformal fold is recognisable over several miles, and appears to be related to, and the same age as, the Meall Bhasiter Dome (Fig. 54). The effect of this antiformal fold is to infold the Garnetiferous Pelitic horizon such that it occurs as a folded outcrop on the southwest coast of Knoydart (Fig. 54). The sideways closing western limb of the Meall Bhasiter Dome whose domal "hinge" in this region trends east-west is refolded by a fourth generation fold such that it trends south-west (Fig. 54). This F_3 antiformal "offshoot" is here called the Beinn Bhuide antiform, and is equivalent to Powell's (1974) fold 3a. In the coastal region where exposure and consequently interpretation are best (Figs. 45 and 46, ProjectionF), minor structures associated with this antiformal closure show that the fold plunges to the ENE at approximately 15^{o} and its axial plane dips to the southeast at approximately 26^{o}.

Minor structures associated with the Ladhar Beinn Synform, the Meall Bhasiter Dome, and the Beinn Buidhe antiform, include minor crenulation folds (F_3), a crenulation schistosity S_3, and an intersection (S_3/S_1) lineation (L_3). Both major and minor structures are shown in Figures 45 and 46 on stereo-projections E to H, and Plate 33 (a-h). The trend and orientation of third generation structures in east Knoydart is more variable than in west Knoydart or South Morar. This is partly a reflection of the original variable attitude of the layering produced by deformation during D_1 and D_2, and is also related to subsequent deformation during D_4. Linear elements (Fig. 45, Projections E-H) trend northeast or southwest, usually plunging at shallow angles; minor folds and lineations associated with the Meall Bhasiter Dome (Fig. 45, Projections G and H) show more variation in amount of plunge and direction reflecting the position of minor structures on the dome.

Third generation planar elements show a relatively consistent southeasterly dip of shallow to steep angles (fig. 46, Projections

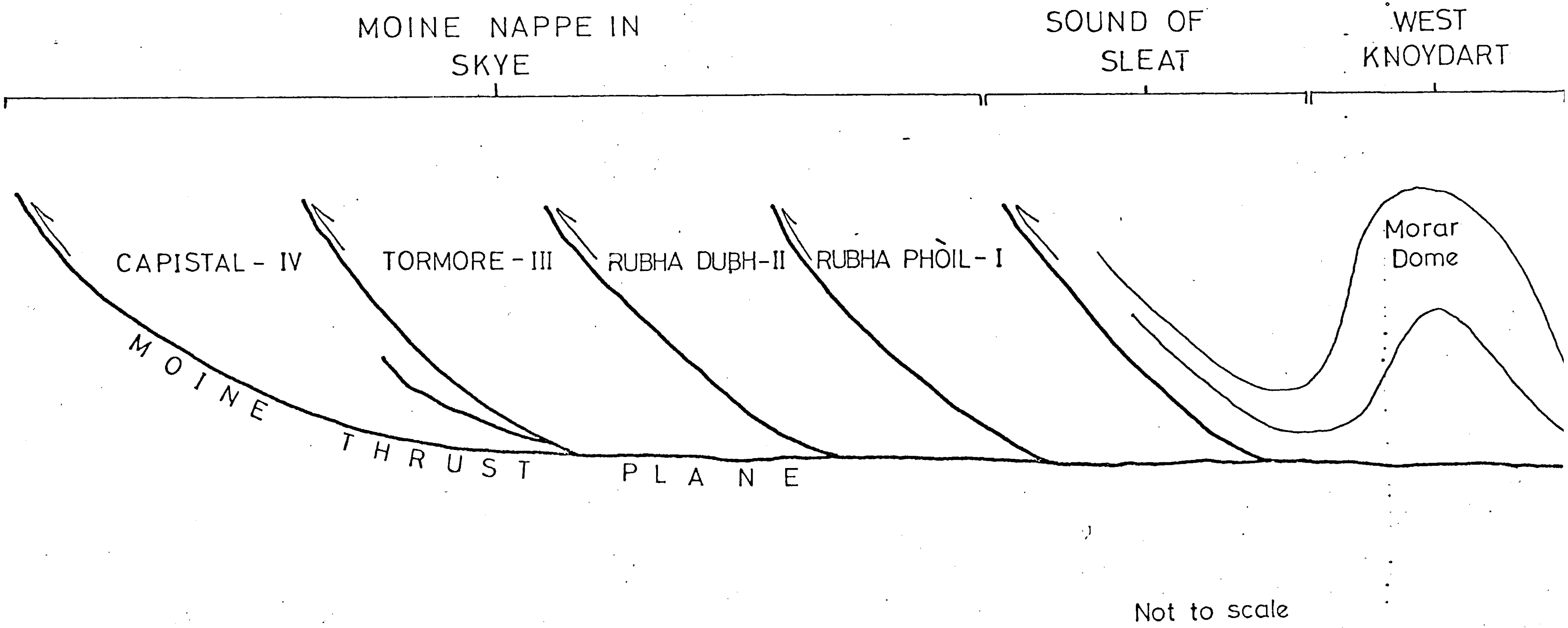
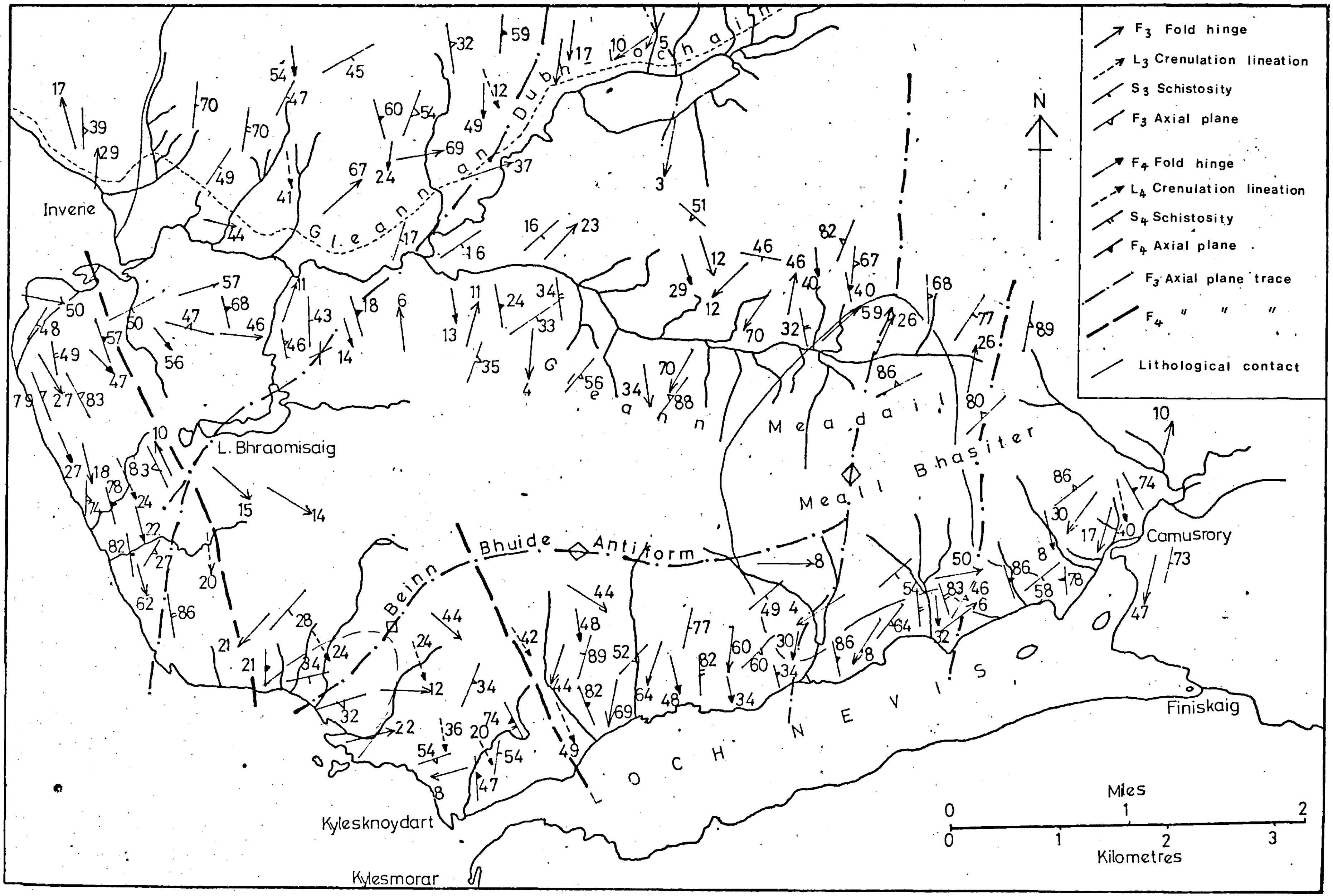
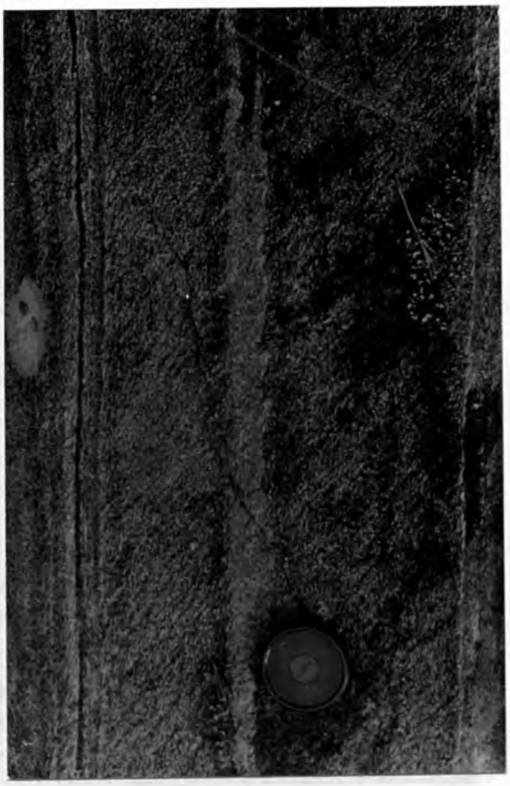


Fig.53. Diagrammatic sketch from the Moine Thrust to West Knoydart to show the possible relations of West Knoydart to the imbricate structure above the Moine Thrust plane.

FIGURE 54. D_3 and D_4 structures of Eastern Knoydart



a.



b

c.

Plate 33: F_3 folds, Gleann Dubhlochain and Gleann Meadail, East Knoydart.

(a) Small scale crenulation folds and S_3 crenulation schistosity.

(b) Small scale F_3 fold with quartz-feldspar pegmatite parallel to the axial plane.

(c) F_3 crenulation folds deforming S_2 schistosity and pre-existing quartz veins.

d.

f.

e.

Plate 33: F_3 folds, Inverie-Kylesknoydart Section.

(d) Mesoscopic open profile F_3 fold with coaxial crenulation folds.

(e) F_3 crenulation folds.

(f) Open profile F_3 fold refolding F_2 isoclinal fold.

g.

h.

ate 33: F_3 folds, Kylesknoydart-Camusrory Section.

(g) F_3 mesoscopic fold with quartz veins parallel to S_3 axial plane schistosity.

(h) F_3 crenulation of S_2 schistosity axial plane to F_2 folds.

E and F), except where again associated with the Meall Bhasiter Dome where planar elements dip northwest and southeast at moderate to steep angles (Fig. 46, Projections G and H). Plates 33a-h show the typical fold styles developed. Apart from deforming earlier linear and planar fabrics in the rocks, D_3 deformation also deforms pre-existing quartz veins (Plate 33c) and pegmatites. One of the most important pegmatites to be deformed by F_3 folds is the Knoydart pegmatite, showing it to be pre-D_3 (see Section 4.5.3). Muscovite "books" up to 30 cm long and 3 cm wide become crenulated at the margins of the pegmatite lenses.

5.3 Structures associated with the fourth phase of deformation, D_4

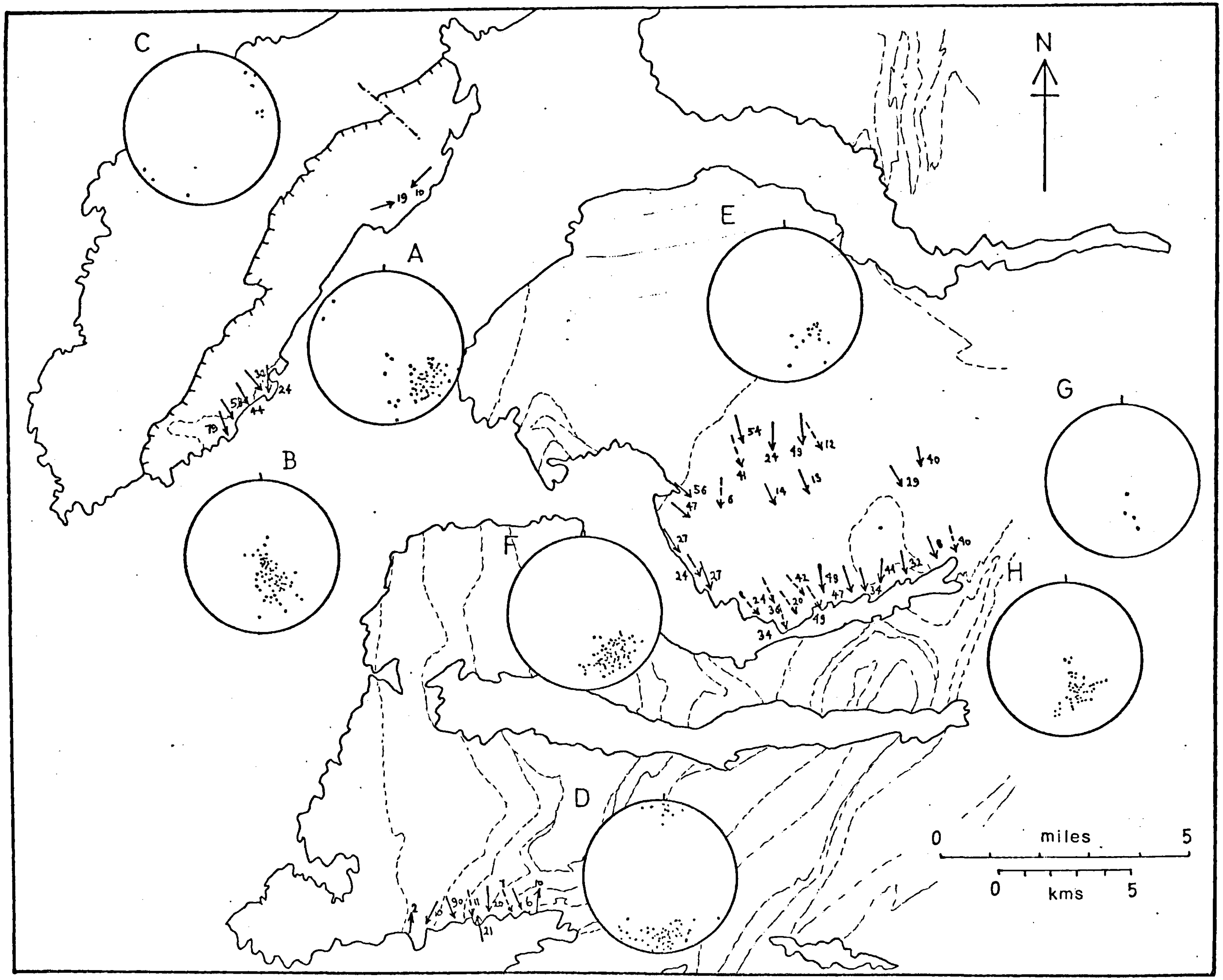
5.3.1 Introduction

The last phase of deformation to affect the Moine rocks of the west coast on a regional scale is referred to as D_4 (fourth phase). Regionally, this episode was quite extensive, but D_4 structures occur only in restricted areas throughout the region.

As this was the last major phase of deformation prior to thrusting in the area, the attitude of the structures developed is very consistent (Figs. 55 and 56), with variation attributable to pre-existing attitudes of layering.

F_4 folds occur as either open profile, shallow amplitude folds on a mesoscopic scale, or as steeply plunging crenulation folds. The plunge direction of fold axes and intersection lineations is consistently to the southeast, and these folds have near vertical or steeply dipping axial planes and associated S_4 schistosity. Occasionally conjugate sets of intersecting fold pairs develop, with the more dominant fold plunge direction continuing to be to the southeast, with the complimentary folds plunging to the south or south-southwest. This is particularly well illustrated in Arisaig (Fig. 55).

All D_4 structures deform pre-existing linear and planar fabrics produced during earlier phases of deformation.



PROJECTIONS

A Rubha Dubh - Sheet I

B Tormore - Sheet III

C Knock and Aird - Sheet IV

D Arisaig (South Morar)

E Gleann Dubhlochain

F Inverie-Kylesknoydart

G Gleann Meadail-Carnoch

H Kylesknoydart-Camusrory

KEY TO PROJECTIONS

F_4 fold hinges and

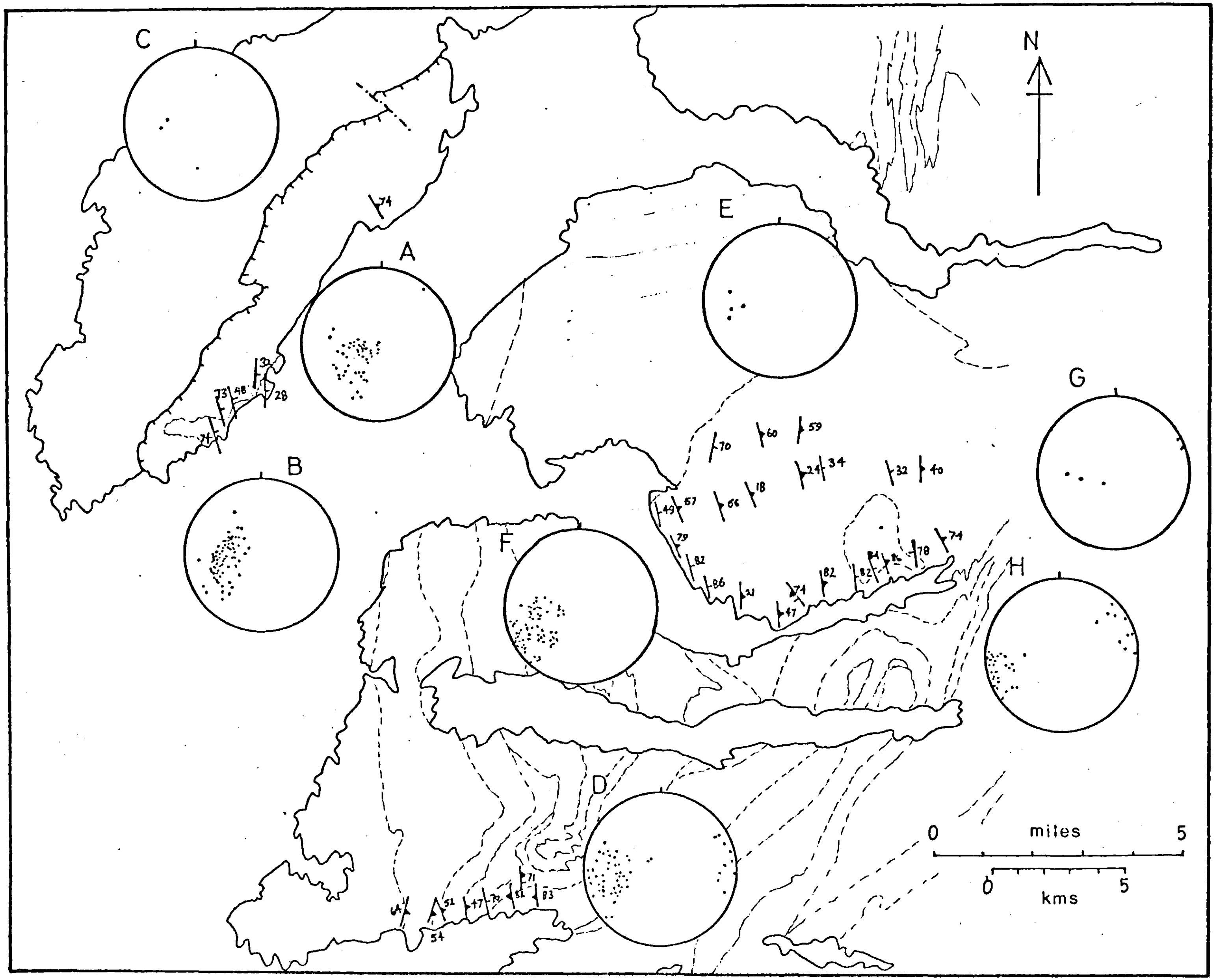
L_4 intersection lineations

KEY TO MAP

F_4 fold hinges

L_4 intersection lineations

Fig.55. D_4 Linear Structures in the Moine nappe.



PROJECTIONS

A Rubha Dubh - Sheet I

B Tormore - Sheet III

C Knock and Aird - Sheet IV

D Arisaig (South Morar)

E Gleann Dubhlochain

F Inverie-Kylesknoydart

G Gleann Meadail-Carnoch

H Kyles-Camusrory

KEY TO PROJECTIONS

• Poles to S_4 and F_4 axial planes

KEY TO MAP

S_4 schistosity

F_4 axial planes

Fig.56. D_4 Planar Structures in the Moine nappe.

5.3.2 D_4 structures of the Moine Thrust Zone

Within the thrust zone on the Sleat Peninsula of Skye, D_4 structures are well developed in imbricate Thrust Sheets II and III, and are poorly developed in Sheet IV, and apparently totally lacking from Sheet I (see Fig. 48).

The uppermost sheet to be affected - Rubha Dubh, Sheet II - in this zone shows excellently developed linear structures of D_4 generation. Small scale crenulation folds (F_4) and crenulation fold axis/ S_o intersection lineations (L_4) plunge to the southeast at moderate angles (Fig. 55, Projection A). D_4 planar structures are less well developed, but show S_4 and axial planes dipping at moderate degrees to the northeast (Fig. 56, Projection A). These D_4 structures deform F_3 and F_2 folds on the Rubha Dubh headland, and crenulate pre-existing planar fabrics.

D_4 structures in Sheet III (Tormore) are the type example of structures associated with this phase of deformation. Both large and small scale folds are developed, plus a crenulation schistosity which is parallel to one or other of the limbs of the microcrenulations (Plate 34). Linear elements plunge at moderate to steep angles to the southeast (Fig. 55, Projection B) deforming steeply dipping limbs of F_2 isoclinal folds and S_2 schistosity planes (see Fig. 57). Small scale crenulation folds, especially prominent in pelitic layers, are coaxial with mesoscopic (wavelength of less than 10 metres), open, low amplitude folds. Axial planes and S_4 dip steeply to the east-northeast (Fig. 56, Projection B).

D_3 structures are not represented in thrust Sheet III, whereas they are in thrust Sheet II. D_4 structures of Sheet II deform all the pre-existing structures (D_1, D_2 and D_3) and develop similar structures to those representing D_4 in the Tormore thrust Sheet III. Thus it is possible to correlate D_4 deformation in the two thrust sheets.

The lowermost imbricate sheet, Sheet IV (Capistal) shows only limited development of D_4 structures with isolated "late" folds plunging to the southeast (Fig. 55 Projection C), deforming earlier linear and planar fabrics in the rocks. The correlation of these folds with D_4

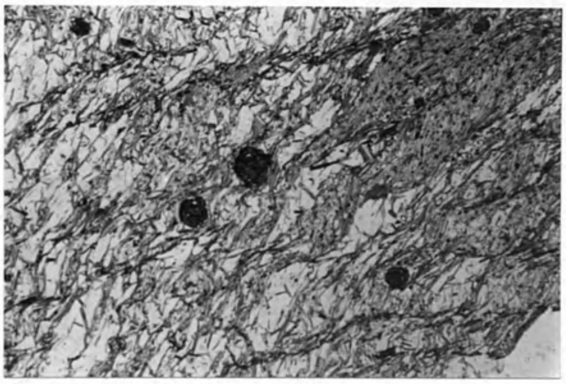


Plate 34: Photomicrograph of F_4 crenulation folds and S_4 schistosity. D_4 structures post-date crystallization of garnet. (x4, P.P.L.). Location - Tormore, Skye.

Plate 35: Small scale F_4 folds and "late" quartz-feldspar pegmatite. Location - Druimindarroch, South Morar.

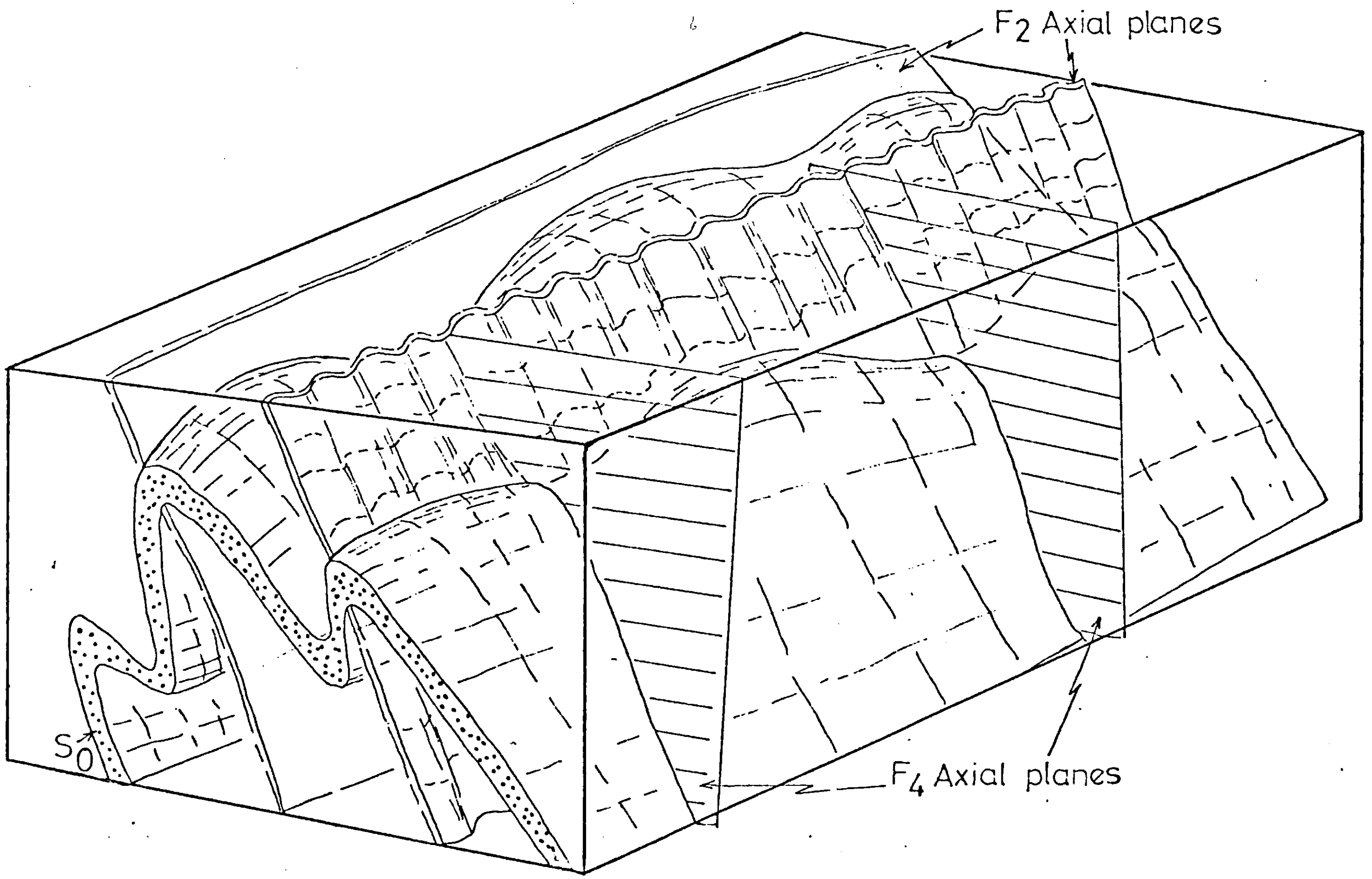


Fig.57. Block diagram to show the intersection of D_2 and D_4 structures, Tormore Skye. NE-SW trending F_2 folds, with a southeasterly dipping axial plane schistosity are deformed by open profile F_4 folds with coaxial crenulation folds. F_4 folds plunge steeply to the SE. (Not drawn to scale).

structures elsewhere, is based on fold style and the southeasterly trend of the plunging fold axes.

