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R.L. Langford, June 2015

DEFORMATION IN THE MOINE
SOUTH-EAST OF GLEN CARRON
HIGHLAND REGION
SCOTLAND

- by -

Richard Llewellyn LANGFORD BSc (Dunelm)

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Enclosures (at end of thesis)

Enclosure 1. Topography, drainage and place names
Enclosure 2. Geology south-east of Glen Carron, Highland Region, Scotland
Enclosure 3. Trends of planar structures in the Moine of the Glen Carron region
Enclosure 4. Trends of linear structures in the Moine of the Glen Carron region
Enclosure 5. Structural overlay for the Moine of the Glen Carron region

ABSTRACT

Most of the Moine south-east of Glen Carron, Highland Region, Scotland, is psammites and striped psammites. The mapping methods used are considered appropriate for use on these lithologies in an area of extensive shear belt development. The main indicators of deformation in the reasonably homogeneous psammites are a subjective assessment of flagginess and grain size. Indications of the extent of shearing can be gauged from sedimentary cross-bedding, quartz veins and pegmatites, minor folds and quartz aggregate platy and linear fabrics.

A new method of studying quartz petrofabric data is proposed. Examples of all commonly used contouring techniques are presented, and the new technique shown to be superior in ease of operation and reproducibility. Petrofabric data from the area is presented as supporting evidence for the proposed deformational history.

The deformational history has four main episodes (D_1 - D_4). Two major shear belts are used to invoke a deformational front, the 'Monar Front', as the western limit of D3 (Monar) shearing and fabric overprinting. The 'Monar regime' to the east is related to the early development of the Moine Thrust Zone (MTZ). The slide rocks identified in Killilan (May, pers. comm.) find analogies in the Bendronaig Slide and Monar Front.

As a lithostructural marker the Sgurr Beag Slide (SBS) (D_2) is the lateral equivalent of the Glenuig Slide (D_3), thus confirming the postulated position of the SBS north of the Strathconon Fault (Tanner and others, 1970).

The MTZ changes structural level in the north, dropping rapidly and changing strike trend. The regional implication is that if the MTZ had not dropped the ultimate major dislocation (D_4) would have followed the line of the Bendronaig Slide and ultimately the SBS.

The block left between the MTZ below and the Monar Front above contains early (D_1 - $_2$) structures and is possibly the most northerly area preserving the Morarian orogenic event unaffected by Caledonian reworking.

1. INTRODUCTION AND HISTORY OF RESEARCH

1.1 Location, extent and geography of the project area

The project area is located to the south and east of Glen Carron, Ross and Cromarty District, Highland Region, Scotland (Figure 1.1). The location of the area is shown on Figures 1.1, 1.2 and Enclosure 1, which also gives all place names. To the south the boundary of the area runs from Attadale House on Loch Carron to Pait Lodge on Loch Monar, to the east and north the boundary runs through the summits of Sgurr a' Chaorachain and Sgurr nan Ceannaichean to Moruisg, and to the north and west Glen Carron forms the boundary.

The project area is about 150 square kilometres in area, and ranges in height from sea-level in the south-west to six peaks of over 900 metres in the east. The highest point, on the edge of the area, is Sgurr a' Chaorachain at 1053 metres. Enclosure 1 shows the topography of the project area. Most of the area is peaty and sparsely vegetated hillside, with some natural deciduous forestation in the western parts and small areas of coniferous plantation around Attadale in the south and in Achnashellach Forest in the north.

There are five estates covering the area, the boundaries of which are shown in Figure 1.2. The largest deer forest is Attadale Estate, stretching 20 kilometres from west to east across the area. West Monar Forest in the east is part of the much larger Monar and Pait Estate, and the third important deer forest is Glencarron in the north. Achnashellach, owned by the Forestry Commission, is mainly concerned with forestation, and New Kelso is a small, barely productive area above Strath Carron. Because of the concern for preserving the deer forests much of the south and east of the project area is closed to access at the end of June each year, while in other areas access may be restricted at various times to preserve the game in an undisturbed habitat.

Rock outcrops over much of the area are confined to steep mountain sides and streams, and in some areas access is difficult. However, the west and south-west of the area displays good and easily accessible rock outcrops. Certain large areas, such as the south side of Meall Mor, the basin of

Loch an Laoigh and the northern slopes of Sgurr na Feartaig, are virtually devoid of outcrop except in a few streams.

The project area was geologically mapped at a scale of 1:10,000 in eleven months' fieldwork spread over three long field seasons. Figure 1.2 shows the bases used to allow access to the remote parts of the area. These were Bendronaig Lodge (Shepherd's Cottage) on Attadale Estate, Pait Lodge (Stalker-Shepherd's Cottage) on Pait Estate, Glenuig Lodge on Glencarron Estate and Achnashellach Hostel at Craig.

1.2 History of research in the region of the project area

a) The Geological Survey

The first work to provide a detailed geological account of any part of the area was 'The Geological Structure of the North-West Highlands of Scotland' by Peach and others (1907), in which mention was made of the “Moine Series”. Inliers of Lewisian gneiss were noted above the south-east shore of Loch Dughaill and the Moine Thrust was believed to be not far below the floor of Glen Carron, as is shown in the text figure 53, redrawn as Figure 1.3.

In a general discussion (ibid., p 595-6) the name “Eastern Schists” or “Moine Schists” was used to define “the great series of crystalline schistose rocks which lie upon the uppermost of the major thrust-planes of Sutherland and Ross”. The rocks designated “Moine Schists” were divided into four groups:

a) Mylonised rocks.
b) Phyllitic schists, siliceous schists and limestones.
c) Granulitic quartz-feldspar schists (Moine schists) and associated garnetiferous mica schists.
d) Inliers of micaceous and hornblendic gneiss often similar to Lewisian gneiss.

The last two divisions are the most important in the context of this thesis. Further, it is interesting to note that within the “Moine Schists” the Geological Survey recognised variations in flagginess and the presence of augen of feldspar and quartz which “may represent the remnants of original clastic grains” (ibid., p. 599).

In recognising an ESE lineation of fairly constant trend the Geological Survey noted that this trend was the same as the general direction of movement of the thrust masses. To the east of the Moine Thrust a holocrystalline schist was recognised, while closer to the thrust cataclastic structures were not uncommon. It was thought possible by the Geological Survey that there may have been a generally lower grade of metamorphism along the thrust masses.

A double system of folding was recognised within the “Moine Schists”, and this is summarised below:

1) NNE – SSW striking, ESE dipping axial planes. Presumed to be related to the Moine Thrust belt movements to the WNW.
2) WNW – ESE striking axial planes, with axes WNW or NW.

In the detailed account of the rocks above Loch Dughaill it was noted that “frilled schists of phyllitic type, alternating with flaggy quartzose granulitic bands” pass “south-eastwards into the typical siliceous flagstones” (ibid., p.616). At Arineckaig and on the slopes of Carn Mor two narrow belts of granulitic biotite-actinolite gneiss were found. These were thought to be inliers of Lewisian modified by post-Cambrian movements. No mention was made of a basal or sheathing pelite to these inliers.

The next major work covering the project area was 'The Geology of Central Ross-shire' (Peach and others, 1913), which is the explanation of Geological Survey sheet 82. In this work a major division is recognised between rocks of Lewisian type and the “Moine Series”. Figure 1.4 synthesises the interpretation implicit in the Survey map and memoir, and the sections (Figures 1.5 and 1.6) show the structure and stratigraphy envisaged by the Geological Survey. Beinn Dronaig was taken as the type area for the sequence. The stratigraphy was shown to be complete in only a few places and the relationship of the Lewisian inliers to the stratigraphy was not always clear.

When discussing the rocks to either side of the Moine Thrust Belt the Geological Survey noted that the belt of thrusting was a “marginal phase, produced under less load, of the folding and consequent deformation that prevailed over the whole of the area” (ibid.,p 27).

The Geological Survey believed that a regular gradation in deformation would be found from east to west. They noted the remains of clastic feldspars east of Strath Carron, and pebbly and little granulitised quartz to the west around Lochcarron village. They also noted that original sedimentary structures in the Moine and early structures in the Lewisian became less common eastwards. At Attadale fine grained muscovite-biotite schists were seen, with lustrous slates and fine grained phyllites to the west, marking an increasing intensity of destructive metamorphism towards the thrust, while in the east muscovite-biotite gneiss was identified. The Geological Survey noted the onset of garnet-grade metamorphism to the east and further evidence for increasing eastward metamorphism in the mineralogy of the Lewisian inliers.

A belt of “Moine Flags”, subzone b3, (see Figure 1.4) was recognised surrounding the “Pelitic Gneiss”, b2. Shearing in the flags was thought to be greater than in the “Massive Siliceous Granulites”, b4, but even so the change in the rock type was attributed to a transition between the muddy sediments of the pelite and the arenaceous arkoses of the massive granulites.

Many of the features identified by the Geological Survey, briefly outlined in the description above, were identified during the present work. The interpretation of these features often differs markedly from that of the Geological Survey, as will be detailed later in the text, but it is important to note that the basis for the present methods of interpretation of the Moine of the project area was established at the turn of the century.

b) Mapping after 1950

Following the work of the Geological Survey it was not until the 1950s that detailed mapping in the vicinity of the project area was undertaken. Much of this was done as part of PhD theses, and very little was actually done within the project area.

McIntyre (1952) worked on the pelites and surrounding psammites of Beinn Dronaig, and part of his work extended into the project area. His interpretation of the major structure was based on the trends of a variety of minor structures which he believed to be genetically related. Thus he invoked a single

system of folds with axes of trend 165º/28º plunge, and consequently interpreted the overall structure as a neutral fold closing to the south-west.

Ramsay (1954) mapped on either side of Loch Monar to the east of the project area, and most of his area was to the east of the Strathconon Fault, a major sinistral transcurrent fault. A small part of the area can be related to mapping undertaken in this project in West Monar.

Ramsay found no sedimentary structures, and so established a structural succession. He suggested that the supposed inliers of Lewisian mapped by the Geological Survey were an integral part of the Moine succession. Feldspathisation and migmatisation were thought to have created augen and banded gneisses. Ramsay then assumed that the antiforms were anticlines and arrived at a stratigraphical succession which included hornblendic groups.

Ramsay recognised two episodes of folding and these were subsequently incorporated in a regional synthesis of fold phases. This synthesis, by Tobisch and others (1970), will be used to describe the various fold phases of other authors wherever possible, and the synthesis will also be used to describe fold phases in the project area. The chronological sequence of fold phase names employed is; pre-Cannich, Cannich, Strathfarrar, Orrin, Monar, post-Monar and Affric.

Psammites in the Pait area, the Monar Psammite, contain well developed isoclinal Monar folds with NE – SW trending axial planes and a good axial lineation. Most of the proposed feldspathisation was thought to be related to the Orrin fold phase. Pegmatite intrusions of post-Monar age were also found. A sketch of Ramsay's geological interpretation of the area west of the Strathconon Fault is given as Figure 1.7. Ramsay was unsure whether or not the synformal fold in Garbh-uisge was continuous with the major An Cruachan synform.

Ramsay undertook a petrofabric analysis to test if the supposed Lewisian inliers identified by the Geological Survey had a pre-Caledonian fabric and to discover the effects of the two major fold systems. A complete or partial girdle was found, with the dominant regional lineation always parallel to the girdle pole, and Ramsay concluded that there was no earlier fabric and that the gneissose character of the rocks was acquired during feldspathisation of the Moine.

Concerning the relationship between the Monar and Beinn Dronaig areas (McIntyre, 1952), Ramsay did not believe that the SE plunging minor structures were parallel to the plunge of the major fold as, in the west, Monar folds obliterated Orrin folds. McIntyre had used in his interpretation the most prominent minor structure. This Ramsay believed was superimposed and unrelated to the axial plunge of Orrin folds. As the Beinn Dronaig axial trace was parallel to Monar folds in the Pait area, Ramsay assumed the Beinn Dronaig fold was a major Monar structure.

The work in this project differs from Ramsay in several respects. Sedimentary structures are found to the west of Pait, but no true succession can be established. The processes of feldspathisation probably does not account for all the Lewisian-type rocks seen in West Monar, and the evidence of earlier structures in these rocks leads to the conclusion that they are Lewisian. Although Monar folds are dominant, it is believed that the Beinn Dronaig structure has an earlier deformation history.

Sutton and Watson (1954) worked in the Fannich and Strath Bran area to the north of the project area, and looked at part of the Beinn Dronaig – Fannich pelite with which there are direct links to the project area. The authors established a stratigraphic succession which was the reverse of the Geological Survey interpretation (Peach and others, 1913).

The Beinn Dronaig – Fannich pelite (Meall an t-Sithe Pelitic Group) was near the top of their succession, and the major group to the west of the pelite, near the bottom of the succession, was the Inverbroom Semipelitic Group. The succession was fully developed only to the north-east of Loch Fannich, and the various gneisses called Lewisian by the Geological Survey were given a stratigraphic position within the Moine.

The evidence of sedimentary cross-bedding was used by Sutton and Watson to suggest that the supposed Lewisian inliers were part of the Moine, and was further used to show inversions of parts of the succession which introduced doubts as to the validity of earlier correlations between Moine and Torridonian. A “double system of folding” was envisaged, with all folding synchronous, and various views were expressed as to the relationship between the folding and the dominant SE plunging lineation.

The writer's work in the project area has not recognised the Lewisian-type rocks as part of the Moine succession, thereby differing markedly from Sutton and Watson. Sedimentary cross-bedding is not considered to be as important as Sutton and Watson suggested and a different interpretation to their complex synchronous fold-phase is also proposed.

Johnson (1955) mapped the Lochcarron and Coulin Forest areas immediately to the west and north-west of the project area respectively. In the altered and sheared zone of the Lochcarron area (Figure 1.8) he found the Moine to have structural and fabric similarities with the Lewisian and Torridonian of that area, with only relict feldspars in a recrystallised matrix indicating the polymetamorphic nature of the Moine. Concerning the appearance of garnet in the Moine to the east of the Moine Thrust zone at Lochcarron, noted by Peach and others (1913), p. 29, Johnson suggested that the apparent grade change indicated high grade dislocation metamorphism. Figure 1.8 illustrates the approximate eastern limit of the postulated retrogression in the Moine at Lochcarron. Johnson identified two linear structures, an early one plunging ESE, and a later one plunging NNE or NE.

The Coulin area was found to be structurally similar to the Lochcarron area. The Moine outside the altered and sheared zone were the right way up, dipping gently to the east with a SE plunging lineation. In the transition westwards the earlier fabric was progressively destroyed by folding on easterly plunging axes, found right up to the Moine Thrust zone, with some NNE plunging fold axes. An orthorhombic thrust fabric was seen to be gradually overprinting the older monoclinic Moine fabric.

The current work has used to advantage the structural findings of Johnson in the transition zone up to the thrust. However, the views of the Geological Survey on the relict feldspars and appearance of garnet are accepted in preference to Johnson's views. The evidence is in favour of an increase in metamorphic grade to the east, although retrogression is also important in the Moine Thrust zone.

Clifford (1955) worked in the Kintail district, over 4 kilometres to the south of the project area. He came to three major conclusions. Firstly, there were three major structural events, namely the thrusting and emplacement of the Kintail nappe, isoclinal folding on NE – SW or NNE – SSW axes and

cross-folding prior to and contemporaneously with post-Cambrian thrust movements. Secondly, whereas McIntyre (1952) thought the Beinn Dronaig – Fannich syncline closed to the SW, Clifford thought the structure gaped to the NW. Finally, Clifford thought that lineations in the Moine had formed parallel to the major direction of tectonic transport, after Anderson (1948).

Clifford and others (1957) made some attempt at understanding the regional implications of lineations in complex fold systems. They concluded that lineations in the Moine were parallel to the axes of minor folds and perpendicular to quartz c-axis girdles, but that there was always a complex relation of major and minor structures. Although the dominant regional lineation plunges SE, they did not conclude that regional folding occurred about NW – SE axes, and noted evidence to the contrary. Concluding, they noted that major and minor structures should be mapped together if areas with complex folding are to be successfully interpreted.

May (1959) worked on the Attadale – Stromeferry area of Moine and Lewisian rocks to the south-west of the project area. May recognised the development of hornblende gneiss within the Lewisian south of Attadale, and the development within the gneiss of a hornblende orientation parallel to his second phase lineation. The boundary between the Lewisian and the Moine was thought to be an unconformity modified by deformation. Lit-par-lit quartz-feldspar veins were noted within the Moine, dominantly within the pelitic units.

May recognised a first phase of folding, dominant within the Lewisian, but also shown in the basal pelite as a coarse NNE plunging quartz rodding.

The second fold system had a dominant axial planar cleavage and lineation, best developed in the Moine, and with associated fold axes plunging ESE 10º – 20º, pitching 90º on the axial planes. Tight to isoclinal minor folds with sharp hinges and long limbs were seen, but no major folds. M-type folding was commonly seen. The quartz-feldspar veins were deformed by second folds and were probably pre- or syntectonic. The strong lineation was marked by quartz-feldspar and mica orientations and the intersections of axial planes with primary layering.

The third fold phase was developed in the basal pelite, deforming second phase folds in places. The fourth phase of folding, developed everywhere, was a conjugate fold set giving a mesoscopic orthorhombic symmetry to replace the monoclinic symmetry. A summary of May's sequence of events affecting the Moine is given below:

a) Deposition of Moine sediments.
b) F_1. Interleaving of Lewisian and Moine, possibly equivalent to F1 in Glenelg.
c) Tranquil crystallisation. Garnet formed and stable in the Moine.
d) F_2. Strong recrystallisation and folding. Much mineral instability.
e) F_3. Retrogressive metamorphism. Less plastic folding.
f) F_4 and Moine Thrust Movements. Brittle style conjugate folds. Retrogressive metamorphism, but no recrystallisation.
g) Late stage folding, jointing and faulting.

The work of May is important in understanding the position of some of the Lewisian inliers of the project area. The well defined sequence of events finds parallels in parts of the project area.

Kassler (1961) worked in the Monar Forest, to the east of the project area, between Loch Monar and Glen Fhiodhaig. He recognised three major fold phases, with direct equivalence of the first two phases in the work of Ramsay (1954). The Orrin folds do not occur to the west of the Strathconon Fault, where the Monar folds are the dominant feature. Monar axial planes strike SSW – NNE, and the fold axes and lineation are well developed plunging SE, S or SW, with a strong axial-planar schistosity developed.

Post-Monar folds with axes plunging SE, parallel to the Monar folds, but axial planes striking NW – SE or N – S, are only developed in the north and west of Kassler's area. Monar folds were refolded, but without the development or a new lineation of schistosity.

Kassler recognised flaggy rocks, but attributed them to the metamorphism of a laminated sand – clay sequence or to proximity to the Strathconon Fault. His final conclusion was that there was interbanding of Moine and Lewisian followed by intense deformation in three fold phases.

Parallels with the project area can only be made in the small area to the east of the Beinn Dronaig – Fannich pelite. Kassler's evidence largely supports that of Ramsay (1954), but Kassler concluded that the gneisses were Lewisian and not necessarily part of the Moine stratigraphic succession.

Sutton and Watson (1962) reinterpreted the Moine gneisses as Lewisian bodies along similar lines to those proposed by the Geological Survey. There were, however, some marked differences in structural interpretation, particularly relating to the Scardroy Lewisian. The Scardroy Lewisian, and associated Lewisian over a large part of Central Ross-shire, was proposed as a large wedge tectonically emplaced in the Moine. By contrast, to the west it was thought that the Lewisian was initially emplaced as wedges, subsequently interfolded with a more or less autochthonous cover. The structure now proposed for the project area is in broad agreement with Sutton and Watson's interpretation of the westerly Lewisian wedges.

Barber (1965) studied the deformational history of the Moine Thrust Zone and established a chronology. The close resemblance of the metamorphosed Torridonian and Moine in the vicinity of the thrust led him to support the earlier suggestion that the degree of regional metamorphism decreases westwards. Narrow zones of mylonite separated by broad bands of relatively less deformed rock were found extending into the Moine and Lewisian up to 8 kilometres from the thrust. This relates to the early phases of development of the thrust, preceding the large scale displacement on relatively clean thrust planes.

The main area of agreement between Barber and the current work is in the postulate of upthrust basement blocks with intervening shear belts associated with major folding in the area to the east of the Moine Thrust Zone. These belts would contribute to the eventual major displacement along distinct thrust zones and remain as indicators in the Moine of deep-seated and persistent weaknesses.

Johnstone and others (1969) established a regional stratigraphy for a large part of the Moine. The sequence was established in the south of the Moine outcrop and has been extended north towards the project area, where the terminology has now been adopted. The oldest unit identified was the Morar Division. The division consisted of a basal pelite, and lower and upper psammite, the latter commonly containing

semipelitic bands, with a pelitic assemblage between the psammites. The Glenfinnan Division above consisted of a pelitic unit and a characteristically banded psammitic and pelitic unit. The top of the sequence was represented by psammites of the Loch Eil Division.

Tanner and others (1970) and Tanner (1970) recognised a major tectonic break within the Moine, the Sgurr Beag Slide. This slide was suggested to have considerable extent within the Moine, dividing the stratigraphic sequence tectonically into the Morar Division below and the Glenfinnan and Loch Eil Divisions above. It was postulated that the slide would be a boundary to the Beinn Dronaig – Fannich pelite and associated rocks. The present work in the project area has produced significant tectonic evidence on sliding throughout the Morar Division, but has not confirmed the existence of a distinct slide as postulated by Tanner and others (1970). To the east of the Beinn Dronaig- Fannich pelite, around Loch Monar, the current work has enabled conclusions to be drawn on the postulated position of the Sgurr Beag Slide.

1.3 Regional synthesis

A synthesis by Peach and Horne (1930) represented the earliest concerted attempt to look at the Moine in a regional context. Much of the Moine was thought to be folded on NE – SW axes with horizontal hinges. The Caledonian deformation of the Moine was thought to have resulted in a mass movement towards the stable foreland, ultimately resulting in movement along the Moine Thrust.

The mapping initiated by Imperial College in the 1950s (Ramsay,1954; Sutton and Watson, 1954; Johnson,1955; May, 1959; Kassler, 1961) provided much local detail on the Moine but little in the way of regional synthesis. Fortunately, the work did lead to some later attempts at synthesis (eg. Tanner and others, 1970), and has proved valuable in providing a framework for the current investigations.

A view of Moine sedimentation, deformation and metamorphism in the context of regional orogenies has been progressively built up from a variety of recent research. Moine deformation and metamorphism was until recently assumed to be entirely Caledonian, partly because of the presence of Cambro-Ordovician thrusting on the western margin. However, a significant part of the deformation is now thought to be Precambrian.

Powell (1974) attempted a synthesis of the deformation and metamorphism of a large tract of Moine and Lewisian in the Morar – Knoydart – Glenelg area. He noted apparently conflicting views on the degree of complexity of the deformational history of the Moine. There was also noted the conflict between a view of a Caledonian age for most of the orogenic events affecting the Moine, as opposed to the view that a lot of the deformation and metamorphism was Precambrian. Concluding, he thought that radiometric dating of structurally controlled pegmatites was necessary to give some clear indications of true ages of deformation.

Barber and May (1976) synthesised earlier work between Glenelg and Attadale, and correlated the later Caledonian events with the formation of mylonites in the Moine Thrust Belt. They produced this evidence in support of a Precambrian age for the early metamorphism and structural events in the Moine, thus lending additional support to the early ages now indicated by isotopic dating.

Brook and others (1977), working in Morar, but with some correlations made to the north, found that the main (M_2) metamorphism of the Morar schist was c. 1000 Ma, and that the D_1 deformation phase, with associated low-grade M_1 metamorphism, was responsible for the formation of major isoclinal folds with Lewisian cores. Some minor folds and schistosity predating D_2 (associated with the M_2 amphibolite facies metamorphism) were also found. Deformation phases D_3 and D_4, and the mild retrogressive metamorphism, M_3, were of Caledonian age, but at least part of the Moine was deposited, metamorphosed and deformed before 1000 Ma, and this was ascribed to the Grenvillian orogeny of that age found in North America. However, the Moine in Sutherland may owe all its deformational history to the Caledonian.

The dominant Caledonian deformation of the Moine was Lower Ordovician (450 – 500 Ma) and was ascribed to the Grampian orogeny (Anderton and others, 1979). This was the major event in a series of orogenic events making up the Caledonian orogeny, and was the only one in Britain to produce large areas of metamorphic rocks. The Moine Thrust Zone was also Grampian in age, and the orogeny was dominantly marked by considerable NW – SE compression.

The current work involves detailed structural mapping along similar lines to those employed in the work initiated by Imperial College. As such it fills a gap in the structural map of a large area of the Moine of western Scotland. However, the area can now also be considered in a regional context and used to enhance our knowledge of Moine deformational history. The project area has evidently been affected by the Grampian Moine Thrust. The deformational history in relation to Grenvillian and other Grampian events can now be described in detail (Chapter 6).

2. THE ROCK TYPES AND THEIR ORIGINS

2.1 Historical introduction

The historical division of Moine, rocks has largely been based on variations in lithology observed in the field and laboratory. In areas which include the project area the Geological Survey (Peach and others, 1907 and 1913) and Sutton and Watson (1962) have made lithological distinctions as an aid in defining the structure. In areas adjacent to the project area similar work has been undertaken by various researchers.

Peach and others (1907) divided the "Moine Schists" into four general divisions:

1) mylonised rocks,
2) phyllitic schists, siliceous schists and limestones,
3) granulitic quartz-feldspar schists (Moine schists) and associated garnetiferous mica schist, and
4) inliers of micaceous and hornblendic gneiss often similar to Lewisian rocks.

The last two divisions are dominant in the Moines as observed by the Geological Survey, the first two divisions being restricted to the area of the Moine Thrust Zone (MTZ). Within the "Moine Schists" variations in the flaggy aspect of the rocks were noted, together with augen of feldspar and quartz which were thought to be remnants of original clastic grains.

Peach and others (1913), in the explanation of Geological Survey sheet 82, again recognised a major division into "Lewisian-type" rocks and the "Moine Series". A belt of "Moine Flags" was noted enveloping the "Pelitic Gneiss", and although shearing is stated as being greater than in the "Massive Siliceous Granulites", the main reason for a change in the form of the strata is attributed to a transition between the muddy sediments of the pelitic gneiss and the arenaceous arkoses of the massive granulites.

Sutton and Watson (1962) mapped the area from Loch Dughaill and Attadale in the west to Loch Sgamhain and Loch Monar in the east of the project area. The area was divided into psammitic, striped and pelitic groups, and major structures defined using lithological and structural evidence plus sedimentary structures.

Work done by Ramsay (1954), Johnson (1956), May (1959) and Kassler (1961) in areas adjacent to the project area used mineralogical and petrological distinctions to define lithological divisions. As a consequence, large areas of psammitic rocks have remained undifferentiated or poorly differentiated around the project area.