5.3.3 D_4 structures in the Mobile Belt

Structures associated with the youngest phase of deformation occur sporadically throughout the region of the mobile belt, usually being best developed in more pelitic, less competent, strata.

In the South Morar region, D_4 movements are reflected in the form of conjugate sets of open profile mesoscopic folds with coaxial crenulation folds (Fig. 55 Projection D). The most pronounced member of the pair of the conjugate set is the southeasterly plunging fold. Figure 55 Projection D shows both crenulation fold axes (F_4) and crenulation intersection lineations (L_4) plunging at shallow to moderate angles to the southeast and south (this projection includes both members of the conjugate fold sets). Planar elements - the axial planes and crenulation schistosity (S_4)- associated with these folds are shown on Figure 56 Projection D, dipping vertically or steeply to the east or west. Plate 35 shows F_4 crenulation folds developed in semi-pelitic layers in the Striped and Pelitic Group on the South Morar coast. The steeply dipping crenulation schistosity seen in the photograph is cross-cut by a late stage (possibly post-D_4) pegmatite.

In the Knoydart region, D_4 structures are only developed in the southeast of the region (see Figs. 55 and 56), and are restricted to more incompetent horizons. Figure 55 (Projections E and G) shows linear, and Figure 56 (Projections E and G) planar, structures of this generation developed between Inverie and Gleann Dubhlochain and Gleann Meadail to Carnoch respectively. Linear structures again exhibit a southeasterly plunge direction and planar structures dip moderately steeply to the east-north-east.

Further south in the region, due north of Loch Nevis, D_4 structures are decidedly more pronounced, showing consistent moderate fold and lineation plunges to the south-east (Fig. 55 Projections F and H) and with steep north-easterly dipping planar elements (Fig. 56 Projections

F and H). In the Kylesknoydart region (Fig. 55 Projection F and Fig. 56 Projection F), the minor structures are related to a major F_4 fold which deforms the hinges of F_2 and F_3 (the Beinn Buidhe antiform) antiforms. The axis of this major F_4 fold also plunges steeply to the southeast and effectively deforms the previously east-west trending hinges of F_2 and F_3 generations, into a more south-southwesterly and east-southeasterly direction (see Fig. 58). This major F_4 fold is called the Kylesknoydart Fold.

Folds of this generation can be traced in the central Morar and Ardgour region on Sheet 61 (Geol. Surv. 1971, see also Powell, 1974), but appear to be absent from west and north Knoydart and Glenelg, suggesting that this episode of deformation was perhaps more restricted in its influence than earlier phases (i.e. D_1 to D_3).

5.4 Correlations of D_3 and D_4 throughout the area

Section 5.2 outlined the evidence for the later phases of deformation. Figure 58 outlines the axial traces of major F_3 and F_4 folds.

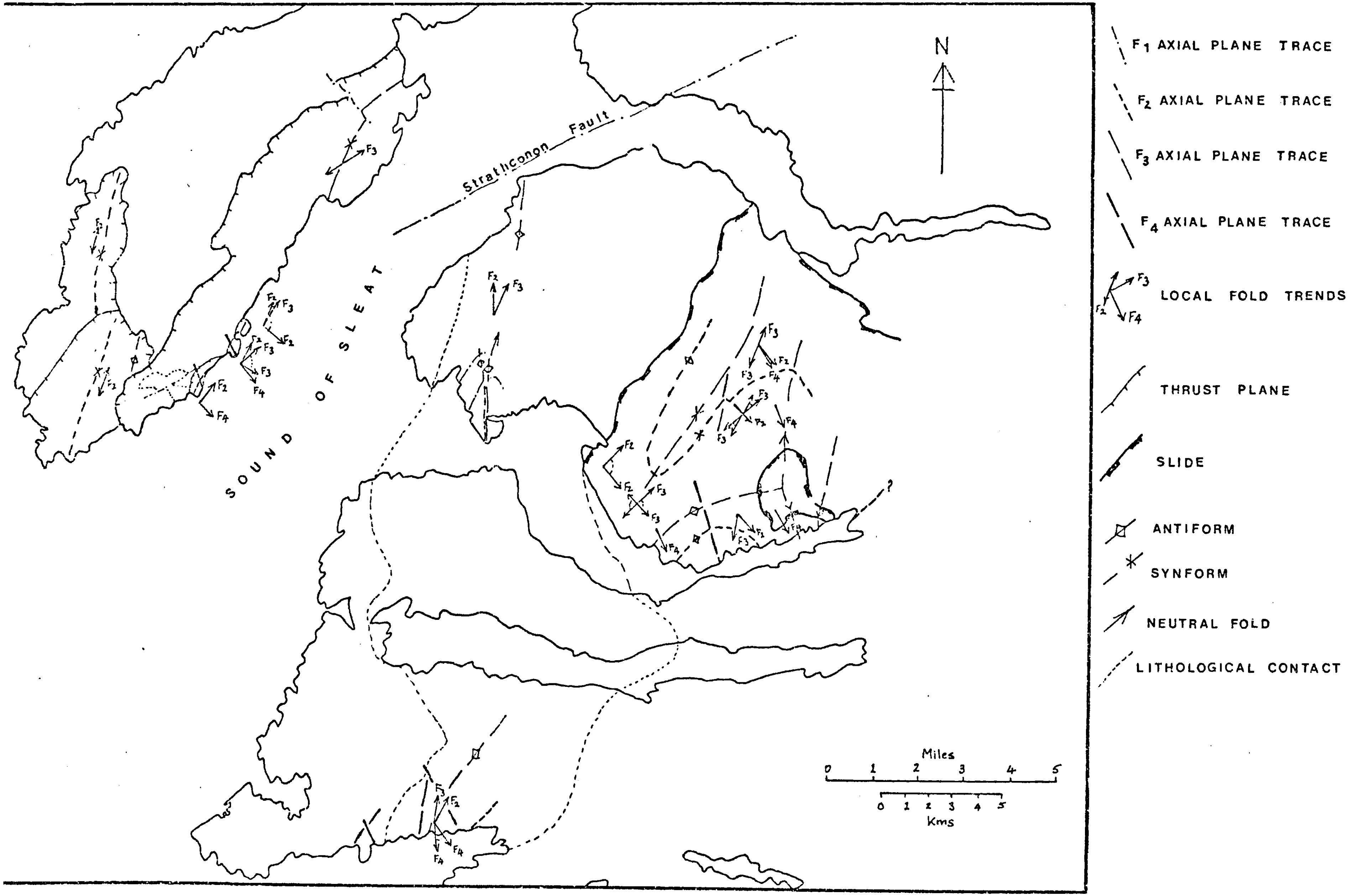
D_3 produced large and small scale folds, a schistosity, and intersection and mineral elongation lineations. The correlation of D_3 structures throughout the area is based on both structural and metamorphic considerations (see Section 5.6). Structural features used in the correlation include:

F_3 fold styles (Plates 24, 27, 29, 30 and 33, and Figs. 47 and 50) which are very similar and develop as open profile folds with coaxial crenulation folds;

the S_3 crenulation schistosity and related crenulation intersection lineations which characterise D_3 in all areas;

that S_3 is the earliest crenulation schistosity to be developed and which is cross-cut by the later S_4 crenulation schistosity. The mineral elongation lineation (L_3') is not so readily used for correlation purposes as this occurs only rarely. In the pelitic rocks of Armadale, Skye, biotite crystals form a lineation at right angles to F_3 fold axes, lying parallel to the limbs of F_3 microcrenulation folds, and contained by S_3. An analogous situation is not found elsewhere in the Moine nappe.

[illegible] established in the research area (F_1 – F_4), and the local fold trends of the various sub-areas.



In areas that have suffered little subsequent deformation, the D_3 structures show relatively consistent trends. F_3 fold axes in thrust Sheet I, thrust Sheet IV, in the region of Knock Peninsula, west Knoydart, and Gleann Meadail in central-eastern Knoydart, show F_3 folds striking NE-SW with shallow to moderate plunges, and moderately east to southeasterly dipping axial planes. These features suggest that the structures are of the same age. It is also possible to trace D_3 structures from west into central Knoydart, and thereby confirm their correlation.

Metamorphic considerations relating to the correlation of deformation structures will be discussed later (Sections 5.6 and 5.7).

The correlation of structures developed during the last regional phase of deformation D_4 is, perhaps, the simplest. D_4 linear features are consistent in their trend to predominantly the southeast, or in the case of conjugate fold pairs also to the south. F_4 axial planes and S_4 also show a consistent north-south strike with a steep easterly dip. In all areas D_4 structures deform, and therefore post-date, all structures relating to D_1, D_2 and D_3 events. Only in the thrust zone at the base of the Tormore thrust sheet are D_4 structures deformed. In this area, F_4 crenulation folds are brecciated and deformed by late stage kink folds, which are associated with the thrusting.

D_5 structures are restricted to the rocks immediately adjacent to the Moine thrust plane, and are interpreted as being related to its formation.

5.5 Structures associated with Moine Thrust Movements (D_5)

The final stages of deformation in this west coast region culminated with thrusting principally along the Moine Thrust Plane, in the later stages of the Caledonian orogeny. Apart from kink folds and brittle localised shear zones in the rocks adjacent to the major thrust plane, a further very localised generation of folds can be recognised (F_5).

Cheeney and Matthews (1965) refer to this generation of folds as the Port a' Chuil folds, so called after their locality near the

Moine thrust plane at its southern extremity on the Sleat Peninsula in Skye. Elsewhere in the Moine nappe on Skye these folds can only be certainly identified at Camas a'Mhuilt (Fig. 1), where the Moine thrust outcrops on the coast northeast of the Knock Peninsula. These F_5 folds tend to be tight to angular in profile (Plate 36a and b) with a lineation formed by the alignment of quartz and feldspar parallel to the axes of those folds which plunge east-north-east (Fig. 59A). This same generation of folds is found in the Tarskavaig Moine rocks beneath the thrust plane (Fig. 59B), and is believed to be of very localised occurrence only, occurring only adjacent to and within 100 m. of the Moine thrust plane (Chapter 6.4.6).

Minor folds adjacent to the imbricate thrust sheets I-III (Fig. 48) tend to be restricted to kink-folds, more indicative of late stage and brittle deformation, than the angular Port a'Chuil folds associated with the Moine thrust plane proper, because of shearing through axial planes of box folds. Kink-folds everywhere cross-cut and deform earlier structures, often forming as conjugate sets (Plates 36c and d) and post-dating all movements and deformations except the minor shear zones or "occasional lines of crush" (Clough in Peach et al. 1907) related to the thrust movements. Analysis of the attitude of kink-fold axes and axial planes shows no obvious strong preferred orientation of structures (Fig. 59c).

Rocks above the Moine thrust plane consist of strongly brecciated chlorite schists and fragmented quartz veins. The foliation in the Lewisian schists is very closely spaced but contorted adjacent to the thrust plane. Rocks below the thrust plane consist of brecciated semi-pelites with white quartz psammite layers. The Port a'Chuil folds are only sporadically developed in the Tarskavaig Moine rocks although the quartz rodding lineation is persistent in places plunging to the east-north-east (Fig. 59B). Elsewhere, contorted folds may be relic Port a'Chuil folds distorted and partly destroyed by thrusting.

Port a'Chuil folds appear to have originally developed by ductile deformation followed by brittle deformation with the breaking up or shearing out of limbs of the folds (Plates 36a and b). Shear planes develop followed by, or associated with, the main thrusting with the formation of brittle kink folds. Thus, the time separating the two

Fig 59A

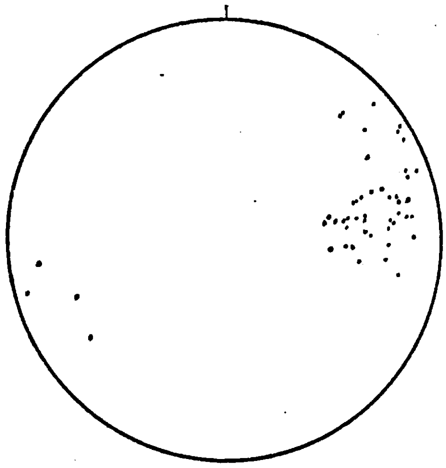


Fig 59B

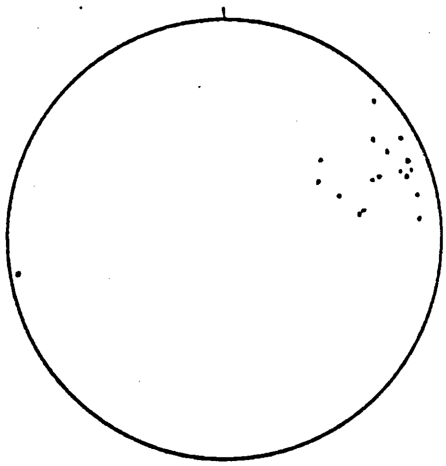


Fig 59C

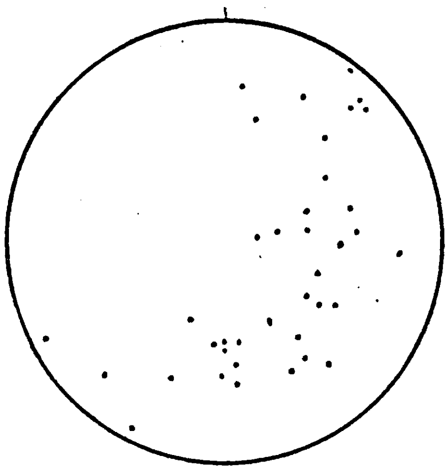


Fig.59A & B Stereographic projections of Port a'Chuil (D_5) structures.
59A - Port a'Chuil lineations and fold axes in the Lewisian rocks above the Moine Thrust Plane.
59B - Port a'Chuil lineations and fold axes in the Tarskavaig Moine rocks below the Moine Thrust Plane.

Fig.59C. Stereographic projection of late stage kink folds which show random orientation.

a

b.

Plate 36a & b: F_5 Port a'Chuil folds in Lewisian rocks above the Moine thrust plane, Skye.

Plate 36c & d: Kink folds in rocks of the Moine Thrust Zone, Skye.

c.

d.

events - i.e. ductile and brittle behaviour - was probably not very great.

Shear planes, or minor thrust planes, occur above the main Moine Thrust Plane, dipping at steeper angles than the thrust plane itself, producing an imbricate structure on a small scale within the upper part of the thrust zone. The zone of brecciation is surprisingly restricted however, and more markedly developed above rather than below the main thrust plane.

5.6 The "Late" Metamorphism (M_2)

5.6.1 Introduction

A second episode of regional metamorphism affected the Moine and Lewisian rocks of the west coast during the later episodes of deformation (D_3 and D_4), overprinting, and in many cases obliterating, mineral assemblages established during the early metamorphic event (M_1). This latter metamorphic episode will be referred to as M_2.

M_2 bears certain similarities to the earlier event M_1. These include its regional extent and the increase in metamorphic grade from west to east. Metamorphic grade related to M_2 in the Moine metasediments ranges from biotite zone in Skye to kyanite-sillimanite zone in extreme eastern Knoydart (Barrovian Zones after Miyashiro, 1973). Crystallisation of metamorphic mineral assemblages can be linked to specific deformation episodes as a result of microtextural-fabric studies.

5.6.2 Evidence for M_2 in the Moine Thrust Zone

In the west of the area, regional metamorphism attained garnet grade during M_1, with the crystallisation of garnet porphyroblasts during D_2 (Chapter 4). Subsequent metamorphism during M_2 within the rocks of the Moine Thrust Zone was at a lower grade. Biotite laths crystallised during D_3 to form the S_3 schistosity axial planar to F_3 folds in Sheets I and II of the nappe pile (Fig. 48 and Plates 26 and 37). There was no further crystallisation or recrystallisation of garnet. Common minerals in this area which recrystallised during M_2 in the Striped and Pelitic group are biotite, muscovite, albite, quartz and minor chlorite. The M_2 metamorphism overlapped at least D_3 in Sheets I and II, because of the recrystallisation of biotite parallel to the S_3 schistosity (Plate 37).

In thrust sheet III (Tormore) where D_3 structures are absent but D_4 structures develop crenulation folds, an associated S_4 crenulation schistosity is formed by the parallel alignment of micas (Plate 38). Garnet porphyroblasts pre-date the S_4 schistosity as can be seen in Plate 38; therefore temperatures rose sufficiently to recrystallise biotite. Very rarely in Sheet III of the nappe pile in the thrust zone microcline crystals are developed; these porphyroblasts overgrow the S_2 schistosity but pre-date the F_4 crenulation folds. The crystallisation of microcline may have occurred during the late stages of D_2, after the formation of the S_2 schistosity.

The lowest sheet in the nappe pile, Sheet IV (Capistal), shows various recrystallisation features related to M_2. In the region of the Knock Peninsula, recrystallisation has occurred on the lower (north west) limb of the Knock Synform. Pods and lenses of amphibolite and gneissic material occur within a zone of chlorite schists which pass transitionally, albeit suddenly, into the coarse grained gneisses of the south-east limb. There is no evidence of retrogression and similar deformation on the south-east limb of the synform. Matthews and Cheeney (1968) refer to recrystallisation of hornblende and biotite during and after the formation of the Knock Synform, which according to the interpretation presented here is of D_3 age. This has been verified by the observation that biotite recrystallised parallel to the S_3 schistosity where present, and spectacular actinolitic hornblende crystals have formed in some areas, parallel to the S_3 schistosity, but also frequently with random orientation oblique to any preferred pre-existing foliation. This evidence suggests that recrystallisation, and therefore metamorphism, post-dated the culmination of the deformation responsible for the formation of the Knock Synform. That is that M_2 in this region was synchronous with, and continued after, the third phase of deformation.

Lewisian rocks within a kilometre of the Moine thrust show

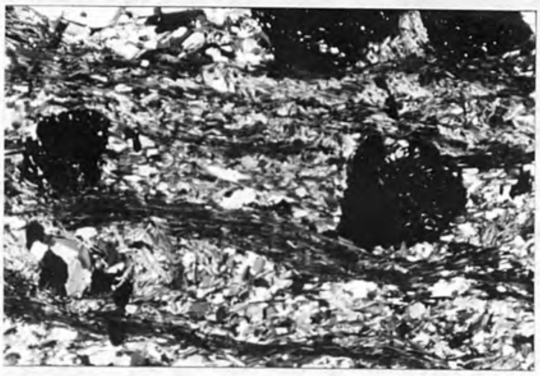


Plate 37: Photomicrograph of Armadale Pelite. S_2 schistosity is deformed by F_3 crenulation folds, biotite is re-crystallised parallel to the limbs of the folds to form S_3 schistosity. D_3 structures post-date the crystallisation of garnet (black). (x10, X-nicols).

Plate 38: Photomicrograph of S_4 formed by the alignment of micas parallel to F_4 crenulation fold limbs. D_4 structures post-date the crystallisation of garnet. (x4, P.P.L.). Location - Tormore, Skye.

retrograde changes with the alteration of garnet, hornblende and biotite, to chlorite pseudomorphs. The retrogressive effects are the result of deformation of the rock mass as a whole. The Moine thrust is entirely a brittle fracture suggesting that it entirely post-dates the cooling of the M_2 event. Primary chlorite and actinolite assemblages are located in the narrow zone of chlorite schists forming part of the lower limb (northwest) of the Knock Synform. Matthews (in Matthews & Cheeney, 1968) suggests that on the northwest limb of the synform deformation was locally more intense resulting in granulation of amphibolites to form hornblende schists and complete reconstitution of some rocks to form chlorite-actinolite schists. This special zone of chlorite schists was thought to be partly developed at the time of formation of the Knock Synform, and partly during the Tormore (F_4) phase of deformation (Matthews & Cheeney, 1968). Restricted structures of D_4 age in these thinly foliated rocks deform (refold) the chlorite-actinolite schists, suggesting that retrogressive mineral assemblages were present prior to D_4 deformation, so retrogression of the original gneisses may have been entirely synchronous with D_3. During D_4 only very restricted structures developed in this area, but metamorphic conditions were such to enable the continued recrystallisation of actinolite with random orientation.

The metamorphic grade attained in the thrust zone during M_2 never appears to attain garnet grade, rather being restricted to biotite grade throughout the pile of thrust sheets I-IV.

5.6.3 Evidence for M_2 in the Mobile Belt

The separation of first and second metamorphic events is not so readily made in the mobile belt as in the Moine Thrust Zone. In South Morar, microcline porphyroblasts frequently occur in semi-pelitic schists. Crystals can be up to 2 cm. in diameter, are pale grey or white, with equidimensional form (see Plate 22, Chapter 4) giving a distinctive spotted appearance to the rock. As seen in plate 22, the microcline porphyroblasts lie within the S_2 schistosity, but post-date the crystallisation of garnet (Plate 23) therefore suggesting a late D_2 age for their crystallisation.

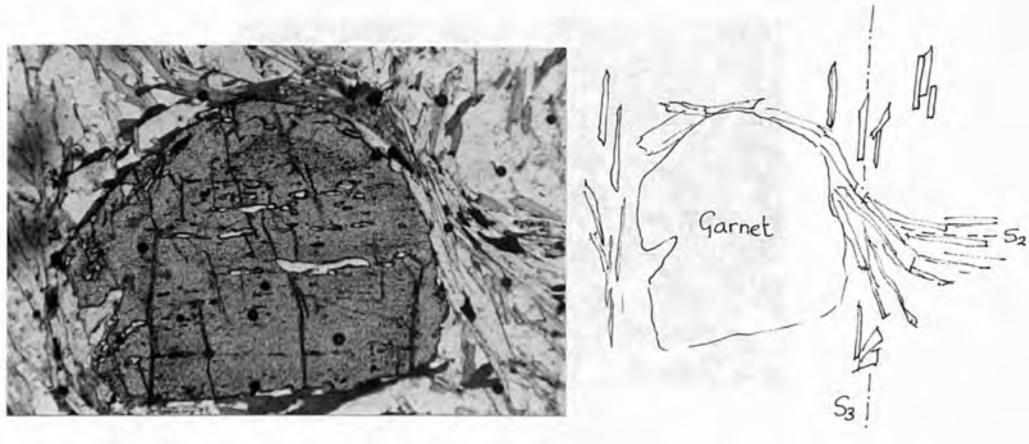
Crystallisation of minerals following the culmination of D_2 in Morar is represented in Plates 39a-c, and Plates 40a-c. Plate 39a shows that 4-zoned garnet porphyroblasts pre-date F_3 crenulation folds, where micas are recrystallised parallel to the axial planes. S-shaped inclusion fabrics within microcline porphyroblasts suggest syn-tectonic crystallisation (Powell 1966) during the formation of F_3 microcrenulation folds (Plate 39b) in some rock samples, however, microcline porphyroblasts overgrow F_3 crenulations (Plate 39c) implying that metamorphic conditions enabled the crystallisation of microcline after the D_3 had ended. From this, it may be concluded that the crystallisation of garnet is entirely related to pre-D_3 events, whilst the micas and microcline crystallised during a later event. Micas are always recrystallised round F_3 minor folds and microcline porphyroblasts appears to have two periods of crystallisation, Post-D_2 and during D_3. Crystallisation of microcline in the South Morar area marks the peak of M_2 metamorphism.

Crystallisation of minerals in relation to late D_3 and D_4 events is more restricted. Plate 40a shows muscovite flakes which cross-cut and overgrow the fabric produced during D_3 - that is the S_3 crenulation schistosity and F_3 microfolds. These late stage mica flakes are deformed during D_4 showing undulose extinction, and distortion of cleavage traces (Plates 40b and c) indicating that metamorphism had largely ceased by the onset of D_4 deformation.

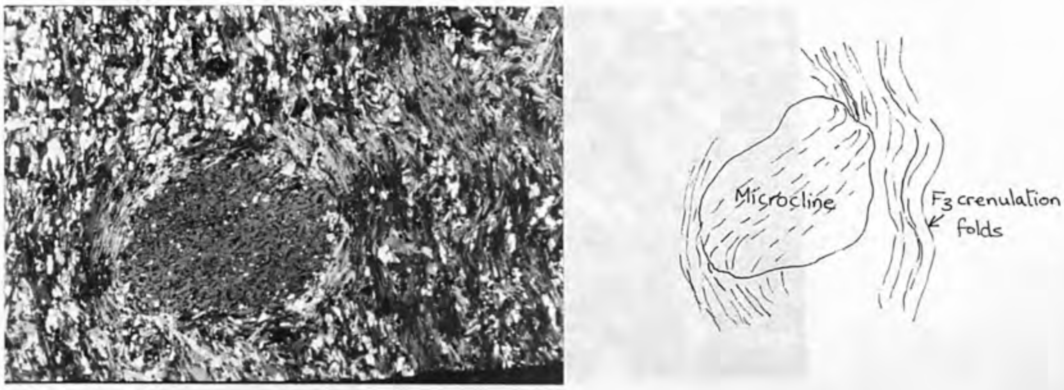
Consequently, the late M_2 metamorphism in South Morar attained a maximum of low amphibolite facies, overlapped D_3 events, but predated the D_4 phase of deformation.

Post-garnet crystallisation of microcline also occurred in Knoydart, west of the limit of migmatisation as mapped by the Geological Survey in eastern Knoydart. Microcline porphyroblasts in the Airor region of west Knoydart show similar relations to zoned garnet porphyroblasts as in South Morar. Plates 41a-d show examples of the development of minerals in relation to late structures. Garnet crystals with inclusion trails that are continuous with S_o/S_1 in the matrix are overgrown by microcline crystals (Plates 41a and b). The crenulation schistosity S_3 in places post-dates the crystallisation of microcline with recrystallisation of micas parallel to the axial plates of the micro-crenulation folds (Plate 41d). Elsewhere microcline appears to show syntectonic inclusion trails (Plate 41c) or overgrows crenulation

a.



b.



c.

Plate 39: Photomicrophs - Arisaig, South Morar.

(a) S_2 schistosity is wrapped around zoned garnet, micas recrystallised at an angle to S_2, parallel to S_3. (x25, P.P.L.)

(b) Microcline porphyroblasts. Inclusion fabric (Si) is continuous with external fabric which is S_2 schistosity (see sketch). Suggests syntectonic crystallisation during D_3. (x10, X-nicols).

(c) Microcline porphyroblasts overgrowing F_3 crenulation folds (see sketch), suggests post-tectonic (D_3) crystallisation of microcline (x2, X-nicols).

a.

b.

c.

Plate 40: Photomicrographs - Druimindarroch, South Morar.

(a) and (b) Mica crystals which overgrow the fabric produced during D_3 (X-nicols, (a) x5 (b) x10).

(c) Biotite crystals which recrystallised after D_3, showing undulose extinction indicating deformation during D_4 with no subsequent recrystallisation (X-nicols, x10).

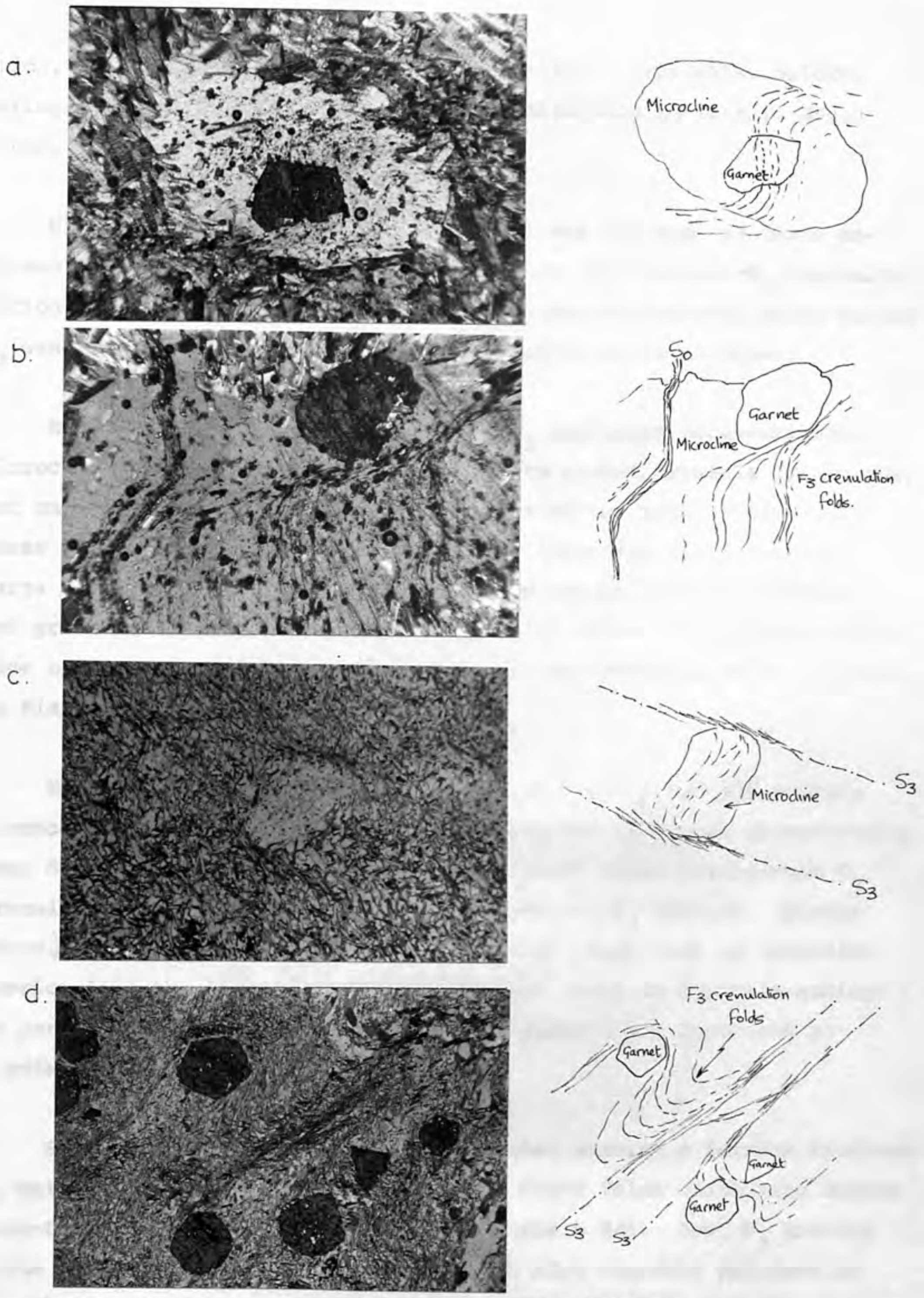


Plate 41: Photomicrographs - Airor, West Knoydart.

(a) Microcline porphyroblast overgrowing garnet. Inclusion fabric within microcline indicates syn-D_3 growth (X-nicols, x10).

(b) Microcline porphyroblast overgrowing garnet and F_3 crenulation folds. Inclusion fabric is continuous with that in matrix. (X-nicols, x20).

(c) Microcline and F_3 crenulation folds, suggesting syn-D_3 crystallisation. (X-nicols, x10).

(d) S_3 post-dates garnet crystallisation. S_3 formed by recrystallisation of micas parallel to axial planes of crenulation folds (see sketch). (x10, P.P.L.).

folds, which implies that microcline was able to crystallise before, during and after D_3 events, an analogous situation to that in South Morar.

Garnets within the matrix of the rock are the same as those enclosed by microcline porphyroblasts, showing that no post-D_2 crystallisation of garnet occurred and that the maximum metamorphic grade during D_3 was insufficient to recrystallise garnet as in South Morar.

Eastwards the metamorphic grade of M_2 increases progressively. Microcline still shows similar relations to garnet crystals (Plate 42a), but small garnets also occur in the matrix of the rock (Plate 42b). These garnets do not always show the same inclusion fabric as the large porphyroblastic garnet crystals, and appear to have nucleated and grown in the matrix at a possibly later date. The recrystallisation of micas around F_3 crenulations, and the formation of S_3 is shown in Plate 42c.

None of the rocks east of Inverie (see Figs. 1 and 22) contain microcline as a mineral phase, as this area has undergone migmatisation (see Section 4.5.2). Micas are recrystallised round post-garnet F_3 crenulation folds. Large mica flakes cross-cut F_3 fabrics (Plates 43a-c.). Small garnets also occur (Plate 43d) which have no inclusion fabrics like the larger porphyroblasts, but occur as crystals making up part of the rock matrix. These small garnets may represent recrystallisation during M_2.

Sillimanite appears in isolated patches marking a further increase in metamorphic grade, but is deformed by minor folds which also deform post-D_3 micas - these are F_4 microfolds (Plate 44). Post F_3 biotite laths and muscovite elongate crystals are also commonly deformed by F_4 crenulations, showing undulose extinction and distorted cleavage traces (Plates 45a and b).

Eastwards to Camusrory, the occurrence of large post-D_4 mica flakes increases, along with sillimanite fibres, that are deformed by F_4 microfolds (Plates 46a-c). Garnets become more skeletal in form with little of the preferred orientation of inclusion fabrics observed further to the west. There is a gradual overall increase in grain

a.

b.

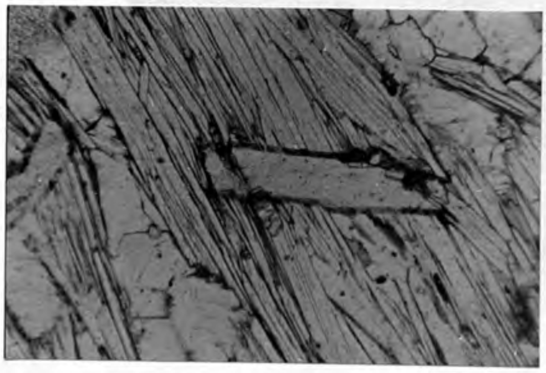
c.

Plate 42: Photomicrophs - Sandaig and Doune, West and Central Knoydart.

(a) Microcline porphyroblast enclosing garnet (x10, X-nicols)

(b) Garnets showing lack of inclusion fabric and apparently unzoned. Possibly recrystallised (x10, P.P.L.).

(c) S_3 formed by micas recrystallised parallel to the limbs of F_3 microcrenulation folds. (x5, X-nicols).

a


b.


c.

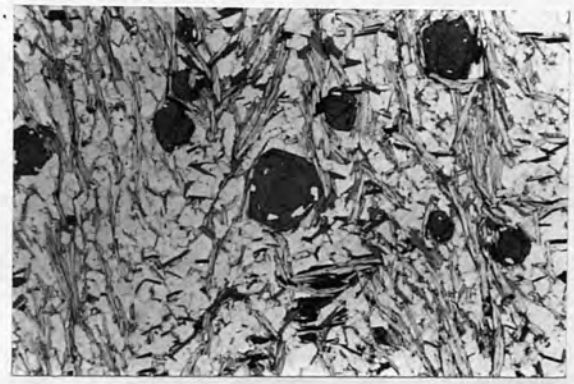

d.


Plate 43: Photomicrographs - Inverie-Kylesknoydart section and Gleann Dubhlochain, East Knoydart.

(a) Large muscovite crystal cross-cuts D_3 fabric (x10, P.P.L.).

(b) Biotite recrystallised during D_3, deformed during D_4. Biotite shows bent cleavage traces and undulose extinction. (x10, X-nicols).

(c) Micas recrystallised parallel to the axial planes of F_3 microfolds. (x10, X-nicols).

(d) F_3 microfolds outlined by recrystallised micas (x10,P.P.L.).

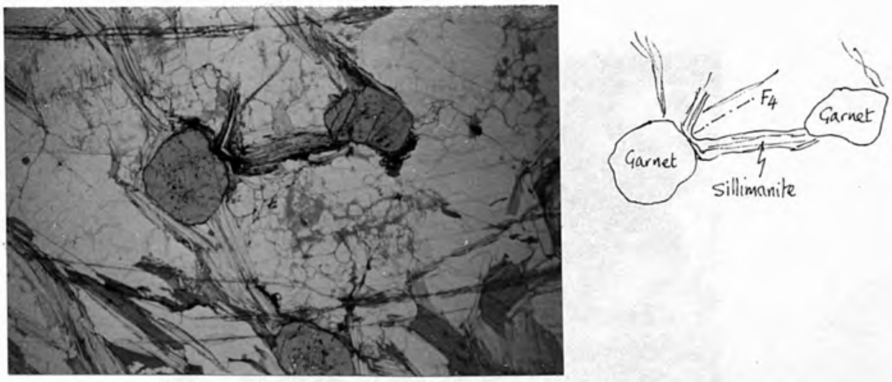
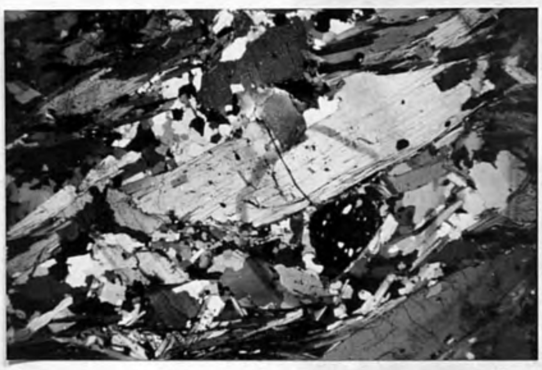


Plate 44: Sillimanite, in isolated patches, deformed by F_4 minor folds (see sketch). (x10,P.P.L.).

a.



b.

Plate 45a & b: Photomicrographs - Gleann Dubhlochain, E. Knoydart.

(a) and (b): Micas deformed by F_4 folds; (a) shows undulose extinction, and (b) folded cleavage traces.

a

b

c

Plate 46: Photomicrographs - Camusrory, East Knoydart.

(a) Large post- D_3 biotite, deformed during D_4, shows marked undulose extinction (X-nicols, x20).

(b) Muscovite deformed during D_4. Note coarser texture of rock due to increased grain size. (x20, X-nicols).

(c) F_4 microfolds. Micas not recrystallised (x20, X-nicols).

size, such that rocks in the eastern part of the research area are gneissose rather than schistose in texture (Plate 46b).

5.7 Relationships between D_3, D_4 and M_2

Section 5.6 has outlined the evidence for a second metamorphic event, M_2, within the research area. Much of the recognition of this event is based on the growth of metamorphic minerals in relation to textures and fabrics produced as a result of D_1 and D_2, and the early metamorphic event, M_1. For this reason much of the discussion on the relations between M_2 and the late phases of deformation D_3 and D_4 has been included in the metamorphic section (5.6).

The crystallisation or recrystallisation of minerals during D_3 and D_4 has enabled a relative timing of M_2 to be made throughout the area.

In the west of the area (Skye) M_2 overlapped D_3 as shown by the recrystallisation of biotite and actinolite parallel to S_3. The random orientation of actinolite in relation to D_3 structures in thrust sheet IV and recrystallisation of micas parallel to the limbs of F_4 crenulation folds (Tormore - Sheet III) shows that M_2 outlasted D_3, and overlapped the D_4 phase of deformation. The maximum grade attained in the west during M_2 was biotite grade.

Further east the evidence suggests that M_2 outlasted D_3, as shown by the recrystallisation of mica round F_3 folds and parallel to F_3 axial planes, and the crystallisation of cross-cutting mica flakes. In South Morar and central Knoydart, however, these post-F_3 micas become deformed during D_4 with no subsequent recrystallisation, suggesting that M_2 culminated prior to D_4. The M_2 metamorphic peak in this part of the region also allowed the crystallisation of microcline but not garnet.

In east Knoydart the metamorphic grade increases markedly, east of the Knoydart slide (Fig. 22). The highest grade "zone" minerals to be crystallised in this area are garnet, sillimanite and possibly kyanite. The evidence suggests that sillimanite crystallised prior to

D_4 as it is deformed by F_4 folds, but not recrystallised. Micas in this area are also folded by F_4 microfolds with no recrystallisation. From this it may be seen that M_2 culminated in the east prior to D_4 events.

Apart from the gradual increase in metamorphic grade from west to east during M_2, as shown by the progressive appearance of higher grade metamorphic "zone" minerals, other features suggest substantial reworking of the rocks during M_2. The appearance of higher "zone" minerals of sillimanite and (?) kyanite coincides with a change in grain size, which results in the rocks in the extreme east having a gneissose rather than schistose texture.

The study of garnet porphyroblasts in relation to M_1 (Chapter 4) also provided evidence of reworking of the rocks of eastern Knoydart during M_2. The garnets in this area show indistinct chemical zones unlike those from elsewhere within the research area. These garmets also have large penetration inclusions which are taken to be evidence of recrystallisation of the matrix minerals, and to a limited extent, garnet, during M_2.

In summary, M_2, like M_1, shows an increase in grade from west to east. In the west it outlasts the major phases of deformation D_3 and D_4, but in the east culminates prior to D_4.

Table 2 summarises all the deformation and metamorphic episodes suffered by the Moine nappe and outlines the relationships between tectonic and thermal events summarised in Sections 4.4, 4.6 and 5.5 and 5.7.

S_0 - layering (bedding)) D_1 structures
S_1 - schistosity)
L_1 - mineral elongation lineation)
F_1 - first generation isoclinal folds)

S_2 - schistosity axial planar to F_1) D_2 structures
L_2'- mineral elongation lineation)
L_2 - intersection lineation of S_2 on S_0 or S_1)
F_2 - second generation class 2-3* folds)

S_3 - crenulation schistosity, axial planar to or fanning round folds) D_3 structures
L_3'- mineral elongation lineation)
L_3 - intersection lineation of F_3 hinges on S_0,S_1 or S_2)
F_3 - third generation open profile, often overturned folds + coaxial crenulations)

S_4 - crenulation schistosity) D_4 structures
L_4 - intersection lineation of F_4 hinges on S_0, S_1, S_2 or S_3)
F_4 - fourth generation open profile and crenulation folds)

L_5 - mineral elongation lineation) D_5 structures
F_5 - fifth generation folds)

Si - inclusion fabric in garnet porphyroblasts

* Classes of folds refers to Ramsay's classification (1967).

Xlln - crystallisation

re-Xlld - recrystallised

The clasisification used with reference to the scale of fold is that outlined by Turner and Weiss (1963) as follows:

Microscopic scale: covering bodies, such as thin sections or polished surfaces, that can be conveniently examined in their entirety with a microscope.

Mesoscopic scale : range from hand specimens to large but continuous exposure.

Macroscopic scale: covering bodies too large or too poorly exposed to be examined directly in their entirety.

TABLE 2: Summary of the phases of deformation recognised in the Moine nappe in the research area, and their possible correlation.

MOINE THRUST ZONE					MOBILE BELT					
SKYE THRUST SHEETS				SOUTH MORAR	WEST KNOYDART	EAST KNOYDART				
IV Capistal	III Tormore	II Rubha Dubh	I Rubha Phoil	Arisaig-Druimindarroch	Doune-Inverie	Gleann Dubhlochlain	Inverie- Kylesknoydart	Gleann Meadail - Carnoch	Kylesknoydart - Camusrory	
S_1 parallel to S_0 Rare L_1	Rare minor F_1 S_1 parallel to S_0 L_1	Rare minor F_1 S_1 oblique to S_0 L_1	S_1 oblique to S_0 L_1	Rare minor F_1 S_1 parallel to S_0	Major and minor F_1 (isoclinal) S_1 parallel to S_0	Assumed major F_1 isoclines, S_1 parallel to S_0 $Si = S_0/S_1$		rare minor F_1		D_1
			QUARTZ VEINS AND PEGMATITES							
Rare F_2 Restricted L_2	Macroscopic and mesoscopic F_2 S_2+L_2 Syntectonic garnet Xlln.	Mesoscopic F_2 S_2+L_2 Syntectonic garnet Xlln.	Macroscopic and mesoscopic F_2 S_2+L_2 Syntectonic garnet Xlln.	Macroscopic(?) & mesoscopic F_2 S_2+L_2 Pre-+syntectonic garnet Xlln. Syntectonic microcline Xlln. Lamprophyre infusion.	Macroscopic & mesoscopic F_2 (includes Morar Antiform). S_2, L_2+L_2' Syntectonic sliding. Syntectonic garnet Xlln.	Macroscopic & mesoscopic F_2 (includes Knoydart fold). S_2+L_2 Pre- and syntectonic garnet Xlln.	Macroscopic & mesoscopic F_2 (includes Knoydart fold). S_2 sub-parallel to S_0, L_2' Syntectonic sliding Pre-+syntectonic garnet Xlln.	Macroscopic & mesoscopic F_2. S_2 parallel to S_0/S_1, $L_2 + L_2'$ Syntectonic sliding pre-tectonic garnet Xlln.	Mesoscopic F_2 S_2 parallel to S_0/S_1, and L_2' Syntectonic sliding pre-tectonic garnet Xlln.	D_2
			QUARTZ VEINS AND PEGMATITES							
Regional, Mesoscopic + crenulation F_3 (includes Knock with syntectonic shearing of lower limb). S_3+L_3	Not represented	Mesoscopic + microscopic F_3 S_3+L_3 L_3' contained by S_3	Mesoscopic + microscopic F_3 S_3+L_3 L_3' contained by S_3	Macroscopic, mesoscopic+microscopic F_3. Curved hinges S_3 and L_3 Pre-, syn- and post-tectonic Xlln of microcline.	Macroscopic, mesoscopic + microscopic F_3. Curved hinges (includes Morar Antiform). S_3+L_3 Syn- and post-tectonic Xlln of microcline.	Macroscopic, mesoscopic + microscopic F_3 (includes Ladhar Beinn Synform, Meall Bhasiter Dome and Beinn Bhuide Antiform) curved hinges S_3 and L_3 Post-tectonic Xlln of micas.				D_3
			QUARTZ VEINS AND PEGMATITES							
Occasional F_4	Mesoscopic + microscopic F_4 S_4+L_4	Microscopic F_4 S_4+L_4	Not represented	Conjugate mesoscopic + microscopic F_4. S_4 and L_4.	Not represented	Rare microscopic F_4 L_4	Macroscopic & microscopic F_4 (includes Kylesknoydart fold). S_4 and L_4 deformation of post-D_3 mica, not re-Xlld.	Rare microscopic F_4	Macroscopic & microscopic F_4 (includes Kylesknoydart fold). S_4 and L_4 deformation of post- D_3 mica, not re-Xlld.	D_4
			QUARTZ VEINS AND PEGMATITES							
Mesoscopic F_5 L_5	Not represented				Not represented			Not represented		D_5
Kink folds + minor shear zones	Kink folds + minor shear zones	Kink folds + minor shear zones	Kink folds + minor shear zones		Kink folds					
North-westerly directed movement along the Moine Thrust Plane with the development of an Imbricate Zone above the thrust plane.					Possible imbricate thrusting. (Now offshore beneath the Sound of Sleat).					

CHAPTER 6. THE TARSKAVAIG NAPPE

6.1 Introduction

During the field season of 1974, a more general survey was undertaken of the rocks forming the Tarskavaig Nappe, which lies beneath the Moine Thrust Plane. This was in order to determine whether the structural and metamorphic histories of the two nappes were similar or not.

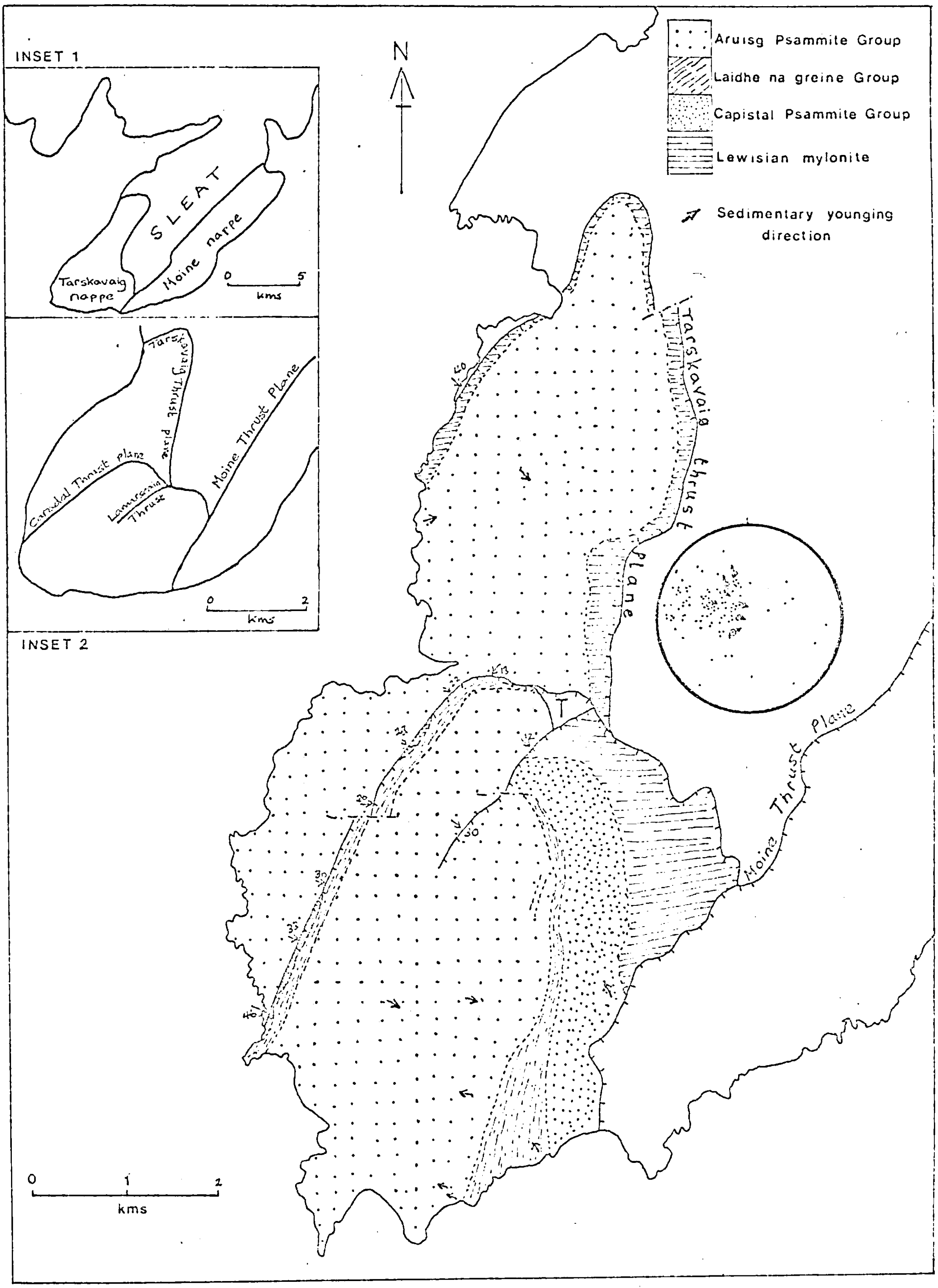
The Tarskavaig nappe is made up of the Caradal nappe lying immediately below the Moine thrust plane in south east Sleat and the Tarskavaig nappe (Fig. 60, inset 2). The Caradal nappe is separated from the Tarskavaig nappe by the Caradal thrust plane, and the Tarskavaig nappe is separated from underlying Torridonian rocks by the Tarskavaig thrust plane. The Lamarscaig thrust (Bailey, 1955; Clough, 1907) or fault (Cheeney, 1961, and Cheeney & Matthews, 1965) duplicates part of the Caradal nappe (Fig. 60 Inset 2). The total area covered by the Tarskavaig nappe is some 35 square kilometres, extending from the west coast of the Sleat Peninsula south of Tarskavaig Bay across to the southeast coast, south of Aird (Fig. 60 Inset 1).