2.2 Mapping techniques

The currently accepted lithological divisions were thought to be inadequate for describing the major structure of the area, and a different approach to the problem of classifying Moine rocks has been adopted. Mineralogical and structural characteristics of a rock are used in conjunction with sedimentary features to assign the rock to a particular lithostructural type. This division is the basis of the lithostructural map and the description of the major structures.

On the basis of preliminary investigations of the variations in mineralogy, structure and associated metamorphic features within the psammite of the Cona Mheallain area, NH 070 485, and around Arineckaig, NG 985 456, a system of outcrop analysis was devised. In a succession of previously undifferentiated or broadly grouped psammites it was found that localities in close proximity could display both subtle and marked differences in a variety of features. These differences were seen as a possible means of describing the major structure within an area of superficially uniform psammite, and a coding system was devised which could be applied to an outcrop.

Although the system was initially created with a view to solving problems within the psammites, it was extended, in modified form, to cover Lewisian-type rocks and the more pelitic divisions of the Moines. The modifications were necessary because an increase in the biotite mica content, found in the pelitic rocks, had a marked effect on lithostructural-type classifications.

In the Beinn Dronaig Pelite (Enclosure 2), lithostructural divisions were of use in a local context, but a conventional approach to structural mapping was more readily adopted. The Monar Banded Psammite, east of the Beinn Dronaig Pelite, is part of a structural regime distinct from the psammites in the west, having more in common structurally with the petite. Again, the lithostructural classification is of limited local use.

2.3 Mapping system

The mineralogical composition of a rock estimated visually in the field was found to vary noticeably within an outcrop and even within a hand specimen. An assemblage, namely the mean of a number of closely related but lithologically distinct outcrops, is conventionally used in drawing a lithological map. The constraints of the scale of the map and the extent of the outcrop make such practices almost inevitable, and to a large extent this subjective assessment of the overall composition of an outcrop as a guide to the assemblage locally was used in mapping the project area. In the area west of the Beinn Dronaig Pelite this gave a limited and often vague division of the area into Basal Semipelite, Strathcarron Banded Psammite Creag a' Chaorainn Semipelite, Achnashellach Banded Psammite and a large area of Attadale Psammite (Enclosure 2). On the basis of mineralogy alone these divisions are poorly defined. However, their importance in defining the major structure is not overlooked.

Because of the remarkably uniform nature of the planar and linear structures over large parts of the project area, such structures could not be successfully used in conjunction with the lithological divisions to provide detailed evidence on major stratigraphy or structures.

A variety of other features recorded at each locality have provided sufficient evidence in themselves for the major structure of the project area to be described in detail, and have provided a more detailed picture than hitherto possible when used in conjunction with evidence from minor structures and lithologies. The features used include grain size, flagginess, sedimentary structures, minor folds, quartz veins and pegmatites, and mineral fabrics. A division on mineralogical characters, essentially the abundance of biotite mica, was included in the coding system applied to an outcrop.

2.4 Grain size variations

Although no absolute measurements of grain sizes were taken from rocks observed in the field, a standard was created

for estimating grain size by comparative methods. Several problems were foreseen or noted in the field:

(a) The original sedimentary character of the Moine rocks would have an effect on the final grain size after deformation and metamorphism.
(b) The different lithologies within an outcrop could have markedly different grain sizes. This could be related to (a), but mineral composition, particularly in semipelites and pelites, was seen as an important factor in the development of mineral grain sizes.
(c) In the light of (a) and (b) it was hoped that direct comparisons would be made between similar rock types. This would generally only be an ideal situation but within the Attadale Psammite the influence of both these factors was assumed to be minimal.

Four codes are used to denote variations in grain size. For psammitic rocks these are as follows:

a) vf (very fine) — glassy appearance with only a few grains, fine biotite needles and smooth muscovite felts visible with a hand lens.
b) f (fine) — quartz/feldspar grains visible, but not easily with the naked eye. The development of mica is variable.
c) no prefix denotes average — quartz/feldspar grains readily distinguishable.
d) c (coarse) — large and average feldspar relicts often seen and a wide variation in grain sizes commonly noted.

Pelitic and semipelitic rocks display a range of grain size variations, but very fine pelites are not found and very coarse pelites, with large aggregates and augen of felsic material, medium to large irregular mica felts and poor layering, are quite common. Fine and very fine semipelites and even fine pelites can take on the superficial appearance of less micaceous rocks, particularly dark psammites. The lack of distinction between lithologies when fine grained presented some problems in the field which necessitated careful and methodical mapping.

Within the large areas of psammite and striped psammite significant zones of fine and very fine grained rocks were found. Figure 2.1 illustrates the variations in grain size found in the project area west of the Beinn Dronaig Petite. The influence of lithological variations has been taken into account and small variations in grain size have been omitted unless they were thought to be important. Each circle represents the average grain size for a single outcrop or a small group of outcrops.

2.5 Fine grain zones (Figure 2.1)

a) Achnashellach Zone

This fine to very fine grained zone shows progressive development of very fine grained and ultimately phyllitic rocks towards the north-west. The significant characteristic of the belt is that it cuts across the general trend of layering and lithological divisions and destroys earlier structures. This was particularly well seen along the north-western slopes of Carn Mor, NG 960 430 to NG 990 460, where very fine grained rocks were progressively developed towards Loch Dughaill. The development follows the strike trend of a single psammitic unit of very uniform mineralogical appearance, the Attadale Psammite, and was traced into the underlying Basal Semipelite. The development of very fine grained rocks was so severe that the effect of lithological variations had little bearing on the lithostructural interpretation. In Allt Coire a' Bhainidh, NH 035 475, the progressive grain fining can be seen from south to north across a variety of subtle changes in lithology from psammite to dark psammite. The overall lithostructural interpretation was unaffected by the changes in lithology, as the deformation resulting in changes in grain size was judged to be very severe and persistent. Along the forestry track east of Craig, NH 038 493, for over 2 km, a variety of psammitic rock types with some thin pelites displayed generally fine grain sizes. Although the deformational influence at the Achnashellach Zone is dominant it is not as strong as seen in the west. This reduction in deformation and loss of very fine grained rocks is typical of psammites east of Craig. (See Plate 2.1).

b) Bendronaig Zone

South of the Achnashellach Zone fine grained psammites were found in a zone extending from the flanks of Beinn Tharsuinn and Sail Riabhach, west to Creag a' Chaorainn, and at least to the southern edge of the project area. The zone is well displayed in Uisge Dubh, NH 018 400, and the development of this fine grained zone was clearly seen on the western flanks of the Beinn Tharsuinn, NH 036 425, where very fine psammites overprint the remnants of a major fold structure (Sgurr na Feartaig Zone) in the east.

Around Creag a' Chaorainn, NH 000 420, in an area of minimal outcrop, fine grained psammites and banded psammites pass westwards into a fine and very fine grained semipelitic assemblage, and in this area the location of the western boundary of the Bendronaig Zone is problematical. However, to the south the semipelitic assemblage becomes less fine grained and psammites with a noticeably coarse appearance are dominant. In the area around Bealach Alltan Ruaridh, NG 980 390, the western boundary of the Bendronaig Zone is readily identifiable. This boundary, extended northwards, probably passes to the east of the Creag a' Chaorainn Semipelite.

To the north the Bendronaig Zone is indistinguishable from the Achnashellach Zone, and to the east, on the southern flanks of Sail Riabhach, the fine grained Bendronaig Zone merges indistinguishably with the extension of the Glenuig Zone. The intervening Sgurr na Feartaig Zone disappears as a distinctly coarser zone.

c) Glenuig Zone

This is a variably developed zone of fine and very fine psammites, striped psammites and semipelites between the Sgurr na Feartaig Zone and the structural base of the Beinn Dronaig Pelite. The zone is well displayed along the eastern flanks of Sgurr nan Ceannaichean, NH 092 486, and across the western ridge of Sgurr Choinnich, NH 060 440.

Changes in lithology within the zone and the proximity to the Beinn Dronaig Pelite were seen as obvious influences on the development of a fine grained zone. Just within the pelite, small lenses of very fine and fine grained psammites were

found, and these are taken as evidence of a transgression of the Glenuig Zone into the pelite. As grain size variations within the pelite are not of assistance in defining zones, the upper boundary of the Glenuig Zone was taken as the base of the pelite.

2.6 Coarse and average grain zones

As an aid to defining areas of consistently finer grained rocks it was essential to map areas of average and coarse grained rocks, and study their relationships with the finer rocks.

a) Attadale Zone

One large area notable for the large scale preservation of a coarse grained psammitic assemblage is the Attadale Zone, lying south and west of the Achnashellach and Bendronaig zones. Although this area was mapped as undifferentiated average to coarse psammites for the most part there are complex local variations.

North of Attadale House, NG 925 392, the lithological assemblage is psammite, striped and dark psammite, semipelite and Lewisian gneiss and quartzite. Although deformation is severe in some respects, an indication of sedimentary differentiation is preserved. Within the Attadale Psammite, above this assemblage, grain size variations are marked in rocks of one lithology. Clastic feldspar relicts up to 10 mm across are preserved in fold hinge belts, and generally, but not exclusively, finer grained psammites are found in fold limbs. The processes of sedimentation and deformation are indicators for splitting the zone into finer and coarser areas, but nowhere is the large scale development of fine grained rocks to be seen. Plate 2.2 shows an occurrence of coarse grained psammite.

The boundaries to the Attadale Zone are usually dramatically marked. For example,the preservation of coarse grained psammites in major fold closures on Carn Mor, NG 980 440, and at Bealach Alltan Ruaridh, within close proximity of fine grained zones, are particularly noteworthy (see 3.6). The deformational influence of the fine grain zones is believed to be overprinting the folds in a direction approximately parallel to the regional lineation (Enclosure 4), and transgresses the limbs of the folds. In the latter case the progressive destruction of the fold hinge preserving coarse grained rocks is possibly a result of further movement of that fold's eastern limb.

b) Sgurr na Feartaig Zone

Although not similar to the Attadale Zone, this zone is distinct from the surrounding finer rocks. Generally average to fine grained, with some coarser rocks, the assemblage is not all pure psammite, but banded for the most part. Complex tectonic structures and many preserved sedimentary structures again distinguish this area. The most pronounced boundary, despite limited outcrop, is to the west. Rocks of essentially similar lithology markedly change westwards from fine to average grained to generally very fine grained. The western boundary marks a structural change related to the early fold structures within the Sgurr na Feartaig Zone and to the development of the Achnashellach Zone, which is itself associated with the Moine Thrust Zone.

2.7 Development of the fine grain zones

The mechanism believed to be the cause of the development of the fine to very fine grained zones in the psammites, from a generally average to coarse grained metamorphosed and tectonised arkosic assemblage, conforms to that proposed by Watterson (1975). The zones of finer grained rocks are seen as persistent tectonic lineaments in which mechanical weakening occurs through grain size reduction. As grain size recovery during metamorphism tends to be a much slower process than grain size reduction during deformation, the zone of mechanical weakness persists and expands.

The Bendronaig Zone, which develops northwards into the Achnashellach Zone and north-eastwards into the Glenuig Zone, is largely associated with the development of early major fold structures in the eastern part of the Attadale Zone and in the Sgurr na Feartaig Zone (see 3.6). The Bendronaig Zone, initially situated on the limbs of these major folds, has progressively and continuously developed by grain fining and by 'erosion' of major folds by lateral extensions (east and west). This zone is probably transgressive on the major folds and also related to large scale sliding.

The fine to very fine grained belt on the western edge of the Beinn Dronaig Pelite, in part the Glenuig Zone and in part the eastern edge of the Bendronaig Zone, is taken as evidence of major sliding. The belt transgresses fold structures in the Sgurr na Feartaig zone (see section 3.6), and totally destroys this zone in the south of the area. The zone results in the movement of the pelite over the psammites in the west, and movement is believed to have been taken up by recrystallisation and gliding within the pelite.

The fine and very fine psammites in the Achnashellach Zone represent the last phase of grain fining in the area. The zone, following the MTZ from the Strathmore Fault by Loch Dughaill, east and then north, represents a considerable extension above the MTZ of sliding and grain fining. The belt destroys all earlier features of the Attadale and Bendronaig zones in their northward extensions.

2.8 Variations in flagginess

In the course of mapping the psammitic assemblages, variations in the form of outcrops were noted which led to a division of the area on the degree of fissility or flagginess. The estimates of flagginess were subjective, and in particular could be confused by the onset of brittle deformation. The form of flagginess of particular interest was that related to the quartz-feldspar shape fabric and the development of fine muscovite mica partings. Consequently, the lithology, grain size, presence of minor structures and presence of faults, kinks and open flexures all had to be considered when determining flagginess.

The classification used, given below, is not as sensitive to lithological influences as the estimates of grain size, and could be applied to semipelites, pelites and gneisses. The classification is best applied over a uniform psammitic assemblage.

a) VFL (very flaggy) — the rock splits into very fine layers, or very fine layers can be distinguished; usually a few mm thick.

b) FL (flaggy) — fissility, often associated with mineralogical layering, is pronounced in one direction; usually less than 10 mm thick.

c) average — fissility is poorly developed or absent, but flat mineralogical layering may be a dominant characteristic; thickness of layers very variable.

d) M (massive) — fissility, if developed, is not in one persistent direction, and any lithological layering will also be irregular; quartz-feldspar microfabric often at high angle to layering; outcrops have distinct blocky, featureless appearance.

In the course of mapping the codes VFL, FL and M were used to describe an outcrop or related small group of outcrops. No code denoted average rocks. The rationalisation of the codes on a regional scale allowed the production of the map, figure 2.2. In naming the zones the map of variations in grain size was used (figure 2.1), and direct comparisons between the equivalent zones can be usefully made. Although, in mapping, average and massive (M) rocks were distinguished, in figure 2.2 the two have been put together. Similarly, the 'flaggy, flat' group includes elements of both flaggy (FL) and average, and the 'very flaggy, fissile' group includes very flaggy (VFL) and flaggy (FL)rocks.

In the pelites and semipelites, which have not generally been split on the basis of flagginess in figure 2.2, the terms massive (M) and schistose (SH) were commonly used, although flaggy (FL) and very flaggy (VFL) fine grained semipelites were not uncommon. The high biotite mica content of the pelitic and semipelitic assemblage can facilitate fissility, and direct comparisons with micaceous or pure psammites are not recommended. In particular, the lack of a direct correlation between flagginess, grain size and observed quartz-feldspar microfabrics in micaceous rocks was noticeable by comparison with the psammites. As apparent flagginess or schistosity derive from a different set of metamorphic and tectonic conditions in psammites and pelites, the lithological constraints applied to comparisons of like-grain size are similar in comparisons of like-flagginess.

A direct comparison of zone boundaries in figures 2.1 and 2.2 shows that flagginess is better defined within a zone than grain size, but flaggy rock zones are more tightly constrained. This is believed to be the result of two factors:

a) When the grain size is appreciably reduced, the flagginess may not be more apparent, particularly as the erosional form of the outcrop tends to give a poor view of the dip slope, best displaying flagginess, until flagginess reaches a particularly severe level (FL to VFL).

b) However, when the grain size is greatly reduced (very fine), subtle distinctions cannot be made between grains of similar sizes in the field, but very subtle distinctions of flagginess can be made on the basis of outcrop form. The quartz-feldspar fabric often becomes the dominant form of flagginess, and comparisons of planes between 1 – 10 mm in width are easily made. Plates 2.3 and 2.4 illustrate the fine comparisons that can be made on the NW limb of the major fold through Beinn Tharsuinn, NH 035 425.

The belts of 'very flaggy, fissile' rocks in figure 2.2 are often apparent from some distance, and sometimes give a characteristic appearance to part of a hillside. Flaggy rocks, by comparison with massive rocks, have an outcrop form and area which often changes markedly, but only a close examination will give details of variations in grain size.

2.9 Flaggy zones (Figure 2.2)

a) Achnashellach Zone

The best developed flaggy area is the Achnashellach Zone. This belt merges with the flaggy Bendronaig Zone north of Sgurr na Feartaig and is well developed as far north-east as Craig, Achnashellach.

To the south and east of Loch Dughaill the zone is comprised of very flaggy psammite, and beneath this, on the shores of Loch Dughaill, is a very flaggy and phyllitic semipelitic assemblage with hornblendic Lewisian inliers.

The extreme development of flagginess, through phyllitic rocks to mylonites, is displayed along the main road (A890) east of Lair, Achnashellach. Here, variations in lithology become difficult to identify, and mylonitic Lewisian gneiss is found close to mylonitic Moinian psammites.

The south-eastern limits of the Achnashellach Zone are well defined. The development of the flaggy zone has led to the progressive and transgressive overprinting of earlier structures to the east. The development of these earlier fold structures is seen as an influence in the initial development of the flaggy zone, but which has now been superseded in importance.

b) Bendronaig Zone

The flaggy Achnashellach Zone merges with this comparatively wide and persistent belt of flaggy rocks trending nearly north – south. The zone extends beyond the southern edge of the project area around Bendronaig Lodge, NG 014 388, where it is at least 2.5 km wide, and beyond the northern edge of the project area across Meall an Fhliuchard; NH 070 490.

The most striking features of the Bendronaig Zone are in the south. Although it is well developed in the north, and has a well defined boundary with the Sgurr na Feartaig Zone to the east, it is indistinguishable in tectonic influence from the Achnashellach Zone.

Two very flaggy zones can be distinguished within the Bendronaig Zone in the south, and these may be parts of a continuous belt. One very flaggy zone, illustrated in Plates 2.3 and 2.4, is on the western flanks of Beinn Tharsuinn at NH 030 425, and the other is well exposed in Uisge Dubh around NH 017 400. The grading from very flaggy to flaggy is gradual, and where exposures give a good view it can be seen over at least 10 to 20 metres thickness.

The south-western boundary of the zone, around Bealach Alltan Ruaridh, NG 990 390, is very sharply defined, but the south-eastern boundary is transitional into normal and massive rocks. Unfortunately much of the western boundary has had to be interpolated from the limited field evidence. The best visual confirmation of a well defined flaggy zone is afforded by the southern slopes of Sgurr na Feartaig, around NH 030 440, where the flaggy nature of the rocks can be seen in the weathered outcrop pattern.

c) Glenuig Zone

Lying beneath the Beinn Dronaig Pelite, the zone is of a more complex and limited nature than the large Achnashellach and Bendronaig zones. The limit of this area is taken as the base of the pelite to the east and the Sgurr na Feartaig Zone to the west. Its character in the north is markedly different from the south, and it affords some of the most spectacular views of very flaggy rocks.

Flaggy and very flaggy rocks form a wide belt on the eastern ridge of Sgurr nan Ceannaichean, around NH 090 485. The belt can be traced southwards, and is discordant with the base of the Beinn Dronaig Petite, eventually becoming a simple flaggy zone west of Sgurr Choinnich, NH 076 446.

On Sail Riabhach, NH 030 400, the narrow belt is very complex, eventually merging with the Bendronaig Zone, and totally overprinting the Sgurr na Feartaig Zone. The rapid variations in lithology and structural type present an unusually complex picture, and one which is more typical of the variations within the Beinn Dronaig Petite.

Figure 2.2 shows some variations of flagginess determined within the pelite. Particularly noticeable is the presence of very flaggy psammites within massive pelites north of Sgurr a Chaorachain, NH 087 447. Generally speaking no relationship can be seen between the Glenuig Zone and features in the pelite. The pelite is a particularly complex tectonic unit, not readily associated with the zones determined to the west.

2.10 Normal and massive zones (Figure 2.2)

a) Attadale Zone

This area has no development of very flaggy rocks, apart from a Lewisian inlier, and a variable and limited development of flaggy rocks. Dominant over large areas are massive rocks, associated with folding, and flat-lying zones. Distinctions between flat belts which are flaggy, and flat belts which are massive, are too subtle to enable the Attadale Zone to be further sub-divided. The overall pattern in this complex area is an expression of massive fold cores and flat to flaggy fold limbs.

The influence of flaggy belts on normal to massive zones is well established in the Attadale Zone. The unusual characteristics of the rocks, evidenced also by variations in grain size, are not made easy to interpret by the progressive internal (to the zone) and external development of flagginess.

b) Sgurr na Feartaig Zone

Lying between the Glenuig and Bendronaig/Achnashellach flaggy zones the area is a complex lithostructural division. The development of flagginess on either side of the zone is independent of variations in lithology, but within the zone a relationship between psammites and flagginess, and banded psammites and massiveness is broadly established. Fortunately, this tends to highlight the zone as one of structural complexity in a similar way to the criteria used within the Attadale Zone.

The progressive overprinting of the Sgurr na Feartaig Zone is seen in Figure 2.2 as a narrowing from north to south. Only by taking the view that the zone is being destroyed and not narrowed can major fold structures be satisfactorily traced through the zone.

Although the zone was not traced across Beinn Tharsuinn, it has been marked as covering the western side of the hill on the basis of evidence from Geological Survey mapping. The apparent narrowing of the zone, and the anomalous widening on Sgurr na Feartaig, are solely functions of topography, which shows extreme variations in this area.

2.11 Development of the flaggy zones

The mechanism proposed for the development of flaggy zones is similar to that proposed for the formation of fine grain zones. The area in Figure 2.2 contains a complex series of fold systems. The flaggy zones represent a comparatively late development of fold limbs and the destruction of fold hinges by simple shear. The resulting predominance of a flat fabric parallel to the lithological fabric is shown by flagginess. Shear zones are delineated by zones of extreme flagginess, and the ultimate result is the development of mylonites. Therefore, the presence of flaggy zones is taken as the onset of the development of a major zone of movement. These zones of movement are interconnected and can be chronologically related.

The last zone to be developed is the Achnashellach Zone, which is directly related to movement in and above the Moine Thrust Zone (MTZ). The influence of the MTZ on the Moine south-east of the Strathmore Fault is well evidenced by the extremes of flagginess developed. The Glenuig Zone is related to the development of a major slide at the base of the Beinn Dronaig Pelite. All the indications are, from the degree of deformation observed, that this zone is earlier than the brittle and mylonitic deformation in the MTZ, which took place at tectonically higher levels. In a sequence of progressive deformation and the development of slide zones the MTZ is the last major event.

The Bendronaig Zone is problematical in that it is related in style to the Glenuig Zone, but merges indistinguishably with the Achnashellach Zone. The trend of this zone is parallel to the MTZ north of Glen Carron, while the Achnashellach Zone parallels the MTZ beneath Glen Carron. The tectonic controls on the development of the Bendronaig Zone are the MTZ and the Glenuig Zone slide/base of the Beinn Dronaig Pelite.

The early genesis of all three major flaggy zones is believed to be related to major folding broadly along NE – SW axes, although this trend is more N – S north of Glen Carron. The succeeding deformation along the zones has followed ultimately different courses. The least persistent zone, chronologically, is the Bendronaig Zone, while major sliding is associated with the Achnashellach and Glenuig zones. The ultimate development of the Achnashellach Zone into the MTZ is evidence of its long and persistent history of development.

2.12 Sedimentary structures

This section deals with features seen which can be attributed to sedimentary causes, other than the variations in grain size described in 2.6. There are two categories of features; one is cross-bedding, and the other is miscellaneous structures believed to be sedimentary in origin.

a) Cross-bedding

The only feature which could be positively identified as being sedimentary in origin was the cross-bedding. At many

localities this structure is unambiguously displayed, and these localities always lie within the normal to massive zones (Figure 2.2). Only at two localities does possible cross-bedding lie in a flaggy zone.

The most important zone for the development of cross-bedding is the Sgurr na Feartaig Zone, where both upright and inverted cross-bedding can be seen in the psammites of the Achnashellach Banded Psammite. To the north of the Cona Mheallain, around NH 067 489, upright cross-bedding can be seen as seven intersecting sets. To the east, at NH 071 486 inverted cross-bedding is clearly displayed (Plate 2.5), and on Cona Mheallain, NH 068 485 cross-bedding is found in a major fold closure, with the angle of rest strongly exaggerated by deformation.

When viewed at right angles to the regional lineation, except in the fold closures, the cross-bedding in this area appears to show little deformation, but nowhere are normal angles of rest seen on faces parallel to the lineation. This is not believed to be the result of a predominant palaeocurrent direction at right angles to the lineation, but is a function of severe extension, and consequent masking, of features parallel to the lineation.

Near Pollan Buidhe, around NH 070 460, also within the Achnashellach Banded Psammite, further cross-bedding can be seen (Plate 2.6). Although inverted here the layering is generally upright, and the cross-bedding does not show signs of severe deformation. However, to the west of this area, cross-bedding is distorted within a major fold zone, and both upright and inverted attitudes are to be found. On the western margin of the Sgurr na Feartaig Zone upright cross-bedding is seen and this is believed directly related to the upright cross-bedding north of Cona Mheallain, indicating a major fold axis running just to the east of the Achnashellach/Bendronaig flaggy zones.

On the western ridge of Sgurr Choinnich, NH 065 447, possible inverted cross-bedding can be seen in the Glenuig Zone. The feature is attenuated and poorly preserved, but might indicate an inversion of the bedding in the lower part of the Glenuig Zone. Combined with the marked narrowing of the Sgurr na Feartaig Zone this may indicate a transgression of the flaggy Glenuig Zone over earlier fold structures.

In the flaggy Bendronaig Zone, at NH 020 392, in a southerly extension of the banded group of psammites, a single, strongly attenuated possible cross-bedding locality was found. Although it appears to be upright, lending support to the existence of a major fold axis in the west of the Sgurr na Feartaig Zone, which is being progressively overprinted, it is too isolated and uncertain a locality from which to draw any firm conclusions.

Significant occurrences of cross-bedding are to be found within the Attadale Zone, in the Attadale Psammite and Creag a' Chaorainn Semipelite. North of Bealach Alltan Rhuaridh, NG 980 390, psammites with fine micaceous banding display clear cross-bedding. Some, with the angle of rest greatly exaggerated, lies within the closure of a major fold (Figure 2.3), and some lies on the inverted eastern limb of the fold (Plate 2.7). Upright cross-bedding is found to the west of the major fold and in the middle of the semipelitic assemblage to the north, the cross-bedding actually being found in banded psammites. The implication of cross-bedding evidence is that a major synclinal fold axis exists within the Creag a' Chaorainn Semipelite.

Another locality displaying cross-bedding was found about one kilometre east of Strathcarron railway station, at NG 948 422. The cross-bedding in inverted and occurs in conjunction with what may be graded bedding.

From a stratigraphic point of view the most interesting occurrence of sedimentary cross-bedding is in the Monar Banded Psammite to the east of the Beinn Dronaig Pelite. At NH 105 410 multiple occurrences of upright cross-bedding can be seen, and these are illustrated in Plates 2.8 and 2.9. Plate 2.9 illustrates the fine preservation of the cross-bedding, although it would appear that the angle of rest has been somewhat exaggerated. Although the strata are clearly younging to the east at this locality the complex structure of the area, and the fact that this is the only cross-bedding locality, make large-scale stratigraphic extrapolations difficult. The structure and stratigraphy of this area are discussed in detail in Chapter 6.

b) Other structures

Relict clastic feldspars, described in section 2.6(a) and illustrated in Plate 2.2 are commonly developed in the south-westerly units of the project area, namely the Strathcarron Banded Psammite and Attadale Psammite. This preserved sedimentary feature has been much altered by metamorphism, and in most cases totally obliterated by deformation, both of which produced a reduction in grain size. Some preserved relict feldspars up to 10 mm across have been seen, although the more usual size is a few mm across. The fact that preservation has been limited to the south-west is taken as indicative of a reduction in regional metamorphism in this direction. The coarse clastic feldspars, intermixed with sandy and muddy layers in the banded psammite, indicate an environment of deposition associated with arkoses, probably on a shallow marine shelf.