The dip of the Tarskavaig thrust plane varies considerably because it has been folded; the Caradal thrust plane dips consistently east-south-east, as does the Lamarscaig thrust. The majority of the rocks making up the Tarskavaig nappe are a series of low grade metasediments named the "Tarskavaig Moines" by Clough (in Peach et al., 1907, p. 590). At the base of the Tarskavaig nappe, above the Tarskavaig thrust plane there is a sheet of mylonised Lewisian. Similarly slivers of Lewisian mylonite occur on the Caradal thrust plane (see Fig. 60).

Rocks within the Tarskavaig nappe pile have suffered two major phases of deformation prior to the localised Port a'Chuil folds and conjugate kink folds which developed marginal to, and in association with, the overthrusting of the Moine nappe (see Chapter 5.4).

The metamorphic grade of the rocks is low, with biotite being the most common porphyroblastic mineral.

FIGURE 60. Location and stratigraphy of the Tarskavaig nappe, Skye. Projection shows poles to bedding (S_o); younging direction indicated by arrows.



6.2 Previous work on the Tarskavaig Nappe

Some of the earliest work on the Tarskavaig nappe was published by the Geological Survey in 1907 (Peach et al., 1907) at which time the rocks making up the Tarskavaig nappe were provisionally correlated with the Moine rocks of the Moine nappe, and hence called the "Tarskavaig Moines." Prior to this Clough (in Geikie, 1897 and 1898) had thought that the rocks were Torridonian in age, but finally (1907) decided on a "Moinian" age because of the similarity of rock types and stratigraphic order. The Tarskavaig rocks are phyllites, siliceous schists and psammitic grits, as opposed to the Epidotic grits, conglomerates and shales of the Torridonian. Structurally Clough proposed that four thrusts had affected the Tarskavaig nappe, these being the Moine, Lamarscaig, Caradal and Tarskavaig thrusts in descending order; each thrust being deformed as the higher one was thrust over.

Apart from the Tarskavaig Moine rocks, Lewisian mylonites are also present within the Tarskavaig nappe occurring as a continuous sheet adjacent to the Tarskavaig thrust plane, and as isolated slivers adjacent to the Caradal thrust plane. Clough recognised the mylonites as Lewisian and suggested that the Tarskavaig thrust plane developed at the top of the original Lewisian gneiss basement, converting the gneisses to mylonites during movement of the overlying Tarskavaig nappe pile.

Bailey (1955) largely agreed with Clough's ideas on the Tarskavaig nappe with the exception that he suggested (p.147) that the Lewisian rocks at the base of the nappe were an accretion picked up at the base of the advancing Tarskavaig Moines. Bailey did not, however, commit himself on the problem of correlation of the Tarskavaig rocks with either the Moines or the Torridonian.

Phillips (1939) from evidence derived from a micro-fabric study of both the Moine and the Tarskavaig nappes suggested (p. 236) "that the Moine rocks were of pre-Torridonian age, whilst the Tarskavaig Moines are sheared representatives of part of the Torridonian Series."

Kennedy (1955) in a synthesis on the evolution of the Skye-Glenelg region proposed (p. 374) that the Tarskavaig nappe represented the overridden, less highly metamorphic frontal portion of the Moine nappe.

Cheeney and Matthews (1965) discuss the structural evolution of both the Tarskavaig and Moine nappes in Skye, outlining 5 generations of folds in each nappe, but showing no direct correlation of all 5 fold phases. They also propose that features associated with the Caradal and Lamarscaig thrusts (as thought by Clough,1907, and Bailey, 1955) differ from those developed in association with the Tarskavaig thrust to such an extent, that the former two structures should be described as faults belonging to a different period in the structural history (p. 266).

Reconnaissance mapping of the Tarskavaig nappe has largely confirmed the structural history proposed by Cheeney and Matthews (1965). It has also enabled a correlation of major phases of deformation between the Tarskavaig and Moine nappes.

6.3 Stratigraphy of the Tarskavaig Nappe

The Lewisian that occurs beneath the "Tarskavaig Moines", above the Tarskavaig and Caradal thrust planes is invariably mylonitic. It is greenish-grey in colour, soft and flaggy with red felspathic spots and streaks. Relic hornblende occurs rarely. All the constituent minerals have been sheared and granulated such that the foliation of the Lewisian mylonites parallels that in the Tarskavaig phyllite that lies directly above it. The foliation in the west is slightly steeper than the bedding outlined in the phyllite by thin sandy seams. The thickness of the sheared Lewisian in the region of Tarskavaig Bay on the west coast (see Fig. 60) varies from a few centimetres to tens of metres. Where the thrust plane disappears out to sea south of Tarskavaig Bay the Lewisian is approximately 100 metres wide. Similarly the Lewisian mylonite of the Caradal part of the nappe further south covers several hundreds of metres at present erosion level beneath the Moine thrust plane (Fig. 60).

The "Tarskavaig Moine" rocks have been divided into three major groups by Clough (1907), Bailey (1955, after Clough, 1907) and Cheeney and Matthews (1965). Despite the different structural interpretations of the area the three main stratigraphic groups are broadly equivalent (see Table 3). The rocks adjacent to the Lewisian are termed the Capistal Psammite group and everywhere tend to be phyllitic. Thinly bedded phyllite rocks are interbedded with sandy, gritty and occasionally calcareous layers. The proportion of pelitic layers increases towards the transitional boundary with the Laidhe na Greine group which lies above it. Graded quartz pebble grit bands are fairly common and provide way-up evidence, showing younging away from the Lewisian towards the Laidhe na Greine group. The lower part of the Capistal Psammite group has become mylonitised locally so that the junction between the base of the Tarskavaig Moines and the Lewisian is commonly tectonic, leaving little trace of any possibly pre-existing unconformity.

The Laidhe na Greine group conformably overlies the Capistal Psammite group. It consists of interbedded psammites, semi-pelites and pelites, tending to become increasingly psammitic towards the top of the group. Graded and cross-bedded units are common showing younging towards the Aruisg group.

The majority of the Tarskavaig nappe pile is composed of the massive coarse gritty psammite which makes up the Aruisg Psammite group. Frequent cross-bedding is evident, although often deformed. Grit layers with blue quartz pebbles up to 1" long are common (Plate 47).

The Aruisg Psammite group is more felspathic, but with less chlorite and epidote than the Capistal Psammite group. Feldspar pebbles are generally reddish in colour and are frequently microcline. In thin section they appear to be less deformed than quartz pebbles.

Contacts throughout the entire sequence are transitional and conformable.

The lithologies present resemble both Torridonian and Moine rocks.

TABLE 3: STRATIGRAPHY OF THE TARSKAVAIG NAPPE.

BAILEY 1955 (After Clough 1907)	CHEENEY and MATTHEWS (1965)
Main Gritty Schist	Aruisg Psammite Group
Siliceous Schist-	Laidhe Na Greine Group
Thin Phyllite with Siliceous Interbeds. Some Calcareous Grits.	Capistal Psammite Group Tarskavaig Mylonite
Lewisian Mylonite	Lewisian Mylonite

Plate 47: Elongated quartz pebbles at the base of a gritty psammite unit in the Aruisg Psammite Group. Location - Tarskavaig nappe, Skye.

The pebbly units in the Aruisg Psammite are similar to the conglomeratic units of the Torridonian, but are not found in Moinian rocks. The Capistal Psammite resembles psammites within the Morar succession (Moinian) but is lacking in the heavy mineral bands and calc-silicates which characterise the Moine Psammites.

It is therefore difficult to correlate conclusively the Tarskavaig Moines with either the Torridonian or the Moinian assemblages on the basis of lithological similarities. Isotope work may help to clarify the possible correlations.

6.4 Structure of the Tarskavaig Nappe

6.4.1 Introduction

Apart from minor structures associated with the Tarskavaig and Moine Thrust planes, deformation of the Tarskavaig Nappe can be divided into two distinct episodes, separated by the period of thrusting which brought the Tarskavaig Nappe to its present position. Cheeney and Matthews (1965) termed the earliest main phase of deformation in the Tarskavaig Nappe the Capistal fold episode, and the latest the Caradal fold episode. Both produce folds which develop axial plane cleavages which in turn give rise to intersection lineations of cleavage and bedding planes. The terms suggested by Cheeney and Matthews (1965) will be retained here, but will be prefixed by D_1, D_2, etc., to indicate chronological order, and correlation with rocks of the Moine Nappe.

6.4.2 Pre-Tarskavaig Thrust Structures

Figure 61 shows the geographical distribution of linear and planar structures associated with the earliest phase of deformation (D_1 Capistal) in the Tarskavaig Nappe. Minor structures commonly developed include small scale tight to isoclinal fold closures with a strongly developed elongation lineation parallel to fold hinges, commonly represented by an elongation of quartz and feldspar grains (Plots A and B Figure 61). Elsewhere an intersection lineation of S_1 and S_o occurs (see Figure 61, Plots A and B). The cleavage associated with the first generation structures (S_1) is axial planar to minor folds,

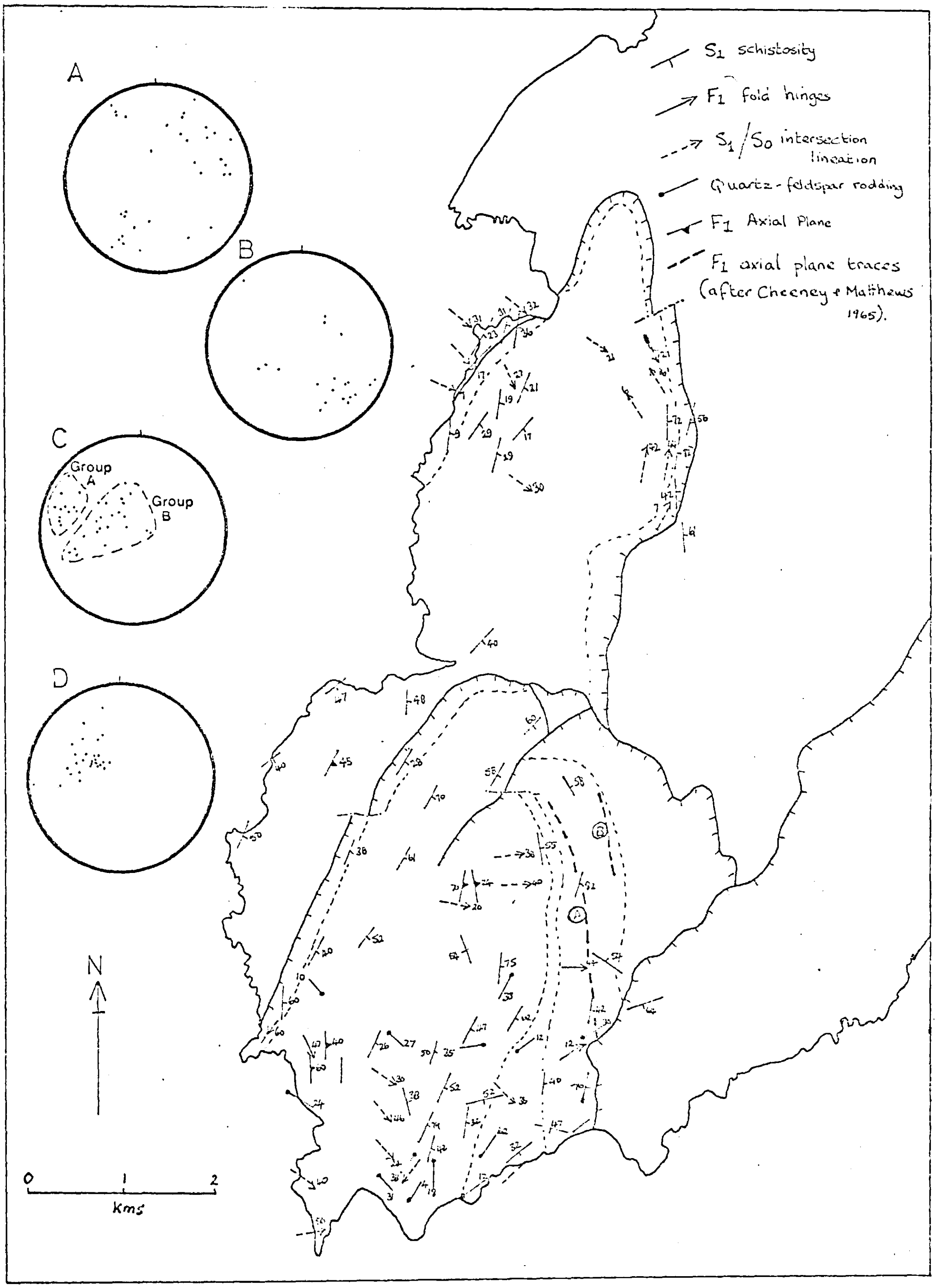
FIGURE 61. D_1 structures of the Tarskavaig nappe

F_1 axial plane traces are those suggested by Cheeney and Matthews (1965). (A) - Capistal Antiform; (B) Capistal Synform.

Projections A and C: F_1 linear and planar structures on the eastern limbs of the Tarskavaig and Caradal Synforms.

Projections B and D: F_1 linear and planar structures respectively on the western limbs of the Tarskavaig and Caradal Synforms.

Grouping in Projection C refers to Fig. 63.



and is generally sub-parallel to the lithological layering (Figs. 60, 61, C and D),

Cheeney and Matthews (1965) suggest that two large folds of this generation exist in the Tarskavaig Moine rocks to the west of the Moine Thrust Plane (see Fig. 61), in the eastern part of the nappe. The axial traces of these folds were established by Cheeney and Matthews by mapping "S" and "Z" profile parasitic folds. Bailey (1955) also suggests that the phyllitic rocks occurring near the base of the Tarskavaig succession (Laidhe na Greine group, Table 3) form an anticline which is overturned to the west and pitches to the north, to coincide with the narrowing of the Laidhe na Greine group towards Sgurr nan Caorach (Fig. 60). The lithological layering dips consistently to the east, and sedimentary structures where evident, show that much of the ground west of Aird consists of inverted bedding (Fig. 60). Similarly, measurements of lithological layering across the strike of the phyllitic Laidhe na Greine group, show steeper dips on the west than on the east (Figs. 60 and 61 C and D).

Much of the ground to the west of the Moine Thrust Plane is poorly exposed, and small scale F_1 fold closures occur only sporadically. The number of "S" and "Z" profile parasitic folds is therefore limited, and do not offer conclusive evidence for a major F_1 fold closure, as suggested by Cheeney and Matthews (1965). A relatively angular complimentary anticlinal and synclinal structure does occur to the immediate west of the Moine Thrust at Aird, but discrepancies in the direction of dip of the layering and sedimentary younging evidence in the Tarskavaig Moine sequence suggest that this anticline may be a parasitic fold on the eastern limb of the Caradal synform which is D_2 in age (see following Section 6.4.4 and Fig. 63).

6.4.3 Movements on the Tarskavaig Thrust Plane

Small irregular folds occur within the mylonitic rocks adjacent to the Tarskavaig Thrust Plane, deforming the mylonitic banding in both the Lewisian and Tarskavaig phyllitic mylonites. These folds, termed the Doire na h-Achlais folds by Cheeney and Matthews (1965), are tight in profile, rarely more than several centimetres across and develop very restricted axial plane cleavage. The trends of the fold axes show little preferred orientation and are thought to be directly related to the thrusting. Conjugate kink-folds also occur in association with both the Tarskavaig and Caradal thrust planes, showing completely random orientation. Brecciation of both Doire na h-Achlais and conjugate folds is obvious close to the thrust planes suggesting that both stages of folding occurred prior to the event which caused the overthrusting of the Tarskavaig Nappe.

6.4.4 Post-Tarskavaig Thrust Structures

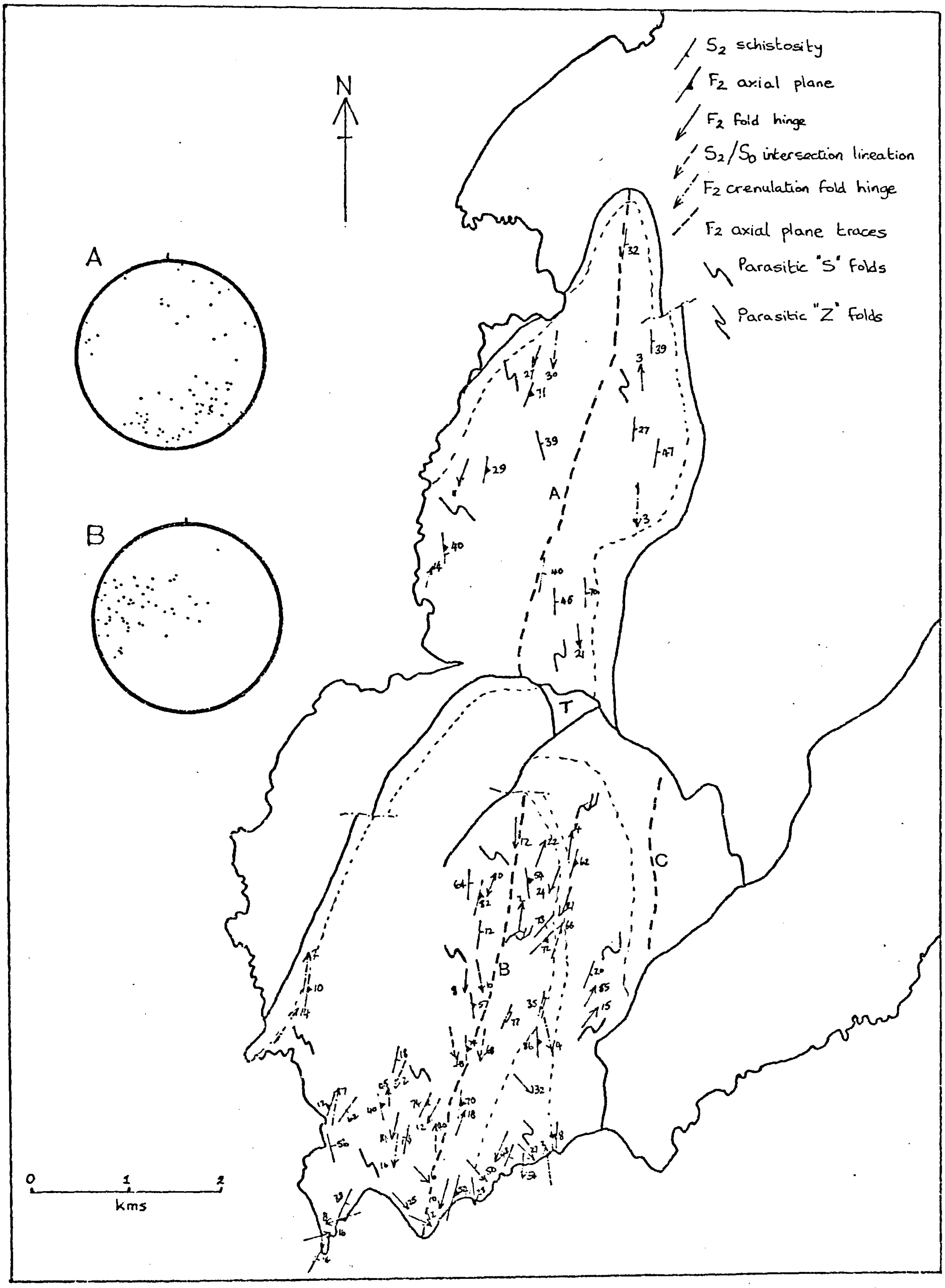
Large scale open profile folds which are overturned westward are representative of the major phase of deformation which occurred after thrusting on the Tarskavaig thrust plane, as a result of which the Tarskavaig thrust plane is itself folded (Fig. 60). Three major folds occur, accompanied by small scale parasitic folds. The large folds are the Tarskavaig Synform, Caradal Synform and Caradal Antiform (Fig. 62 and 63). Pre-existing linear and planar structures have been refolded by these folds - termed the Caradal generation by Cheeney and Matthews (1965), and here referred to as D_2.

Figure 62 shows the geographical distribution of minor structures associated with the D_2 phase of deformation, as well as associated "S" and "Z" profile minor folds which indicate the vergence for the major fold closures. Small scale folds are invariably open profile forms, often overturned westwards which deform the bedding and earlier S_1 cleavage, the latter commonly by crenulation folding co-axial with mesoscopic folds. A coarse crenulation cleavage is frequently developed axial planar to the mesoscopic folds (Figs. 62 A and B). Axial planes of minor folds dip east at moderate angles.

The close similarity between the attitude and style of the Caradal generation structures (D_2) in the Tarskavaig Nappe and the third generation structures in the Moine Nappe on Skye, particularly in the regions of Armadale and Knock Bay have led to a correlation of these two generations of structures here (see Section 6.6).

As seen in Fig. 62, the axial plane traces of the Tarskavaig and Caradal synforms are approximately parallel but marginally offset by

FIGURE 62. D_2 structures in the Tarskavaig nappe.
Projection A: D_2 linear structures
Projection B: D_2 planar structures
F_2 axial plane traces: A: Tarskavaig Synform;
B: Caradal Synform; C: Caradal Antiform



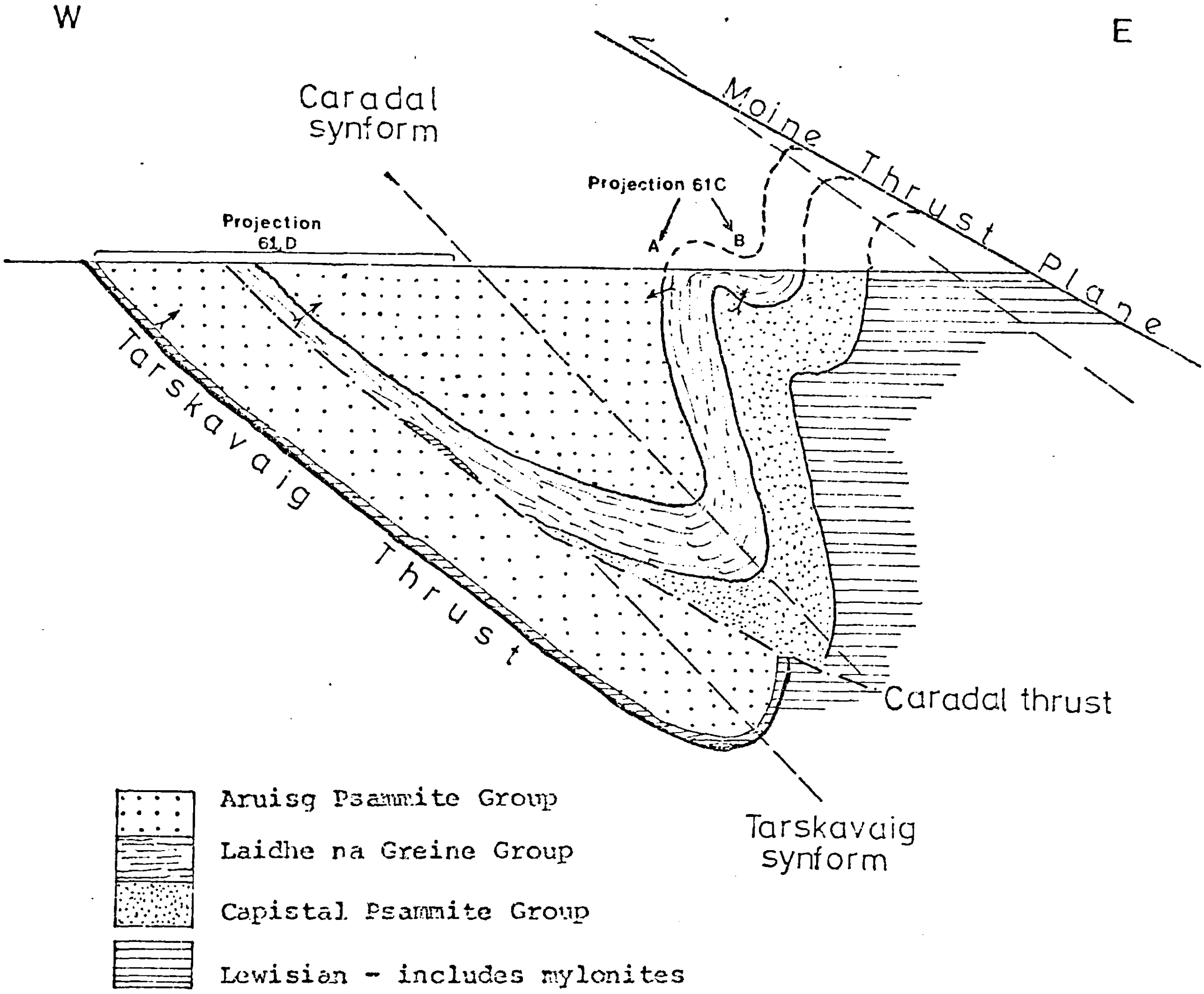


FIGURE 63. Diagrammatic cross-section across the Tarskavaig nappe.
Shows the location of projection readings for D_1 planar structures.
Projection 61C - Group A is from the steep easterly limb of the Caradal Synform, and Group B is from the less steep limb of a parasitic fold on the Caradal Synform.

(Not to scale)

the Caradal thrust plane, thereby implying that Caradal thrusting post-dated the formation of the large scale D_2 fold structures. Small outcrops of Torridonian Epidotic Grit bounded by the Lamarscaig and Caradal thrusts in the central eastern part of the Tarskavaig Nappe (see Fig. 60) are thought to have been emplaced during movements on these dislocation planes. Bailey (1955) assumed that the Epidotic Grits were tectonic pickups displaced during movement on the Caradal Thrust Plane. The attitude of the "Tarskavaig Moine" rocks above the Caradal thrust, and the relatively shallow dip of the thrust plane suggests that the rocks above the thrust have moved westward relative to those beneath. Consequently the Tarskavaig and Caradal Synforms cannot be offsets of the same synformal fold - i.e. the axial trace of the Tarskavaig synform is west of the axial trace of the Caradal synform. It is therefore possible that the Caradal dislocation represents part of a complimentary antiform previously existing between the Tarskavaig and Caradal Synforms. The implication of this is that the Caradal thrust - and here the term "thrust" is preferred to "fault" because of the sense and direction of movement of rocks above the plane of dislocation - developed during the late stages of the D_2 phase of deformation which produced the large scale overturned folds, and carried the Caradal "nappe", including the Caradal Synform and Antiform over the underlying Tarskavaig synform. During this process the complimentary Tarskavaig anticline would have been either obliterated or sheared out by thrusting. Slivers of Lewisian mylonite on the Caradal thrust plane suggest that the dislocation occurred close to the Tarskavaig Moine-Lewisian junction, in a manner similar to that on the Tarskavaig thrust plane. The triangular outcrop of Torridonian Epidotic Grits may well have been incorporated in this westward moving sheet.

The relationship of the Lamarscaig fault (thrust) is not so clear, but may well represent a similar mode of origin. The rocks above the fault or thrust plane however, travelling only a limited distance westwards, and possibly pivoting such that the rocks to the north were originally deeper than those adjacent to the southern end of the fault where it dies out west of Loch an t-Seilich (Fig. 60).

This interpretation follows that proposed by Cheeney and Matthews (1965) except that the term "thrust" rather than "fault" is favoured because of the westward sense of movement of the rocks overlying the dislocations, relative to those beneath it. A similar situation has already been referred to in the Moine nappe (Section 5.2.2, Table 2, Figures 48 and 53) where a pile of nappe sheets are separated by minor thrust planes, with restricted movement by each nappe sheet above the next.

6.4.5 Structures associated with Moine Thrust Movements

In the rocks immediately below the Moine thrust plane, in the southeastern part of the Tarskavaig nappe, structures are developed which are related to the thrust movements. These structures are identical to those developed in the rocks above the Moine thrust (Section 5.4) and are restricted to within 100 m. of the thrust plane. Sharp angular to tight folds occur - termed the Port a'Chuil (D_5) folds in the Moine nappe - but are more limited in the Tarskavaig Moine rocks. Conjugate kink-folds are common in the phyllitic rocks below the thrust plane often associated with minor brittle shear zones, the folds showing random orientation of hinges similar to those in the Moine nappe (see Fig. 59, Chapter 5).

6.5 Metamorphism of the Tarskavaig Nappe

The Lewisian rocks in the Tarskavaig nappe are entirely mylonitic, represented by a greenish flaggy schistose rock with pink felspathic spots (augen) and streaks. The foliation is frequently contorted on a microscopic scale and constituent minerals - quartz, epidote, micas, chlorite and occasional hornblende - are granulitised and streaked out. Clough (1907) refers frequently to "sheared gneiss", and evidence for this original Lewisian texture is more evident in the eastern outcrop of the Lewisian, above the Tarskavaig thrust plane, where the mylonitic foliation is more widely spaced and reminiscent of a gneissic foliation. In thin section, however, the minerals are strongly granulitised and streaking out of grains is common, with little evidence of recrystallisation. The metasediments of the Tarskavaig nappe all show low grade metamorphic mineral assemblages. Graded bedding visible in outcrops and hand specimens is also reflected on a microscopic scale. Quartz and feldspar (often microcline) occur as detrital grains, often granulitised with crenulated margins and showing strain shadows. Mica - usually muscovite and more rarely biotite - occurs as disseminated flakes in the matrix of the more siliceous rocks, and finely crystalline calcite in the calcareous seams. A bedding foliation is commonly observed in pelitic layers with micas lying parallel to bedding planes, except where affected by crenulation folding where parallelism tends to be towards one or other crenulation fold limb. Epidote is common throughout the sequence.

Porphyroblasts only develop in the southeast corner of the Tarskavaig nappe, being restricted to the more phyllitic rocks of Laidhe na Greine group. Their growth, however, is not stratigraphically controlled as porphyroblasts are absent from this group where it outcrops elsewhere in the nappe. Biotite is the most common porphyroblastic mineral with Fe ore and rarely chlorite occurring infrequently. The biotite crystals show no obvious preferred orientation but overgrow the layering (modified bedding) in the rock (Plate 48); they do, however, show evidence of post-crystallisation deformation which has resulted in the crenulation or kink-folding of the porphyroblast crystals (Plate 48). These kink-folds, within the biotite crystals, sometimes develop as conjugate sets and undulose extinction shows that no recrystallisation has occurred since their deformation. The deformation responsible for this kink-folding may be either the second main phase of deformation in the Tarskavaig nappe (D_2) or may be a forerunner to the thrusting on the Moine thrust plane. Mesoscopic kink-folds are located either side of the Moine thrust plane and are interpreted as being formed prior to the ultimate brittle failure of the thrust.

The reason for biotite porphyroblast crystallisation being restricted to the southeast corner of the Tarskavaig nappe may reflect an easterly increase in metamorphic grade, similar to that seen in the Moine nappe. However, no occurrence of any Tarskavaig Moine rocks further east makes this hypothesis only tenuous.

A further suggestion is that the crystallisation of biotite in the Tarskavaig nappe was syn~~onom~~chronous with biotite grade metamorphism in the western part of the Moine nappe during the M_2 metamorphic event (Chapter 5.6).

Plate 48: Crenulated biotite porphyroblast from the Laidhe na greine group, southeast corner of the Tarskavaig nappe. (x20,P.P.L.).

6.6 Correlations between the Tarskavaig Nappe and the Moine Nappe

The correlation of Tarskavaig nappe D_2 events with Moine nappe D_3 events is based on the following evidence: both phases of deformation produce open profile overturned westward folds, with shearing out of the overturned limb. This is shown in the Knock Synform in the Moine nappe and the Caradal Synform in the Tarskavaig nappe. Minor F_3 folds at Armadale develop an east-south-east plunging mineral elongation lineation (formed by the parallel alignment of biotite) which is at right angles to the fold hinges, which strike NE-SW. A similar east-south-east plunging lineation is formed on the eastern limb of the Caradal Synform as a pebble elongation lineation which is also at right angles to the fold hinge. Both the D_3 (Moine nappe) and D_2 (Tarskavaig nappe) planar structures - schistosity and axial planes - dip moderately to the southeast.

This evidence is thought to warrant the correlation of these two phases of deformation across the Moine thrust plane (Table 4).

Prior to this the correlation of events is more speculative. D_2 structures of the Moine nappe may be equivalent to D_1 structures in the Tarskavaig nappe as both deformations produce isoclinal folds (although not proved in the Tarskavaig nappe) and a layer parallel schistosity.

The initial trends and attitudes of D_2 structures in the Moine nappe are difficult to interpret because of subsequent polyphase deformation. This renders any correlation on the basis of similar trends or attitudes of structures almost impossible.

There is no evidence in the Tarskavaig nappe for the D_1 structures found in the Moine nappe. This suggests that this phase of deformation did not affect the Tarskavaig Moine rocks.

Evidence of metamorphism in the Tarskavaig nappe is limited to the southeast, in rocks adjacent to the Moine thrust plane. The maximum metamorphic grade reached was biotite grade, with the crystallisation of biotite porphyroblasts in phyllitic rocks. These crystals overgrow the layering in the rock but show no specific relationship to either D_1 or D_2 structures. Although the biotite porphyroblasts are deformed

TABLE 4 : CORRELATION OF EVENTS BETWEEN THE MOINE AND TARSKAVAIG NAPPES, SKYE.

Tectonic or Thermal Event	MOINE NAPPE - In Skye	Tectonic or Thermal Event	TARSKAVAIG NAPPE
D_1	Oblique S_1 schistosity, presumed large scale isoclinal folds		Not represented
D_2/M_1	Large scale isoclinal folds, syntectonic garnet crystallisation, S_2 layer parallel schistosity	D_2/M_1 Capistal	Large isoclinal fold possible. Thin section evidence of a bedding schistosity = S_1 ?? Post D_1 crystallisation of biotite porphs. Formation of mylonites and restricted angular Doire na h-Achlais folds in mylonites plus some kink folds.
			Movements on Tarskavaig thrust plane
D_3/M_2	Large and small scale open profile overturned westward folds; crenulation schistosity - S_3, crystallisation of biotite. Northeast/southwest axial trend.	D_2/M_1 Caradal	Open profile (large and small scale) folds, overturned westwards restricted crenulation schistosity, possible deformation of post-D_1 biotite porphyroblasts. Syntectonic thrusting. East south east plunging elongated quartz pebbles.
D_4/M_2	Southeasterly plunging crenulation folds and open profile warps. Recrystallisation of micas parallel to S_4 crenulation schistosity.		
D_5 Port a'Chuil	Angular folds adjacent to above Moine thrust plane	D_3 Port a'Chuil	Angular folds adjacent to below Moine thrust plane
	Conjugate kink folds		Conjugate kink folds

MOVEMENT ON MOINE THRUST PLANE

(Plate 48) it is not possible to determine which generation of structures is responsible for their deformation.

As M_2 in the Moine nappe reached biotite grade, it is possible that the biotite in the Tarskavaig nappe crystallised during this M_2 event. M_2 (Moine) is synchronous with D_3 which has been correlated with D_2 (Tarskavaig). If this structural correlation is correct, the biotite porphyroblasts may have crystallised during early stages of D_2 (Tarskavaig) and become crenulated during the late stages of D_2.

However, M_2 (Moine) outlasted D_4 (Section 5.6.2) in the Moine nappe, which would have enabled the recrystallisation of biotite after it had been deformed in late D_2 (Tarskavaig).

Alternatively, the biotite porphyroblasts may have developed during D_2 and become deformed during late stage deformations associated with Moine thrust movements.

The problem of stratigraphic correlation of the Tarskavaig Moine rocks remains, and will only be conclusively determined by isotope work.

CHAPTER 7. DISCUSSION OF POSSIBLE REGIONAL CORRELATIONS

7.1 Introduction

The study area presents particular difficulties for the correlation of structural and metamorphic events because of the presence of major dislocations and the varying metamorphic grade. Structural style criteria are, therefore, suspect by themselves. However, the combination of style, overprinting and metamorphic criteria has allowed a satisfactory correlation to be made in the research area.

It can be shown that the proposed correlations are consistent both with the stratigraphic controls on the age of the fold phases within the Moine thrust zone, and with the radiometric controls within the Moine nappe. The extension of the correlations is made in two stages: first to the immediately adjacent areas with which the author has some direct acquaintance (7.2), and then to areas further afield which have been discussed in the literature (7.3).

7.2 Structural and Metamorphic correlations in immediately adjacent areas.

During the final field season, brief visits were paid to the immediately adjacent areas to collect rock samples to compare the metamorphic textures with those of the research area, and where possible to extend the correlation of events established in the research area.

Samples collected were, where possible, related to fold closures of known generation, such that they might be correlated to the structural chronology of the research area. Four locations were studied (shown in Figs. 1, 22 and 41):-

(a) the area around Kylesmorar in North Morar, where the Garnetiferous Pelite outcrops

(b) the southern coast of Loch Hourn in northern Knoydart from Barrisdale Bay to Camus Domhain

(c) East Glenelg, primarily in Glen Arnisdale due east of the hamlet of Corran

(d) the Sandaig Islands in West Glenelg where the junction between the Moine and Lewisian occurs.

(a) Kylesmorar North Morar

Thin sections of rocks collected from Kylesmorar show various features that can be correlated with similar rocks on the opposite shore of Loch Nevis. Firstly, garnet porphyroblasts show the development of two zones. The innermost zone has pre-tectonic inclusion trails, outlined by elongated grains or trails of quartz and feldspar. The outer zone in some crystals shows syntectonic inclusion trails, but elsewhere the outer zone has a ragged outline and large biotite crystals forming penetration inclusions (Rast, 1965). These garnet crystals are very similar to specimens P13, P20 and P23 in eastern Knoydart.

F_3 micro-crenulation folds are also evident in these rocks, showing near complete recrystallisation of micas round the folds. Only very occasional cross-cutting micas are present.

(b) Barrisdale, North Knoydart

Very limited reconnaissance mapping in this area established that both F_2 and F_3 folds on a mesoscopic scale occur. F_3 microcrenulations, coaxial with the larger folds, show recrystallisation of micas round the folds, and cross-cutting large micas. There is little evidence of D_4 on either a microscopic or large scale. Garnet porphyroblasts occur in pelitic horizons of the Ladhar Bheinn Pelite on the north shore, but the Garnetiferous Pelite horizon does not occur stratigraphically above the Lower Psammite as elsewhere (see Figs. 22 and 41). It is possible that this unit has been cut out against the slide which forms the junction between the Lower Psammite and Ladhar Bheinn Pelite (=Striped and Pelitic Group).

Garnet crystals show no real evidence of zoning except very occasionally where there appears to be a very thin outer rim to the crystals. This lack of colour or textural zoning is probably due to garnet recrystallisation during the second metamorphic event.

(c) Glen Arnisdale, East Glenelg

Glen Arnisdale is due north of Barrisdale on the opposite side of Loch Hourn. Structures in the rocks in Glen Arnisdale include well developed F_2 isoclines with a penetrative S_2 axial planar schistosity, which are refolded by open profile F_3 folds. Small scale F_3 crenulation folds are developed in the less competent layers with an S_3 crenulation schistosity. Thin sections show that micas have recrystallised round these folds, and occasionally large micas cross-cut, and therefore post-date, these minor D_3 structures. There is no evidence of D_4 in this region.

The rocks in this area are largely Lewisian gneisses or massive psammites (= Lower Psammite Group) and no suitable garnet porphyroblasts were found for comparison of garnet inclusion fabrics.

(d) Sandaig Islands, West Glenelg

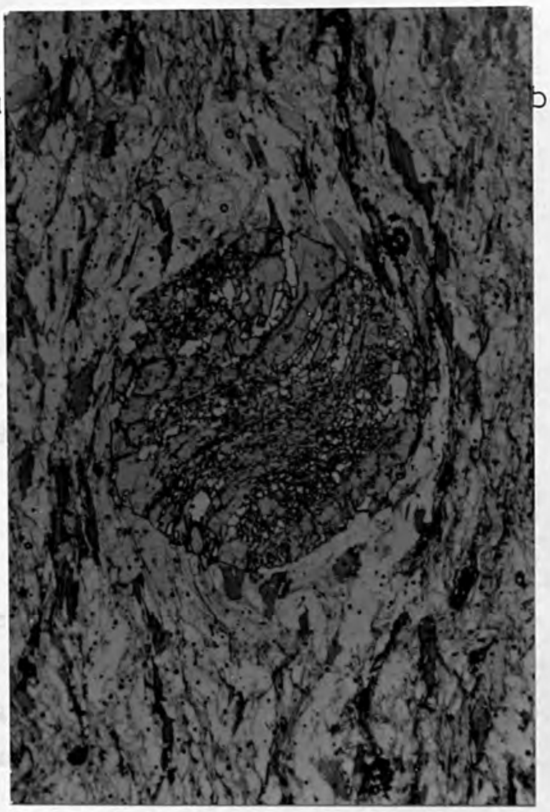
The headland of An Gurraban in west Glenelg, which forms the promontory adjacent to the Sandaig Islands exposes Moine and Lewisian rocks. The Moine rocks are essentially pelites with thin ($\lt 3$ cm) intercalated psammite ribs. The pelitic units, frequently < 30 cm thick contain numerous garnet porphyroblasts (Plate 49). In thin section, the garnets show well preserved syntectonic inclusion fabrics which are continuous with the matrix fabric (Plates 50a and b), but the crystals show no colour or optical zoning.

The textures in these rocks are thought to have evolved in the same way as those in Skye and west Knoydart - with syntectonic growth of garnet during the second phase of deformation (D_2). Unfortunately, no mesoscopic F_2 folds occur in this area, so the garnet porphyroblasts cannot be directly related to F_2 closures, but the similarities are sufficient to warrant the correlation.

Lewisian rocks east of the Moines at Sandaig also show analagous features to some of the Lewisian rocks of Skye. Gneisses forming the Knock Peninsula in Skye have developed elongate actinolite crystals which are randomly orientated relative to the metamorphic gneissic banding. Actinolitic hornblende crystals, also showing random orientation, occur in the Lewisian gneisses east of the Moine-Lewisian junction at Sandaig. The random orientation of this mineral in both instances is indicative of post-tectonic crystallisation. In the Knock region D_3 structures are the latest to be developed, producing the Knock Synform, and M_2 was synchronous with and continued after, the end of the third phase of deformation (M_2 in Skye culminated after D_4 in the Tormore

Plate 49: Moine Basal Pelite, Sandaig Islands, Glenelg.

a



b.

Plate 50 (a) and (b): Photomicrographs of garnet porphyroblasts from the Basal Pelite, Glenelg. Garnets show syntectonic inclusion fabrics (S_i) which are continuous with the matrix layer-ing (S_o). There are no textural or colour zones. ((a)x20,P.P.L; (b)x20, X-nicols).

region further south on the Sleat Peninsula).

It is suggested that the large south-easterly plunging Beinn a'Chaoinich-Beinn Mhialairidh fold (Ramsay's F_2 of 1958, and F_3 of 1960), whose axis lies to the east of the area where the actinolite crystals are located in Glenelg, belongs to the same generation as the Knock Synform in Skye - that is, D_3. The axial traces of both folds trend NE-SW, and the axial planes dip moderately south east. Ramsay (1958) states that the metamorphism and this (F_3) phase of deformation were synchronous, which further supports the correlation.

Although only a limited time was spent in the Glenelg region, no evidence of the D_4 phase of deformation, either in the field or in thin sections, was found. Powell (1974) suggests that the Beinn a'Chaoinich-Beinn Mhialairidh fold is a fourth generation structure, but the present author feels that this correlation is incorrect.

Brief studies of rocks in these four areas have shown that the metamorphic and structural correlations established in the Moine nappe of the research area can be extended to adjacent Moine nappe regions.

7.3 Regional Correlations

7.3.1 Introduction

Polyphase deformation and metamorphism has been reported elsewhere in the Moine nappe of the Northwest Highlands by numerous authors. An attempt is made here to relate the structural and metamorphic sequence of the research area to those proposed by other authors, elsewhere. It must be stressed that the correlations outlined (Table 5) are suggestions only, and may well prove to be incorrect.

7.3.2 Correlations within the Mobile Belt

Whilst the majority of correlations in Table 5 are thought to be acceptable, there are various instances where the reported evidence

TABLE 5

SUMMARY OF THE PHASES OF DEFORMATION AND METAMORPHISM RECOGNISED IN THE MOINE AND TARSKAVAIG NAPPES AND THEIR POSSIBLE REGIONAL CORRELATION

van Breeman et al. 1974	SKYE James 1976	MOIDART-ARDGOUR Brown et al. 1970	MORAR-LOCH EIL T Powell 1974 Powell et al. 1976	MORAR-KNOYDART James 1976	GLENELG-ARNISDALE Ramsay 1960, 1963	KINLOCH HOURN Tanner 1971	STRATHCONAN-GLEN AFFRIC Tobisch et al. 1970	CARN CHUINNEAG Shepherd 1973	MOINE THRUST ZONE-SOUTH Barber 1965 and 1973	MOINE THRUST ZONE-NORTH Soper 1971 and 1973	TARSKAVAIG NAPPE James 1976
	D_1	F_1	F_1	D_1	F_1	Pre-F_1 F_1	Pre-Cannich				
730±20 Ma Pre-F_2				Quartz and pegmatite veins							
	M_1	M_1 Regional Migmatites	M_1 Ardgour Gneiss 1050±40 Ma	M_1 Knoydart Pegmatite 720±15 Ma	M_1	M_1	M_1	D_1 and M_1 Zircon 1200 Ma from Carn Chuinneag Granite			
	D_2	F_2	F_2 Sliding	D_2 Sliding	F_2	F_2 Sliding (includes Sgurr nan Eugallt fold post-sliding)	Cannich				D_1 Capistal ? M_1
450±10 Ma Post-F_2, Pre-F_3			428±6 Ma 423±10 Ma	Quartz and pegmatite veins. Lamprophyre intrusion				Intrusion Carn Chuinneag Granite 560±10 Ma	Sliding, formation of primary mylonites	D_1 Formation of primary mylonites. Vagastie Intrusions = Pre- or syn- D_3 Pegmatites of Mobile Belt	Formation of Tarskavaig mylonites Doire na h' Achlais folds. Conjugate kink folds. Movements on Tarskavaig Thrust Plane
	D_3 and M_2	F_3	F_3 and M_2 Sliding	WEST EAST D_3 and M_2 Quartz and pegmatite veins	F_3 and M_2 Beinn Sgriol Synform Beinn a'Chaoinich-Beinn Mhialairidh fold	F_3 and M_2	Strathfarrar Orrin M_2	D_2 and M_2	Isoclinal minor folds and coaxial lineation plunging ESE	D_2 ESE plunging folds L and S fabric	D_2 Caradal and M_2
445±10 Ma Post-F_3 Intrusion of lamprophyres	D_4 and M_2	? some F_3	F_4	D_4 Quartz and pegmatite veins			Monar Post-Monar Affric Not correlated with D_4 but post-D_3 and pre-D_5 of Research Area	D_3	Asymmetric folds N-S hinges	Main crystallisation	
	D_5 Port a'Chuil									D_3 NNE trending folds	D_5 Port a'Chuil
	Conjugate kink and box folds			Conjugate kink and box folds in extreme west	Conjugate minor folds adjacent to Moine thrust			D_4	Monoclinal Minor Folds	D_5 box and kink folds	Conjugate kink and box folds

MOVEMENTS ON MOINE THRUST PLANE

does not fit easily into the structural and metamorphic history advocated for the research area. Of particular note is the Tanner (1971) - Ramsay (1960, 1963) - James (1976) structural correlation, with that suggested by Powell (1974).

Tanner (1971) makes reference to two pre-F_2 episodes of deformation, here referred to as F_1 and Pre-F_1 (equivalent to Powell's, 1974 F_1 and F_{1a}). He (Tanner 1971) also correlates his F_2 generation structures with Ramsay's F_2 structures in Glen Arnisdale (East Glenelg), both authors having covered the intervening ground between Kinloch Hourn and Glen Arnisdale (unpublished results, see Tanner, 1971).

During the present study D_2 structures (folds, schistosities and metamorphic textures) of the Knoydart region have been correlated with the F_2 generation structures of Ramsay (1960, 1963) in Glen Arnisdale, Glenelg (Section 7.2c).

If Tanner's (1971) F_2 is equivalent to Ramsay's (1960, 1963) F_2 which, in turn, has been correlated with the D_2 structures presented here, then the overall correlation of these F_2/D_2 structures is feasible.

This correlation of second deformation structures especially with reference to those of Tanner (1971), is further supported by his referral to a pre-F_2 phase of static garnet growth. Elsewhere, in South Morar and central and eastern Knoydart, it has been shown (Chapter 4) that the onset of metamorphism (M_1), with pretectonic growth of garnet, predates the beginning of the second phase of deformation. This situation is analagous to that evident in the Kinloch Hourn area.

Movement on the Sgurr Beag slide in this area is accepted (Tanner 1971, p.459(b)) as taking place during the F_2 deformation, with the deformation locally outlasting, the slide movement and causing a small scale folding of the slide plane by the Sgurr nan Eugallt Synform. Consequently the argument put forward by Powell (1974) that deformation of the Sgurr Beag Slide occurred during F_3, because of its earlier formation during F_2/D_2 is not supported.

This, however, gives rise to problems in the area to the southwest of Kinloch Hourn which was not covered by Tanner (1971), nor the present writer, and about which there is little published information.

Powell (1974) (see Fig. 64) extends the Sgurr nan Eugallt fold southwest to North Morar, and in doing so, suggests that it deforms the Knoydart fold. The Knoydart fold is a D_2 structure, as is the Sgurr nan Eugallt fold (Tanner 1971). In this region, southwest of Tanner's ground, Powell (1974) shows the axial plane trace of the Barrisdale Synform (which is equivalent to the Knoydart antiform) as a bifurcating structure. The most northerly branch of this axial plane is that which is refolded by Tanner's (1971) Sgurr nan Eugallt Synform. The Barrisdale Synform continues southward to become the Loch Eilt Synform (Fig. 64). The southern branch of the Barrisdale Synform axial plane trace is refolded by an F_3 fold (=fold 8 of Powell 1974) such that the F_2 axial plane trace runs south to the head of Loch Nevis (Fig. 64, fold 10). He (ibid 1974) suggests that the Barrisdale Synform is refolded over the Meall Bhasiter Dome (which is a D_3 structure) "to reach ground surface as fold 4" (Fig. 64). He does not, however, explain what fold 10 is, although his map (Fig. 64) and interpretation suggest that it is the equivalent of fold 4, which is the refolded Barrisdale Synform.

Whichever of the F_2 axial plane traces is the refolded Knoydart fold, the problem remains in that the northerly extension (Fig. 64 fold 1) is refolded by Tanner's (1971) F_2 Sgurr nan Eugallt Synform (Fig. 64, fold 13).

The present writer agrees that the Knoydart fold is D_2 in age, but also supports Tanner's argument for both the Sgurr Beag Slide and the Sgurr nan Eugallt Synform to be formed during D_2. F_2 folds in the Kinloch Hourn and Barrisdale regions (Tanner's ground) have been correlated by the present author with D_2 structures of East Knoydart.

Although it is unsatisfactory to do so, the present writer feels that the problems of correlation in this region will only be resolved by detailed structural mapping, and the correlation outlined here (Table 5) must be regarded as provisional only.

The problem of correlation of events prior to D_2 also remains. D_1 structures of the research area have been equated with F_1 structures of Glen Arnisdale, Glenelg, and it seems likely that Tanner's F_1

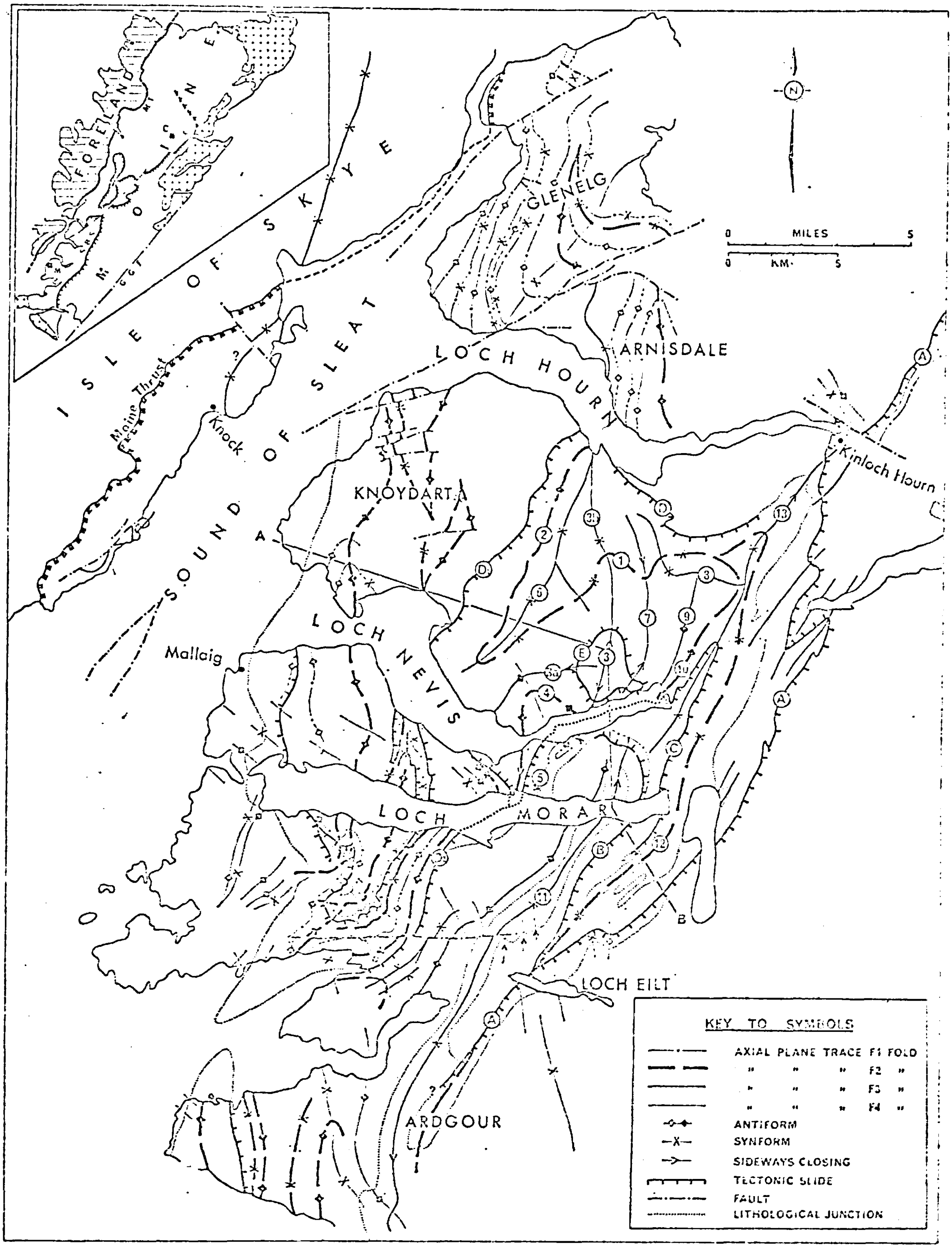


FIG. 2. Structural map of the Morar-Knoydart-Glenelg area. Numbers in circles refer to folds mentioned in the text, letters in circles to slides. Section A–B shown in Fig. 5.