Within the Dughaill Semipelite, at NH 005 475, there is the limited local development of an apparently conglomeratic band in the fine grained, flaggy semipelites and pelites. The degree of deformation in this unit is so severe that it cannot be concluded with certainty that this is a sedimentary feature. However, the 'pebbly' band is very unusual, and it is believed to be sedimentary and not structural in origin. It would not be unreasonable to expect to find the deposition of a conglomeratic band in a series of muds and sands at the base of the sedimentary succession as postulated in section 2.16.

Within the Achnashellach Banded Psammite south of Pollan Buidhe, around NH 076 465, apparent contortions in the layering are believed to be sedimentary in origin. These features cannot be related to a phase of deformation and appear to be the result of movements in the sediments before or during consolidation. The slumps are found in close proximity to numerous occurrences of preserved sedimentary cross-bedding, all within the Sgurr na Feataig Zone.

Within the Attadale Banded Psammite characteristics of the original sediments are thought to be preserved in the often marked large-scale irregularities in the layering. Irregular flexures with amplitudes of a few metres and variations in the thickness of lithologies are well displayed along the Strathcarron to Attadale road. In spite of the high level of deformation in the project area this unit has escaped the more severe deformations found to the north and east. However, the undulations may be related to the late-stage brittle and semi-brittle deformation associated with the Moine Thrust Zone and not of sedimentary origin.

2.13 Lithological variations

Lithological mapping of the project area was completed using divisions derived from generally accepted nomenclature originally suggested by Tyrrell (1921). He defined a "psammite" as the metamorphosed derivative of an arenite, such as a sandstone, and "pelite" as the metamorphosed derivative of a lutite, such as a siltstone or mudstone. Following the lead of earlier researchers in the Moine the following types are used. The codes used in mapping outcrops are given in parentheses:

a) Psammite (ps) — quartz feldspar schist or granulite with secondary muscovite and little or no biotite.
b) Striped psammite (sps) — quartz-feldspar-biotite schist with secondary muscovite. The mica tends to be in distinct layers or stripes.
c) Dark psammite (dps) — similar in composition to striped psammite, but the mica tends to be evenly distributed throughout the body of the rock.
d) Semipelite (spel) — biotite rich quartz-feldspar schist, often with muscovite. Biotite mica is dominant in the appearance of the rock.
e) Pelite (pel) — biotite-muscovite schist with subsidiary quartz-feldspar.

Although lithological types can be readily identified an outcrop or series of outcrops often displays a range of lithologies, giving rise to the use of lithological units to describe an area. A unit can display a wide range of lithological types, but is described on the basis of the dominant mineralogy and appearance. "Banded psammites", for example, are a complex series of psammites, striped and dark psammites and semipelites, but the dominant mineralogy is quartzo-feldspathic with subordinate mica, and the dominant form is layered, banded and striped. The units used in describing the area are psammites, banded psammites, semipelites and pelites.

The lithological map (Enclosure 2) was compiled to show the distribution of the broadest readily identifiable lithological units. However, the finer divisions of lithology, not fully detailed on this map, are important because of their effects on the determination of grain size and flagginess zones, and on studies of fabrics, quartz veins, pegmatites and folds.

Consequently, this section will briefly describe the extent of each lithological unit and the variations in lithology within the units.

Throughout the project area there tends to be a gentle south-easterly dip to the layering, although this is not true of rocks in the most easterly part of the area. The following list of lithological units therefore represents a broad apparent stratigraphy going up from west to east. Within the lithological units of the Moine rocks of Lewisian affinities are found. These were concordant with the layering in the Moine and always found within a unit, not on the boundary between two units. The Lewisian rocks are noted beside the unit in which they are found:

1) Dughaill Semipelite + Lewisian amphibolite.
2) Strathcarron Banded Psammite + Lewisian quartzite and gneiss.
3) Attadale Psammite + Lewisian hornblendic acid gneiss.
4) Creag a' Chaorainn Semipelite.
5) Achnashellach Banded Psammite.
6) Beinn Dronaig Pelite + Lewisian amphibolite and gneiss.
7) Monar Banded Psammite + possible Lewisian gneiss.

The stratigraphic significance of the units in a regional context is discussed in section 6.

a) Lithological units

1) Dughaill Semipelite

This thin band is exposed NE – SW along the eastern shore of Loch Dughaill, NG 995 470. The outcrop is about 3.5 km long, and the exposed thickness of the semipelite unit is less than 25 metres perpendicular to general dip. The base of the unit is not seen, being below the level of the loch. The upper boundary of the unit is with the Attadale Psammite and is very sharp and clearly defined in several sections.

The lithologies recognised within the unit range through psammite, semipelite and pelite, and they are closely inter-banded, creating a semipelitic unit. Although tectonic influences on the unit are strong, it is possible that in part of a semipelite a pebbly horizon is developed (see 2.12b).

2) Strathcarron Banded Psammite

This unit is exposed for 4 km NE – SW along the eastern shore of Loch Carron. The most northerly outcrops are in the River Taodail by Strathcarron, NG 945 423. To the south outcrops are found up to the southern limit of the project area near Attadale House, NG 926 391. The base of the unit is not seen, being below sea-level, but the maximum thickness perpendicular to dip is about 200 metres. The upper boundary with the Attadale Psammites is not clearly defined, but is gradational in character. The gradation can be traced in the section of the River Taodail. In the north the boundary with the psammite is downfaulted to the north beneath Strath Carron.

The lithologies recognised within the unit include psammite, striped psammite, dark psammite and semipelite. In the River Taodail a striped semipelite with bands of psammite is found close to the top of the unit. Along the road from Strathcarron to Attadale, psammite and semipelite with pelitic bands is found, and just north of Attadale House a wide range of lithologies are to be seen. For example, within small rock specimens both sharp and broad gradations between psammite, with coarse relict feldspars, and fine semipelite can be seen. The variety in the rock types is viewed as an expression of great variety in the original sedimentary environment of deposition.

3) Attadale Psammite

This unit covers some 80 km^2 in the west of the project area, and extends both north and south of the area. The unit outcrops for 10 km between Attadale House and Bendronaig Lodge, NH 014 388, in the south, and for 5 km between Lair, NH 010 485, and Glencarron, NH 065 510, in the north. The western edge to the unit lies in and above Strath Carron, and the eastern boundary lies to the west of Sail Riabhach, Coire Seasgach and Beinn Tharsuinn, and north of Sgurr na Feartaig. The appearance of this eastern boundary on the lithological map is strongly influenced by the sharp changes in topography;

the strike is a more or less constant NNE – SSW. Between Strath Carron and Bendronaig, perpendicular to the normal regional dip of the strata, the thickness of the unit is 4 km, excluding the Creag a' Chaorainn Semipelite lying in the centre. Between Lair and the summit of Sgurr na Feartaig, perpendicular to regional dip, the thickness is less than 3 km.

The lower boundary to the Attadale Psammite is in part a gradational boundary with the Strathcarron Banded Psammite, and in part a sharp boundary with the Dughaill Semipelite. The upper boundary is poorly defined over its whole length, and is in fact gradational with the overlying Achnashellach Banded Psammite. The boundary with the Creag Chaorainn Semipelite is poorly defined and is probably gradational to some extent.

Generally speaking the Attadale Psammite is a series of fairly pure psammites. However, striped psammites occur in many parts of the unit, particularly around the edges of the Creag a' Chaorainn Semipelite. The gradation up into the Achnashellach Banded Psammite is marked by the appearance of striped and dark psammites in the psammitic group east of Craig. A similar grading is evident over the more limited outcrop east of Bendronaig Lodge into Allt Coire na Sorna.

Very pure psammites were noted around Bealach Alltan Ruaridh to the south of the Creag a' Chaorainn Semipelite and associated with this clean psammite is the occurrence of small knots of magnetite on the bedding planes. The magnetite is found to the south-west, south and east of the semipelite, and was also noted in the psammites to the north-east in Allt Coire a Bhainidh.

Fine schistose pelites and semipelites were noted within the psammite as thin, distinct bands. Occurrences are limited to the western side of the unit and in the gradational zones to the east. To the west, pelite is found on Carn Mar above Arineckaig, at NG 987 445, and to the east of Attadale House, at NG 935 393. Similar thin bands are found on Carn Mor, NH 027 459, north of the Creag a' Chaorainn Semipelite and within the striped and dark psammites east of Craig.

Unusual rock types are developed in the northern part of the Attadale Psammite, around Lair and Craig, Achnashellach. The psammite progressively develops phyllitic and iron-stained slickenside surfaces to the west of Craig, and becomes virtually unrecognisable as a psammite by the railway bridge, NH 014 489. Close proximity to the Moine Thrust Zone is responsible for the local development of this progressively sheared, recrystallised and mylonitised psammite.

4) Creag Chaorainn Semipelite

This unit stretches from Carn Geuradain in the south, NH 980 400, for nearly 8 km to Coire Leiridh, NH 020 455. The area of outcrop is about 4 km^2, but the unit is poorly defined. The maximum thickness, perpendicular to the regional south-easterly dip, is probably 500 metres, and the outcrop closes to both the north and south.

The upper and lower boundaries with the Attadale Psammite have not been accurately mapped anywhere in the unit and they are probably gradational over the entire length. The contrast in eroded outcrop form between psammites and the semipelite allowed an assessment of the extent of this unit from aerial photographs.

The semipelite unit is dominantly a semipelitic lithology with some striped psammite, pelite and psammite. To the north-east of Creag Dhubh Mhor, around NG 990 410, psammite found in the centre of the unit contains some cross-bedding. The unit grades into the Attadale Psammite from semipelite through striped psammites into the psammite.

5) Achnashellach Banded Psammite

This unit extends from north to south across the project area, covering about 23 km^2 from north of Sgurr nan Ceannaichean, NH 090 480, to Coire na Sorna in the south, NH 030 390. The unit lies on the western flanks of Sail Riabhach and Bidein a' Choire Sheasgaich, across Beinn Tharsuinn, west of Sgurr Choinnich and to the north and east of Sgurr na Feartaig. The sharp variations in topography have a marked influence on the boundary position and the width of the unit. However, perpendicular to the shallow south-easterly regional dip of the layering the unit is 1500 metres thick across Pollan Buidhe, narrowing steadily southwards until it is 800 metres thick across Sail Riabhach.

The lower boundary of the unit is with the Attadale Psammite, but this is a gradational boundary which is generally poorly defined. The upper boundary, with the Beinn Dronaig Pelite is very clearly and sharply defined, even in the more semipelitic parts of the unit on Sail Riabhach.

The unit consists of a series of psammites, striped psammites, dark psammites and semipelites, with the rare occurrence of pelites. However, the unit is mainly striped and dark psammites occurring in such a manner as to give the overall appearance of a banded psammite. The other lithologies generally occur as thin bands, but there is an extensive outcrop of psammite below the Beinn Dronaig pelite south of Sgurr nan Ceannaichean, and there are thick bands of semipelite at several localities within the unit.

6) Beinn Dronaig Pelite

This large unit extends from north to south of the project area across some 30 km^2. The unit was not mapped in its entirety from east to west except across Meall Mor. The pelite was found as far north as Moruisg, NH 100 400, and south to Loch Calavie, NH 050 390, just north of Beinn Dronaig. The western boundary is with the Achnashellach Banded Psammite and the eastern boundary (edge of the project area) is through Sgurr na Conbhaire and Sgurr a' Chaorachain to Moruisg. The outcrop width (horizontal) is up to 6 km on Meall Mor, and a study of earlier work (Peach and others, 1913) shows that it rapidly narrows to 1 – 2 km in the north. Boundaries to both the east and west are very sharp, and the contrast with the Monar Banded Psammite in the east is very pronounced (Plate 2.10).

The unit consists of a series of semipelites and pelites, with some psammite and striped psammite, usually as thin, impersistent bands. Gneissose pelites and semipelites are commonly developed, and in the variety of rock types and forms it is not readily possible to make divisions into smaller units. This is largely the result of rapid changes in mineralogical composition and grain size within the pelites and semipelites.

7) Monar Banded Psammite

The mapping of this unit was limited to an area of about 6.5 km^2 to the east of the project area. Only the western stratigraphic boundary of this unit was seen. Loch Monar lies to the north and east and Garbh-uisge and Allt Loch Calavie to

the south and east. The western boundary with the Beinn Dronaig Pelite is very clearly defined, even within the area of limited outcrop on the southern flanks of Meall Mor.

The unit is dominantly siliceous with some semipelite and gneissose semipelite, which may be of Lewisian origin. Striped psammites are dominant, and the occurrence of psammites gives the unit a banded appearance overall. This banding and striping is far more prominently displayed than in the banded units in the west, giving the unit a characteristic appearance (Plate 2.11).

b) Sedimentary history

The metamorphosed sediments of the Moine were originally deposited as sands and muds. Sedimentary cross-bedding, characteristic of the Morar division (Johnstone and others, 1969), is locally preserved in the Attadale Psammite and particularly in the Achnashellach Banded Psammite, and a heavy mineral band seen over several kilometres is also noted. Such features, together with broad shallow channels, wave ripples and the absence of cyclicity found elsewhere in the Moine, are consistent with a high-energy shallow marine shelf to beach environment of deposition (Anderton and others, 1979). Muds and thin sands interbedded with muds originally constituted the pelitic and semipelitic divisions, but the intensity of deformation is so severe that the depositional environment cannot be reliably assessed.

The gradational nature of several of the major lithological boundaries is largely attributed to gradual changes in the type of deposition and not to structural changes. The particularly sharp boundary between the Beinn Dronaig Pelite and Monar Banded Psammite may be the result of a very rapid change in deposition or a tectonic break.

At many localities thin bands of contrasting lithology were found within the major units, for example the pelites in the Attadale Psammite. The lateral persistence of such bands was difficult to assess, and in some cases there was strong evidence that the lithology was pinched out laterally. Although this may be entirely tectonic in origin such impersistent lithologies are not inconsistent with the presence of broad shallow channels of sedimentation. These bands, noted throughout the lithologies of the area, may lend support to the idea of a broad shelf environment of deposition.

c) Lewisian inliers

1) Dughaill Semipelite

Within this unit a Lewisian inlier composed largely of an amphibole mineral was found at NG 9897 4590, just to the south of Loch Dughaill. This amphibolite, showing no noticeable signs of schistosity or foliation, is fine grained and intensely quartz veined, with the veining forming an irregular, fine network through the rock. The amphibolite lies in a zone of retrogressive metamorphism in the Moine and was probably a hornblende schist or pyroxenite before the severe deformation associated with the Moine Thrust Zone. The veining is also believed to be Lewisian in age as it is in marked contrast to the quartz vein deficient surrounding semipelite.

Just to the west of Loch Dughaill, at NH 0109 4810, a banded felsic and micaceous rock may be Lewisian in origin as there are few mineralogical features in common with the surrounding semipelite. The rock has been chloritised and pyrite cubes up to 10 mm across are developed on the parting planes. These cubes have been stretched at some localities and they are also occasionally surrounded by felsic material. Throughout this unusual rock type calcite is developed in the matrix. The exact relation of this small area of possible Lewisian rocks to the surrounding Moine is unclear.

2) Strathcarron Banded Psammite

Rocks which appear to be Lewisian in origin are to be seen in close association with a variety of psammitic rocks just north-west of Attadale House at NG 9246 3934. Bands of quartzite and amphibolite gneiss occur, and the presence of siliceous gneisses is believed to be marked by the presence of much quartz veining and significant areas of chlorite development. The chlorite, a product of retrogression in this area (Johnson, 1955) indicates the presence of unusual rock types which do not find a parallel in the normal Moine succession of the immediate area.

The relation of these Lewisian rocks to the surrounding Moine is difficult to unravel because of the problems of defining all those rocks belonging to the Lewisian suite. Undoubtedly the Moine has suffered from severe deformation and metamorphism despite the apparent low metamorphic grade. The Lewisian may be stratigraphically related to the Moine, representing a true basement to the sediments, or may have been tectonically emplaced.

3) Attadale Psammite

Although the Geological Survey recorded Lewisian above Strath Carron on Carn Mor, and to the south of Strathcarron (Peach and others, 1913), only the outcrops on Carn Mor were found. The major occurrence is siliceous, hornblende bearing gneiss found as a thin impersistent band stretching from above Arineckaig, at NG 9895 4521, south-westwards for about 750 metres. A biotite gneiss found about 1500 metres further to the south-west is probably Lewisian and directly related to the hornblende gneiss.

The most northerly outcrop of gneiss is thin, highly weathered and fine grained, with hornblende laths clearly visible. The body is only a few centimetres wide and lies within a pelite about 1 metre wide. Further south-west the gneiss is 1 – 2 metres wide and situated within psammites with no evidence of a surrounding pelite. The gneiss is fine grained and almost pure white, with about 15 per cent of the rock composed of green hornblende laths. These are aligned with their long axes roughly within the regional plane of dip of the psammites, but with no obvious linear orientation. The laths are 5 – 10 mm long and 1 – 2 mm thick. The gneiss is strongly quartz veined, with the veins forming an irregular network through the rock.

Further to the south-west, at NG 9835 4460, the hornblende gneiss is seen again, but the laths are often larger and are not consistently oriented relative to the regional layering. Coarser and finer parts create a banding within the gneiss, and only in the finer parts does the hornblende show some degree of alignment relative to the regional layering. A fine quartz vein network is again present. About 4 metres vertically below the gneiss is a very fine grained chloritised amphibolite within the psammites.

The biotite gneiss at NG 9710 4360 is a fairly coarse grained, flaggy to very flaggy banded rock within a normal

Moine psammite. Quite large feldspar crystals are developed, and thin pegmatitic layers with feldspar augen are found in association with thin quartz veins. The quartz veins are abundant and roughly parallel to the marked layering in the gneiss. Feldspathisation of the psammites above the gneiss was noticeable for some distance.

4) Beinn Dronaig Pelite

At several localities within this unit there is the presence on a large scale of Lewisian rocks. However, the Lewisian is more or less entirely confined to a belt running down the centre of the pelite from Moruisg to Loch Calavie.

The most northerly outcrops were only briefly studied, being to the north of the project area and largely inaccessible. Around NH 110 400, some 800 metres east of Moruisg summit, a wide variety of siliceous and hornblende bearing gneisses are to be seen. They occur in a belt at least 200 metres wide within the pelite, but could not be seen in the pelite to the south.

Just west of Glenuig Lodge, at NH 1042 3755, a thin amphibolite band was noted in the pelites. The band, composed of amphiboles and felsic minerals, is only 11 metres wide. Close by, within the pelite, there is a banded siliceous rock with augen of feldspar and feldspathic segregations. The similarity to other rocks more evidently of Lewisian age indicates that this is probably a Lewisian gneiss. As this gneiss and the amphibolite occur in the middle of the pelite they are probably related to the Lewisian on Moruisg.

On the northern flanks of Sgurr a' Chaorachain, around NH 088 453, a flaggy siliceous gneiss can be seen. The rock is coarse grained, displaying feldspathic bands and augen. A fine needle-like lineation is visible in biotite, and the overall planar structure is well developed. Flaggy and very flaggy pelites and semipelites, with much quartzo-feldspathic veining, are to be seen on both sides of the Lewisian.

The greatest outcrop area of Lewisian rocks within the project area is to the north of Loch Calavie between NH 057 393 and NH 055 405. A massive outcrop of coarse grained siliceous gneiss with dominant pink and white feldspar, quartz and thin bands of mica is seen to the south. A variety of garnetiferous and siliceous gneisses, plus some amphibolites, outcrops to the north. Strong rodding is developed in quartz veins and pegmatites, and the gneisses commonly have a strongly linear fabric. Amphibolites and gneisses display folds with orientations unrelated to regional trends in the Moine, but with regional penetrative planar fabrics superimposed. To the north of the area of Lewisian rocks a quartzose rock displays a fine, needle-like biotite lineation, and this is also thought to be Lewisian, probably originating as a quartzite.

The rocks described so far have been centrally placed with the pelite, but just to the east of Coine na Sorna, at NH 0398 3944, an amphibolite occurs. This may be Lewisian, or a metamorphosed Moine basic dyke.

5) Monar Banded Psammite

Rocks of possible Lewisian origin are found to the south of Loch Monar between NH 109 427 and NH 108 419. By the side of the loch a structurally complex area consists of strongly banded biotite gneiss. Quartz veins and pegmatitic quartzo-feldspathic bands are commonly developed parallel to layering.

To the south a fine grained, biotite rich schistose rock bears some similarities to the gneisses by Loch Monar. Finely streaked quartz veins are common and this location also displays the only clear example of a refolded isoclinal fold. Bands of marble or talc-silicate are also seen, and as this area can be structurally related to the gneiss by Loch Monar it is viewed as Lewisian.

6) Moine Thrust Zone

Between Craig and Lair, up to the postulated position of the Moine Thrust zone at NH 020 489, a phyllitic psammite is seen. The thrust is marked by the appearance, to the west, of a mylonitised gneiss. The rock is chloritised, and small relict feldspars and remnant crystals of hornblende can be seen. Further west phyllitic gneiss gives way to a dark fine grained hornblende gneiss just by the railway bridge. These Lewisian rocks are separated from the Moine by the Moine Thrust and are not tectonically related to Lewisian found elsewhere in the project area.

7) Origin of Lewisian

The origin of the Lewisian and its relations to the surrounding Moine are largely to be dealt with in the sections dealing with the structure. It is thought probable that the contact between the Moinian and Lewisian in the west of the project area is sedimentary, but elsewhere there are complex structural relationships. The emplacement of the Lewisian involves large-scale disruptions of the Moine, and these are considered in Chapter 6.

d) Igneous intrusions

One small, vesicular basaltic dyke was found just to the west of Loch Calavie at NH 0284 3942. The dyke, 1 metre thick with a 50 mm chilled margin, trends about 064º and dips 67º north. The dyke is probably Tertiary in age, as dykes of this type and age are known in the region (Phemister, 1960).

2.14. Quartz veins and pegmatites

Throughout the rocks of the project area a variety of small quartzose and quartzo-feldspathic bodies are developed. These have been described during mapping as quartz veins, quartzo-feldspathic segregations and coarse grained quartzo-feldspathic pegmatites. A note was made of the abundance of each of these types of body at each outcrop as a proportion of the whole rock. A comparative approach was adopted, using the following three broad categories:

- Absent — very few or no bodies developed.
- Rare (R) — bodies obviously developed but accounting for only a small proportion of the rock.
- Common (C) — bodies prominent or dominant, and on rare occasions accounting for a high proportion of the rock.

Each outcrop was coded (absent, R and C) in the hope of producing density distribution maps in a similar way to those produced for grain size and flagginess. However, the complexity of the occurrence of these bodies makes this difficult and only the broadest of divisions is possible.

Consequently, both regional and local variations will be described in detail for each type of body.

a) Quartz veins

These generally take the form of thin planar bodies parallel or sub-parallel to layering, and irregular, thicker bodies at a higher angle to layering or in fold cores. The veins were probably formed in a conjugate joint set which later suffered from flattening deformation. Individual veins can be very persistent laterally, and uniform in appearance. The thickness of the veins parallel to the layering can vary from a few millimetres to several centimetres. The cross-cutting veins can be up to 300 mm across, and they often form large masses as illustrated in Plate 2.12.

The veins are mostly composed of pure, finely equigranular quartz. Small areas of pink feldspar are commonly found, often showing some broad relation to the orientation of the planar structures in the host rock. The quartz is probably locally derived from the surrounding rocks and the feldspar indicates the position of the layering before mobilisation and recrystallisation of the quartz. Mica is not developed in the veins, but occasionally, and more so in the semipelitic units, muscovite-biotite mica selvages have formed to the veins.

It was noted that across the project area as a whole there are marked variations in the abundance of quartz veins which are not always attributable to the lithological preferences shown in their development. Within small areas veins will show marked variations in density distribution. The veins will often be found grouped together within one outcrop, with neighbouring outcrops or parts of the outcrop devoid of veins (Plate 2.13). Such irregular development is difficult to interpret, unlike that due to lithological preferences (Plate 2.14), where the quartz veins preferentially developed in the pelitic parts of the outcrop.

On a larger scale the veins are distributed throughout the more psammitic lithologies and also occur in some semipelitic units but are all but absent in the Beinn Dronaig Pelite. The psammitic units to the west of this pelite provided a suitable area for the detailed study of the distribution of quartz veins, although unlike grain size and flagginess a distribution map was not produced. Each category of abundance (absent, R and C) was more or less equally represented in the area as a whole, but three large areas stand out as showing unusual concentrations.

The relative increases in the quantity of quartz veining correspond closely to the areas where major folding is pronounced. Thus, in the west of the project area, in part of the Attadale massive zone, quartz veins are well developed. In the psammites in the folded zone to the north and south of the Creag a' Chaorainn Semipelite quartz veins are also well developed, although they are not developed in the semipelite itself.

In the Achnashellach Banded Psammite immediately to the west of the Beinn Dronaig Pelite quartz veining is not well developed, but as one moves into the zone of large scale folding corresponding to the massive Sgurr na Feartaig Zone, quartz veining becomes pronounced. Tracing the fold zone south the fold core is progressively overprinted by the flaggy zones, but evidence of more extensive quartz veining is still visible.

Although most obviously developed in the folded zones, quartz veins are also present in the flaggy Bendronaig Zone. The increased development is irregular but may be useful in indicating earlier fold cores which have now been wholly overprinted by flagginess.

The overall decrease in quartz veining towards the north of the project area corresponds closely to the flaggy Achnashellach Zone and is very pronounced and uniform. Only several kilometres away to the south and east of the Moine Thrust Zone does quartz veining reappear. Evidently the development of the thrust has either prevented quartz veining from forming or the quartz veining has been obliterated in this zone of severe shearing. It is significant in this context that Lewisian rocks within the Dughaill Semipelite, that is within the flaggy Achnashellach Zone, show marked quartz vein development.

In the Monar Banded Psammite quartz veins are absent or poorly developed over much of the area studied. However, within the biotite gneiss at NH 108 415, and in an area of about one square kilometre surrounding this, quartz veins are comparatively well developed. This area roughly corresponds to that mapped as Lewisian gneiss by the Geological Survey. The proposed interpretation is that the development of quartz veins indicates an early fold closure with which a small area of Lewisian is associated.

There is virtually no development of quartz veins in the Beinn Dronaig Pelite. Some do occur in semipelites close to the Achnashellach Banded Psammite, and some very thick veins were found in pelites near Loch Calavie at NH 0609 3807. Generally speaking the development of any veining within the pelites is quartzo-feldspathic and not quartzose.

(b) Quartzo-feldspathic pegmatites and segregations

Quartzo-feldspathic bodies were only rarely found to the west of the Beinn Dronaig Pelite. That they are limited to the rocks of the east is another indication of the higher degree of metamorphism in these rocks. The origin of most of these bodies is thought to be as a localised metamorphic segregation of the micaceous and quartzo-feldspathic elements of the rocks. The variety of bodies found includes 'lit-par-lit' layers, gneissose segregations, strongly deformed and streaked pegmatites, discordant deformed pegmatites and discordant undeformed pegmatites. The structural significance of each of these types is discussed in Chapter 6.

Within the Monar Banded Psammite there is a 'lit-par-lit' development of quartzo-feldspathic bodies. These are fairly coarse grained and parallel to the layering in the unit. They tend to be restricted to the more micaceous parts of the unit and are illustrated in Plate 2.15. The strongly banded nature of the banded psammites is evident, and the quartzo-feldspathic bands can be seen in the centre and to either side of the photograph. Although laterally persistent and fairly uniform, the competence contrast is illustrated by small folds in the band. Plate 2.16 illustrates this even better, with ptygmatic folding developed in the band in an open fold closure.

The poor competence of the pelites and semipelites has not allowed the formation of 'lit-par-lit' layers. The segregation of the quartzo-feldspathic element is akin to the development of gneissose banding, but has not progressed that far. The result is either strings or knots of quartzo-feldspathic material, irregularly distributed within the petite, but with a broad planar element parallel to the schistosity. The gradation from coarse grained pelite to a pelite full of these quartzo-feldspathic segregations is subtle. Taken one stage further, these knots of

quartzo-feldspathic material can be found on a larger and more persistent scale as pegmatitic layers and pods. In surfaces perpendicular to the regional layering these larger bodies, which are roughly parallel to the layering, are very irregular in form. However, it was often noted that they had a persistence parallel to the lineation and developed rodding. Plate 2.17 illustrates an irregular layer of pegmatitic augen within a semipelite. The semipelite in this photograph also contains a few small segregations. The pegmatite is broadly concordant with layering, and the highly irregular development to be seen is typical. The pegmatite, because of its lack of lateral persistence, probably originated in this irregular form and not as a subsequently deformed, more persistent layer.

Within the Monar Banded Psammite there are irregular pegmatitic layers and pods which have been strongly deformed. The layers are not laterally persistent and are broadly parallel to the layering in the psammites. Plate 2.18 illustrates several of these pegmatites originating as localised segregations from the psammites; their form may have been as layers or pods. If they were layers they have been boudined before being compressed laterally. The sequence for the origin of these bodies is illustrated in Figure 2.4. In the Achnashellach Banded Psammite to the west there are similar bodies but on a much larger scale, just below the Beinn Dronaig Pelite. Plate 2.19 illustrates these larger pegmatitic bodies which appear to have been stretched and boudined.

Within the Monar Banded Psammite discordant pegmatites are rare. The pegmatites are illustrated in Plate 2.11 and as can be seen they can be very irregular, in form. Subsequent deformation has been lateral compression which has distorted the relationship of the banding in the psammite to the pegmatite. Genetically, there may be little to distinguish these pegmatites from bodies previously mentioned which are broadly parallel to layering.

Another group of quartzo-feldspathic bodies are the relatively rare undeformed, discordant pegmatites. Two types were identified, one with pink feldspar dominant, and the other white feldspar dominant. A thin white feldspar pegmatite in Plate 2.17 is nearly perpendicular to layering in the Beinn Dronaig Pelite. Generally speaking the white pegmatites are thinner and finer grained than the pink pegmatites. Although both types are found in the east of the project area, the occurrences to the west of the area are very rare.

Because of the variety of quartzo-feldspathic bodies, and the complex structural interrelations between some of them, it was not possible to produce a useful distribution density map. Where such bodies occur in large quantities the appearance of the rock type is gneissose, and such variations are treated as different rock types. The only important distribution factor, already detailed, is that the quartzo-feldspathic bodies are largely confined to the rocks in the eastern half of the project area.

2.15. Mineral fabrics

During metamorphism of the Moine there was recrystallisation and reorientation of quartz-feldspar aggregates and mica flakes. The mica, often forming layers of sedimentary origin, may have a mineralogical orientation not related to the layering. The quartz-feldspar aggregates form a fabric with both linear and planar elements, generally with the same orientation as the mica fabric. Again, this orientation does not always coincide with the layering. However, because of the intense isoclinal folding and sliding in the western part of the project area the general case was that the layering and fabric elements were co-planar. In these circumstances a structural analysis is not easy and one part of the study of fabrics was to show a direct relation to studies of flagginess and grain size.

As the types of fabric seen have some importance in defining the structure of the area their orientations are detailed in Section 3. However, the relative degree of development of a fabric is important in defining domains covering many square kilometres. Flagginess and grain size are two other elements which broadly define these domains, and as with these features the area where those domains have been studied in detail is to the west of the Beinn Dronaig Pelite.

Psammitic rocks are ideal for the study of quartz-feldspar fabrics, with mica fabrics complementing the study. The pelitic rocks have a dominant micaceous schistosity which is of value in the structural analysis, but the irregular development of which is not helpful in defining rock types. The metamorphic and tectonic history of the psammites to the east is such that a study of fabric domains is not practicable or useful.

The mica fabrics seen are planar, with the development of a partial girdle. The girdle defines the observed linear element. The linear element is fine or very fine grained elongated quartz-feldspar aggregates. The mica tends to lie around these aggregates, so it appears to have a marked linear element. This is by far the commonest expression of lineation observed in many areas of the psammites to the west of the project area, and it gives a good indication of the fabric development and quartz-feldspar grain size.

Within the Achnashellach, Glenuig and Bendronaig flaggy/fine grain zones a study of fabric development was a useful adjunct to the studies already described. No firm criteria were applied and it is not possible to produce any sort of distribution density map. Plate 2.1 illustrates the extremely fine fabric where mica partings illustrate the fabric development. Within the Sgurr na Feartaig and Attadale zones the fabric development is sufficiently variable for it to be a useful consideration in analysing grain size and flagginess. Generally speaking the more clearly defined fabrics are found parallel to layering, but a fabric at right angles to the layering clearly indicates a very massive rock type, illustrated in Plate 2.12.

2.16 Summary

A large part of the project area is formed of psammitic rock types which are considered as a relatively homogeneous unit. This assumption led to the study of the rock types as outlined in this Chapter. The conditions of deformation, with the development of large belts of flaggy, fine grained rocks, are particularly suitable for this approach.

While the psammites to the west of the Beinn Dronaig Pelite proved ideal for studying the relative development of a variety of features, the Beinn Dronaig Pelite and Monar Banded Psammite were not. In the case of the pelites this is largely attributable to the relative competence of the quartzo-feldspathic psammites as opposed to the strongly planar and relatively easily reoriented micaceous nature of the pelites. The Monar Banded Psammites in the east are clearly part of a different regime as regards their tectonic style and degree of metamorphism. Consequently, the approach adopted by other

workers looking at small areas of the Moine (eg. Ramsay, 1954; Kassler, 1961) are better applied to this area.

Regionally, the project area lies in the westernmost part of the Moine belt (Figure 1.1). The psammites to the west of the area have been found to fall into a belt in which tectono-metamorphic styles can be zonally identified by studying qualitatively such features as grain size, flagginess, sedimentary structures, quartz veins and mineral fabric development. A study of variations of lithology within this area is not only important from the stratigraphic viewpoint but is also a useful adjunct to a structural analysis. The influence of lithology on the relative development of many of the observed features was noted in this context.

Although an outline tectonic and metamorphic interpretation of much of the project area could be based on the evidence put forward in this section, a detailed study of minor structures, structural trends and fabric elements is considered essential before doing so. However, the following conclusions can now be borne in mind:

a) Sedimentary history — the area of psammites contains features which indicate a shallow marine shelf or beach environment. The observed boundaries between units are largely sedimentary and this may even be true of the Lewisian/Moine boundary in the west. Little can be said of the sedimentary origin in the pelites.

b) Metamorphic history — the Beinn Dronaig Pelite and Monar Banded Psammites are of an apparently higher metamorphic grade than the rocks to the west of the project area. Although retrogression has been important towards the west there is also significant evidence that the most westerly parts of the project area were of an originally lower grade of metamorphism.

c) Tectonic history — to the east of the project area the structural evidence so far outlined points to episodes of intense folding and refolding with the consequent tectonic emplacement of Lewisian rocks. However, although to the west the rocks have been intensely deformed by folding, the later stages of tectonic development have been by progressively intensifying slide zones. These zones have been noted as being marked by increased flagginess and finer grain sizes. The final development of the most northerly zone is directly related to the formation of the Moine Thrust Zone. This development occurs not only after major folding but also after development of the other two major slide zones.

3. THE STRUCTURAL ELEMENTS AND THEIR ORIENTATIONS

3.1 Introduction

A range of structural observations were made in the field, and the types of structures observed and their orientations are described in this section. The information outlined is provided to aid in understanding the structural history of the area. To this end it is considered important that groups of structural elements should be identified. Without this information a comparison of elements of like orientation but dissimilar genesis may be made.

Three broad categories of structural element will be considered:

1) Planar structures
2) Linear structures
3) Minor folds, with associated planar and linear elements.

The planar and linear structures are nearly always apparent on the mesoscopic scale, the former much more than the latter. The linear element almost invariably expresses itself within one of the planar elements of an outcrop, and as such the two are structurally inseparable. Although minor folding is less frequently readily identifiable, a study of the macroscopic folds, both observed and inferred, relies on evidence from minor folding as well as planar and linear orientations. The relationship of minor fold patterns to major folds is well established, but must be treated with caution in an area of repeated deformation (see Section 1).

3.2 Fabric element groups

Fabric element groups, with style as the basis of the group, are important in defining generations in the deformational sequence. A group can be defined using the strength of development of a fabric element as well as its form. A combination of fabric elements into groups gives an impression of the overall fabric. The most important fabric elements defined in the area are the planar and linear.

The planar fabric falls into two broad categories:

1) Layering — a foliation defined by lithological layering, formed by parallel layers of contrasted mineral assemblages. In the project area these are almost invariably micaceous and non-micaceous layers.
2) Foliation — any other foliation or schistosity, often noted as axial planar to a fold generation. This is either formed by the orientation of mica flakes within the lithological layering or by the planar preferred orientation of quartz grain aggregates giving a platy fabric.

The lineations fall into five categories:

1) Quartz rodding lineation — this is the preferred orientation of elongated quartz grain aggregates in the psammites, almost invariably associated with a foliation of platy aggregates.
2) Mineral lineation — this term is used in the area to describe instances where the expression of a quartz rodding lineation is seen in the preferred orientation of mica flakes lying in a partial girdle about the elongated aggregates. This lineation, which is very common in the area, is found in most fine and very fine grained psammites.
3) Crenulation lineation — the expression of a lineation by crenulation of mica is common in the pelites and semipelites of the area. It is believed to be related to the mineral lineation in mode of formation, but is much coarser.
4) Intersection lineation — the intersection of a quartz or mica platy fabric with lithological layering is common. The resultant lineation is generally parallel to a quartz rodding lineation. However, complex intersection patterns do develop in the area as a result of repeated deformation without a single dominant phase to obscure earlier structures.
5) Quartz vein lineation — this lineation is formed by quartz rodding as above. However, there is no internal lithological reference in these bodies and their generation is tectonically controlled. Hence it is important that such an obvious group of lineations should be separately identified.

On the basis of the fabric elements defined above the point diagrams will separately identify the following categories of fabric element:

1) Layering, often parallel to an axial planar fabric
2) Axial planar fabrics, where oblique to layering
3) Axial planes of minor folds
4) Lineation (quartz rodding, mineral, intersection, crenulation)
5) Quartz vein lineation
6) Axes of minor folds.

3.3 Method of analysis

The observations of the orientations of structures can often be compiled into point diagrams. For a study of the orientations of the planar and linear structures, including such elements as are observed in minor folds, the project area is split into five areas. The boundaries for these areas (Figure 3.1) are broadly based on the zones of grain size and flagginess (Figures 2.1 and 2.2). Because of the wide range of internal complexities in some of the larger areas a series of sub-areas are used. A split into smaller areas as opposed to sub-areas is not considered useful because of the basic structural integrity of the five large areas. The areas and sub-areas are:

a) Attadale area
   1) Attadale West sub-area
   2) Attadale South-East sub-area
   3) Attadale North-East sub-area
b) Bendronaig area
c) Achnashellach area
d) Sgurr na Feartaig/Glenuig area
   1) Sgurr na Feartaig North sub-area
   2) Glenuig North sub-area
   3) Sgurr na Feartaig/Glenuig South sub-area
e) Monar area
   1) Monar North sub-area
   2) Monar West sub-area
   3) Monar South-East sub-area
   4) Monar North-East sub-area

To the west of the Beinn Dronaig Pelite most of these boundaries are the same as those for the zones of flagginess. The Bendronaig and Achnashellach areas are readily comparable, but as the Attadale and Sgurr na Feartaig/Glenuig areas are structurally more complex, they have been split into a more complex arrangement of sub-areas. The Attadale sub-areas are by far the most complicated and the Attadale West sub-area in particular stands out structurally.

Within and to the east of the Beinn Dronaig Pelite the split into sub-areas is partly to aid in studying widespread parts of the area, and to isolate the complexity of folding in the Monar North sub-area. The Monar sub-areas cover parts of the Beinn Dronaig Pelite and Monar Banded Psammite as the lithological boundary between the two has no readily apparent structural significance.

3.4 Point diagram interpretation

All the observations were plotted as points on equal area stereographic projections. Before detailing each area it should be noted that the dominant linear and planar trends show a remarkable uniformity over the project area. The dominant planar surface in all sub-areas strikes about 030º/30º E dip. Only in one sub-area is there any large scale deviation from this trend. There is also one broadly dominant linear trend to 155º/25º plunge, ie. pitch 60º from SW. However, there are some sub-areas with a dominant lineation of about 124º/28º, ie. pitch 87º from SW, and one area with a variety of linear trends displayed. A synthesis based on the observations from each of the sub-areas is given in Table 3.1.

Table 3.1. Synthesis of point diagram data for the areas and sub-areas of the project area

Area	Sub-area	Mean fold axial plane	Mean dominant lineations	Pitch of lineation on fold axial plane	Comments on fold style
a) Attadale	1. Attadale West	021º/28º E	125º/27º	78º f. South	Isoclinal with complex lineation pattern
	2. Attadale South-East	033º/29º E	123º/29 º 153º/18º	90º 61º f. South	Tight
	3. Attadale North-East	026º/31º E	157º/25º 114º/30º	53º f. South 87º f. North	Isoclinal
b) Bendronaig		033º/32º E	154º/28º	63º f. South	Isoclinal
c) Achnashellach		~021º/23º E	143º/19º 080º/19º	39º f. South 62º f. North	Isoclinal refolded about open axis 060º/15º
d) Sgurr na Feartaig/ Glenuig	1. Sgurr na Feartaig North	015º/32º E	~160º/18º	44º f. South	Tight, about axis 165 /16º
	2. Glenuig North	027º/26º E	149º/22º	60º f. South	Isoclinal
	3. Sgurr na Feartaig/Glenuig South	040º/32º E	161º/27º	62º f. South	Isoclinal
e) Monar	I. Pelite North	022º/35º E	160º/24º	46º f. South	Isoclinal
	2. Pelite West	~028º/38º E	~152º/36º	72º f. South	Isoclinal
	3. Monar South-East	038º/37º E	160º/33º	64º f. South	Isoclinal, coaxial open refolding
	b. Monar North-East	108º/42º S (limbs of fold 022º/40º E 148º/82º W)	154º/32º	53º f. East (56º f. South) (32º f. South)	Isoclinal, coaxial refolding about open axis

a) Attadale area

1) Attadale West sub-area (Figures 3.2 and 3.3)

The layering poles are quite tightly clustered, defining an average plane of 021º/28º E. Here, as elsewhere in the rest of the project area, the evidence of minor folds (section 3.6) is used to show the relation between layering and axial planes. The axial planar fabric poles show essentially the same distribution as the layering, and the pattern indicates tight folding (Fleuty, 1964b).

The lineation broadly lies within the mean layering plane but there is a wide spread of lineation pitch. The dominant lineation is about 125º/27º, ie. pitch 78º from SW, and there are a few between 030º and 100º. The quartz vein lineation shows a broader spread, with essentially the same dominant lineation direction, but there are minor concentrations to 045º and 080º. A few fold axes are represented in the girdle, generally between 040º and 140º. There is a noticeable concentration relative to other linear elements between 040º and 070º. Overall, the pattern of lineations of the various groups is very complex.

2) Attadale South-East sub-area (Figures 3.4 and 3.5)

The layering poles are generally quite tightly clustered, but do show some spreading into a girdle with an axis of about 116º/29º. This may indicate tight folding with the axial plane about 033º/29º E, but the axial planar fabric poles broadly compare with the layering in orientation, with a similar degree of spreading.

The lineation lies generally close to the mean planar fabric and is confined in trend to 090º to 170º. There is a distinct maximum to 123º/29º, ie. pitch 90º, and a smaller point concentration to 153º/18º, ie. pitch about 61º from SW. There are very few quartz vein lineations, but what there are only coincide with the main maximum concentration. The few fold axes also coincide with the main maximum with the exception of one to 020º/12º. The lineation is axial to a dominant fold phase producing a strong fabric in the psammites and quartz veins and with many associated minor folds.

3) Attadale North-East sub-area (Figures 3.6 and 3.7)

The layering poles are very tightly constrained to a point maximum with no girdle development. The mean layering orientation is 026º/31º E. Partly because of the nature of the dominantly semipelitic lithologies in this sub-area no distinct axial planar fabrics are noted.

The limited information on lineations indicates a dominant lineation to 160º/25º, ie. pitch 53º from SW, with one lineation to 118º/32º, ie. pitch about 90º. The quartz vein lineation is only closely associated with the main lineation maximum, and although one fold axis is also associated with this maximum there is a second at 110º/30º. The lineation pattern is quite similar to that in Attadale South-East.

b) Bendronaig area (Figures 3.8 and 3.9)

The layering poles are tightly constrained, with a dominant single maximum and only a slight spread. A slight swing in strike trend towards the north in the south of the sub-area (Enclosure 3) gives the spread. Otherwise, there is no evidence of folding and layering is to 033º/32º E. No distinct axial planar fabrics are noted.

The lineation similarly lies within a fairly tightly constrained maximum. The mean trend is 154º/28º, ie. pitch 63º from SW, and there is a single observation to 110º/28º, ie. pitch about 80º from NE. The few quartz vein lineations coincide with the main lineation maximum, but no fold axes are noted.

c) Achnashellach area (Figures 3.10 and 3.11)

The poles to layering show a spread along part of a small circle girdle with the axis approximately 060º/15º. A study of the trend map (Enclosure 3) shows a broad swing in strike trend matching the observations from the point diagram. The interpretation is of gentle or open folding of flat layering. The mean layering, corresponding to a concentration of the layering poles in the girdle, is 021º/23º E, but there is a spread from 054º/45º E to 120º/20º E. The few axial planar fabric poles noted match the spread of layering poles.

The variations in orientation of the lineations are not entirely the result of the folding, as can be seen in the trend map (Enclosure 4). The dominant lineation is approximately 143º/19º, ie. pitch 59º from SW, but there is a significant lineation development to 080º/19º, ie. pitch 62º from N. The quartz vein lineations are well represented in the main lineation maximum, but also have a spread of orientations. The few minor fold axes are similarly irregular.

d) Sgurr na Feartaig/Glenuig area

1) Sgurr na Feartaig North sub-area (Figures 3.12 and 3.13)

The layering poles have a broad spread on a girdle with an axis of 165º/16º. A fairly well constrained maximum in the girdle coincides with the axial planar fabric poles, both trending 018º/32º E. A study of the trend map (Enclosure 3) indicates an open hinge zone in the south to which there are no recorded axial plane poles.

The lineation is clustered around the mean layering plane broadly between 115º and 180º. Although the main concentration is spread over about 20º of the plane the mean lineation is about 160º/18º, ie. pitch 44º from SW, which is very close to the fold axis as postulated in section 3.6. The quartz vein lineation is generally parallel to the lineation, as are the many minor fold axes. However, there are several lineations spread between 000º and 075º which are related by trend to lineations in the west and south-west of the area.

2) Glenuig North sub-area (Figures 3.14 and 3.15)

The layering poles lie in a tightly constrained point maximum corresponding to 027º/26º E. No distinct axial planar fabrics are noted. The lineations lie broadly within the mean layering plane between 115º and 180º with no other trends noted. Most of the lineations lie within a good point maximum to 149º/22º, ie. pitch 60º from SW. The quartz vein lineations coincide with this maximum, as does the only minor fold axis noted. The overall lineation pattern is consequently very simple.

3) Sgurr na Feartaig/Glenuig South sub-area (Figures 3.16 and 3.17)

The layering poles fall close to a single maximum and are generally fairly tightly constrained about 040º/32º E. No distinct axial planar fabrics are noted in the sub-area.

The lineations are almost entirely confined to a single maximum within the mean layering plane of 161º/27º, ie. pitch 62º from SW. Two lineations are noted between 090º and 110º, possibly related to trends in the Sgurr na Feartaig North sub-area. The quartz vein lineations all lie within the main lineation maximum, but no minor fold axes are noted.

e) Monar area

1) Monar North sub-area (Figures 3.18 and 3.19)

The layering poles are nearly all tightly constrained to a single maximum in which there is a good point concentration. The mean layering plane is 022º/35º E. The open style of the fold hinges noted in 3.6 is indicated by a sharply deviating planar orientation. The axial planar fabric pole and minor fold axial plane pole lie within the single point concentration.

The lineations are largely confined to a point maximum, on the mean axial plane, of 152º – 170º, with a mean of 160º/24º, ie. pitch 46º from SW. There are a few lineations to about 180º, and the overall spread is from 180º to about 130º. The only quartz vein lineation noted coincides with the main maximum, but the two minor fold axes lie to about 180º. As well as the dominant lineation direction there is evidently a swing to a more southerly trend.

2) Monar West sub-area (Figures 3.20 and 3.21)

The poles to layering show some spread over a girdle, believed to be a great circle, for which the axis is 084º/20º . A distinct concentration of layering poles corresponds to a mean layering of 028º/38º E. This more constant layering is found in belts to either side of the sub-area (section 3.6 and Enclosure 3).

The lineation shows a broad spread in plunge but the trend is generally confined between 130º and 170º. The mean lineation is taken as 152º/36º, ie. pitch 72º from SW. The spread in plunge (4º – 53º) is the result of the expression of a fairly constant lineation trend on planar surfaces of differing strike and dip in the centre of the sub-area (Enclosure 3). Only one quartz vein lineation is noted with a trend related to the broad maximum of the lineation. No minor fold axes are noted.

3) Monar South-East sub-area (Figures 3.22 and 3.23)

The poles to layering, including those from the Lewisian in the centre of the Beinn Dronaig Petite, broadly define a single point concentration. However, there is some spread over a great circle girdle with the axis to 160º/33º. The main maximum is equivalent to layering to 038º/37º E. There are only a few distinct axial planar fabric poles noted, with the same orientation as the layering maximum. The divergence of layering poles is the result of the same generation of folding seen in the Monar North-East sub-area.

The lineations are almost entirely confined to a small point maximum parallel to the open fold girdle axis at 160º/33º, ie. pitch 64º from SW on the dominant planar surface. The open folding is clearly coaxial with the tight folding defined by the layering and mean axial plane. The single quartz vein lineation, occurring in a quartz-feldspar segregation in the pelite, has an unusual orientation. The only fold axis noted, to 032º/10º, is in fact the axis of a series of gentle flexures in the semipelite.

4) Monar North-East sub-area (Figures 3.24 and 3.25)

The layering pole pattern is the most complicated of any of the sub-areas. However, all but one of the poles to layering lie in a girdle with an axis to 154º/32º. There are two distinct maxima representing planes to 022º/40º E and 148º/82º W, which correspond to the limbs of open folding with axial plane 108º/42º S. The inter-limb angle is about 105º. The limbs of the open folding are also believed to represent the approximate axial planes of tight to isoclinal folding within the limbs. No distinct schistosity was noted, but the minor fold axial planes lie within the girdle, having been refolded by the open folding.

The lineation in this sub-area is perhaps the simplest of any sub-area. There is a distinct, tightly constrained point maximum with about the same orientation as the open folding axis, that is 154º/32º. There is only a slight deviation from this trend and it is concluded that the open folding is coaxial with the dominant lineation of an earlier fold phase. The quartz vein lineations and minor fold axes show the same trend as the lineation, confirming the coaxial nature of the fold structures.

3.5 Lineation development

The degree of development of the planar fabric has been described in section 2, and a map showing zones related to development has been produced (Figure 2.2). The lineations noted in the area also have varying degrees of development. It is useful to outline these variations as they can be an aid in the structural interpretation. The trends (Enclosure 4) have been described by sub-areas, and the degree of development can also be described using these boundaries, (Figure 3.1). An assessment of development is largely subjective, with grain size and lithology having obvious influences on interpretation. However, the following should be noted:

a) Attadale area

1) Attadale West sub-area

The ESE lineation is strong in the south of the sub-area and weak in the centre. The E to NE lineation is rarely developed in the south but well developed in the middle of the sub-area. Any lineation found in the extreme west and south of the sub-area is very poor. To the north the trends and development of lineations is mixed.

2) Attadale South-East sub-area

The ESE lineation is strong and dominant in the south of the sub-area but weakens further north. The SE lineation only appears in the extreme south-east, where it is well developed.

3) Attadale North-East sub-area

Lineation development in the sub-area is poor, weak and often irregular.

b) Bendronaig area

Nearly all the lineations, regardless of trend, are poorly developed and weak.

c) Achnashellach area

Nearly all the lineations are poorly developed and weak. However, some of the atypical trends close to the MTZ have a good development.

d) Sgurr na Feartaig/Glenuig area

1) Sgurr na Feartaig North sub-area

The SE lineation is strong in areas of obvious folding, but to the east and west of the central fold zone weakens markedly. The atypical orientations are always weak.

2) Glenuig North sub-area

Generally weak and poorly developed lineations, but good in a few places.

3) Sgurr na Feartaig/Glenuig South sub-area

Generally weak and poorly developed lineations. A few places where the lineations are well developed are related to the major fold closure believed to be central to the sub-area.

e) Monar area

1) Monar North sub-area

Very weak or absent along the western margin of the sub-area, becoming strong and well developed to the east (centre of the Beinn Dronaig Pelite).

2) Monar West sub-area

All lineation development is poor and weak.

3) Monar South-East sub-area

Mostly strong and well developed lineations.

4) Monar North-East sub-area

Mostly strong and well developed lineations.