Inset map: Dots-Cover rocks, C-Carn Chuinneag, M-Morar, MT-Moine thrust SBS-Sgurr Beag Slide, GGF-Great Glen Fault.

FIGURE 64. Structural map of the Morar-Knoydart-Glenelg area after Powell (1974)

structures also belong to this generation. There is no published description of Tanner's (1971) pre-F_1 structures so correlation of this event is difficult and in Table 5 it has been coupled with F_1 events.

Further problems of correlation arise when consideration is given to the Carn Chuinneag area, and the work of Johnson and Shepherd (1970) and Shepherd (1973). The Carn Chuinneag intrusion is dated at 560$\pm$10 Ma (Long & Lambert 1963, Long 1964) and was formed after D_1 and prior to D_2 (Shepherd 1973). Powell's (1974) correlation of phases of deformation in this region is generally accepted (see Fig. 13, Chapter 2 and Table 5). Dunning (1973) however, quotes a possible age of 1200 Ma for the Carn Chuinneag intrusion. If this age is correct, then the correlation of events shown in Table 5 for this area may prove to be incorrect.

In more central parts of the mobile belt, the structural history would appear to be more complex than that in more marginal areas. Tobisch et al. (1970) present a seven-fold sequence of deformation for the area between Strathconan and Glen Affric, which is tentatively correlated with the research area in Table 5.

The correlation is based on the relationship between various phases of deformation and the two metamorphic peaks recorded in the area (Tobisch et al. 1970) and similarities in structural features.

The seven phases of deformation of Tobisch et al. (1970) are termed the Pre-Cannich, Cannich, Strathfarrar, Orrin, Morar, post-Morar and Affric phases; the Pre-Cannich phase is the oldest, and the Affric phase the youngest.

The two earliest phases of deformation have been correlated with D_1 and D_2 structures of the research area, respectively, on the following basis; both phases produce tight to isoclinal folds, both with an axial plane schistosity, and the Cannich phase also develops a mineral elongation lineation similar to L_2' in the research area. The earliest Pre-Cannich structures are only locally developed, often being obscured by subsequent deformation, as is D_1 in the research area.

Further evidence supporting the correlation of the Pre-Cannich and Cannich phases with D_1 and D_2 phases of the research area is based on metamorphic considerations.

Upper amphibolite facies metamorphic conditions leading to the crystallisation of kyanite and sillimanite were broadly contemporaneous with the Cannich phase of deformation. M_1 in the research area increases from west to east, with garnet grade being the highest grade recognisable in the east. The occurrence of kyanite and sillimanite further east within the mobile belt shows a further increase in grade eastward during M_1. Thus supporting the correlation of early deformation (D_1 and D_2) and metamorphism (M_1) with the early tectono-thermal history in the Strathconan-Glen Affric area.

Subsequent deformations of Tobisch et al. (1970) develop more open profile, upright structures similar to those of D_3 and D_4 of the research area.

The Strathfarrar and Orrin phases are representatives of F_3 structures (of Tobisch et al. 1970) in the east and west of the area respectively. The two phases, however, show variable trends of axes and axial planes, varying from north-south in the east to ENE and ESE in the west. Eastward the structures become overturned westward,becoming more upright towards the east.

Metamorphic grade in the east may have been as low as greenschist facies during the Strathfarrar deformation, but was more intense in the west, being "within the amphibolite facies" during the Orrin phase.

The F_3 phases of Tobisch et al. (1970) - Strathfarrar and Orrin - are provisionally correlated with D_3 of the research area on the basis of similar structures and the onset of a second phase of metamorphism.

Structures related to the Morar phase of deformation are variable throughout the area, in some places showing similarities to D_4 structures of the Morar-Knoydart-Skye area - open profile folds, coaxial crenulations, crenulation schistosity - and elsewhere different structures - "similar" folds (class 2 and 3 of Ramsay,1967) and axial plane cleavage.

The present writer feels that the Morar, post-Morar and Affric phases of Tobisch et al. (1970) are not represented in the Morar-Knoydart-Skye area. This is perhaps a reflection of more complex deformation in the central part of the orogen during its progressive development, than that seen in marginal areas. For this reason these later phases of deformation are included in Table 5 as post-dating D_3 structures and pre-dating D_5 structures (associated with Moine thrust movements) of the research area.

7.3.3 Correlations within the Moine Thrust Zone

Regional correlations so far have dealt with regions within the mobile belt. An attempt will now be made to include the Moine thrust zone of northern Scotland, and to show that D_2 structures of the research area (of Precambrian age) cannot be correlated with D_2 of the thrust zone (which is Caledonian), as commonly suggested.

Soper (1971 and 1973) outlines a four-fold sequence of deformation for the Moine thrust zone in the Loch Eriboll area in northern Scotland. The earliest of these structures (D_1) is post-Arenig in age, because D_1 structures affect members of the Durness Limestone Formation. Consequently none of the structures in the Loch Eriboll Moine thrust zone may be correlated with the Precambrian orogenic event (D_1, D_2 and M_1) outlined in this thesis.

It would appear that the Loch Eriboll structures are, in part, analagous to the structures developed in the Moine thrust zone of Skye. D_1 at Loch Eriboll develops mylonites from both basement and cover rocks (Soper 1971); these mylonites are not represented in the Skye Moine thrust zone. Quartz and pegmatite veins postdate the mylonites, but antedate D_2 structures. Second generation structures in the Eriboll area include ESE plunging folds, an L-S fabric, where the direction of maximum finite extension is parallel to F_2 fold axes. This group of structures (D_2) is correlated with the D_4 phase in Skye (Table 5), on the basis of a similar trend of fold axes to the ESE at Eriboll and southeast in Skye; and the possibility that the intersection lineation (L_4) in Skye may be equivalent to the extension lineation at Eriboll, as both are related to an L-S fabric. Further to this, Soper (1971) states that the main crystallisation in the thrust zone occurred after D_2. In Skye, M_2 (the latest metamorphic event) outlasts the formation of D_4 structures, with recrystallisation of minerals to form D_4 fabrics. The same (M_2) metamorphic event may have been responsible for crystallisation in the thrust zone further north.

Further support of this correlation of D_2 (Eriboll) with D_4 (Skye) is gained from the presence of the pre-D_2 quartz veins and pegmatites. Similar veins and pegmatites occur within the Moine nappe prior to D_4 events, and may be analagous.

D_3 structures in the Eriboll area may be tentatively correlated with the D_5 Port a'Chuil structures in Skye (Table 5). The latter are restricted to the rocks immediately adjacent to the Moine thrust plane (within 100 m. either side) and have ENE plunging axes. D_3 structures at Eriboll are NNE-trending folds, which post-date the main crystallisation. The generally similar trend of the D_3 (Eriboll) and D_5 (Skye) structures is the basis for correlation of these structures, but is admittedly only tenuous.

The final stage of deformation D_4 at Loch Eriboll culminates with thrusting on the Moine thrust plane. In Skye, conjugate kink folds and box folds develop prior to, and are disrupted by, thrusting on the Moine thrust plane. It is suggested that these folds are analagous to the F_4 folds at Loch Eriboll (Table 5).

CHAPTER 8. SUMMARY OF CONCLUSIONS

8.1 Introduction

This chapter will summarize the conclusions reached within the research area, and discuss the implication of the structural and metamorphic sequences in terms of orogenic events, and the development of this marginal part of the orogen.

8.2 Stratigraphic Correlations

8.2.1 Moine lithologies in Skye

The presence of Moine rock units overlying Lewisian schists above the Moine thrust plane on Skye has long been recognised (Clough, 1910; Bailey, 1955) but no conclusive correlation with the Moine succession of Morar had been proposed. Evidence presented in Chapter 3.3 of this thesis allowed the division of the Moine lithologies on Skye into three distinct units, each of which has been correlated with units within the Morar Division of the Moinian assemblage (Richey & Kennedy, 1939; Ramsay & Spring, 1962, and Johnstone et al., 1969).

The Tormore Psammite is equivalent to the Lower Psammite (probably the upper part). The Armadale sequence consists of a psammite which passes conformably upwards into a garnetiferous pelitic unit. The pelitic unit is correlated with the Garnetiferous Pelite of the Striped and Pelitic group of South Morar. Because the underlying psammite is conformable with the pelite it is correlated with the upper part of the Lower Striped group (Fig. 14, Chapter 3).

Rare isolated outcrops of pelitic and semi-pelitic material in the lowermost thrust sheet, which is composed largely of Lewisian rocks, have been tentatively correlated with the Basal Pelite of the Morar Division.

The Moine rocks on Skye have been thrust into their present position at a late stage in the deformational history, and it is suggested that they occur within an imbricate zone above the Moine thrust plane. The amount of displacement on the thrust planes in the imbricate zone is difficult to determine, but each successive thrust sheet is made up of progressively younger units within the Morar Division. The direction of transport has been towards the northwest, which implies initial sedimentation of the Moine rocks in an area southeast of their present position. The progressively younger units within successive thrust sheets suggests that the stratigraphic units were initially disposed with the oldest in the west and youngest in the east.

8.2.2 Moine lithologies in Eastern Knoydart

Semi-pelitic and psammitic rocks of Moine age occur in the region of Ladhar Bheinn and Meall Bhasiter in Eastern Knoydart and are equivalent to stratigraphic units within the Morar Division of the Moine succession (Richey & Kennedy,1939; Ramsay & Spring,1962, Johnstone et al. 1969).

The Ladhar Bheinn Pelite which dominates the ground east of Inverie (Figs. 1 and 22) in eastern Knoydart,is confirmed as being equivalent to the Striped and Pelitic group of the Morar Succession (Ramsay & Spring,1962, and Powell,1974). The psammitic rocks forming the summit of Meall Bhasiter structurally underlie the Ladhar Bheinn Pelite, and the junction between the two groups of rocks has been tectonically modified. Observation of sedimentary structures in the Meall Bhasiter Psammite and their constant upward facing direction towards the Ladhar Bheinn pelite lends to the inference that the units are in their original stratigraphic relationship. Consequently, it is possible to correlate the Meall Bhasiter Psammites with the Lower Psammite Group of the Morar Division of the Moinian assemblage.

The Aonach Sgoilte psammite (Ramsay & Spring,1962) is accepted as being equivalent to the Upper Psammite of the Morar Division (Johnstone et al.,1969).

8.3 Structural and metamorphic correlations within the Research Area

8.3.1 Introduction

Results concerning the tectono-thermal history of the rocks in the research area (Chapters 4-6) have enabled three main conclusions to be drawn.

These include the recognition of the same structural and metamorphic history for rocks in the thrust zone and the mobile belt of the Moine nappe (Section 8.3.2); the correlation of events above and below the Moine thrust plane from the Moine nappe to the Tarskavaig nappe (Section 8.3.3); and the recognition of two distinct orogenic events, the earliest of which is Precambrian, and the latest, Caledonian (Section 8.4).

8.3.2 Moine Nappe correlations

Contrary to earlier beliefs (Dunning, 1972), it is possible to trace the structural and metamorphic histories of the rocks forming the Moine Nappe from the Moine thrust zone into the centre of the mobile belt.

The whole region has suffered four major phases of deformation and two metamorphic episodes. Table 2, in Chapter 5, summarizes these events and notes the occurrence and intensity of deformational and metamorphic effects in the different areas.

The earliest phases of deformation, D_1 and D_2, produced large and small scale isoclinal folds throughout the region, and were associated with an early metamorphic event, M_1. The latest phases of deformation resulted in large and small scale open profile folds with coaxial crenulation folds. The second period of regional metamorphism, M_2 was associated with this later episode of deformation.

8.3.3 Correlations between the Moine Nappe and the Tarskavaig Nappe

It is possible to correlate the events represented within the Moine nappe with those recorded in the Tarskavaig Moine rocks which make up the Tarskavaig nappe. The two nappes are separated by the Moine thrust plane, and the Tarskavaig nappe is separated from the underlying Torridonian by the Tarskavaig thrust plane.

Two major periods of folding have affected the Tarskavaig Moine rocks, as well as locally developed additional structures. The correlation of events above and below the Moine thrust plane is shown in Table 5, and this correlation is extended to include events in the mobile belt.

It will be seen from Table 5 that the events recorded within the two nappes are not exactly the same. The Tarskavaig nappe appears to have suffered fewer phases of deformation, and a lower grade of metamorphism than the Moine nappe.

8.4 Evidence for, and the age of, the two orogenic events

Textural studies suggest that the fabrics within the Moine rocks are the result of two distinct orogenic episodes, each associated with its own metamorphic peak.

The earliest orogenic event was responsible for the structures associated with the D_1 and D_2 phases of deformation and the earliest metamorphic event, M_1. The latest orogeny produced D_3 and D_4 structures and was associated with the M_2 metamorphism. The details relating to these events are presented in Chapters 4 and 5.

Further to the microfabric work, regional mapping enabled the recognition of various stages of pegmatite intrusion related to the metamorphic events (Chapters 4 and 5), which in turn have been related to the structural chronology. Some of these pegmatites have been dated by isotope methods, producing both Precambrian and Caledonian ages (Gilletti et al., 1961; Long & Lambert, 1963, van Breeman et al., 1974).

8.4.1 The Precambrian Orogeny

The age of the earliest of the two orogenic events may be determined by considering the relative chronology of the pegmatites and the relationships of the early deformation (D_1 and D_2) and metamorphism (M_1).

From the evidence presented in Chapter 4, it can be seen that M_1 predated D_2 structures in the east of the area under review. In the west, however, D_2 and M_1 are synchronous. The implication of this is that the metamorphic "front" advanced from the east in a northwesterly direction, at a slower rate than the D_2 deformation "front". Pegmatites associated with this metamorphic event may be formed in the east prior to D_2 and therefore become folded by F_2 folds, but further west the same suite of pegmatites may post-date (i.e. cross-cut) F_2 folds. So both the pegmatites which are pre-F_2 in the east, and those that are post-F_2 in the west, are related to the same metamorphic event (M_1) and the same orogenic episode (producing D_1 and D_2 structures).

Van Breeman et al. (1974) have recently dated pegmatites in the Glenfinnan area (Fig. 65) at 730 ± 20 Ma, referring to them as pre-F_2. Recent work on the Ardgour Gneiss (Brook et al., 1976) has produced a date of 1050 ± 40 Ma, (Rb/Sr whole rock isochron) for the formation of the Ardgour gneiss, which was produced during the earliest metamorphism (M_1). Earlier workers (Harry, 1953; Dalziel, 1963) propose a post-D_1, pre-D_2 age for the Ardgour gneiss and Harry (1953) suggests that it was derived by in situ metasomatism. Using this same evidence, Brook et al. (1976) argue that if the 1050 ± 40 Ma date marks the age of the early metamorphism (M_1), then the sediments from which the Ardgour gneiss was derived must have been in existence (i.e. deposited) prior to that date. They (ibid 1976) further suggest that the M_1 metamorphic event corresponds to the Grenville orogeny (lasting from 1000 to 880 Ma, Myashiro 1973) of eastern North America.

The suggestion is put forward here that the formation of the Ardgour gneiss at 1050 ± 40 Ma marks the onset of regional metamorphism (M_1) to the east of the area where van Breeman et al. (1974) have dated pre-F_2 pegmatites (Figure 65). The pre-F_2 pegmatites give an age of 730 ± 20 Ma and occur approximately 8 km. west of the Ardgour gneiss. These pegmatites are also the result of the earliest metamorphism (M_1), representing a later stage than the formation of the Ardgour gneiss. Both the gneiss formation and the "pre-F_2" pegmatites are Precambrian.

Textural studies (Chapter 4) have confirmed that D_2 events are consistently related to M_1 metamorphism. Chapter 4 provides evidence that the onset of M_1 may be both pre- and syn-D_2. There is no evidence

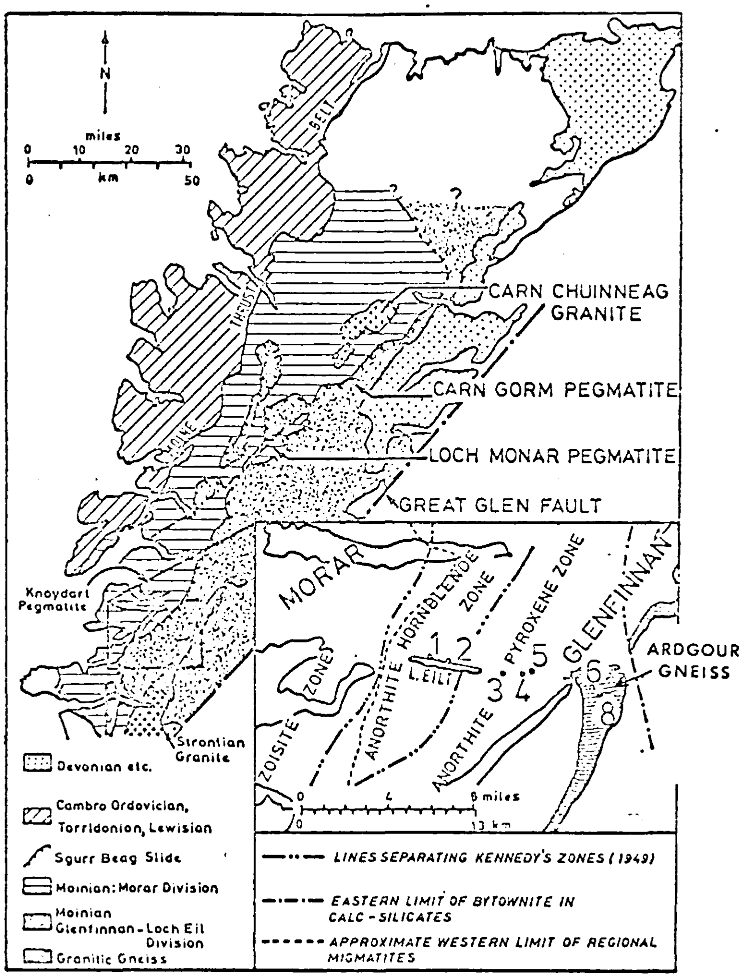


Fig.65. Geological sketch map showing the location of the pegmatites dated by Van Breeman et al. (1974) and the Ardgour Gneiss dated by Brook et al. (1976). (Modified from Van Breeman et al. 1974, Fig. 1).

of any break in the sequence of events from D_1 through to the end of D_2 and the related metamorphism M_1. Consequently, D_2 and all preceding events are related to the earliest orogeny, which began prior to 1050 ± 40 Ma, with the formation of D_1 structures, and continued until the end of D_2/M_1. This means that all D_1 and D_2 structures and the M_1 metamorphism belong to a Precambrian orogeny.

If the 1050 ± 40 Ma date for the Ardgour gneiss (Brook et al, 1976) marks the onset of M_1 metamorphism, and the "early" pegmatites of 730 ± 20 Ma mark its decline, it would appear that M_1 lasted for approximately 300 Ma. A metamorphic event of this duration is difficult to accept, and perhaps two Precambrian metamorphic events are represented in this area.

8.4.2 <u>The Caledonian Orogeny</u>

The age of the later orogenic episode may also be investigated using textural evidence which relates structure and metamorphism, the relative structural chronology of the pegmatites and the "ages" of lamprophyre sills.

The suite of pegmatites giving an average age of 450 ± 10 Ma apparently range structurally from post-F_2 to post F_3 in the region of sampling (van Breeman et al., 1974). In detail, however, van Breeman et al. (1976) argue that the older age limit for F_3 deformation is 450 ± 10 Ma, and that the younger age limit is set by a date of 445 ± 10 Ma for a suite of post-F_2 lamprophyres. The inference being that the F_3 deformation lasted for the duration of the intervening 5 million years. It seems probable, however, that the lamprophyre sills do not belong to a single intrusive post-F_3 event, but span a longer time range. Evidence from South Morar (Section 5.2.3) suggests intrusion of the lamprophyre sills post-F_2, pre-F_3 (see also Smith (in discussion of van Breeman et al., 1976)). Consequently, the pegmatites that appear to have formed at different times pre- and post-dating lamprophyre intrusion, could be of the same age.

In all the areas there is evidence for M_2 and D_3 being synchronous. In the west this is represented by crystallisation of biotite parallel to the S_3 schistosity, and in the central area by the syntectonic growth of microcline in relation to F_3 folds. In the extreme east, the M_2 metamorphic event has resulted in the appearance of kyanite and sillimanite and a general coarsening of texture in the rocks. By the time the D_4 phase of deformation occurred in the east, the metamorphism (M_2) had begun to wane, as evidenced by deformation of post-F_3 micas with no subsequent recrystallisation. In the west, however, the metamorphic effects outlasted D_4 with the crystallisation of micas parallel to the S_4 crenulation schistosity.

From this it would appear that M_2 lasted longer in the west than in the east, which conflicts with the evidence of a metamorphic front moving from east to west. It is therefore suggested that the D_4 phase of deformation was diachronous, occurring in the west during M_2 and moving eastward so that D_4 structures were formed after M_2 in the east.

In summary it can be seen that the timing of metamorphic and structural events in the later orogeny was similar to that evident during the earlier one - i.e. deformation and metamorphism being synchronous in the west, but not in the east.

The intrusion of "late" pegmatites (the 450 ± 10 Ma group, van Breeman et al,1974) may also therefore pre- or post-date different fold generations whilst still being related to a single metamorphic event. Pegmatites related to the later metamorphic event (M_2) can be seen to extend from pre-F_2 (van Breeman et al.,1974; Powell,1974, and Section 5.2.3 and Table 2 of thesis) to at least post-D_4 (Section 5.3.3, Plate 35 and Powell 1974). The youngest pegmatites dated by van Breeman et al. (1974) are post-F_3, which have ages of 448 ± 6 Ma and 449 ± 8 Ma. As already stated, this allows a period of 5 million years for D_3 structures to be developed. Because the "late" pegmatites are here all thought to be related to the latest metamorphism (M_2), dating of a post-F_4 pegmatite might give a better idea of the duration of the Caledonian metamorphism, which does not end everywhere at the culmination of D_3. It may also indicate the duration of the second orogeny which includes both D_3 and D_4 phases of deformation and must therefore culminate later than 448 ± 6 Ma.

8.5 The evolution of this marginal part of the orogen

The present attitude and disposition of the Morar Division of the Moine, and Lewisian rocks of this part of the Northwest Highlands is the result of the tectonic and thermal events of two orogenic episodes. The earliest occurred during the Precambrian, and the later is the Caledonian orogeny (s.s.).

Sedimentation of at least the lower Moine Series occurred prior to 1050 ± 40 Ma (Brook et al., 1976). The Moine sediments were deposited on Lewisian basement rocks, probably unconformably, but nowhere is an angular unconformity visible.

Precambrian orogenic events also began prior to 1050 ± 40 Ma (Brook et al., 1976) which is the age of the Ardgour gneiss which post-dates D_1 structures. Early crustal movements produced isoclinal folds (F_1) on a regional scale (Ramsay, 1961) and caused the infolding or thrusting of Lewisian rocks into the Moine cover rocks. During this stage the rocks were ductile and undergoing metamorphism (M_1).

Subsequent deformation (D_2) refolded these early isoclines, resulting in large scale often recumbent isoclinal folds. The metamorphic grade of the rocks prior to the onset of D_2 in the east was garnet grade, which also continued after D_2 deformation began. The grade increased sufficiently to allow the crystallisation of microcline as well.

In the west D_2 and M_1 are synchronous which suggests that the metamorphic "front" advanced in a northwesterly or westerly direction at a relatively slower rate than the D_2 deformation "front". Consequently D_2 and M_1 are synchronous in the west.

All these events, which occurred during the Precambrian orogeny produced essentially isoclinal, possibly flat-lying structures, where schistosities are frequently parallel to the lithological layering, and the rocks were in a ductile condition.

On the other hand, tectonic events during the Caledonian orogeny produced essentially upright, open profile structures, also developed on a regional scale, and also associated with a metamorphic front which advanced from east to west.

The grade of metamorphism associated with the Caledonian orogeny was not as high as that associated with the Precambrian orogeny, and the rocks were probably less ductile as a result.

Caledonian orogenic events culminated with thrusting of the complexly folded "orogen" rocks over the foreland rocks on the Moine thrust plane. The thrusting which is an entirely brittle phase of movement indicates that the rocks were no longer ductile (except perhaps those immediately adjacent to the thrust where heat would be generated during movement), and progressive metamorphism had consequently ceased.

The stress field during the Caledonian orogeny would appear to have been orientated such that the maximum pressure was at right angles to the trends of the structures produced during that orogeny, i.e. east-west. It is more difficult to determine the orientation of the stress field during the Precambrian orogeny, but it is possible that the maximum principal stress was also in an east-west direction.

In conclusion, the author feels that several important points have been established. A structural and metamorphic chronology may be recognised in the Moine nappe, from the Sleat Peninsula of Skye eastwards to central Morar and eastern Knoydart. This sequence of events may be further traced into adjacent areas with some conviction. Further afield the correlation of orogenic events becomes more speculative and may well prove to be invalid. The study has nonetheless proved that in areas of complex polyphase deformation and metamorphism, orogenies may be deduced, and correlations over wide areas attempted. The proof of these correlations will only be established by further research on a regional scale and relevant structurally controlled radiometric dating.