3.6 Minor folds

The style and orientation of minor folds (Fleuty, 1964b) can be used to give some indication of the location and form of major fold belts and in some cases sense of shear can be gauged (Dennis, 1972). The interference patterns seen in the minor folding also find a parallel in the major folds and form of lithological outcrops.

Although a variety of minor folds may be divided into a series of fold generations, these are not always characterised by a consistency of style and orientation (Park, 1969). However, any generations which can be identified will be useful in the interpretation of the deformational history of the area and as an aid in regional correlations. In addition, certain fabric elements, eg. 'platyness' and quartz aggregate elongation lineations, can sometimes be genetically related to folds and ultimately to fold generations. Such correlations increase the usefulness of minor fold data in both local and regional structural correlations.

The same areas and sub-areas used for describing the planar and linear features (Figure 3.1) are used to describe the occurrences of minor folding. The results are correlated to give a broad picture of the major fold patterns and generations throughout the area. As all the folding seen is between class 2 and 1C on the basis of dip isogon parallelism (Ramsay, 1967, p. 363 ff) this is not noted unless the folding is a particularly good or clear example of 'similar' (class 2) style folding.

a) Attadale area

1) Attadale West sub-area

This is the largest and most complex area/sub-area in which evidence of intense folding remains. Several distinct belts with varying styles and amounts of minor folding can be seen. Broadly, these are; a major fold belt parallel to and within the NE – SW trending Strathcarron Banded Psammite (Enclosure 2); a very small part of the sub-area below the thin Lewisian inliers on Carn Mor, around NG 970 440, in which a clear, single fold generation is developed; a belt about 3 km wide across much of the southern half of the sub-area in which there is one dominant fold generation, distinct from that to the west of Carn Mor; and the remaining large part of the sub-area in which a variety of poorly preserved fold generations can be seen.

In the Strathcarron Banded Psammite, which outcrops between Attadale House and Strathcarron (Enclosure 1), there is a poorly preserved group of open to tight (Fleuty, 1964b) minor folds with little or no, axial or axial planar fabric. One fold axis is to 102º/low plunge and another to 100º/23º, both on single intrafolial tight folds about 5 – 10 cm across. There is one tight minor fold pair about 30 cm across in the section of the River Taodail at NG 9465 4217. The axis is 048º/13º, and on the assumption that its vergence (Dennis, 1972, p. 152) indicates a major first-order fold (Ramsay, 1967, p.355) the closure is up to the north-west.

To the west of the Lewisian inliers on Carn Mor there is a fold hinge belt about 200 m wide stretching NE – SW along the hillside. The hinge displays open folding of 1 m and more in wavelength, generally irregular in form but with a good axial planar quartz-shape fabric parallel to layering locally, ie. about 045º/25º E. The fold axes are consistently indicated by a strong quartz rodding lineation to about 080º/20º. The limbs to the fold hinge have no minor folds, and up the hillside towards the Lewisian inliers the fold axis related lineation gradually diminishes in intensity. The fold hinge belt disappears to the north-east under the influence of the flaggy Achnashellach Zone (Figure 2.2).

To the south-west of this open style fold hinge a few folds of the same style are found, but in isolated bands. There is an open fold about 1 m across with axis to 064º/14º and a good axial planar quartz-shape fabric. An intrafolial tight fold about 10 cm across with axis to 096º/16º is of an atypical style when compared to the folding found east of Attadale House, and indicates that this part of the sub-area may be transitional in the development of fold generations, with some refolding. Minor fold interference patterns (Figure 3.26) found in the area to the east of Strathcarron confirm this view, as they show refolded intrafolial isoclinal folds on a small scale (about 1 cm across).

To the east of Loch Carron, up to about 0.5 km above the Strathcarron Banded Psammite, there is a narrow NE – SW trending belt in which there is no minor fold evidence. To the east of this is a major tight fold hinge zone about 0.5 km wide, stretching from the River Taodail (Enclosure 1) to the south-west for 3 km. The typical fold style, with strong axial planar fabric, is illustrated in Figure 3.27. The axial direction of the minor fold generation associated with this hinge is parallel to the local, dominant quartz rodding lineation, ie. about 125º/25º. The tight fold pairs illustrated in Plate 3.1 and Figure 3.28 are typical of the folds seen to the west of the hinge,

occurring as they do in bands less than 1 m wide and consistently indicating a synformal closure to the north-east, ie. within the fold hinge belt. Plate 2.12 illustrates the broader belts of folding characteristic of the fold hinge and displaying no preferred vergence.

About 1.5 km to the east of Loch Carron there is a flat belt with very few minor folds trending NE – SW. The occurrence of minor folds increases towards the south-west, with folds of a generation related to the fold belt immediately to the west being present Within the flat belt there are several intrafolial isoclinal folds, only about 10 cm across, and one having an axial lineation to 045º/15º.

Continuing eastwards out of the flat belt, to about 2 km from Loch Carron, there is the start of another major fold hinge, about 0.7 km wide, with tight to open folding, the style and scale of which are illustrated in Plate 2.14. The fold axes are parallel to the local quartz rodding lineation of 120º/25º, and essentially the same as that seen in the fold belt to the west. No minor fold evidence is noted which would indicate the direction of closure, and the belt of folding passes to the east into a flat lying area devoid of minor folds about 3 km from Loch Carron. The flat belt marks the approximate junction with the Attadale South-East sub-area.

The most complex area is that which lies between the Lewisian inliers on Carn Mor and the fold hinge belts to the east of Loch Carron. Traced northwards the westerly fold hinge (synformal) merges with the folding below the Lewisian. The flat belt between the folds extends north across the River Taodail and broadly connects with the flat belt surrounding the Lewisian inliers. The easterly fold belt disappears into badly exposed ground, although some evidence of a possibly related NE – SW trending belt can be seen in the western part of the Attadale North-East sub-area.

Between the River Taodail and Carn Mor there are only a few recognisable minor folds, and the majority of the evidence of major structures has to be taken from the fold generation related lineations. Some of the open style folds seen have good axial and axial planar fabrics, with axes to about 050º/10 – 20º plunge. They are in belts up to 2 m across, and contrast with small (1 – 10 cm) intrafolial tight folds of apparently the same generation. This generation is related in style and orientation to that seen below the Lewisian inliers. The evidence of quartz rodding lineations points to the folds of 120º/20º plunge found in the south influencing this part of the sub-area, but nowhere were folds of that generation found.

2) Attadale South-East sub-area

There is a distinct fold hinge belt just to the north of Bealach Alltan Ruaridh around NG 985 390. The belt has much minor folding of open style, but widely varying scale, with a very well developed quartz rodding and platy shape fabric axis and axial plane. The axis is about 123º/29º and the axial plane is parallel to layering seen either side of the fold, ie. 033º/29º E. The development of the fold hinge is good in the south, but moving northwards between the Creag a' Chaorainn Semipelite and the Bendronaig area in the east the belt diminishes. Although there are no minor fold pairs, strike trend analysis would indicate a closure to the north- east (Enclosure 3). The fold hinge is traceable from the edge of the project area north for about 1 km, and is 0.5 km wide at its maximum. To the west, around the southern end of the Creag a' Chaorainn Semipelite, there is a flaggy belt with no minor folds. In a belt about 0.7 km wide along the western edge of the sub-area a complex minor fold pattern appears. There are intrafolial tight folds about 10 cm across with at least one axis to 020º/12º, and there is one intrafolial minor fold pair illustrated in Figure 3.29. In narrow belts 1 – 2 m across there is tight – open folding with a good axial planar platy shape fabric and axes parallel to the local quartz rodding lineation of about 130º/25º. These tight – open folds in narrow belts are believed to be of the same generation as the major fold core to the north of Bealach Alltan Ruaridh, while the rarer intrafolial tight folds are of the generation of folds with north-east trending, low plunge axes found only to the north and west.

3) Attadale North-East sub-area

Minor folds are rare over much of the sub-area. Within the Creag a' Chaorainn Semipelite, 3 km west of Loch an Laoigh, there are intrafolial isoclinal folds about 10 – 20 cm across. The axis of one is 145º/22º, parallel to the local quartz rodding lineation, while other axes are between 130º and 170º with a similar plunge. They are probably genetically related to the major fold hinge in the Attadale South-East sub-area which has a similar axial trend.

Intrafolial tight fold pairs about 10 cm across can be seen to the west of Loch an Laoigh and on Carn Mor to the north, around NH 030 460. Although determination of fold axes is not always possible, in one instance on Carn Mor it is to 110º/30º, not parallel to the locally developed quartz rodding lineation. However, the sense of vergence of the fold pairs is consistently to the north-east along the whole of the eastern edge of the Creag at Chaorainn Semipelite. This may indicate a major closure in the semipelite to the north-east, which is consistent with the outcrop pattern (Enclosure 2), or a uniform shearing direction with the Bendronaig area overriding the Attadale area from the SSE.

A belt of better preserved folds in the sub-area lies well to the north around NH 012 458. Tight folds several metres across, but with open style hinge zones, can be seen. The folding has no preferred vergence, and the fold axis of about 100º/20º is parallel to a strong, fine quartz rodding lineation in the immediately adjacent Achnashellach area. The axial planar fabric is well developed and the fold generation is probably related directly to the easterly fold hinge belt in the Attadale West sub-area and also to the strong fold hinge belt in Attadale South-East.

b) Bendronaig area

There are very few minor folds in this dominantly flaggy area. Only in the half of the area close to the boundary with the Attadale area in the west, where the intensity of flagginess gradually diminishes, are traces of minor folding found. About 1 km north-east of Bealach Alltan Ruaridh there is an intrafolial isoclinal fold about 15 cm across, but of indeterminate axial direction (Figure 3.30). This fold is very close to the Attadale area. About 0.7 km west of Loch an Laoigh (specimen 216, Figure 4.27) there are extremely faint traces of a tight minor fold with open hinge about 5 cm across. The fold axis is parallel to the very faint, fine quartz rodding lineation of 137º/33º.

c) Achnashellach area

The majority of folds are of a style and generation associated with the late-stage brittle to semi-ductile deformation above the Moine Thrust Zone (MTZ). From Craig to Lair such folding is of increasing intensity, but over large parts of the south and east of the area there are virtually no folds observed. A gentle flexure, with axis to 040º/low plunge and several metres across, is probably related to the major swing in strike trend of the Moine about a broadly north-easterly axis and apparent in Enclosure 3.

Between Loch Dughaill and Carn Mor, just above the Dughaill Semipelite, there is a small part of the area close to the boundary with the Attadale area where faint tight minor folds as illustrated in Figure 3.31 can be seen. Although there is a quartz platy fabric parallel to the axial planes this is probably not axial planar in generation, the folding being a remnant in the flaggy Achnashellach Zone (Figure 2.2) of major folding to the south-west in the Attadale West sub-area. The axial direction of these folds is about 075º/15º, and there are also some intrafolial isoclinal folds with axes broadly 060º – 090º, parallel to the faint locally observed and similarly variable lineations.

There is no minor folding immediately below the Lewisian inliers on Carn Mor, but just above them there is tight folding on a small scale (of the order of 10 cm wavelength) with axes to 076º/14º. This fold style disappears in the flaggy belt below the thin petite on Carn Mor, and elsewhere in the immediate vicinity flagginess and a total lack of minor folding is normal.

There are no minor folds seen in the east of the area for about 5 km east of the MTZ. In the area close to Glencarron Lodge intrafolial tight folds of the order of 10 cm across can be seen, but axes are indeterminate and this part of the area is isolated by virtue of poor exposures.

d) Sgurr na Feartaig/Glenuig area

1) Sgurr na Feartaig North sub-area

The sub area is characterised by a central region with a wide variety of fold styles and scales, but these do not clearly point to the major interference pattern postulated in Chapter 5. This central region between Sgurr na Feartaig and Pollan Buidhe shows a marked swing in strike trend through 360º (Enclosure 3) and the area is characterised by massive open folds on scales from 0.5 m to several metres, with possibly more than one generation being present. There is a consistent axial direction parallel to the local quartz rodding lineation, with open folds being noted to 180º/11º, 169º/13º, 152º/20º and 157º/18º. As well as this open folding there are tight to isoclinal folds of a smaller scale, with axes noted to 160º/18º and 158º/7º. The axial planar fabric to all these folds is poorly developed or absent.

At the northern end of Beinn Tharsuinn, around NH 060 445, the open folding on a large scale is still present. A hinge zone about 10 m across has a weak axial planar fabric, with the weak lineation of 154º/14º probably axial to the folds. Whereas to the north the strike trend is highly irregular, here the layering locally, parallel to the axial plane of the open folding, is to about 031º/20º E and constant.

To the north of the sub-area, around Cona Mheallain, there is a clear, tight fold about 200 m across, with associated third-order folds. There is on Cona Mheallain a clear belt of folds with no preferred vergence and axes to about 130º/26º. Intrafolial tight isoclinal minor fold pairs about 10 – 20 m across clearly indicate a closure to the south and good axis parallel to the quartz rodding lineation as seen on Cona Mheallain. To the east of the large belt of open folding west of Pollan Buidhe a similar major fold, also closing to the south, can be identified.

The east of the sub-area is marked by the appearance of flagginess in the Glenuig sub-area, but to the west, along the ridge between Sgurr na Feartaig and Cona Mheallain, the position is less clear as there are no minor folds recorded.

2) Glenuig North sub-area

There are very few minor folds in this sub-area, which is equivalent to part of the flaggy Glenuig Zone (Figure 2.2). There are some intrafolial isoclinal folds a matter of 10 cm across, and one with axis to 150º/low plunge can be seen on the western ridge of Sgurr Choinnich. The axis is parallel to the quartz rodding lineation of the area to 149º/22º (Table 3.1), and the fold has a small, open style hinge. The overprinting of shear induced flagginess in the sub-area has left few remnants of a fold generation probably related to that seen in the Sgurr na Feartaig North sub-area.

3) Sgurr na Feartaig/Glenuig South sub-area

There are virtually no minor folds across the southern part of the sub-area in Coire na Sorna. Moving northwards onto the south-west flanks of Sail Riabhach there are intrafolial tight to isoclinal folds only a few cm across, but with an axial planar platy shape fabric slightly discordant with the local layering (Table 3.1). Such folds are only found in a NE – SW trending belt in the middle of this part of the sub-area.

On Sail Riabhach, lying below (to the west of) the Beinn Dronaig Pelite, there are some intrafolial, tight minor fold pairs up to about 30 cm across, similar to those illustrated in Plate 3.2 and Figure 3.32. The axes are difficult to determine in most cases, as are other fabric elements in the very fine grained striped psammite, but they appear to be parallel to the lineation locally, about 161º/27º. The fold pairs have a consistent north-easterly vergence as seen perpendicular to dip of the layering (approximately south-east). They probably indicate a major closure to the south below the Beinn Dronaig Pelite and not a shearing direction, as a major southerly closure can be seen further north.

To the south of Beinn Tharsuinn, around NH 040 420, there is a belt of tight to open folding 200 – 400 m wide with folds of the order of 1 – 10 m across. There is a good axial planar platy fabric parallel to the layering in the sub-area (Table 3.1) and the fold axes are to about 170º/20º, parallel to the quartz rodding lineation locally. Figure 3.33 illustrates the fold style in the centre of the major fold hinge, which strike trend analysis indicates as closing to the south. In generation the fold is probably the same as that responsible for the major closure in the Sgurr na Feartaig North sub-area, and relates to minor fold evidence already noted to the south.

e) Monar area

1) Monar North sub-area

The sub-area includes the Lewisian inliers (Enclosure 2) on Moruisg, west of Glenuig Lodge and on Sgurr a' Chaorachain. Minor folding is confined to a narrow belt in the sub-area, and elsewhere there are no folds recorded. The Lewisian on Moruisg possibly has an internally complex structure for which there are no details available, as it is outside the project area.

The narrow belt without folds at the base of the pelite is only a few metres wide, and the overlying belt of folding is less than 100 m wide but traceable for about 5 km north-east to south-west. Within the belt there are bands of tight folding about 0.5 – 1 m wide as illustrated in Plate 3.3, and these are best developed in the less pelitic parts of the assemblage. Although in one locality about 1.5 km south of Pollan Buidhe the fold axial plane can be measured as 030º/34º E, that is broadly parallel to the layering locally, there is no axial planar shape fabric. The local quartz rodding lineation is also parallel to the fold axis, noted as about 180º/20º. Within the fold belt there is no preferred sense of vergence, indicating a fold hinge, but there are fold belts of consistent north-easterly vergence below the hinge, indicating that it is a closure to the south-west, ie. an antiform.

2) Monar West sub-area

This poorly exposed sub-area extends only as far into the Beinn Dronaig Pelite as the Lewisian inliers north of Loch Calavie, but not into them. Fold evidence is scant and poorly preserved, but is broadly confined to a central NE – SW trending belt. There are narrow belts about 100 – 200 m wide without any recorded folds to either side at the central belt. In most of the central belt only the less pelitic areas display minor folds, and these are intrafolial isoclinal folds of the order of 10 cm across with indeterminate axes. In a small part of the centre of the central belt, 3 km north of Loch Calavie, around NH 054 408, there are intrafolial tight fold pairs on the same scale, but with no consistent sense of vergence and indeterminate axes. It is probable that the wide belt of poorly preserved folding is a relic of a hinge zone in this vicinity.

3) Monar South-East sub-area

Throughout most of this large sub-area, which includes the Lewisian inliers north of Loch Calavie, there are few minor folds. Around Pait Lodge tight – open folds of only a few cm wavelength, but in belts several metres across, indicate a major fold hinge by the lack of preferred vergence. There is a very strong axial planar quartz platy fabric, with lithological layering faintly indicating the fold style (Figure 3.34) and axes to about 160º/30º, parallel to the lineation locally. There is no observed minor fold vergence to indicate the closing direction of the major structure.

Throughout the rest of the area there are a few small intrafolial isoclinal folds recorded. About 0.7 km south-east of Loch Calavie there is intrafolial tight – open folding about 10 cm across and of indeterminate axis. The fold development is asymmetrical but vergence is not known.

Within the Lewisian north of Loch Calavie there are some unusual folds, believed to be of Lewisian age. One recorded axis is 182º/10º, but there is no axial or axial planar fabric. The folds, with open hinges, are only about 20 cm across and show no consistency of style or orientation.

The only other area of folding is between 1.5 and 2.5 km east of Loch Calavie. There are isolated areas in which open folding on a large scale can be seen. The axial plane to one fold, about 5 m across, is approximately 070º/30º S, and the fold axis to 162º/32º is coaxial with the regional lineation of about 160º/33º (Table 3.1). The open folding is of a generation very common throughout the Monar North-East sub-area.

4) Monar North-East sub-area

There is a dominant single open style of folding affecting most of this sub-area. At least two first-order fold axial planes separated by several hundred metres can be identified (see Chapter 5). Generally, there is a second-order open fold style of 2 – 5 m wavelength, and a third-order of around 10 cm wavelength. This is illustrated in Plate 3.4, and it can be seen also that the folding is very close to class 2 ('similar') style. Figure 3.35 also illustrates the second-order open folding, but closer to class 1B in style. The mineral fabrics found in the folds are generally parallel to the layering, and therefore folded by the open folding. Only rarely is an axial planar platy fabric to be seen. However, axes to the folds are always clearly marked because the open folding is coaxial with the existing linear quartz rodding fabric. The linear element is marked, and consistently to about 154º/32º (Table 3.1).

Although the open folding has had a marked effect on the appearance of the rocks, it does not completely mask the small amount of earlier folding present which is similar to that seen in the Monar South-East sub-area. Within Plate 3.4 it may be possible to pick out some possible early isoclinal folds, but Figure 3.36 clearly shows such folds, and to the right of the open fold in Figure 3.35 an early minor fold pair can be identified. The intrafolial isoclinal folds are generally no more than 30 cm across, but no axial directions have been determined. In an area to the west of the belt of open folds, about 1.5 km north-west of Pait Lodge, intrafolial tight – isoclinal folds of similar scale have axes to about 178º/33º, ie. quite close to the local quartz-rodding lineation.

3.7 Kink bands and gentle folds

Throughout the project area there are a variety of kink bands and gentle folds to be seen. The best areas to see such folds are close to the Moine Thrust Zone (MTZ) in the Achnashellach area, and in the flaggy areas or flaggy parts of areas, eg. Bendronaig area, Glenuig sub-area and southern part of the Sgurr na Feartaig/Glenuig area. The kink structures vary widely in scale, and two typical examples are shown as Plates 3.5 and 3.6 from the south-west flanks of Sail Riabhach. The style and scale illustrated in Plate 3.6 is very characteristic of the structures seen around Craig, between 1.5 and 3.5 km east of the MTZ.

Gentle folds, of small amplitude and wavelength of up to 5 m, are found scattered throughout the area. They are attributed to the generation of semi-ductile to brittle deformation also responsible for the formation of kinks, and very late in the history of the Moine.

3.8 Summary

The trends of planar and linear structures are summarised in Figures 3.2 to 3.25 and in Enclosures 3 and 4, which also give regional trends. The major fold structures and shear belts are summarised in Enclosure 5, which also acts as a structural overlay to Enclosures 3 and 4. The major structure will be discussed in Chapter 5, and before going on to the supporting evidence available in petrofabrics (Chapter 4) the structural elements described so far are summarised.

At least three shear belts and three or four major fold closures are identified in the complex **Attadale West sub-area** (Figure 3.1). What is believed to be the oldest group of linear fabric elements trend NE – ENE (Figure 3.3), and although generally rarely preserved there is one major synformal north-easterly open fold closure on Carn Mor with this orientation. The major structures in the south of the sub-area are a pair of open – tight neutral folds, the one to the west closing NE, possibly also younging to the north (Figure 2.2), and the one to the east closing SW. The dominant linear feature (Figure 3.3) plunges ESE, ie. pitch 90º. Traced to the north the extent of both these structures becomes uncertain.

The same neutral open – tight folding can be found in the **Attadale South-East sub-area** (Figure 3.1; Figure 3.5), and around Bealach Alltan Ruaridh the closure and younging is to the north-east (Enclosure 5; Figure 2.2). Both here and traced to the north there is evidence of a south-easterly linear element (Figures 3.5 and 3.7) and this is believed to be the result of rotation due to the influence of the overlying shear belt (Bendronaig area; Figure 3.1). The folding in the **Attadale North-East sub-area** (Figure 3.1) is probably isoclinal, and because of the rotation the fold is synformal (and synclinal).

The **Bendronaig area** (Figure 3.1) is a major shear belt with virtually no earlier folding and a dominant south-easterly lineation (Figure 3.9). However, by comparison with sub-areas to the east the fabric is weak, also contrasting markedly with the **Achnashellach area** (Figure 3.1) to the north. A broad swing in strike trend is evident in the latter area (Figure 3.10; Enclosure 3). The dominant linear fabric remains south-easterly in trend, and the majority of the other trends (Figure 3.11) are probably associated with the final phases of movement in the Moine Thrust Zone (north of Lair; Enclosures 1 and 2).

The **Sgurr na Feartaig North sub-area** and at least part of the **Sgurr na Feartaig/Glenuig South sub-area** (Figure 3.1) display a dominantly south to south-east linear trend (Figures 3.13 and 3.15) and there is strong evidence (section 3.6; Figure 3.12) of major tight – open folding in the belt. A southerly antiformal closure is postulated (Enclosure 5) and the structure is believed to have been strongly affected by shear induced rotation similar to that seen in the Attadale area, with the result that the originally ESE plunging fold is now paralleling the dominant surrounding south-easterly fabric. Cross-bedding evidence indicates an antiform (Figure 2.2), with the conflicting evidence around Cona Mheallain related to a second-order synformal syncline on the limb of the major folding (Enclosure 5).

The **Glenuig North sub-area** (Figure 3.1) represents the belt of shearing which affected the major fold below and ultimately merged with the Bendronaig area shear belt to remove most traces of the antiform in the southern part of the Sgurr na Feartaig/Glenuig South sub-area. The belt of shearing has a dominantly SE – SSE linear fabric (Figures 3.15 and 3.17) and parallels that seen dominantly throughout the Monar area.

In the **Monar North sub-area** (Figures 3.1) folding is confined to a narrow south-westerly closing antiformal belt (Enclosure 5), and on the basis of the observation of a major synformal north-easterly closing fold (Watson, pers. comm.) east of the central belt of Lewisian, the Lewisian probably lies within the sheared limbs of the complementary fold pair.

The **Monar West sub-area** (Figure 3.1) is problematical, and the evidence of linear and planar fabrics and minor folds is not conclusive. However, the spread of planar poles (Figure 3.20) probably indicates some remnants of early folding, and it is believed that there is a fold closure related to the closure in Monar North but very much overprinted by shearing related to the south-easterly lineation.

Within the pelite (Enclosure 2) in both the **Monar North-East** and **South-East sub-areas** there is no evidence of the southerly extension to the fold seen by Watson (pers. comm.) south of Glenuig Lodge (Enclosure 1). In both sub-areas there is a dominant open folding of the layering (Figures 3.22 and 3.24) coaxial with the dominant south-easterly lineation (Figures 3.23 and 3.25). On the basis of strike trends (Enclosure 3) several major open fold axes are traced on Enclosure 5. Also within these sub-areas there is evidence of a synformal north-easterly closure on a tight to isoclinal fold running through Pait Lodge (Enclosures 1 and 5). There is limited evidence also of an antiformal south-westerly closure running through the possible Lewisian rocks south of Loch Monar (Enclosures 2 and 5). This may link to a structure proposed by Kassler (1961) to the north. As the earlier folding is probably isoclinal it is not possible to draw any firm conclusions from the evidence of cross-bedding (section 2.12a).

4. STATISTICAL ANALYSIS OF ORIENTATION DATA

4.1 Introduction

This section outlines the statistical methods applied to three-dimensional orientation data, and gives a critical assessment of techniques used to analyse petrofabric data.

A new method of contouring is proposed, and this is compared with other methods which have been used. A review of the interpretation of certain petrofabric data from a variety of sources is given and petrofabric analyses from the project area are described in detail.

A. REVIEW

4.2 Statistical methods

Fairbairn (1949) published the first comprehensive study of the interpretation of three-dimensional data. Initially he considered a model of normal distribution, that is a population which has equal in frequencies in equal areas. Fairbairn noted that the methods using this model, such as the empty-space test, give values of chi-squared (χ^2) which are so sensitive that isotropism and preferred orientation do not stand as exclusive alternatives. He applied several other tests and came to the conclusion that samples were clearly indicative of a Poisson distribution for the population, that is there is a clearly defined mathematical relationship between frequencies in equal areas. The tests he applied included visual estimation of preferred orientation. It should be noted that the mathematical techniques did not give a clearer picture in his analysis than the visual techniques.

Pincus (1953) studied many aspects of orientation data and reviewed the methods of analysing bivariate data. This closely followed the work of Fairbairn, but he also noted a method of accurately quantifying a point distribution. Pincus recognised the limitations of statistical analysis and stated that statistical methods applied to geological studies only serve to sharpen the questions and answers.

Vistelius (1958, 1966) critically analysed contouring techniques such as those of Winchell (1937) and Pincus, and gave a detailed account of the vector representation of Pincus and Braitsch (1956). This he thought to have limited application, and he proposed a new method of working with structural diagrams. Having applied a simple χ^2 test he proposed two techniques for producing a supposedly statistically based visual display. In an attempt to compare diagrams analysed by his methods, Vistelius proposed a mathematical technique to replace the commonly accepted visual comparison.

Flinn (1963) critically assessed the methods of Vistelius and found them to be the result of a misunderstanding of pole distribution in random diagrams, and statistically unsound. Flinn came to the conclusion that there is “no test or connected scheme of tests available to the structural geologist for the statistical analysis of complex structural diagrams... At best, there is a series of unrelated and overlapping tests and some information on random diagrams which can be used for rough qualitative tests”. Flinn noted that Vistelius finally contours by eye, which must negate a lot of the detailed mathematical procedures in favour of intuition. A discussion between Vistelius and Flinn (1964) only served to highlight the lack of agreement on any statistical approach.

Kalsbeek (1963) proposed the use of a hexagonal net for counting-out and testing fabric diagrams. Up to this time various circle methods and derivatives had been commonly used. The net has certain advantages and formed the basis of the proposed new system of contouring.

Stauffer (1966) reviewed the study of fabric diagrams and conducted the first published survey of a variety of samples from an isotropic population. He proposed the use of a square-grid for contouring and stated that this compares favourably with the variable-ellipse method. He came to the conclusion that the sample should be compared with a Poisson distribution and also stated that “No single statistical test presently available is satisfactory itself for determining the significance of weakly developed fabrics”. Stauffer also noted that a practised eye can identify most features, but that the geologist is more likely to call a diagram preferred than random. In discussing optimum sample size he stated that four points per counting cell on his squared grid is a minimum to fit with a Poisson distribution, and that in his opinion too much published information has too few observations to justify the interpretations made from them.

Watson (1970) provided an up to date assessment of statistical methods and stated that early work tended to be a justification of a particular technique. Watson noted that various 'contouring' methods were used to display the data in a smoothed form, and that the significance of various features could be tested against various null hypotheses. There is, he stated, rarely a specific alternative hypothesis, and many geologists have been rightly critical of testing. As a result Watson proposes the use of AVA, or axial distribution analysis (Sander, 1930). As no account is taken of grain position in the general view of statistics and petrofabrics, Watson follows Flinn in suggesting that a full view of a preferred orientation and its significance is only obtained by relating grain orientation to position.

To summarise the review of statistical methods it should be noted that quantitative mathematical analysis is possible. However, the structural geologist requires a clear and simple method of studying fabric diagrams, and a contouring method is proposed as an aid in interpreting a microfabric.

4.3 Criticism of present contouring methods

For the rapid and easily interpreted display of petrofabric data it is believed that some method of contouring should be employed. A visual estimation of fabric elements should be used to supplement contouring and the end result should be be used as as aid in defining the deformational history.

Various methods of density contouring have been employed, and these are appraised below:

a) Schmidt method

Figures 4.1 and 4.2. This is one of the most widely used methods of contouring. As with most methods this requires the data to be plotted on a 20 cm diameter equal area projection. Details of the exact method and counting ruler can be found in Turner and Weiss (1963). This was recommended by these authors for diagrams with more than 400 points. Basically, a 1 cm squared grid is placed beneath the data, and at the intersections of the grid a 1% area (2 cm diameter) circle is placed. The number of points falling in the circle is counted and plotted at the grid node. Contours are drawn between

numbers representing percentages of the total number of points. Sander and other authors have proposed that greater or less detail can be obtained by varying the size of the counting circle.

For practical considerations the method can be criticised on the following grounds:

1) The overlap of the circles is not uniform. Individual points will be counted 2, 3 or 4 times. Contouring an isotropic distribution will give apparently significant maxima.
2) The use of a circle creates strong distortions near the edge of the net. As an equal area projection is used there is a distortion from circular to elliptical at the edge, but this is not taken into account in the Schmidt method.
3) The use of a special counter at the edge of the net distorts the counting area. The centres of the circles on this counter are 20 cm apart. The primitive does not bisect the circle exactly, leading to an error in counting points per unit area. A greater or lesser distortion applies to any intersection of primitive and counting circle.
4) A rotation of the points on any axis can lead to noticeable changes in the position and number of contours. This is partly a function of the high density of counting points (grid intersections), partly a function of the use of a square grid on a circle and partly the result of unequal counting of points.
5) There are 321 counting points on the net shown in Turner and Weiss (1963), reproduced as Figure 4.1. This number is largely determined by the use of a 1% circle area, but will vary with different workers. It is considered too large and cumbersome in operation, and inevitably creates a high density grid to be contoured. It is the view in this study that the number of counting points should be closely related to the total number of points.
6) The contours produced (Figure 4.2) show a great amount of detail. Although rotation of the points relative to the squared grid can markedly change this detail, it has been taken as significant by some authors.
7) Statistical comparisons of contours in different diagrams are not advisable because the sum of the values used for contouring bears no fixed relation to the total number of plotted points, and can vary with rotation of one set of points as well as between different sets of points.
8) The lack of a statistical basis means no limits of significance can be applied to the contour values.

b) Free counter method

This method, described in Turner and Weiss (1963), removes the 1% counting circle from the constrictions of the squared grid. Many of the criticisms applied to the Schmidt method apply to this method. Turner and Weiss consider its main application to be in the range of 200 to 400 plotted points. In practise the method is cumbersome and time consuming. The results vary little from those of the Schmidt method. Summarised briefly, the following criticisms can be made:

1) There are distortions introduced by the use of a circular counter, increasing in degree closer to the primitive.
2) The choice of a 1% counter is arbitrary and considered too small to distinguish significant details from the effects of random distributions.
3) The lack of a statistical basis means no significance levels or meaningful comparisons between diagrams can be applied.

c) Circle method (Mellis method)

Figures 4.3 and 4.4. This method is considered by Turner and Weiss (1963) to have a use for diagrams with less than 150 points, for weak concentrations and for drawing a contour defining minimum density. The method entails drawing a 1% area circle around each point. The size of this circle can be varied as in other methods, and has been used at 0.5% and 2% areas. Contours are drawn by studying the overlap of circles, such that the 3% contour will be the area of overlap of 3 or more 1% circles. The following points can be made:

1) The method is believed by some authors to produce identical contours for the same diagram studied by different workers. Rotation of the points about any axis other than perpendicular to the primitive will change contour shapes and maxima because of the shape distortions created within an equal area projection. As rotation is important in petrofabric diagrams, the equality of contoured results comes into question.
2) An arbitrary circle size is used, which is considered to be too small and the detail of contouring becomes impossible for anything above the '4% contour'.

The method has been used for some supposedly statistical tests, either by estimating areas of overlap or using a planimeter to measure the area (Flinn, 1958). This method works on the assumption that Mellis contours are exact contours of density of pole distribution, unlike the Schmidt contours which are estimates. This is demonstrably unsound, and further, any attempt to use this method for a large scale study is unworkable through extreme complexity.

d) Mellis variable circle method

This is a derivative of the Schmidt and Mellis methods. A stereographic projection is used (Wulff net) and an overlay prepared which has 181 (Vistelius, 1966) circles of equal area marked on it. Being equal angle the diameter of circles increases closer to the primitive. The number of points in each circle is counted and contours drawn in a similar way to the Schmidt method. This method has many of the disadvantages of the earlier methods, notably:

1) Use of a 1% counting circle.
2) Unequal overlap of circles gives biased counting.
3) Complexity of net and of operation.
4) Dubious significance attached to detail of the contours.

However, it has the advantages of a fixed set of counting points, although 181 is considered too high a number to use, and it does provide a consistent edge correction for opposite sides of the net. If the overlap of the counting circles did not

present problems the net would be adequate to solve the problems associated with point rotation and recontouring.

e) Variable ellipse method

This is almost identical to the variable circle method, with ellipses used instead of circles. This means it can be applied to the equal area or equal interval projections, but in the case of the former, for example, there will be a unit area circle in the centre and an ellipse of axial ratio 0.707 : 1.414 at the primitive, that has the same area. The end result is 244 ellipses (Vistelius, 1966). The points in each ellipse are counted and contoured as before. The same criticisms and advantages apply as in the variable circle method, particularly the greater complexity of the net.

A general criticism of all the methods using ellipse or circle overlap is that the point counting is statistically unsound. The unequal and unquantifiable overlap leads to a bias in point counting, and the fine details of the counting net and contours are of greater complexity than would normally be expected in the average 200 point fabric diagram. Complete or partial lack of rotational symmetry also presents problems when dealing with data in different nets and attempting to make comparisons.

f) Squared grid method

Figure 4.5. This method, described in Stauffer (1966), has the advantage over circle methods of simplicity. A circle of 20 cm diameter is divided into 100 squares, each of side π^{-2} cm, that is 1% of the area. Points in each square are counted and contoured accordingly. Stauffer found his contours to be almost identical to those produced by the variable ellipse method. The lack of precision of the primitive is noted by Stauffer, although the severity of the error is probably underestimated. At the primitive Stauffer recommends summing counts in areas of opposite sides of the squared grid. The combined area generally deviates significantly from 1% of the total area, although a smaller error would result if adjacent areas of partial squares were combined. The following points should therefore be noted:

1) Stauffer's work showed that he required 400 points, or 4 points per area, but he did not consider changing the 1% area to reduce the number of points required.
2) The edge correction is poor, and probably worse than that of the Schmidt method.
3) Rotation of the points gives noticeably different results in both contour position and strength of maxima.
4) It is a simple net to construct and use, but the cell shape is not uniform over the surface of a sphere.

g) Vistelius method

Figures 4.6 and 4.7. Vistelius describes various methods of contouring, although these are supposed to be only a visual representation allied to various statistical tests. Full details can be found in Vistelius (1966, 1967). The supposedly statistical tests he uses are open to question, and the assignation of significance levels to his data can be shown to be very strongly dependent on the shape of the counting cells in the nets. The nets for use with his two initial hypotheses have widely varying shapes. It should be particularly noted that on one part of the primitive there lies a roughly rectangular shaped cell which is not significantly different in shape from the rectangular cells near the centre of the net, but perpendicular to these cells is an elongate triangle (Figure 4.6). Vistelius did not consider that the shape of these figures was significant in determining the anisotropy of a fabric or the shape of the 'isolines'. It can clearly be shown that this assertion is false. Any strong symmetry in a counting grid can be closely related to the resultant contoured fabric symmetry.

h) Braitsch overlay

This is an overlay of 200 equal area rectangles. It has been used for representing a vector by relating corresponding cells and applying a weighting to each cell. The net can be adapted for use in simple contouring rather than vector analysis. Being a logical extension of the squared grid method it was thought to have several advantages, namely:

1) ease of construction and use;
2) good edge corrections;
3) good rotational symmetry;
4) adaptability to varying numbers of counting cells.

It was, however, found to have some drawbacks, mainly in the recontouring of the same fabric diagram. Wide differences in shape and position of maxima were found, and the use of a rectangular grid was considered unsuitable for petrofabric analysis.

i) Variable curvilinear cells

Denness (1970, 1972) produced a net which was almost identical to the modified Braitsch overlay proposed in (h) . However, he followed convention and stated that the cell area should be 1% of the total net area. He compared his diagrams with those contoured by the squared grid and Mellis variable ellipse methods. The methods are in very close agreement, but it can be shown that methods using 1% counting areas give basically similar results.

j) Kalsbeek hexagonal net

Figure 4.8. Kalsbeek (1963) described a net divided into 600 equal area triangles. The triangles could be combined to form equal area hexagons. The centre of the hexagon (the meeting point of six triangles) was taken as a counting point, and all the points in each hexagon were counted. The result is 301 counting points, with each plotted point counted about 3 times. An error comes in with the use of semicircles at six places on the primitive, combined from opposite sides of the primitive to give three circles of the same area as a hexagon. The method is fully described by Kalsbeek and in Ragan (1968). The following points should be noted:

1) Kalsbeek considered the method to be quicker and simpler than any previously proposed, but it could hardly be considered that writing 301 numbers on a net and contouring them is a rapid analysis.
2) The observation points are fixed, making comparative diagrams easier.
3) Most points are counted exactly three times. In the outer band most points are counted three times but some

are counted four times. The percentage of the total area in which points are counted four times is 1% exactly.

4) The areas of the triangles are not exactly equivalent and may deviate by plus or minus 1 or 2%. The addition of six triangles to form a hexagon can be shown to minimise this error rather than enhance it.
5) Kalsbeek believed the net could be used for certain statistical tests with greater confidence.
6) The net has good rotational symmetry and the variations in contouring with rotation are minimised.
7) The number of counting points is very high relative to the number of points being studied in an average fabric diagram, about 200. This is believed to create additional work and contouring complications which are not justified in view of the nature of the data.
8) Construction of the grid is laborious, and involves careful calculations of ring areas. This, however, is a criticism that can be levelled at most methods. Even the accurate drawing of a 2 cm diameter circle around a point when using the Mellis circle method requires patience and some degree of skill. At least, once an accurate net has been produced it can be used many times.

4.4 Aims of a statistical investigation

The proposed method of contouring has been devised in response to certain problems highlighted by a review of other techniques of analysis. This study will not adhere to the long established arguments that the Schmidt net is widely used and is therefore best for the comparison of various analyses. The review has shown that the relative orientation of the point diagram and contouring grid is important in petrofabrics and other similar density distributions.

Fundamental errors of interpretation may be introduced by not taking into account the effects of rotation, so it was decided that the proposed system of analysis would be shown to give consistent results in all net orientations.

It was decided, following Stauffer (1966), Vistelius (1966) and others, that the analysis of a probability density would be based on the Poisson distribution. This requires a minimum of 4 points per counting area for the orientations to be considered significant and reliable. By limiting counting areas it was hoped that the conditions of the Poisson distribution would be adhered to.

4.5 Sampling and errors

The nature of petrofabric data and the errors which can be introduced are important. Sampling can introduce questions of homogeneity. Orientation of the specimen can introduce several rotational errors. Errors in individual point orientations can be high as it is not possible to measure exactly, by conventional optical means, the position of a c-axis, as it is not exactly defined by extinction positions. Errors in sampling and measuring procedures would be difficult to quantify consistently, but it should always be noted that they are present.

The measured fabric of a rock generally consists of 200 quartz c-axis measurements, although some authors go to 300 and even 400 plots. This is a sample, from a population, which is initially assumed to be representative and homogeneous. The aim of any contouring must be to show where there are significant clusters of points. The maxima so defined should then be related back to the thin section either by axial distribution analysis (Sander, 1930; Harris and Rast, 1960) or by visual estimation of the relations between grain orientation and position relative to other grains.

4.6 Symmetry concepts in fabric analysis

Paterson and Weiss (1961) and Turner and Weiss (1963) provide a comprehensive study of symmetry and a kinematic interpretation based on symmetry. It is generally accepted that the symmetry of structural features of a strongly deformed rock reflects the symmetry of the “movements” involved in the deformation and it is possible to assign a mineral fabric to a particular symmetry class. This subfabric can be combined with other subfabrics to give the overall fabric symmetry of a rock. For example, quartz and mica subfabrics combine with mesoscopic linear and planar subfabrics to give an overall fabric symmetry. The classes of symmetry of subfabrics are :

a) Spherical — the symmetry of a sphere. Random orientations, for example in a hornfels.
b) Axial — an infinite number of symmetry planes through one point which is normal to another symmetry plane.
c) Orthorhombic — three mutually perpendicular symmetry planes.
d) Monoclinic — a single symmetry plane.
e) Triclinic — no symmetry planes.

A homotactic fabric is one in which a subfabric is symmetrically related to the fabric elements. A heterotactic fabric is one in which the subfabric does not vary, but is not regularly related to other fabric elements.

There will be a close correlation between the tectonite fabric and the corresponding kinematic picture. The detail of the pattern has assumed less significance with time, but homogeneity and symmetry have retained their importance. The ultimate orientation pattern may embrace several processes of formation. Even though the mechanisms are little understood for quartz the patterns are well described:

a) The parallel alignment of (001) in mylonites within the prominent S-surface and parallel to or normal to the lineation. The fabric is homotactic orthorhombic.
b) Quartz maxima grouped symmetrically relative to the S-surface and lineation is S. The fabric is homotactic orthorhombic.
c) In high grade granulites and quartzites, quartz is concentrated in a single direction normal to the prominent S-surface. The symmetry of the quartz subfabric is axial, or orthorhombic with a partial girdle, and the mesoscopic subsurface is orthorhombic. The supposed total fabric is orthohombic or slightly triclinic, and Turner and Weiss thought recrystallisation a probable mechanism.
d) A fabric dominated by a mesoscopic lineation which is parallel to the minor fold axes. This is equivalent to Sander's B-tectonite. There is sometimes a peripheral or cleft c-axis girdle normal to the lineation and the fabric is homotactic monoclinic. The individual maxima have been equated with slip planes in the past, but Turner and Weiss believe this unjustified.

e) A common fabric is monoclinic or orthorhombic quartz plus a monoclinic mesoscopic and mica fabric. These have been thought of as evidence of repeated deformation, although there is no evidence to support the view that quartz will reorientate when mica is unaffected. Simultaneous development of a mimetic mica subfabric and a quartz subfabric will give a heterotactic fabric with deformation symmetry only reflected in the quartz.

f) Orthorhombic diagrams with two girdles at right angles have been attributed to repeated or simultaneous folding about crossed B-axes, but Turner and Weiss suggest that the girdle axes should not be called B-axes. There is an orthorhombic or tetragonal homogeneous quartz subfabric.

Turner and Weiss believed that it is possible to equate the intersections of planes of orthorhombic symmetry with σ_1, σ_2 and σ_3. They also state that the normal to the girdle in monoclinic fabrics may have special significance, and may be equated with σ_2 or σ_3, thus σ_1 lies in the girdle plane. When dealing with the fabric of mica, Turner and Weiss believe it only has significance in giving information on the time sequence of the appearance of mesoscopic elements.

There is evidently some correlation between the latest ideas on quartz preferred orientation and the symmetry observations. With the information presented it should be possible to define fabric variations and equate them with postulated stress or strain axes.

4.7 Theoretical conclusions

The mechanisms for the formation of mineral orientations are still not clear, particularly in the case of quartz. However, the development of patterns of symmetry can be shown for certain physical conditions. The aim of any study of quartz fabrics should be to define the symmetry, relate this to overall symmetry, and ideally to study the relationship of defined maxima by axial distribution analysis. The proposed method of contouring is thought to aid in the interpretation by clearly defining maxima and minima, and by removing the spurious and confusing contours produced by other methods. Mathematical methods are believed to have little use to those wishing to study large numbers of data in the most simple and visual way. They are not dismissed totally, but it has been illustrated that certain methods are dubious in application. It should be possible after contouring to define the following features of a fabric:

1) symmetry of mineral fabrics.
2) symmetry of the whole specimen fabric.
3) strength and size of maxima and minima.
4) relationship between orientations and positions in the thin section, from which can be estimated,
5) the homogeneity of all fabrics and elements.

B. THE NEW METHOD AND COMPARISON OF RESULTS

4.8 The new method of contouring

Two nets have been devised, figures 4.9 and 4.10, one with 49 counting points (cp) and the other with 28 cp. They are derived from the Kalsbeek counting net, but one has 96 triangles and the other 54 triangles, compared with the 600 of Kalsbeek's net. A range of sizes are possible, but it is believed that the two sizes shown will effectively cover all sample sizes dealt with in petrofabrics. If more than 300 points are obtained it should be possible to go to a 150 triangle (75 cp) net.

The 49 cp net has four bands, with 6, 18, 30 and 42 triangles to each band, while the 28 cp net has three bands, with 6, 18 and 30 triangles each. The area ratios of the bands are 1:3:5:7 and 1:3:5 respectively. The area of a segment equals $2\pi.R.h$, where R is the radius of the net (hemisphere) and h is the thickness of a segment of the hemisphere, from which it is possible to calculate the angular width of the segments in the equal area projection. Working from the centre of the net these are 20.60º, 21.05º, 22.65º and 25.94º for the 49 cp net and 27.27º, 28.98º and 33.75º for the 28 cp net.

The division of each band into triangles using straight lines leads to small area errors. Measurement of these errors has shown it to be no greater than ±5% of the mean area of a triangle, and much less when the areas are summed to make a hexagon, so for ease of construction only straight lines are used to divide the bands into triangles.

The net is used in the same way as the Kalsbeek net. Six triangles are taken together as one hexagon and at the centre of the hexagon is the counting point. All the points in one hexagon are counted, thus all the points will be counted almost exactly three times each. Contours are constructed between the numbers, expressed as percentages of the total.

As there are six points at the periphery of the net where hexagons cannot be constructed, semicircles are used. Semicircles are constructed with an area equal to that of three triangles. Measurement on a 20 cm equal area projection has shown that for the 49 cp net the radius of the semicircle should be 2.6 cm and for the 28 cp net it should be 3.5 cm.

The use of a semicircle in the correction can lead to several criticisms. As the projection is equal area a circle at the centre would be an ellipse at the edge of the net. An ellipse was constructed, but was found to make no noticeable difference to the shape of the contours and the overall interpretation. As a circle is easier to construct and more closely approaches the shape of a hexagon it was decided not to use an elliptical edge correction.

Because of the use of semicircles some points are counted four times and some three times. Over the whole net the area where points are counted four times is 6.25% for the 49 cp net and 11.1% for the 28 cp net. Whether the figure is a semicircle, hexagon or semi-ellipse is not too important, and the overlap error has virtually no effect on the final interpretation.

A criticism may be made that each point is counted more than once. Few alternatives have been put forward, and analyses of the use of such grids and nets which only count points once, has shown that the contouring is very unreliable on rotation. In these cases, regardless of the number and shape of the counting areas, it was found that small rotations lead to big changes in interpretation.

Having accepted that it may be advantageous to use a net with overlapping counting areas the proposed hexagonal net has the advantages of flexibility in number of areas and consistency in counting nearly three times.

The summation of all the cp values is considered important. As the points are counted on average just over three times each it is considered advisable to use the sum of cp values for calculations of mean and percentage. For example, for a 200

point sample the summation is theoretically 2.1% too big, that is about 613, which one would expect from the area error as the 49 cp net of 6.25%. The effect of this order of magnitude error on the contours is very small. Therefore, before contouring, the cp values should be summed, a mean estimated to make sure that it exceeds 12 (effectively a minimum of 4 points per cp), and contour percentage values calculated. Contouring is done by eye between appropriate values.

It has been clearly demonstrated in practical application that for all possible rotations the results obtained are essentially identical. In such cases significant maxima and minima appear in the same positions, generally with the same shapes and contour values. The overall symmetry has not been shown to vary.

In conclusion, it is suggested that for the problems of dealing with a sample from a population approaching infinity, such as found in petrofabrics, the hexagonal counting net should be used. It is believed to have no significant disadvantages within the applied limits of operation, and the following advantages:

1) Comparative ease of construction and use.
2) Readily varied to suit sample size, assuming a Poisson distribution for the population.
3) Consistent results in all orientations.
4) The reliable comparison of different samples contoured with the same net.

It should be noted that the net is considered suitable for giving some indication of the disposition of the large population when a small sample is available, but is not considered suitable for use in problems with small populations. For observations such as fold axes and poles to bedding, deviations of only one observation can be significant and it is not advisable to smooth out such deviations. The method is considered ideal for an initial appraisal of the fabric of a rock in petrofabric studies as it smooths the contours of a sample using the method of moving averages, assuming the population is large enough to have a near perfect form. It does not consider fine detail of contouring to have any significance and effectively eliminates it.

4.9 Application to published data

Various contouring techniques have been attempted for a wide variety of natural fabric data and data from a computed isotropic population. Stauffer (1966) employed the squared grid method to contour various samples from a 10,000 point random population produced by computer. He provides point diagrams for the two 200 point samples and for the 100 point sample. The latter is considered too small a number of points for significant observations using the proposed system of contouring, so a comparison will be made using the two 200 point samples.

Figure 4.11 shows the first sample and Figure 4.12 shows this sample contoured by the squared grid method, both being redrawn from Stauffer (1966). The contours show concentrations of up to 4% per 1% area, with most of the points falling between 0% and 2% density. There is much detail to the contour outlines, but no noticeable pattern. Figure 4.13, the same points contoured by overlapping hexagons, clearly shows that nearly all the points fall between 1% and 3%, whereas the expected density for perfect isotropy is 2%. Only about 4% of the total area falls outside these limits, with a maximum density of 3.1 and a minimum of 0.7. While Stauffer's method shows much possibly confusing detail, the new method simplifies the pattern.

Assuming the sample to be isotropic, and as the new contouring method keeps a minimum of 4 points per cp, conforming to the requirements of a Poisson distribution, it can be seen that in practice the limits of random distribution would be 1% to 3% for the 49 cp net. Therefore, there is no significant density above or below the isotropic level ± 50%.

Figure 4.14 shows the second sample of 200 points, and Figure 4.15 shows Stauffer's contours, both redrawn from his paper. Here the contour range is not so great, but there is much meaningless detail. By using the new method, Figure 4.16, the pattern is clearly shown to be insignificant. Again, there is no great departure from the isotropic density of 2%, and only 1 – 1½% of the total area of the net is over 3% density. This again confirms in practise that a random distribution is shown by the isotropic level ± 50% ie. 1% to 3%.

Phillips (1937) provided some uncontoured quartz c-axis diagrams of sediments. It is possible that he considered them to be a random spread of points or to have a very weak preferred orientation. Using the new method of contouring it was hoped that the results obtained from Stauffer's diagrams could be tested on real data. Phillips' first diagram, redrawn as Figure 4.17, is of 300 quartz c-axes from the Basal Cambrian Quartzite. This he notes as being an even grained rock, with practically no signs of strain. The contoured diagram, Figure 4.18, shows very little outside the proposed limits for a random distribution. Only about 11% of the total area falls above 3% and below 1%. From this it is postulated that we are dealing with a sample from a random population.

Figure 4.19 is of 300 quartz c-axes, redrawn from Phillips, from an apparently undisturbed Serpulite Grit. Contouring of the diagram, Figure 4.20, shows virtually no density distribution below 1%, but a larger area above 3% density, about 3% of the total area. The contouring net was rotated and the recontoured diagram is shown as Figure 4.21. Basically the same pattern emerges, and the area above 3% density is in the same place on the net and of the same size. The maximum cp value has only changed from 3.3% to 3.8%. It can only be postulated that there may be a significant preferred orientation. The sample size of 300 points may not in this case be adequate, and if one was searching for a weak orientation another sample would be required, preferably from a thin section with a different orientation. If a succession of diagrams show the same very weak maximum then it may be concluded that a preferred orientation is present. Considering the origin of the Serpulite Grit it is possible that a sedimentary preferred orientation is shown, originating in the alignment of inequant quartz grains, but without further information it could equally be attributed to preferential observation of grains in the thin section.