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APPENDIX

Relationships between deformation and garnet growth in Moine (Pre-Cambrian) rocks of Western Scotland.

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Submitted to the Bulletin of the Geological Society of America in July, 1975; accepted for publication August, 1975.

Relationships between deformation and garnet growth in Moine (Precambrian) rocks of Western Scotland

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ABSTRACT

Textural and chemical zoning and the inclusion fabrics displayed by garnet crystals from regionally metamorphosed Precambrian metasedimentary rocks reveal that the relationships between garnet growth and deformation change in space and time. At the margin of part of the Caledonian orogenic belt in Northwest Scotland garnet growth is entirely synchronous with the early phases of the second deformation whereas towards the interior of the belt garnet growth becomes progressively earlier relative to the same deformation. It is suggested that garnet growth (metamorphism) and deformation are diachronous through a 15 km. thickness of the crust. Key words: garnet zoning, metamorphic textures, metamorphism and deformation, Moine, Scottish Caledonides.

INTRODUCTION

The Moine Series of the Morar-Glenelg region (Fig.1) comprises medium to high grade regionally metamorphosed sedimentary rocks. They are part of a major, largely psammitic sequence in the Scottish Caledonian orogenic belt. In the northwest they overlie the Moine thrust zone, the margin of the orogenic belt, and they extend some 55 km south eastward to the Great Glen Fault (Fig.1).

Fig.1. about here

The Moine Series has a complex tectono-metamorphic history (Ramsay, 1963; Johnstone and others, 1969; Tobisch and others, 1970; Powell, 1974), which, in the area under discussion, includes at least four phases of deformation (Brown and others, 1970) and two phases of regional metamorphism (Long and Lambert, 1963; Powell, 1974).

The Moine rocks in the west are low grade: pelite contains biotite, muscovite and garnet, and calc-silicate rocks contain zoisite, calcite, garnet; toward the east the grade increases and pelitic rocks contain biotite, muscovite, garnet, sillimanite ± staurolite, and calc-silicate rocks contain bytownite, hornblende and garnet (Kennedy, 1949; Winchester, 1974; Powell, 1974). Garnet crystals are largest and most abundant in the Morar Pelite (Fig.1).

ZONED GARNET

Most of the garnet crystals studied were taken from one unit, the Garnetiferous Group (Richey and Kennedy, 1939) of the Morar Pelite, so that differences in textures and zoning which might arise from nucleation and growth in different chemical environments could be minimized. Several thin sections from most of the sample stations were examined.

The garnet crystals form idio- to xenoblastic crystals which usually exhibit distinct optical, chemical and textural zoning and range from 0.1 mm. to 6.0 mm. in diameter (Figs.2 and 3). Table 1 and Figure 2 summarize and illustrate zones in crystals from South Morar and Moidart (sample stations 126A, 334, 631, 694); Figure 3 represents the chemical zoning. Three textural zones occur in garnets at all of these sample stations (Fig.1) but not in every crystal. Some crystals are composed wholly of Zone 1, others of Zones 1 and 2, and others show Zone 2 and an incomplete Zone 3. All types may be found in a single thin section

Fig.2. about here

and since there is no systematic correlation between crystal size and the number of zones present it appears that these variations reflect differences in patterns of growth. Crystallographic control of the zoning, and the lack of geometric relationships between zones and crystal outlines, strongly suggests that the zoning is primary and not the result of later chemical readjustment.

Table 1 about here

Chemical zoning in garnet has been reported by Atherton and Edmunds (1966), Harte and Henley (1966), Hollister (1966, 1969), Leake (1968), Atherton (1968), Anderson and Buckley (1973), and Crawford (1974). Most of these authors show that the zoning develops during prograde metamorphism. The chemical zoning in five garnets from Morar and Moidart is related to the textural zones (see sample 631, Fig.3). Note the marked changes in concentration of CaO and FeO within textural Zone 2. The distribution of FeO, MnO and CaO in Zone 1 and the inner part of Zone 2 is similar to that reported by the other authors for whole crystals; it appears that growth in these garnets was continuous from nucleation to at least the middle of Zone 2. Moreover, inclusion fabrics in the crystals indicates continuous growth from nucleation to the outer limits of Zone 3.

Fig.3. about here

Correlations between the chemical and/or textural zones in the South

Morar/Moidart material can be made among samples 594C, 601, 604, K643 and P13 (Figs. 4 and 5). Samples from Skye (89A and A9) and West Knoydart (k644 and K34) (Fig.5) do not exhibit textural zoning that can be related to the South Morar type; however, the distribution of FeO and MnO closely

Fig.4. about here

resembles Zones 1 and 2 of the South Morar material (Fig.3).

Garnets from East Knoydart (231, P20, P23 and P44) (Figs.1 and 6) lack internal color differences and well defined textural zones. Some, however, exhibit differences in abundance, orientation, and composition of inclusions. A larger inner area with numerous parallel inclusions is surrounded by a discontinuous zone with fewer inclusions (Fig.6). Inclusions in the outer part of some crystals are oriented parallel to plane surfaces, at an angle to those of the inner part (Fig.6). At sample station P13 textural zoning occurs in a few crystals that is similar to that seen in the South Morar/Moidart samples (Fig.6).

Fig.5. about here

In garnet crystals from these eastern localities unlike those from the west, relatively large inclusions and semi-inclusions of biotite, muscovite, plagioclase and quartz (Fig.6 and 7) occur that appear to be penetration inclusions (Rast, 1965). That garnet, in the eastern parts of the area, may have suffered recrystallisation or at least chemical exchange with the matrix is further indicated by the lack of distinct chemical zoning (Sample P4, Fig.3), the increase in roundness of inclusions, and the development of irregular garnet outlines.

The textural and chemical zoning exhibited by some of the garnet crystals from East Knoydart may therefore represent a relic feature that has survived recrystallisation.

Figs.6 and 7 about here

In most of the garnet crystals studied a planar inclusion fabric made up of quartz, zoisite, opaque grains and opaque dust is preserved. The fabric comprises three elements: preferred shape orientation of individual quartz and opaque grains and groups of crystals; a banding which results from differing concentrations of inclusions; and trails of opaque dust and of quartz crystals (Figs.2 and 4). These elements are co-planar and represent a pre-garnet rock fabric (see also Powell, 1966). Samples from Skye demonstrate continuity of this included fabric with a planar structure in the host rock that represents bedding modified by the earliest recognisable schistosity (Fig.8).

Fig.8 about here

In most garnet crystals the inclusions have a very much smaller grain size than crystals of the same mineral species in the matrix, indicating that substantial matrix recrystallisation has taken place. The grain size of inclusions does not change from the centres of garnet crystals to their margins, indicating that matrix grain enlargement took place after the growth of garnet.

As inclusion fabrics pass from one garnet textural zone into another not only are there no abrupt changes in grain size but also, in most cases, no sudden changes in the curvature of inclusion trails (Figs4 and 5). Since the preservation of smoothly curving inclusion trails must be the result of garnet growth during continuous deformation these features together with the nature of the chemical zoning, support the contention that the garnet crystals grew without interruption from nucleation to their present form. The origin of the textural, and probably chemical, zones must therefore be considered as part of a continuous process.

RELATIONSHIPS BETWEEN GARNET GROWTH AND DEFORMATION

The four main phases of folding affecting the Moine rocks of the Morar-Glenelg region are witnessed on a mesoscopic scale by early isoclines associated with a penetrative schistosity (S^1) which often lies parallel to bedding (S^o); a second phase of generally tight to isoclinal folds with an attendant penetrative axial planar schistosity (S^2); a third pahse of generally open to tight folds associated with a crenulation schistosity (S^3); and a fourth phase which is generally expressed as crenulations of the earlier planar fabrics (Powell, 1974).

Figures 8 and 9 illustrate relationships between the inclusion fabrics within garnet crystals; S^o; S^1; S^2; and fold structures, at Armadale on Skye. The inclusions form rotational fabrics and the changing sense of rotation with respect to position around the second folds clearly indicates that garnet growth was syntectonic with respect to at least part of the second deformation. The changes in the geometrical relationships of the rotational fabrics to bedding around third phase folds shows that garnet growth preceded this fold phase. Similar relationships in other parts of the region place garnet growth as earlier than the third deformation and at least partly syntectonic with the second.

Fig.9. about here

There has been some debate regarding the nature of fabrics included within metamorphic porphyroblasts and the recognition of syntectonic and static growth. It has been claimed that inclusion fabrics represent relics of bedding or an early pre-porphyroblast planar fabric (Schmidt, 1918; Powell and Treagus, 1970) or alternatively, that they represent a new schistosity generated during the growth of porphyroblasts (Elliott, 1972). The perfect continuity of planar fabrics in the matrix (slightly modified bedding) with the inclusion fabrics of the garnet crystals as illustrated by the Armadale examples (Fig.8), proves that here the inclusion fabric is earlier than garnet growth.

Whilst it is generally agreed that rotational inclusion fabrics of the kind illustrated by the Armadale, West Knoydart and Glenelg samples (Figs.1 and 5) indicate syntectonic growth, the interpretation of plane inclusion fabrics as a product of static growth has been questioned. Elliot (1972) has argued that such fabrics can result from syntectonic growth. If strain axes are coaxial throughout growth Elliot (p.2636) suggests that planar inclusion fabrics would be preserved. If discussion of this point is restricted to examples where the inclusion fabric represents an earlier planar fabric then this situation could only arise if such a fabric lay at right angles to the maximum compressive strain axes throughout deformation or if rotation of the growing crystal kept pace with rotation of the fabric being overgrown. Under the former conditions pressure shadow patterns would develop about, and be overgrown by, the growing crystal, resulting in the preservation of, not a flat planar fabric, but "onion scale" types (Zwart, 1963). Where crystals rotate with the matrix fabric, porphyroblasts would have to be elongate in shape and all of the same dimensional proportions otherwise some would show flat planar fabrics whilst others, of different shapes, would preserve curved inclusion trails. We conclude therefore that flat planar inclusion fabrics, where they are preserved in crystals of differing shapes, indicate growth under static conditions.

In the study area the relationships between zones in garnet crystals and the type of included fabric, whether pre or syntectonic to the second deformation, reveals that these differ systematically from northwest to southeast (Fig.1). In Skye and West Knoydart growth of Zones 1 and 2 was entirely syntectonic with respect to at least part of the second deformation. In North and Central Morar and Southwest Knoydart Zone 1 was pretectonic and Zones 2 and 3 were syntectonic with respect to the same deformation; in South Morar/Moidart and East Knoydart Zones 1 and 2 were pretectonic and only Zone 3 syntectonic. The only exception to this pattern occurs at station P4 where syntectonic fabrics are preserved throughout garnet crystals. In this case, however, it is not clear from the nature of the inclusions or the chemistry of the garnet crystals which zones are represented.

Thus if the correlation of zones in garnet crystals between the different sample stations is correct, deformation and garnet growth can be put in a relative time scale and the progress of deformation and metamorphic activity can be investigated through a considerable thickness of the crust.

CONCLUSIONS

In a twenty five kilometer traverse from the margin of the Caledonian orogenic belt toward its interior the relative timing of garnet growth changes, within at least one metasedimentary unit, with respect to the second deformation. Syntectonic growth characterises the margin of the belt at the present level of exposure whereas substantial pretectonic growth occurred in the interior. It appears therfore that relative to one another, a metamorphic front, as witnessed by those conditions which initiate and promote garnet growth, and a deformation front, in this case the onset of the second deformation, do not coincide in space and time. It seems reasonable to assume that metamorphic fronts move from depth both vertically and horizontally towards the margins of orogenic belts. Deformation fronts may equally well migrate in a similar manner but the interrelationships of the two as in the present case, maybe diachronous both to absolute time and each other (Fig.10).

Fig.10 about here

ACKNOWLEDGEMENTS

The authors are grateful to D.E. Anderson, J. Olympio and J. Woodhouse of the University of Illinois for the microprobe analyses which contribute greatly to the work; to D. Wood for initiating arrangements whereby the analyses could be done; and to P.H. Banham for his encouragement and critical reading of the manuscript. Financial support from the U.S. Atomic Energy Commission (AT11-1-1198), the National Science Foundation (DMR-72-03026), N.E.R.C., and the London University Central Research Fund has made the work possible.

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TABLE 1. SUMMARY OF THE TEXTURAL ZONES

Zone	Characteristic Features
Z.1.	Inclusions - quartz, opaque mineral, zoisite (?) and dust (graphite?); size range 0.02 to 0.15 mm. Quartz occurs as single crystals and aggregates. Fabrics - shape orientation with long dimensions of crystals and aggregates lying parallel to co-planar surfaces; trails of inclusions and changes in the abundance of inclusions parallel to same surfaces. In some cases (e.g. Fig.2) inclusions are concentrated in sectorially arranged areas.
Z.1/Z.2 boundary	Anhedral to subhedral in form; marked by change in color of garnet, concentration of elongate opaque minerals parallel to boundary, and the sudden incoming of abundant inclusions in Z.2.
Z.2.	Inclusions - quartz as single crystals and aggregates; opaque minerals; rare biotite and dust; size range 0.02 to 0.10 mm. Fabric - as in Z.1. Abundance of inclusions varies, high at Z.1/Z.2 boundary, decreasing to very low at Z.2/Z.3 boundary.
Z.2/Z.3 boundary	Marked by sudden increase in abundance of dust inclusions in inner part of Z.3. Usually euhedral but often abuts crystal margin. No color change in garnet.
Z.3.	Inclusions - as Z.2., size range .02 to .015 mm, biotite up to 0.7 mm in eastern localities. Fabric - as in Z.1 and 2. Highest concentration of inclusions of all zones, particularly dust.

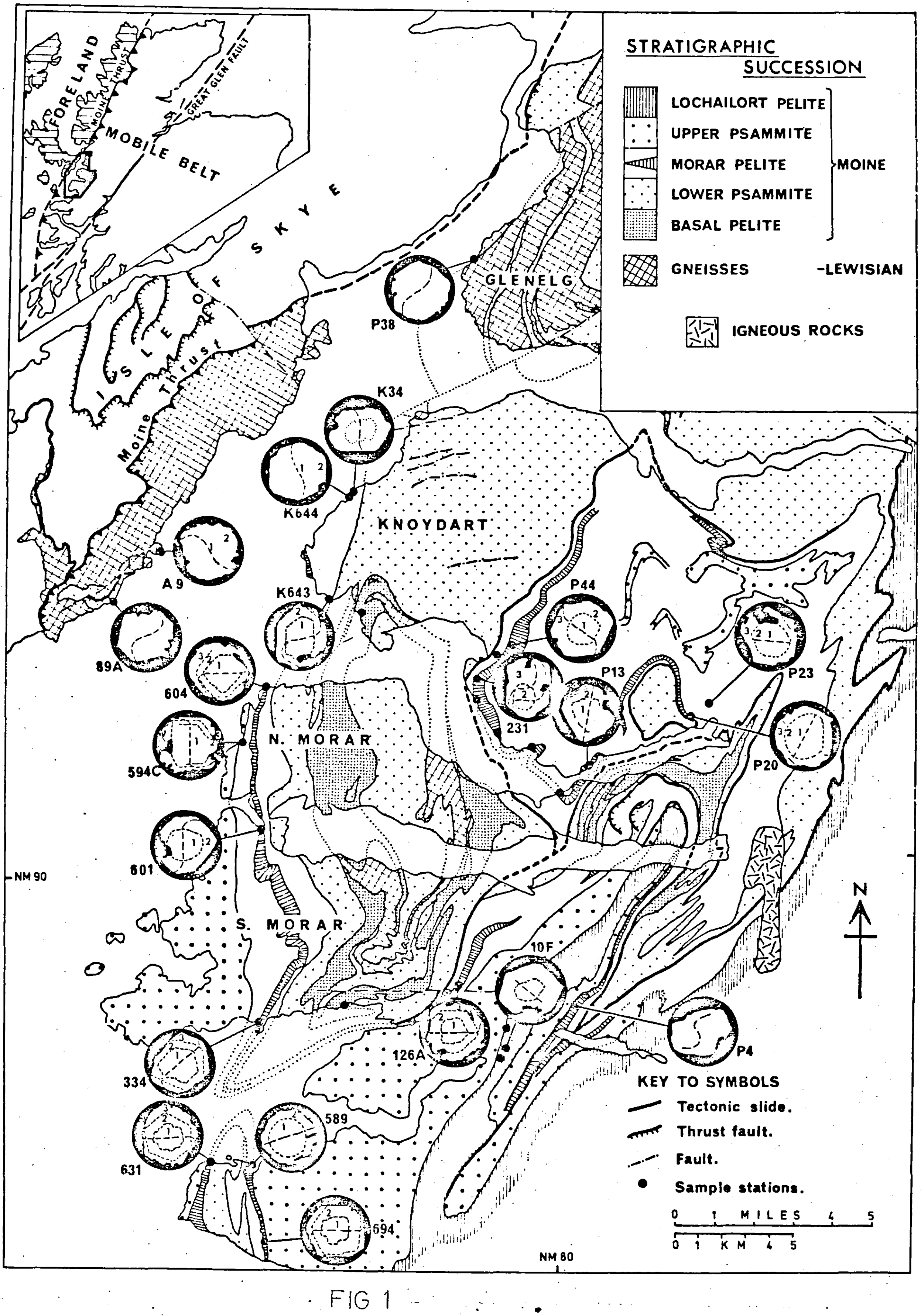
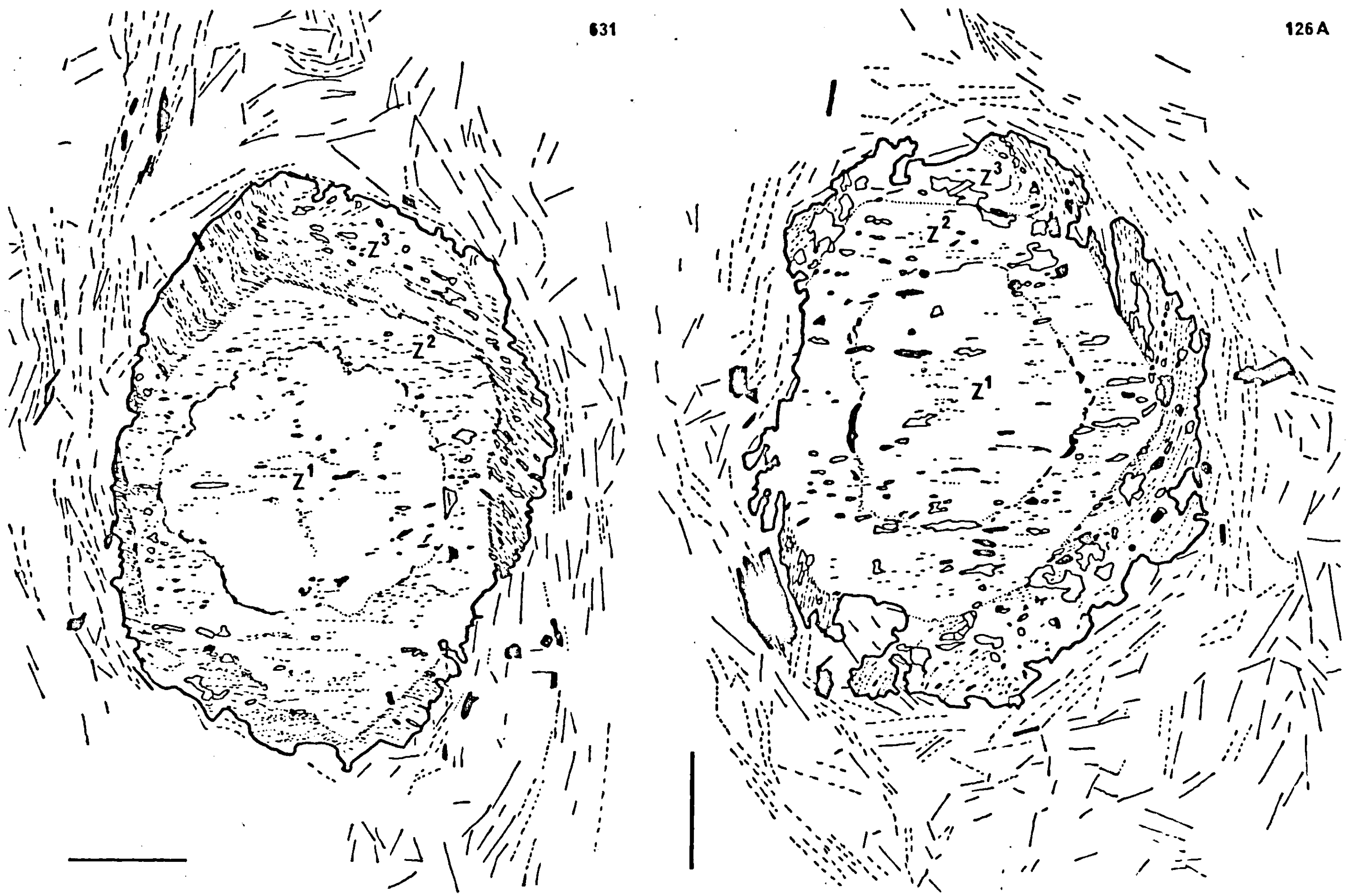

STRATIGRAPHIC SUCCESSION
LOCHAILORT PELITE
UPPER PSAMMITE
MORAR PELITE
LOWER PSAMMITE
BASAL PELITE
MOINE
GNEISSES
-LEWISIAN
IGNEOUS ROCKS
FORELAND
MOINE THRUST
MOBILE BELT
GREAT GLEN FAULT
ISLE OF SKYE
Moine Thrust
GLENELG
KNOYDART
N. MORAR
S. MORAR
P38
K34
K644
A9
K643
89A
604
594C
601
P44
P13
231
P23
P20
10F
P4
126A
334
589
631
694
NM 90
NM 80
N
KEY TO SYMBOLS
Tectonic slide.
Thrust fault.
Fault.
Sample stations.
0 1 MILES 4 5
0 1 KM 4 5

FIG 1

FIG 2



Scale bar = 0·5mm.