The next diagram, Figure 4.22, shows 300 quartz c-axes from a sheared Torridonian sandstone, again redrawn from Phillips. The contoured diagram, Figure 4.23, shows large areas above 3% and below 1% density, 15% and 10% of the total area respectively. As a significant area of the diagram area is outside expected limits for a random distribution, showing a maximum density of 3.8% and a minimum of 0.3%, it may be postulated from this one contoured diagram that a weak preferred orientation is present. Maxima and minima have a symmetrical arrangement and although it may be

advisable to take another sample in a different orientation, the overall pattern is of a discontinuous small circle girdle with the axis perpendicular to bedding.

This range of diagrams taken from Phillips illustrates the sensitivity of the contouring technique for distinguishing between random and supposedly non-random samples. However, problems of interpretation can arise when dealing with small samples. Phillips (1944) gives a point diagram for a hornfels, redrawn as Figure 4.24. The 200 quartz c-axes were contoured and a small maximum found (Figure 4.25). The contouring net was rotated, and on recontouring two small maxima were found (Figure 4.26). The size and position of maxima in the two diagrams varies, therefore the rotation test casts doubt on the significance of the results.

Looking at just one diagram one may be tempted to come to certain conclusions about the symmetry and deformation. This attempt to find a preferred orientation and symmetry has been made where one cannot be shown to exist with certainty. Further information on the thin section and more fabric data are certainly needed in this borderline case.

4.10 Application to new data

Moving on to the fabric data obtained from the Moine and associated rocks of the project area there is a wide range of fabrics developed. All the specimens are shown on the map, Figure 4.27.

Starting with the weakest fabric (22), a Lewisian hornblende gneiss occurring as a thin slice in Moine psammites, the point diagram for quartz, Figure 4.28, has only 130 observations. Contouring by the Schmidt method was undertaken, Figure 4.29, and with the exception of perhaps one maxima the pattern appears to be random. Contouring by the Mellis method gave an essentially similar picture.

Before further contouring was undertaken a 'goodness-of-fit' χ^2 test of significance was attempted. The technique is described by Vistelius (1966) and is an attempt to compare the observed distribution with a hypothetical distribution using the H_0 (null) hypothesis. With an overlay net of 24 equal area triangles χ^2 was calculated using the method explained by Vistelius, and for specimen 22 gave a value of 22, equivalent to a probability $\alpha = 0.500$. The overlay net was rotated and χ^2 calculated again. This time $\chi^2 = 45.5$, giving $\alpha < 0.005$. Therefore, with the net in two different positions one first obtains a result not distinguishable from the uniform distribution and then a result which indicates a significant preferred orientation. In conclusion, this test as applied by Vistelius is not useful for defining weak fabrics. A criticism of χ^2 tests can be made that they are too sensitive, and this is upheld by the example given.

The quartz data for 22 was then contoured using a 28 cp overlapping hexagon net, and the net was also rotated relative to the points and recontoured. The results are shown as Figures 4.30 and 4.31. They are almost identical in size and position of maxima, which at 7.6% and 7.9% density respectively are certainly significant considering isotropy for a 28 cp net is 3.6%. Smaller maxima are found in each diagram at 5% and 4.5% density respectively, but their significance is less clear. The quartz fabric symmetry is probably monoclinic, a proposition which could not be made with certainty from the point diagram or Schmidt contours. The dotted line refers to a strong mica fabric, the point diagram, being given as Figure 4.92 and the combined mineral fabric is considered to be monoclinic.

21 comes from the psammites close by 22, and the 200 point quartz c-axis diagram is given as Figure 4.32. There is an obvious strong peripheral concentration, and the Schmidt contours show this (Figure 4.33). Basically a monoclinic quartz fabric symmetry is shown, with two peripheral maxima. Contoured by a 49 cp overlapping hexagon net the result is the same, and with the counting net rotated, the result does not vary significantly (Figures 4.34 and 4.35). This illustrates that for a clearly defined fabric the Schmidt method and new method of contouring are similar, but that the new method gives a visually much clearer picture which is also consistently reproducible. The mica poles are given as Figure 4.83 and they show a clear point concentration giving a monoclinic symmetry to the combined mineral fabrics.

98 displays an apparently similar fabric to 21 looking at the 188 quartz c-axes given as Figure 4.36 and the Schmidt contours given as Figure 4.37. However, despite one obvious area of maximum density concentration the symmetry is clouded by too much detail. Figures 4.38 and 4.39 show the same points contoured by overlapping hexagons, and although some differences can be seen in size of the maximum density area the position is identical in the two diagrams. When the points are rotated towards the net centre and recontoured the pattern becomes even clearer (Figure 4.40). The symmetry is orthorhombic, although almost axial. The mica poles (Figure 4.96) show a clear axial symmetry perpendicular to the quartz maximum, and give an orthorhombic symmetry to the combined fabrics.

The fabric diagram for 44 presents a striking contrast when the different contouring techniques are considered. When the point diagram for quartz (Figure 4.41) is contoured by the Schmidt method three distinct maxima appear (Figure 4.42). When contoured by overlapping hexagons two maxima and two minima are seen, and the symmetry of the maxima and minima is strongly related (Figure 4.43). The inability of the Schmidt method to define large concentrations of points and areas of significantly low point density is clearly illustrated. The mica poles, Figure 4.56, show a clear axial distribution, particularly when shown rotated to the centre of the net (Figure 4.48). The relationship of the orthorhombic symmetry of the quartz fabric to the axial symmetry of the mica fabric gives an orthorhombic symmetry to the combined fabrics.

A final example of confusion in interpretation arising by use of the Schmidt method is seen in 233, a quartz vein. The diagram of 180 quartz c-axes is shown as Figure 4.44. Contoured by the Schmidt method in Figure 4.45 the fabric elements may be interpreted as a small circle, crossed girdles or three small unrelated maxima. Contoured by overlapping hexagons in Figure 4.46 the symmetrical pattern of maxima and minima is clarified and when the contours are rotated in Figure 4.47 the fabric can be seen to be orthorhombic, possibly tending towards triclinic. The significant maxima and minimum point concentrations are approximately perpendicular to one another, but as no other mineral fabric existed and only 180 c-axes could be measured in the thin section it is clear that further analysis would clarify this interpretation.

In conclusion it is important to note the improved interpretation produced by rotation of the net relative to the points. Results from the rotation of points and recontouring, or rotation of the counting net, are greatly simplified and speeded

up by use of the overlapping hexagon net, as opposed to the more complicated and time-consuming Schmidt method.

C. INTERPRETATION OF FABRICS IN THE PROJECT AREA

4.11 Petrofabric data from the project area

A total of eighteen specimens from the area were studied by Universal Stage analysis of quartz c-axes (0001) and mica poles to (001). Of these, five have already been described as examples for the use of the new contouring methods. The remainder will be described and additional details provided for the five samples already briefly described. The map, Figure 4.27, gives the sample location and rock type for each of the petrofabric analyses. Bearing in mind the zones described in Chapter 2 and the sub-areas of Chapter 3, the analyses can be divided into five groups. All but one of these groups is to the west of the Beinn Dronaig Pelite.

The specimens chosen for analysis are generally psammites or striped psammites, and are typical of the area from which they came in most cases. Two specimens were taken from quartz veins for comparison with psammites, and two specimens were of Lewisian gneiss, also taken for comparative purposes. The specimens for which there is a petrofabric analysis are viewed critically with respect to any possible imbalance that may arise from the study. The analyses are useful in broadly comparing three areas:

1) the complex folded area in the south-west (Attadale massive, coarse grained zone; Attadale sub-areas).
2) the flaggy belt to the east of this, below the Beinn Dronaig Petite (Bendronaig flaggy, fine grained zone; Bendronaig sub-area).
3) the Moine Thrust Zone (MTZ) affected flaggy area to the north-west (Achnashellach flaggy, fine grained zone; Achnashellach sub-area).

The Lewisian rocks lie between the first and last of these areas, and the quartz veins lie within the first area.

There are no analyses from the Sgurr na Feartaig Zone (Figure 2.2) in the north-west, the flaggy zone above it, or flaggy areas in the centre of the project area. However, extrapolation based on the structural similarities described in Chapters 2 and 3 is possible.

Furthermore, only one analysis has been made to the east of the Beinn Dronaig Pelite, although evidence from the work of earlier researchers can be used here (Ramsay, 1957).

The map (Figure 4.27) shows the areas in which the following five groups of specimens occur:

a) Attadale area
   1) Attadale West sub-area
   2) Attadale East sub-area
b) Bendronaig area
c) Achnashellach area
d) Lewisian
e) Monar area

The specimens will be described with reference to these areas.

a) Attadale area

This large area can be logically split into two sub-areas, west and east.

1) Attadale West sub-area

Five specimens were analysed from this area. Four of them, numbered 232, 274, 44 and 30, are psammites, and the fifth, 233, is a quartz vein from the immediate vicinity of 232.

232

In this specimen the layering strikes 178º/27º E dip, and there is a quartz rodding lineation trending 134º/17º plunge. This coarse grained rock has a generally poor mesoscopic fabric, although the lineation is well developed. Within the immediate vicinity the rocks are markedly folded, and the specimen is taken from the limb of a major fold. The psammite has little mica, but many quartz veins (see 233). For this sub-area the rock type and tectonic style are fairly typical, although the platy fabric is better developed close by.

The mica poles (Figure 4.48) clearly define a schistosity which is approximately parallel to the measured layering. There is a slight girdle development in the fabric which defines the observed lineation, and the intersection of the layering and mean mica fabric plane also defines the lineation.

The quartz c-axes (Figures 4.49 and 50) have a clear monoclinic symmetry. Two maxima lie in the symmetry plane, one of 4.9% and the larger of 6.5%. The quartz symmetry plane does not intersect the mica plane at right angles to the lineation and the symmetry plane is not perpendicular to the lineation. The combined fabrics on the mesoscopic and microscopic scales result in a triclinic symmetry.

233

In this specimen of a quartz vein there is a quartz rodding lineation of 082º/34º. The platy fabric in the surrounding psammites is 033º/35º E, and there is much folding of the psammite layering. The lineation in the vein is parallel to that in the psammites. The relationship of the quartz vein fabric to that of the adjacent psammites (cf. 232) is of interest.

There is no mica, making orientation of the specimen difficult, but it was sectioned approximately perpendicular to the quartz vein lineation and the layering in the psammite. The quartz c-axes (Figures 4.51 and 52) have a clear monoclinic symmetry. Two maxima lie in the symmetry plane, one of 6.5% and the other of 5.4%. The symmetry plane is not perpendicular to the lineation. The fabric bears strong resemblances to that of 232 and the overall symmetry is similarly triclinic.

It would appear that the fabric development in the quartz veins parallels that in the psammites. Major deformation involving quartz fabric development therefore post-dates quartz vein formation.

274

The layering is 018º/24º E and there is a very faint lineation of 126º/23º. The rock is an average to coarse grained psammite from an area with much folding in evidence. The platy fabric and observed mica fabric in the layering are axial planar to

minor folding in the layering. The specimen, which is typical of the area, is believed to be from the core of a major fold.

The mica poles (Figure 4.53) clearly define a schistosity which is divergent from the observed layering. The intersection of the two planes is close to the lineation. There is no girdle developed and the fabric is axial.

The quartz c-axes (Figures 4.54 and 55) have a clear monoclinic symmetry. Two maxima lie in the symmetry plane, one of 3.6% and the larger of 7.2%. Although perpendicular to the layering, the symmetry plane is not perpendicular to the mica fabric or lineation. However, despite the overall triclinic symmetry, the fabric is similar to that from other parts of the sub-area (cf 232 and 233). As the fabric appears to be better developed in 274 than to the west, this may indicate an increase in the degree of deformation to the east.

44

The layering is about 036º/10º E and there is a fine lineation to 132º/12º. In the immediate vicinity the layering is 168º/15º E and the specimen is from an area where the layering is oblique to the general trend. As such it is atypical. The specimen is from an area of average to fine grained psammite with some much coarser elements, and is close to the core of a major fold. As the layering is not in a typical orientation it is hoped that better evidence can be obtained as to the relation of the fabrics and layering.

The mica poles (Figures 4.56 and 57) define a clear schistosity, but there is no girdle development defining a lineation. The intersection of the mica fabric and the layering is perpendicular to the lineation. The mica fabric is a plane of 015º/33º E, therefore unrelated to layering here or regionally.

The quartz c-axes (Figures 4.58 and 59) have a clear monoclinic symmetry with one maximum of 6.7% and the other of 4.6%. The symmetry plane is not perpendicular to the mica fabric or layering, but the intersection of layering and quartz fabric is close to the lineation. In common with other specimens from the sub-area the overall fabric is triclinic.

30

The layering is 153º/36º E and although for the sub-area the specimen is atypical, it is characteristic in both rock type and orientation of the Strathcarron Banded Psammite. There is a very weak lineation in the specimen of 057º/36º. The area appears to have been deformed less than the Attadale Psammites to the north-east and east, and an analysis of the fabric is useful in testing this hypothesis.

There was very little mica in the part of the specimen analysed. The quartz c-axes (Figures 4.60 and 61) have a monoclinic, almost orthorhombic symmetry. Three maxima lie in one symmetry plane, one of 4.2% being close to the intersection of two symmetry planes and the others of 4.7% and 4.5% lying symmetrically about the layering.

The comparative weakness of the fabric and dissimilarities with the fabrics to the east would confirm the hypothesis that the specimen has been subjected to a deformation of different tectonic style to the rest of the sub-area. An extrapolation of this deformational style to the whole of this south-western corner of the western edge of the area appears reasonable (see Chapter 3).

2) Attadale East sub-area

Four specimens from this sub-area were analysed, of which only two are psammites (252 and 123). One other is a striped psammite from the Creag a' Chaorainn Semipelite (267) and the fourth a quartz vein from within the psammites (202). Unlike the quartz vein from the West sub-area (233) this specimen is not from a locality close to any of the other rocks analysed.

252

The observed layering is 074º/45º E, but is poorly developed and evidently oblique to the mineral fabric. The rock is a fine, massive psammite from an area in which sedimentary cross-bedding is preserved. The specimen is typical of the area and of the rocks from the major fold to the east (cf. 123). The lineation is the dominant fabric element and a study of its relations to the mineral fabric is useful.

The mica poles (Figure 4.62) have a poor fabric, with slight girdle development. The observed planar structure does not correspond to the mica fabric, but the intersection of mica with the layering is equivalent to the lineation.

The quartz c-axes (Figures 4.63 and 64) have a poorly defined monoclinic fabric. The two maxima lying in the symmetry plane are of 5.8% and 4.8%, and the larger maximum is at right angles to the lineation. As the symmetry plane is not perpendicular to any other fabric elements the overall symmetry is triclinic.

123

The platy quartz fabric is 035º/36º E and there is a dominant quartz rodding lineation at 119º/36º. The rock is a coarse, massive psammite which is almost an L-tectonite, having only a weakly defined layering. The specimen is taken from the centre of a major fold zone of which 252 lies to the west.

The mica poles (Figure 4.65) form a girdle which is perpendicular to the lineation, and which has a weak maximum defining the platy fabric.

The quartz c-axes (Figures 4.66 and 67) have a monoclinic fabric. There is one strong maximum of 10.5% lying more or less within the plane of the platy fabric and perpendicular to the lineation, but the maximum is elongated in the symmetry plane. The symmetry plane is only approximately perpendicular to the lineation, and the overall symmetry is triclinic.

The fabric can be broadly compared to that of 252, but the much stronger maximum is associated with the development of a good axial planar fabric in the major fold. The overall lack of better symmetry is the result of an earlier fabric surviving in this area. The earlier fabric becomes more noticeable to the west.

202

This quartz vein lies in a fine, massive psammite/striped psammite with a platy fabric of 030º/28º E. The lineation in the quartz vein, parallel to that in the psammite, is 120º/28º, and there is also a platy fabric in the vein. The fabric and layering in the psammite are poor and any fabric development in the quartz veins is considered important in understanding that in

the psammite. The specimen is taken from the east of the major fold from which 123 is taken. There is a very weak lineation in the quartz veins parallel to that in the psammite.

The quartz c-axes (Figures 4.68 and 69) have a good but not perfect axial symmetry. The maximum lies in the plane of the quartz vein platy fabric and perpendicular to the lineation. The simple overall axial fabric bears comparison with 123. The quartz veins have a fabric solely related to the major folding which affects 123, and indicate that the irregularities in the psammite fabric are the result of an earlier fabric development.

267

The layering and platy fabric appear co-planar at 042º/20º E. No lineation is apparent and the platy fabric is weak. Regionally, the lineation pitches at 90º. Apart from the fact that it is from the more psammitic part of the Creag a' Chaorainn Semipelite, the rock is characteristic of the area. The few minor folds in the area indicate that the specimen is from the limb of a major tight fold to the west.

The mica poles (Figure 4.70) have a poor fabric but define a schistosity with a slight girdle development. The girdle and the intersection of mica with layering define a point, pitching 90º, equivalent to the regional lineation.

The quartz c-axes (Figures 4.71 and 72) have a clear monoclinic symmetry, with three maxima of 5.5%, 4.5% and 4.2% lying in the symmetry plane. This plane is perpendicular to both the mica fabric and layering. The overall fabric has a monoclinic symmetry. In most respects the fabric of the specimen is atypical of the sub-area.

b) Bendronaig area

This area is confined to the flaggy zones below the Beinn Dronaig Pelite. Three specimens of psammite (216, 197, 152) were analysed, and for comparative purposes one specimen of striped psammite (127).

216

The specimen contains minor folding, and to either side of the folding the layering is 045º/33º E. There is a poorly developed axial planar fabric and an extremely fine lineation approximately to 135º/33º. The rock is a fine grained psammite, and the specimen is taken from the lower part of a fairly extensive flaggy zone. The specimen is typical of a large surrounding area.

The mica poles (Figure 4.73) lie in a fairly clear point maximum which defines a plane approximately parallel to the layering and faint platy fabric.

The quartz c-axes (Figures 4.74 and 75) generally lie in one large maximum of 9.3% and there is a small, barely significant maximum of 2.2%. The fabric is broadly monoclinic, although a critical interpretation may be triclinic. The monoclinic symmetry plane is perpendicular to the smaller maximum.

The fabric is neither directly comparable with those to the west nor with those to the east, and it is considered that this flat area shows a transitional fabric.

197

The layering is 050º/22º E and there is a quartz rodding lineation to 154º/22º. The lineation is strong, but no quartz platy fabric is evident. The rock is an average grained, flaggy psammite, and lies close to the centre of the flaggy belt, some way above 216.

There is insufficient mica in the specimen for fabric determination. The quartz c-axes (Figures 4.76 and 77) have a clear monoclinic symmetry, although there is only a single maximum of 8.7%. The symmetry plane is perpendicular to both the layering and lineation, so the overall symmetry is monoclinic.

127

The layering is 024º/33º E and there is a faint lineation of 158º/22º. The rock is a fine, flaggy striped psammite which is typical of the area. There is some highly attenuated cross-bedding locally. The mica poles (Figure 4.78) form a good point maximum with slight girdle development perpendicular to the lineation.

The quartz c-axes (Figures 4.79 and 80) have two weak maxima of 5.0% and 3.9% lying in a girdle. The fabric symmetry is monoclinic, and the symmetry plane is perpendicular to both the layering and lineation. Thus the overall monoclinic fabric symmetry is maintained.

Although the fabric is essentially the same as others from the area (cf. 197 and 152), the more micaceous nature appears to have had an effect in retarding fabric development.

152

The layering is 033º/42º E and there is a very fine lineation to 168º/32º. The rock is flaggy, average to fine grained psammite. Most of the rocks in the area are striped psammites (cf. 127), but in view of the fabric development apparent in the striped psammites it is believed that the psammites are better for fabric comparison.

There is insufficient mica in the specimen for a fabric determination. The quartz c-axes (Figures 4.81 and 82) have a clear monoclinic symmetry with a single maximum of 9.2%. The symmetry plane is perpendicular to the layering and lineation. The overall fabric has a monoclinic symmetry and is very similar to that of 197. The monoclinic fabric with a single maximum is therefore considered to be typical of this flaggy belt.

c) Achnashellach area

Only two specimens from this area (21 and 339), both psammites, were analysed. Specimen 21 is useful for comparing with the fabrics in the Lewisian from the edge of the Achnashellach Zone (Figure 2.2).

21

The layering is 034º/20º E and there is a very fine lineation to about 132º/20º. The layering is parallel to a well developed platy fabric. The rock is a very flaggy psammite, the flagginess being directly related to the platy fabric.

The mica poles (Figure 4.83) form a well defined point maximum which is parallel to the layering. The fabric is clearly axial and does not define the lineation.

The quartz c-axes (Figures 4.84 and 85) have a clear two maximum monoclinic symmetry. The larger maximum of 7.3% lies within the plane of the layering/mica fabric, at right

angles to the lineation. The weaker maximum of 5.3% lies in a symmetry plane which is perpendicular to layering/mica fabric. Overall the fabric is monoclinic, and a notable feature from the point of view of fabric development is the quartz maximum parallel to the observed quartz platy fabric.

339

The layering is 023º/30º E and there is a very fine quartz lineation of 120º/24º. The rock, a very fine, very flaggy psammite, is taken from the middle of the flaggy zone and is typical of the area.

The mica poles (Figure 4.86) define a clear point maximum with only slight girdle development. The mica fabric is more or less parallel to layering.

The quartz c-axes (Figures 4.87 and 88) have a clear two maximum monoclinic symmetry. The maxima, of 5.6% and 4.1%, are symmetrically disposed about the layering/mica fabric and the symmetry plane is roughly perpendicular to the lineation. The overall symmetry is still monoclinic.

d) Lewisian

Two specimens of Lewisian acid hornblende gneiss (319 and 22) were analysed. Both came from a thin band of Lewisian close to the boundary between the Achnashellach Zone and Attadale Zone (Figure 2.2). The closest comparative psammite fabric is 21.

319

The specimen is from an area with a typical platy fabric of 042º/46º E. The most noticeable lineation is 066º/30º in a quartz vein, but a weak quartz lineation was noted in the specimen to 168º/40º. The fabric in the gneiss is very poor, but more noticeable than in 22. The specimen is located in a more massive and persistent part of the Lewisian inlier.

The mica poles (Figure 4.89) have a poor axial symmetry with no girdle development. This fabric is approximately parallel to the noted planar fabric.

The quartz c-axes (Figures 4.90 and 91) have a clear monoclinic symmetry, with three maxima in the symmetry plane. The maxima are of 5.3%, 4.9% and 4.6%, and although none of them lie within the planar fabric, the intersection of the girdle and mica fabric is perpendicular to the weak lineation. The overall fabric is triclinic, but almost monoclinic.

The Lewisian has a fabric which bears close comparison with the nearest psammite, 21, and which is almost identical to that of 339. It could also be compared with some of the psammites from the south-west, and it is clear that there is a Moine fabric in the Lewisian. Bearing in mind that unlike lithologies are being compared it is very difficult to find justification for any remnant Lewisian fabric.

22

This massive gneiss has no well developed planar or linear features. The regional layering in the psammite is 040º/30º E, but this bears little relation to the observed fabric in the gneiss.

The mica poles (Figure 4.92) have a poor fabric which is essentially axial. The defined mica layering dips 45º to the east.

The quartz c-axes (Figures 4.93, 94 and 95) have a very weak fabric which is barely adequately defined at the limits of the new contouring technique. The symmetry is monoclinic, and as the symmetry plane is roughly perpendicular to the mica fabric the overall symmetry remains monoclinic.

The fabric in this specimen has the same symmetry as other Moine and Lewisian rocks in the area. However, the fabric is quite unusual in several respects and by comparison with 319 the specimen is structurally inhomogeneous. It is believed that the very poor fabric development represents a transition from a truly Lewisian fabric to a Moine fabric.

e) Monar area

This area is structurally distinct from the areas to the west, and the analysis of specimen 98 is to allow for a fabric comparison both with the earlier work of Ramsay (1957) and with the analysed specimens to the west.

98

The layering is 040º/40º E and there is a fine lineation to 160º/37º. The area displays much minor folding and the mica fabric is axial planar to this folding. The specimen is of a banded psammite and the fabric described below can be compared to two specimens of psammite analysed by Ramsay to the west of the Strathconon Fault (Ramsay, 1957, Fig. 19, Nos. 12 and 13).

The mica poles (Figure 4.96) have a good single maximum fabric with girdle development. The maximum is almost perpendicular to the layering. The intersection of the mica fabric and layering coincides with the observed lineation.

The quartz c-axes (Figures 4.97 and 98) have an orthorhombic, almost axial symmetry. The single maximum of 6.9% lies in a girdle which is perpendicular to the lineation. The maximum also lies very close to the plane of the mica fabric. Overall the symmetry is therefore only monoclinic.

Ramsay (op. cit. p.301) noted that a single girdle as the dominant fabric feature, which is clearly very similar to 98, was the result of dominant isoclinal folding, which in this area was of Monar generation. The fabric is similar to those from the Bendronaig sub-area (cf. 216, 197, 127, 152), and to some of those from the Attadale East sub-area (cf 123). The evidently marked fabric development has obvious implications for a wider structural synthesis, as well as indicating a single dominant deformation in the Pait area.

4.12 Summary

The new contouring technique (4.8) has clearly provided a more suitable method of comparing fabric diagrams. The fabric similarities that have been found across the project area are important and the conclusions that can be drawn are:

1) In the Monar area to the east of the Beinn Dronaig Pelite the dominant fabric is clearly related to a Monar phase of folding. Correlations across the project area can be made (see section 5) and hypotheses presented on the age of deformation phases in the west, partly on the basis of fabric evidence.
2) The Bendronaig area flaggy belt immediately to the west of the Beinn Dronaig Pelite has a simple, strong microfabric in which a quartz c-axis girdle is perpendicular to a single, dominant lineation. There is a

marked decline in the development of the microfabric towards the west.

3) The Achnashellach area flaggy belt is largely associated with the MTZ, but displays essentially the same fabric as the eastern part of the Bendronaig area. However, as the zone is the result of MTZ overprinting the fabric is correspondingly more complex.

4) The Attadale area major fold structure immediately to the west of the Bendronaig area flaggy belt is in part marked by a stronger improvement in microfabric development. Also evident are the effects of an earlier fabric, noticeable by its absence from the quartz veins.

5) Further west into the Attadale area some elements of the microfabric remain strongly developed, but overall there is an increase in complexity and ultimately a marked weakening of the fabric.

6) The microfabric development across the area points to a series of strong fabric development phases, each one dying out westwards, leaving an earlier fabric unaffected. The ultimate conclusion must be that the oldest folding occurs in the westernmost part of the Attadale area.

5. STRUCTURE AND DEFORMATIONAL HISTORY

A study of the major structures and sequence of deformational events in the comparatively small area south-east of Glen Carron can provide a key to a much larger region of the Moine (Chapter 6). The observations made in Chapters 2, 3 and 4 can now be usefully brought together to give a unified structural picture for the project area. The major details of the lithology and structure are shown in Enclosures 2 – 5. Enclosures 3 and 4 (planar and linear trends) can also be used in a regional context, while the lithologies shown in Enclosure 2 and the major structural features shown in Enclosure 5 relate only to the project area. Wider correlations of these aspects are given in Chapter 6.