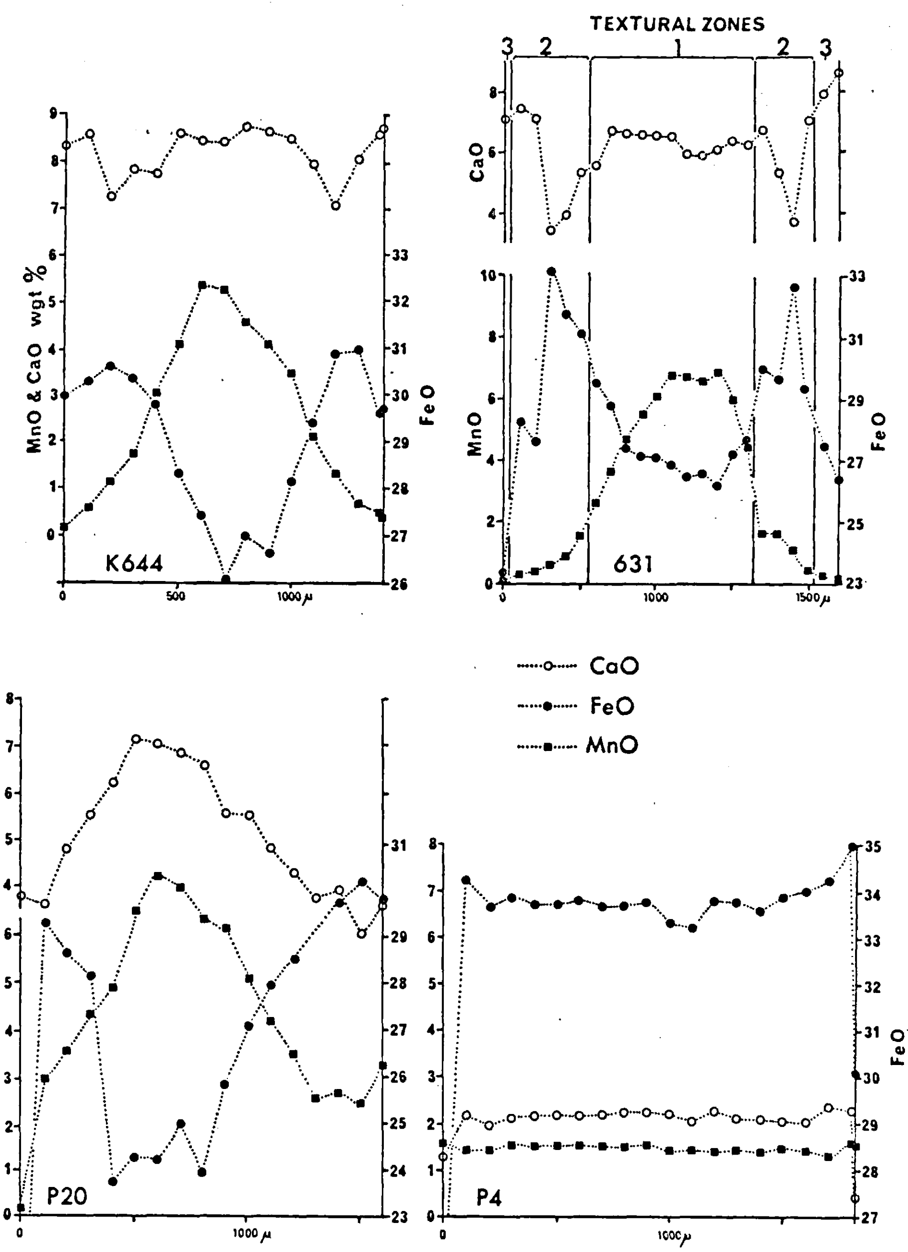

TEXTURAL ZONES
3 2 1 2 3
CaO
MnO
FeO
MnO & CaO wgt %
K644
631
P20
P4
CaO
FeO
MnO

FIG 3

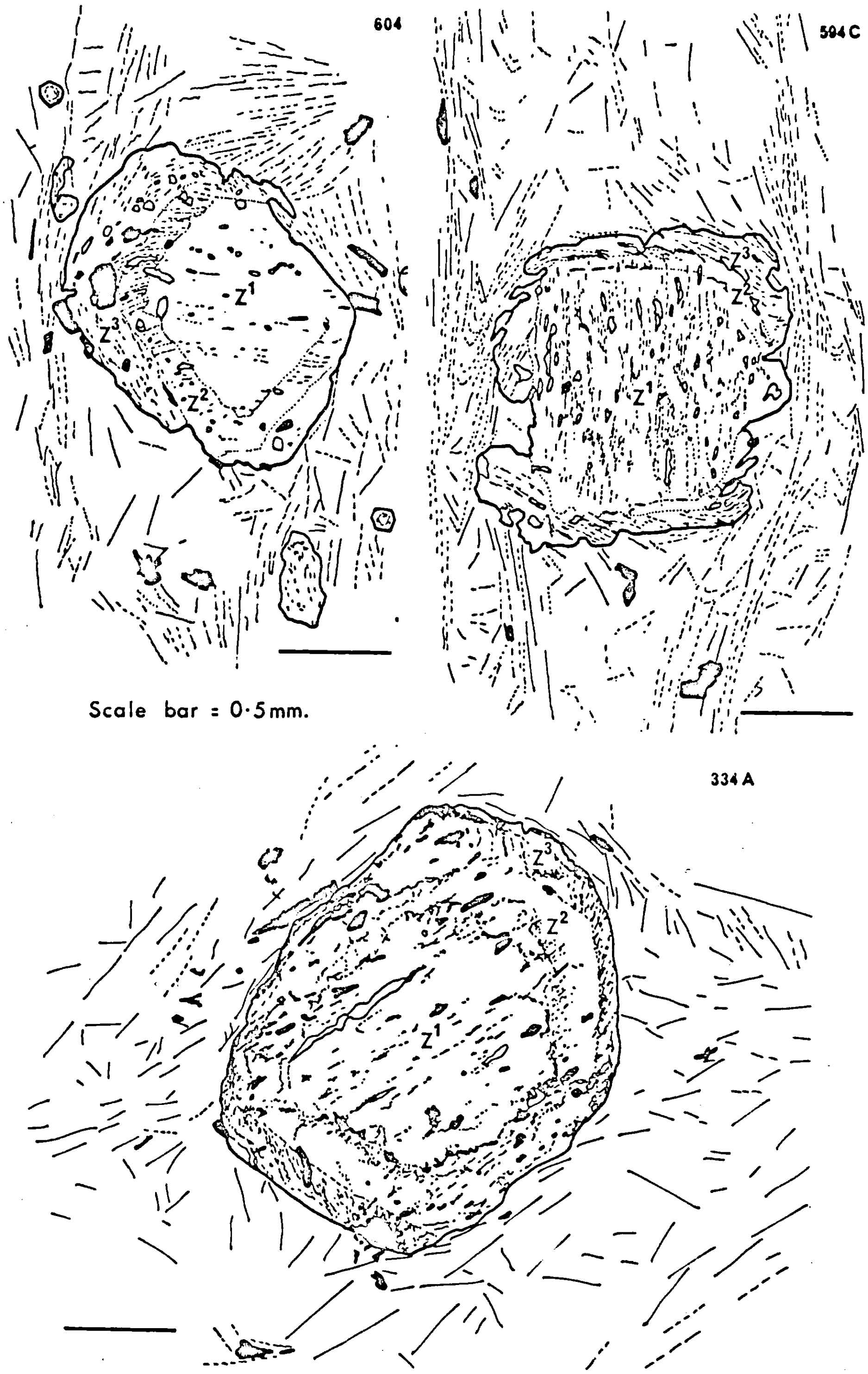


FIG 4

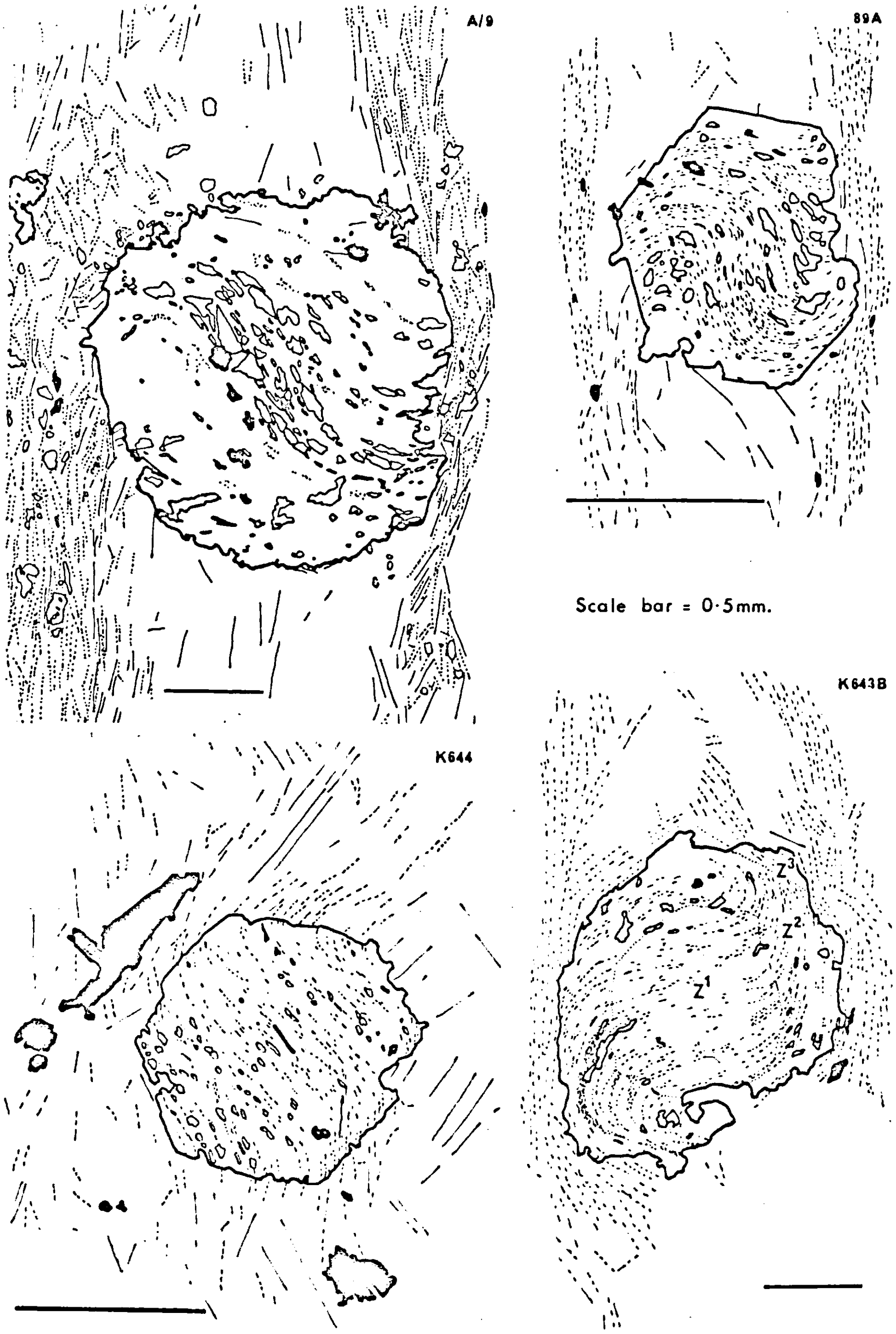
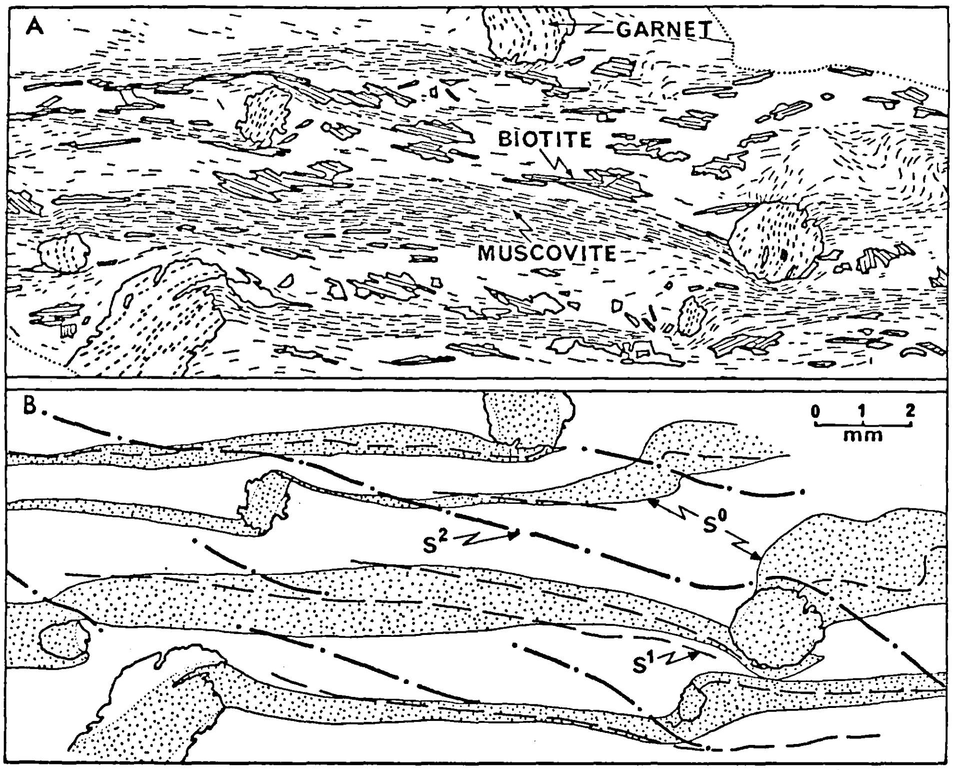


FIG 5



FIG· 6

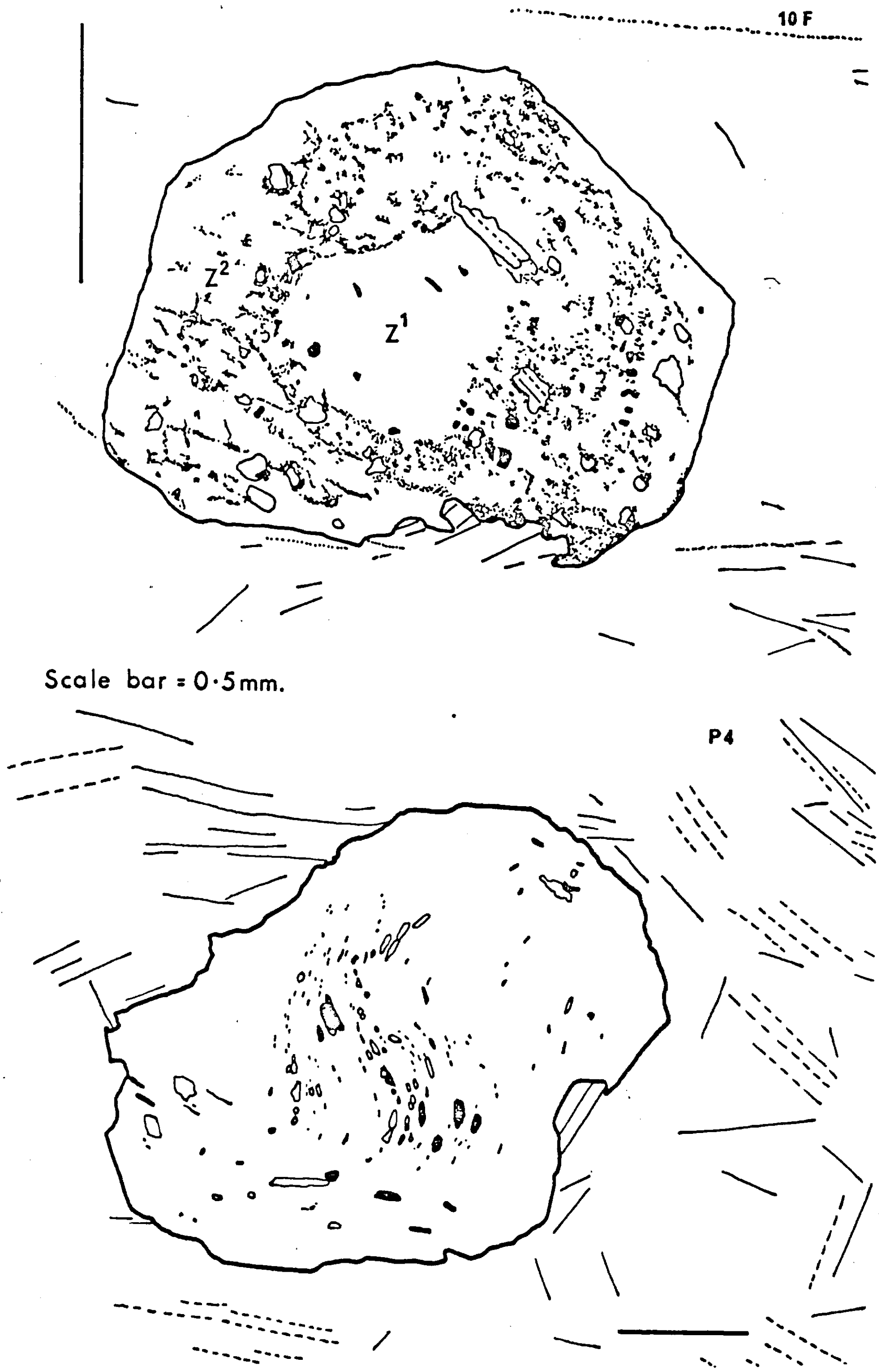


FIG 7

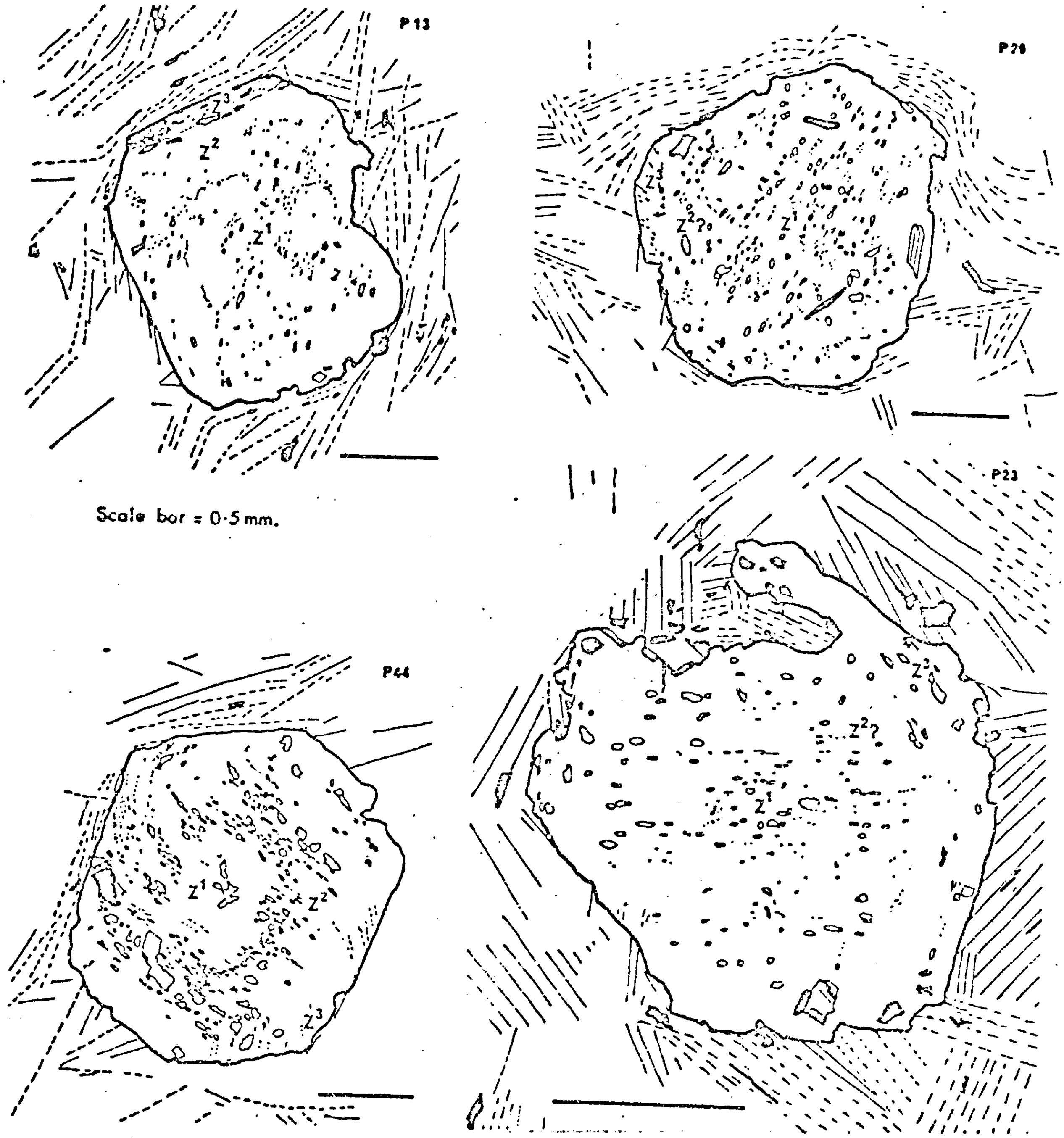


FIG 8

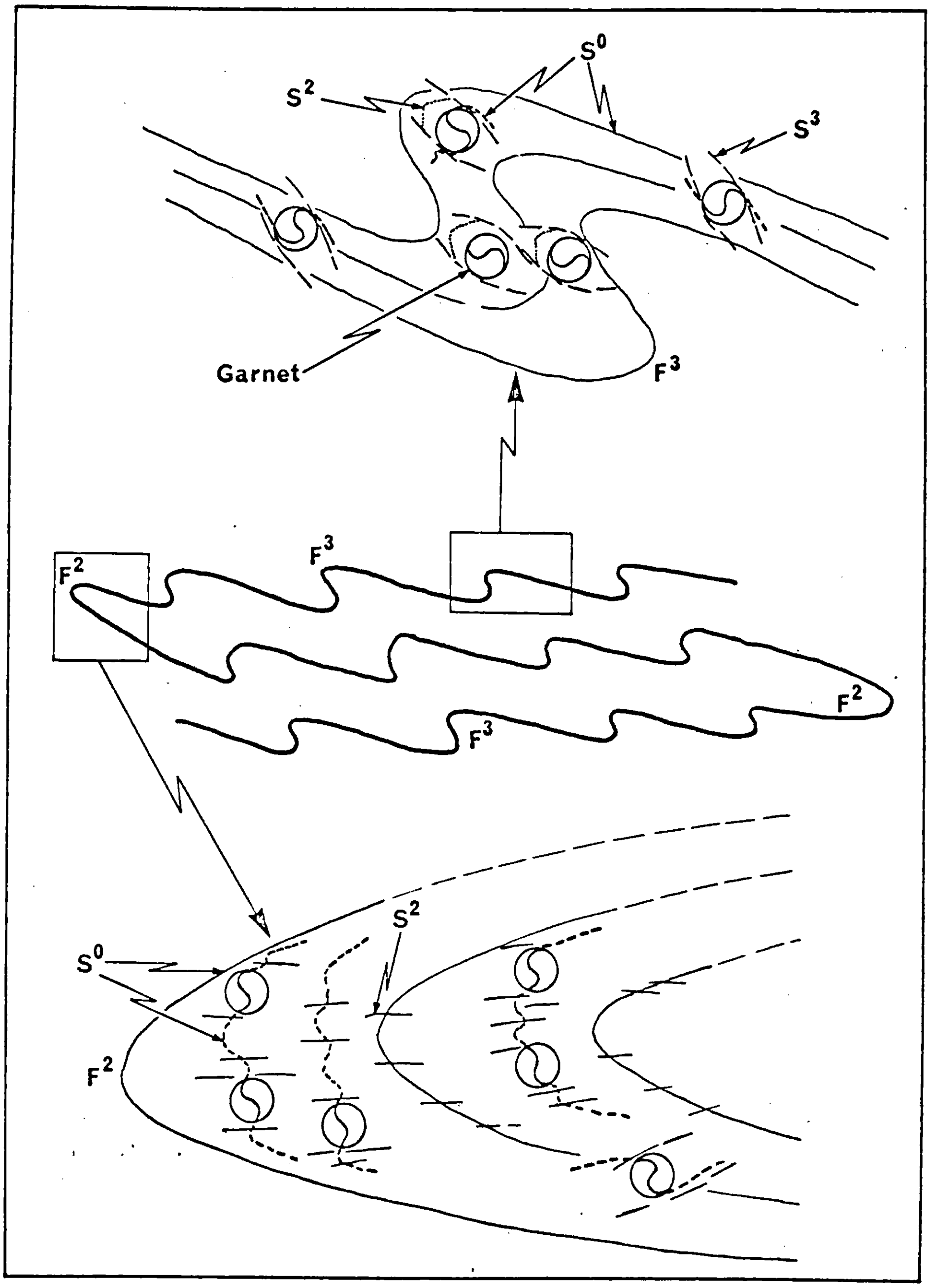


FIG 9

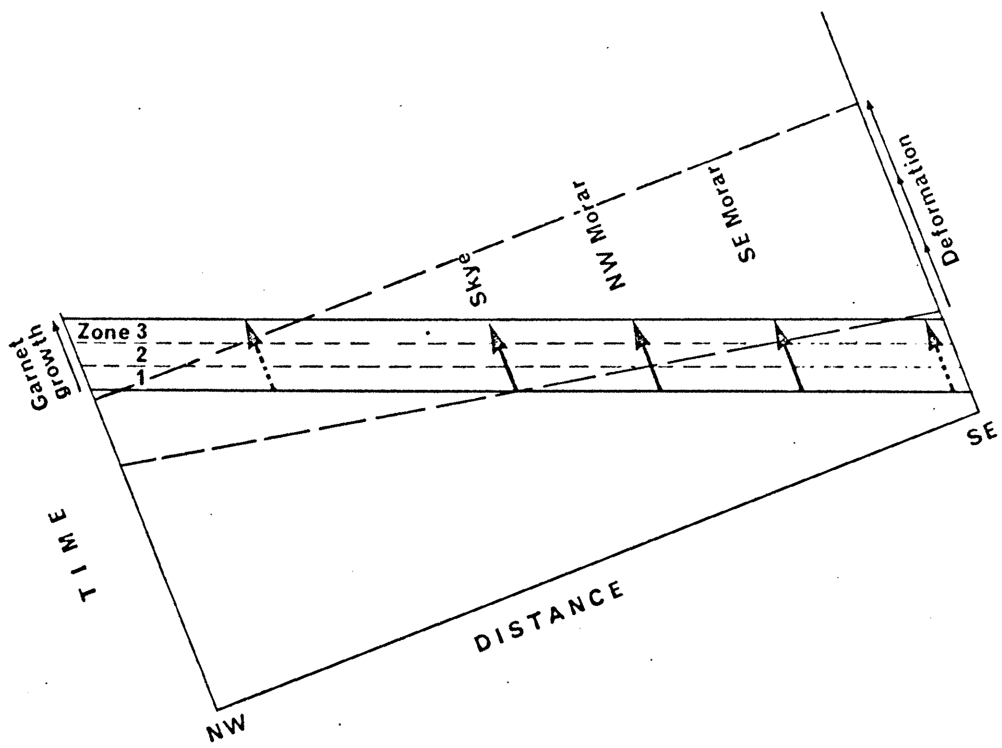

Deformation
Skye
NW Morar
SE Morar
Zone 3
2
1
Garnet growth
SE
TIME
DISTANCE
NW

FIG. 10

Figure Captions

Fig. 1. Geological map of the Morar-Glenelg region based partly on Geol. Surv. Gt. Brit. Sheet 61. Inset gives location of region. Circles enclose sketches of garnet crystals drawn to show zoning and attitude of inclusion fabrics. Structural detail is not shown on the map for the sake of clarity. For this the reader is referred to Powell, 1974. The Garnetiferous Group of Richey and Kennedy, 1939, is indicated by the ornamented band within the Morar Pelite.

Fig. 2. Textural zoning in garnet from South Morar and Moidart. Within the garnets: black-opaques, dots and fine dashes - opaque dust, white - quartz (single crystals and crystal groups). In the matrix: black-opaques, long lines - trend of cleavage in individual biotite crystals, broken lines - cleavage in individual muscovite crystals. Z1-2-3 - Zones 1, 2 and 3 referred to in text. Note particularly changes in the concentration of inclusions with respect to the three zones; the concentration of opaques at the Z1/2 boundary; and the idiomorphic nature of the Z2/3 boundary which is further characterised by the sudden increase in the concentration of fine opaque inclusions.

Fig. 3. Chemical zoning in garnets. Analyses by D.E. Anderson and J. Olympio, University of Illinois. 631 - textural zones 1, 2 and 3 are present (c.f. Fig. 2) and are reflected in chemical changes. K644 - exhibits no textural zoning but by comparison with 631 it appears that Zones 1 and 2 are present. P20 - no textural zones are visible but chemical variations indicate Zones 1 and 2 at least are present. P4 - no textural or chemical zones indicated. The micro-probe traces illustrated are not taken across crystals figured elsewhere in the paper but are for crystals from the same hand specimen.

Fig. 4. Textural zoning in garnet crystals from Central and North Morar. Ornament etc. as in Fig. 2. Each of the crystals exhibits features diagnostic of the three zones, c.f. Fig. 2. Note the continuous curvature of the inclusion fabric across zone boundaries in 604 and 594C, indicating continuity of growth.

Fig. 5. Textural zoning in garnet crystals from Skye and West Knoydart. Ornament etc. as in Fig. 2. All crystals preserve rotational inclusion fabrics. With the exception of K643B textural zones cannot be recognised but chemical zoning is evident from the microprobe traces (Fig. 3 - K644). Note the continuous curvature of the inclusion fabric from Z1 through Z2.

Fig. 6. Textural zoning in garnets from Central and East Knoydart. Ornament etc., as in Fig. 2, plus indication of cleavage in mica inclusions in garnet crystals. In P13 three zones can be distinguished on changes in abundance of inclusions and the preservation of zone boundaries, c.f. Fig. 2. The microprobe trace P20 in Fig. 3 is across a crystal from the same specimen as the P20 illustrated here indicating how the chemical data can be used to supplement inconclusive textural data.

Fig. 7. Textural zoning in a garnet from the southeast of the area. Ornament etc., as in Figs. 2 and 6. P4 is difficult to interpret because the textural zoning indicated is not readily related to that shown in the west nor does the chemical data, Fig. 3, provide alternative evidence.

Fig. 8. Diagram (B) of thin section (A) from Skye (sample station A9) illustrating the relationships between inclusion fabrics in garnet crystals and matrix elements. S_o - bedding, S_1 - first schistosity, S_2 - second schistosity. Note that both S_o and S_1 are overgrown by garnet, whereas S_2 is axial planar to microfolds "keyed" to the porphyroblasts.

Fig. 9. Relationships between rotational fabrics, second (S_2, F_2), and third (S_3, F_3) phase deformation structures; based on field exposures and samples. Note (top), the rotational fabrics in

garnet crystals are refolded around the F_3 fold closures whereas (bottom) the rotational symmetry of the fabrics change from S to Z around the F_2 fold nose.

Fig. 10. Possible relationships in space and time of garnet growth and the second deformation in the Skye-Morar region, Scotland.