On the basis of variations in flagginess and grain size (Chapter 2), and in the occurrence and form of minor structures such as cross-bedding, minor folds and quartz veins (Chapters 2 and 3) it is possible to define belts which have a high degree of homogeneity and areas which are internally inhomogeneous. The zones defined in Figures 2.1 and 2.2 fall broadly into one or the other of these categories. It is considered by the author that the most important zones are the homogeneous, flaggy zones. These are now equated with slides or belts of high shear, and as such are major structural discontinuities in the Moine of the area.

The zones of flagginess (Figure 2.2) clearly identify two significant NE – SW and NNE – SSW trending lineaments. The former lies close to the lithological boundary between the Beinn Dronaig Pelite and Achnashellach Banded Psammite (Enclosure 2) probably within the psammite, and the other lies to the west, within the Attadale Psammite to the east of the Creag a' Chaorainn Semipelite. There is a third belt of flagginess developed on a large scale to the south and east of the Moine Thrust Zone (MTZ).

Broadly speaking the large flaggy slide zones isolate areas where the evidence of intense folding is preserved. The folds lie in tectonic eyes, large 'augen' of generally low strain (Harris & Rathbone, 1980). Internally the augen are complex, and to the south-west of the area (Attadale Zone, Figure 2.1 and 2.2) there is evidence of slide belts being developed within the augen (section 3.6). However, in regional terms the augen can be considered as incidental to the development of a series of slides and deformation 'fronts', ie. lines at which major events cease to have a pervasive influence.

In order to establish a structural sequence a marker event is needed for the area, and it is particularly useful if this can also be used regionally. The author has noted that the Monar (Tobisch and others, 1970) phase of deformation is dominant in the Loch Monar – Pait area (Ramsay, 1955). Taking the Monar phase as a marker event its influence can be traced west by the author, where it weakens and ultimately disappears. The line at which Monar begins to die away appreciably coincides with the very flaggy belt in the middle of the Bendronaig Zone (Figure 2.2). As the belts are thought to be slides (section 2.11) the line is termed the 'Bendronaig Slide'. The line along which the Monar phase effectively disappears is termed the 'Monar Front'. Both are marked on Enclosure 5.

The evidence for the existence of a Monar Front and the associated weakening of the deformational event in the area to the east of the front has been presented in Chapters 2, 3 and 4. The major NE closing fold structure (section 3.6) in the Attadale South-East sub-area (Figure 3.1) abruptly gives way to the flaggy Bendronaig Zone (Figure 2.2). At the junction of the two major features an unusual suite of rocks is developed, including L and LS tectonites. Furthermore, the linear trends change markedly at this junction (Enclosure 4; Figures 3.5 and 3.9) and it is concluded that it is a major tectonic junction in the Moine. Quartz fabric evidence (section 4.12) tends to confirm the supposition that the front is Monar event related. There is evidence of a sharp change in quartz fabric symmetry, strength and orientation, and it is particularly noticeable that the diminution in intensity of shearing, as indicated by flagginess and grain size reduction, is paralleled by a degradation of Monar petrofabric symmetry (compare Figures 4.75 and 4.77).

The Monar Front clearly splits the area into two structural regimes, referred to here as the 'Monar regime' in the east and the 'pre-Monar regime' in the west. Although the implication is that Monar events and fabrics are not to be expected west of the Monar Front, it is quite conceivable that pre-Monar events are still preserved behind (east of) the Monar Front.

When looking at lineations related to fold generations there are two areas where the evidence is particularly clear. To the east, around Pait Lodge, a synformal fold is developed (Ramsay, 1955; Kassler, 1961) which has a good penetrative SSE trending (Figure 3.23) lineation related to the fold hinge. To the west, in large parts of the Attadale area (Figure 3.1), an ESE trending (Figure 3.5) lineation (pitch 90° on the regional layering) is similarly a penetrative axial fabric. However, the existence of a Monar Front indicates that the SSE lineation is Monar in generation and the ESE lineation is pre-Monar.

When considering all the available evidence in the Creag a' Chaorainn Semipelite and Achnashellach Banded Psammite the fold generations are not obviously Monar or pre-Monar. The complexity of the fold areas related to these lithologies, particularly the latter, have been expanded in 3.6. The increase in strain as a result of the Monar phase of deformation is believed to result in the rotation of minor fold axes and lineations towards the extension direction, marked by the dominant SSE Monar lineation (Figures 3.15 and 3.25), in the semipelite, believed to be more susceptible to fabric reorientation than the psammites, the fabric is basically pre-Monar, but rotated towards Monar by the influence of the overlying Bendronaig Slide. The same may also apply to the major fold belt in the Achnashellach Banded Psammite, as the Monar phase is probably responsible only for the belts of high shear isolating this fold structure.

Having identified the Monar Front as a marker event in the Moine south-east of Glen Carron, and also having given some ideas of the relative positions of some of the major structures, a further marker event can be postulated. This event is the last major event to affect the area, namely the Moine Thrust Zone (MTZ). The immediate influence of movement on the discontinuity in a belt just above the MTZ is well documented (eg. Johnson, 1955) but has no direct parallels in the project area.

The structures related to the thrust on a much wider scale (eg. Barber, 1965) are of interest, and establish a second marker event which can be closely related to the Monar Front. The position of the MTZ to the south of the Strathmore Fault (Enclosure 2) is believed to be indicated by the flaggy Achnashellach Zone (section 2.11; Figure 2.2). For some distance above the MTZ (up to 5 km horizontally) the Moine is overprinted with shear induced flagginess. The belt of flagginess trends N – S to the north of the project area

(Johnson, 1955) and is confluent with the Bendronaig Zone on Sgurr na Feartaig (Enclosure 1). However, the belt of flagginess in its boundary with the massive Attadale Zone (Figure 2.2) transgresses the strike trend and several major structures (Enclosures 3 and 5), passing across Carn Mor in a south-westerly direction, eventually disappearing beneath Strath Carron to the south-west of Arineckaig. This line is termed the 'MTZ Front' as it indicates the extent of MTZ overprinting.

The relationship between the Strathmore Fault and the MTZ is not particularly clear; the supposed position of the fault (Peach and others, 1913) is beneath the fluvioglacial sediments of Strath Carron. On the evidence of the existence of the MTZ related Achnashellach Zone the author proposes that the MTZ is about 2 km below the surface at Arineckaig, just 5 km south-west of the surface expression of the thrust at Lair. The Achnashellach Zone points not only to a considerable downturn of the MTZ, but also to a marked swing in trend, probably into near parallelism with the Strathmore Fault.

The author therefore proposes that the Strathmore Fault, downthrowing to the south-east, is of variable throw, with a hinge and point of zero throw both to the north and south. A monoclinal kink with converging axes is partly responsible for the downturn, and wholly responsible for the trend change in the MTZ.

Consequently, the MTZ changes from a structural level more or less parallel to the Bendronaig Slide and Monar Front to one considerably lower in the succession (Figure 6.1). The regional implications are discussed in Chapter 6.

As to the age of the MTZ Front relative to the Monar Front, it is difficult to provide conclusive evidence. The Achnashellach Zone is strikingly similar to the Bendronaig Zone in many respects, and there is also a dominant SE – SSE lineation (Figures 3.9 and 3.11). The swing in strike trend noted around Achnashellach, and the change in direction of the flaggy belt related to the MTZ all have what is ostensibly a dominant Monar fabric. It is therefore concluded that the Achnashellach Zone is in the Monar regime, a hypothesis supported by minor fold evidence from Carn Mor (section 3.6). Thus the early development of the MTZ related shear belt was a Monar initiated event. The fact that the dislocation did not follow the alternative route of the Bendronaig Slide reinforces the importance of the latter regionally (Chapter 6). Furthermore, this links the MTZ to the Monar Front and it is fortuitous that the marked change in structural level of the MTZ has preserved the pre-Monar regime in the Attadale area (Figure 3.1).

Having linked the Monar Front and Bendronaig Slide to the MTZ it remains to provide some evidence on the nature of the Glenuig Zone flagginess (Figure 2.2). This is equated with a 'Glenuig Slide', which is much more confined than the Bendronaig Slide, but is thought to result in a much greater dislocation.

Looking at the disposition of folds of pre-Monar generation (Enclosure 5) they are complementary, ie. NE closure follows SW closure, and so on. The Bendronaig Slide does not alter this pattern, but the fold identified immediately above the Glenuig Slide has a south-west closure (section 3.6), the same as the fold belt below the slide.

On Sail Riabhach further evidence can be found relative to the Glenuig Slide and underlying remnant pre-Monar regime folds. It has been noted in section 3.6 that the vergence of minor fold pairs consistently indicates a closure to the south-west in this area, and such a closure can be found in Beinn Tharsuinn (Enclosure 1). However, only folds of a single vergence are seen, and although it has been suggested that they indicate a consistent sense of shear (section 3.6), the preferred alternative is that the upper limb or the closure has been completely sheared out by the Glenuig Slide. The Glenuig Slide is therefore not only a major shear belt in the Moine, but also represents a considerable dislocation in the succession. As such it could possibly equate with the Sgurr Beag Slide, and this parallel is amplified in Chapter 6.

The majority of the structural hypotheses put forward so far have been related to the west of the project area. It has been proposed (Johnstone and others, 1968; Tanner and others, 1970) that the Sgurr Beag Slide (Tanner, 1970), marking the boundary between the Morar (below) and Glenfinnan (above) divisions passes close to the western edge of the Beinn Dronaig – Fannich Pelite. The hypotheses on the Glenuig Slide do not contradict this, but it is the position of the Sgurr Beag Slide (SBS) east of the pelite about which the authors (op. cit) were unsure. In this respect the author proposes that the Monar Banded Psammite is not lithologically the same as, or similar to, the Achnashellach Banded Psammite (Enclosure 2). The banding and striping in the former is far more pronounced (section 2.13a), and this was recognised (Tanner and others, 1970, p. 300) as a criterion for the division between Glenfinnan and Morar psammites. On this basis the Monar Banded Psammite is part of the Glenfinnan Division, lying above the SBS. No evidence on the position of the SBS in the Pait area can therefore be put forward.

On the basis of the evidence of the observed features (Chapter 2), the trends and styles of minor structures (Chapter 3), the petrofabrics (Chapter 4), and the various hypotheses put forward in this Chapter to link all these, the following sequence of deformational events is proposed for the area south-east of Glen Carron.

1) D_1

The first event preserved in the structural history of the area is folding about NE trending axes, with axial planes parallel to the layering, ie. dipping ESE at about 30º. The folds are characteristically tight to isoclinal and very highly sheared. Minor folds of D_1 generation are only preserved in the Attadale area (section 3.6; Figure 3.1), that is to the south and east of the Moine Thrust Zone and Monar fronts respectively (Enclosure 5). The only major fold structure of this generation is preserved in the Attadale Psammite on Carn Mor, below the Lewisian inliers (Enclosure 2). The fold possibly closes to the north-east and is co-planar with D_2 folds. The D_1 event is probably responsible for the inclusion of the Lewisian bodies in the Moine of the west of the area.

2) D_2

Open to isoclinal folding about ESE axes, pitching 90º on the axial planes dipping about 30º to the ESE in the west of the area, rotating into parallelism with D_3 deformation towards the north and east. Having been subjected to extensive shearing (of late D_2 generation) only the hinge belts of the folds are readily recognisable. Four out of the five major folds recognised (Enclosure 5) are in the Attadale area (section 3.8; Figure 3.1). The major fold, closing to the south-west, in the Sgurr na Feartaig/Glenuig area (Enclosure 5; Figure 3.1) is postulated as being of D_2 generation (see earlier). The D_2 generation folding

is responsible, by refolding of D_1 folds, for the present lithological pattern. The south-westerly closing of the Achnashellach Banded Psammite and the north-easterly closure of the Creag a' Chaorainn Semipelite (Enclosure 2) are both the result of D_2. The repetition in the succession (see Chapter 6), whereby the Attadale Psammite can be found to both sides of the Creag a' Chaorainn Semipelite (section 2.13a), is probably also the result of D_2 refolding of D_1.

3) D_{3A}

The D_3 event can be split into an early fold phase, progressing to a later phase of extensive shearing. The D_{3A} fold phase is isoclinal folding about SSE axes, with the axial planes dipping ESE at about 35º. The only major fold of this generation that can be positively identified is the An Cruachan synform (Ramsay, 1954 and Figure 1.7) which passes through Pait Lodge (Enclosures 1 and 5). The D_{3A} fold generation equates with Monar (section 3.6; Tobisch and others, 1970). Apart from the D_{3A} (Monar) An Cruachan – Pait synform there are two or three other possible D_{3A} folds. One lies to the west of Pait in the Monar Banded Psammite, a second in the Beinn Dronaig Pelite (Watson, pers. comm.) and a third just above the Glenuig Slide. All four structures are shown on Enclosure 5.

4) D_{3B}

It has been postulated that on the field evidence (Chapters 2, 3 and 4) the Monar deformation dies away to the west. A Monar Front has been proposed (see earlier), and the development of this tectonic front is associated with the D_{3B} deformation. D_{3B} is the shearing of major fold limbs to produce slides. The intensity of shearing is greatest in the west along the Glenuig Slide, dying away through the Bendronaig Slide up to the Monar Front. Shear belts in the Beinn Dronaig Pelite (Enclosure 5) can only be postulated on the basis of intervening major fold hinges.

During D_{3B} the Attadale area (Figure 3.1) is structurally more or less frozen. There is no movement on the slides within the area, and the only possible D_{3B} influence is some rotation of linear trends (compare Figures 3.3, 3.5, 3.7 and 3.9) towards the Monar trend. The fabric evidence (section 4c) is particularly useful in defining the extent of the D_{3B} deformation (compare Figures 4.48 - 4.72 with 4.73 - 4.82).

The Moine Thrust Zone (MTZ) related Achnashellach Zone (Figure 2.2; section 2.11) is confluent with the Bendronaig Slide related Bendronaig Zone (Figure 2.2; Enclosure 5). It is postulated that the Achnashellach Zone defines a front of MTZ overprinting, the MTZ Front, and that this is also of D_{3B} (Monar) age. As the Sgurr Beag Slide to the south, equivalent to the extension of the Bendronaig/Glenuig zones, is also D_{3B}, the MTZ and Sgurr Beag Slide are related to the same deformational event.

As the NE – SW trending D_{3B} shear belts develop, the D_{3B} shear belt related to MTZ is developing on a monoclinal flexure which rotates the strike trend and drops the belt to a lower structural level (see Figure 6.1).

5) D_{4A}

The MTZ is initiated along a N – S trending D_{3B} shear zone to the north of Glen Carron, and along the downwarped D_{3B} zone beneath Strath Carron. At this time the Bendronaig Slide and Glenuig Slide are effectively frozen. The MTZ does not follow the logical line directly south and towards the Sgurr Beag Slide. The effects of the MTZ are only seen between Craig and Lair, Achnashellach area (section 3.6).

6) D_{4B}

At about the same time as the MTZ there is the localised development of major open folds. This event is confined to a large area south of Loch Monar, and the several identified fold hinges are shown on Enclosure 5. In the main area of D_{4B} development the axial plane dips 42º SSW (Table 3.1; Figure 4.24). In all D_{4B} development the fold axes are coaxial with the D_3 (Monar) lineation (Figures 4.22 and 4.24).

7) D_5

Throughout the western parts of the area, particularly in the flaggy areas, there are late-stage brittle and semi-ductile features (section 3.7). These comparatively minor structures are formed by the relaxation of stress following the dislocation on the MTZ.

The deformational history can therefore be summarised as follows:

1) D_1. Folding about NE axes; axial planes dip ESE at about 30º; extensively sheared tight to isoclinal folds, only preserved as a major fold in one location in the west; responsible for the inclusion of Lewisian in the Moine.
2) D_2. Open to isoclinal folding about ESE axes (90º pitch) on axial planes dipping ESE at about 30º; extensively sheared, but up to five major fold hinge zones still preserved in the west. By refolding D_1 generation folds, D_2 is responsible for the closures along strike of lithological units (Enclosure 2).
3) D_{3A}. Isoclinal folding about SSE axes; axial planes dipping ESE at about 35º (Monar fold generation, Tobisch and others, 1970) ; major structures only seen in the east.
4) D_{3B}. The development of extensive slide zones on the limbs of major Monar (D_{3A}) folds. Probably co-planar with shearing on the limbs of D_2 folds (which are probably co-planar with D_1 folds). Two major NE – SW trending slides and a third slide related to the ultimate development of the Moine Thrust Zone develop. The easterly slide is the equivalent of the Sgurr Beag Slide (Tanner and others, 1970). The western edge of the area showing the effects of Monar deformation is proposed as the Monar Front.
5) D_{4A}. The Moine Thrust is initiated along a N – S trending line to the north of the area (the lateral equivalent of the Bendronaig Slide), but is affected by the Strathmore Fault and a monoclinal flexure which changes its trend to ENE – WSW and drops the thrust to a lower level in the succession.
6) D_{4B}. Large scale open folds; coaxial with the Monar deformation (D_{3A}); axial planes dipping 42º SSW; affect only part of the east of the area.
7) D_5. Late stage brittle and semi-ductile deformation associated with relaxation of the Moine Thrust deformation.

6. REGIONAL STRUCTURE AND STRATIGRAPHY

Chapter 1 has summarised the history of research and some broad ideas on a regional synthesis. Having now outlined the structure of the area in Chapter 5, it only remains to consider the regional implications of the hypotheses. The possible correlations with work previously undertaken in the surrounding areas are considered to be important in terms of future studies which may be undertaken in the intervening ground between these areas (Enclosures 3 and 4) and in any re-mapping of the areas concerned.

Purely in terms of regional stratigraphy the work south-east of Glen Carron has not revealed any significant new features. Though there is some uncertainty as to the exact position and nature of the Sgurr Beag Slide, it is nevertheless proposed that the Achnashellach Banded Psammite/Beinn Dronaig Pelite boundary (Enclosure 2) is the Morar/Glenfinnan boundary on the basis of lithological correlations with the standard table of Moine stratigraphy (most recently summarised in Harris and Rathbone, 1980). The proposed stratigraphic correlations between the formations of the standard table (op. cit.) and the Glen Carron lithologies (section 2.13; Enclosure 2) is given in Table 6.1. The significant features indicated mostly find parallels in the standard table (op. cit.). The most significant difference is the repetition of the Attadale Psammite, related to tight – isoclinal D_2 refolding of D_1 folds (section 3.8; Chapter 5). This repetition is also related to the occurrence of the Bendronaig Slide (Chapter 5).

If the portrayal of the Morarian as an early orogenic event in the history of the Moine (Johnson, 1975; Harris and others (ed), 1979; Elliott and Johnson, 1980) is correct then the Sgurr Beag Slide (Figure 6.1) assumes an important position in the regional Moine (Piasecki and van Breemen, 1979). The slide will then represent a partition between two orogenic regimes; a pre-Caledonian (Morarian) orogeny and a Caledonian orogeny which almost completely removes all evidence of the earlier event.

Johnson (1975) speculated on the position of Sutherland relative to the supposed Morarian, and Elliott and Johnson (1980) recognise the importance of supposed pre-Caledonian (D_1) events in the formation of the MTZ. Therefore, in terms both of events in the Moine north and south of the Glen Carron area and of the domain of the two orogenic regimes it is important that the slide belts in the region should be carefully assessed.

Having postulated (Chapter 5) the Glenuig Slide beneath the Beinn Dronaig Pelite (Enclosure 5) it is useful to note that Sutton (1960) recognised hornblendic rocks to the west of the pelite both near Loch Sgamhain, NH 100 530, and to the south of Loch a' Chroisg, NH 130 575. The Glenuig Slide can possibly be equated with the Sgurr Beag Slide (Tanner and others, 1970), and Lewisian rocks (ie. hornblendic in part) are closely associated with the slide. On this evidence the Glenuig Slide (Sgurr Beag Slide) outcrops along much of the western boundary of the Fannich – Beinn Dronaig pelite (Figure 6.1) as predicted by Tanner and others (1970). The major break in the Moine succession between Morar and Glenfinnan (op. cit.) therefore splits the project area into an eastern and a western orogenic regime.

A study of McIntyre (1955) and Peach and others (1973) can be used in conjunction with the postulated major structures (Enclosure 5) to throw new light on the area to the south of the Fannich – Beinn Dronaig pelite. Figure 6.2 combines part of sheet 82 (op. cit.) with the unpublished data from part of sheet 72 (May, pers. comm.). The structural interpretation of the project area (Chapter 5; Enclosure 5) indicates two major slide zones (Bendronaig and Glenuig) and the Monar Front (Chapter 5) all converging to the west of Beinn Dronaig. Figure 6.2 is based on an analysis of strike trend on sheet 82 and shows ways in which the three features above might be linked to structures in sheet 72.

The Strathconon Fault constitutes a major tectonic boundary north-west of which the position of the Sgurr Beag Slide can only be speculative (Figure 6.1). On the basis that the Strathconon Fault is a sinistral strike slip fault (Ramsay, 1955; & c.) the Sgurr Beag Slide should outcrop to the north of the fault somewhere in the south-east corner of Figure 6.2.

May (pers. comm.) noted that the Lewisian slices at the lower levels in the Moine (ie, to the west) tend to have associated with them a migmatic psammite and 'quartz-biotite-rock', both rock types not being stratigraphic divisions but products of thrusting. Higher in the succession (ie. to the east) only a flaggy psammite is found in association with the Lewisian. In Figure 6.2, which shows the Lewisian and slide rocks, it is postulated that the Sgurr Beag Slide follows the main belts of slide rocks, thus terminating to the south-east in the expected position. Moving north, the Sgurr Beag Slide may then be aligned with the Bendronaig Slide, whilst the western edge of the slide rocks equates with the Monar Front (see Figure 6.2). The Glenuig Slide finds no equivalent to the south of Beinn Dronaig in the work of May.

Clearly there is a contradiction in the regional correlations; within the project area and to the north all the available evidence (Chapter 5; Sutton, 1960; Tanner and others, 1970; & c.) points to the Glenuig Slide as the equivalent of the Sgurr Beag Slide. To the south there is no evidence of a major break, lithological or structural, in the proposed position of the Glenuig Slide. Instead, the Bendronaig Slide and Monar Front appear to be the dominant features in terms of the slide belts and the occurrence of Lewisian.

Therefore, until further evidence is available it is proposed that to the south the Bendronaig Slide is equivalent to the Sgurr Beag Slide, but to the north the Glenuig Slide is the equivalent. In the ground south of Bendronaig Lodge (Enclosure 1) the two slides (Bendronaig and Glenuig) merge into a single flaggy zone constituting the Sgurr Beag Slide (Figure 6.2).

A study of Figure 6.1 illustrates the comparative complexity of the area south-east of Glen Carron. However, the obvious feature (see also Enclosure 5) is a link between the Sgurr Beag Slide, through the Bendronaig Slide to the Moine Thrust Zone (MTZ).

In producing the sequence of structural events ($D_1 – D_4$) given in Chapter 5 it has been stated that to the south-east of Glen Carron the Bendronaig and Glenuig slides (the latter broadly equivalent to the Sgurr Beag Slide) are of D_3 age. By comparison with the Monar and Pait area (Ramsay, 1955; Kassler, 1961; Tobisch and others, 1970) D_3 is equivalent to F_2 of Ramsay and Kassler, ie. Monar phase deformation (see Chapter 5 for correlations west into the Glen Carron area). It was suggested by Tobisch and others (1970) that the Monar phase of deformation is equivalent to F_3 in the Western Highlands. In this latter area (Ramsay, 1963; Mendum *in* Harris and others (ed), 1979; & c.) a sequence $F_1 – F_4$ is proposed; F_1, the interleaving of Lewisian and Moine, is believed to be equivalent to D_1 south-east of Glen Carron; F_2 is

equivalent to D_2 (cf. F_2 of May, 1959, with ESE axes pitching 90°); F_3 is equivalent to D_3 (Monar) and F_4 is equivalent to D_4 (major dislocation of the Moine Thrust Zone; late brittle and semi-ductile deformation).

A tentative link between the Sgurr Beag Slide and the MTZ is proposed, highlighting the contradiction with the proposal of Tanner (1970) that the Sgurr Beag Slide finished its movement before the end of F_2 (equivalent to D_2), and the evidence from the project area pointing to D_3 movement on the northern extension of the slide. Furthermore, the D_3 movement ultimately gives way, again in a northern extension (Bendronaig Slide, Chapter 5), to D_4 movement on the Moine Thrust Zone. The Sgurr Beag Slide has been proposed as a structural event, not a chronological event (Tanner and others, 1970), and it is now proposed that movement is diachronous relative to the major deformational phases ($D_1 – D_4$), starting as D_2 or earlier in the south, becoming D_3 south-east of Glen Carron, and ultimately ending as the flaggy or mylonitic belt along which D_4 movement took place to create the Moine Thrust Zone (MTZ).

The evidence from south-east of Glen Carron is considered to be of great significance relative to the major orogenic events. The major slide belts above the MTZ (D_4) do not totally destroy the earlier structures, and D_1 and D_2 events (Chapter 5) are well preserved west of the Monar Front (Enclosure 5). The major Caledonian (D_3) reworking of the Moine is patchy, as is illustrated by the wide variations in strain, subjectively assessed from such features as cross-bedding (section 2.12a) and minor folds (section 3.6). Features such as Lewisian inliers (section 2.13c; Enclosure 2), the limbs of major ($D_1 – D_2$) folds (section 3.8; Chapter 5; Enclosure 5) and major lithological boundaries (Enclosure 2) have acted as loci for high deformation rates, giving rise to a series of shear or slide belts.

It is therefore concluded that the active Sgurr Beag Slide, a major D_3 event (Monar) at a very much lower tectonic level than at present, split to the west of Beinn Dronaig into two slides (Glenuig and Bendronaig), producing comparatively weaker shear fabrics in each slide, but over a much wider belt than to the south. The weaker of the two slides (Bendronaig) finds a direct parallel in the 'proto-MTZ', ie. the belt of flaggy rocks of a less competent nature along which the MTZ was the ultimate major dislocation (D_4). Evidence of the dispersion of the effects of shearing over a wider belt is shown in the development of the Monar Front, and as a further consequence of the diminution of the deformational events at least one major D_2 structure is preserved within and between the two slides (Enclosure 5; Chapter 5).

As a result of a sharp change in the level of the proto-MTZ around Achnashellach this D_3 shear belt occurs at a much lower stratigraphic level in the Moine/Lewisian succession. Figure 6.1 illustrates the change to a level such that major Lewisian masses occur between the MTZ and Sgurr Beag Slide.

The area south-east of Glen Carron is therefore believed to hold in the Attadale area (Figure 3.1) the northerly culmination of a belt of pre-Monar or possibly Morarian (pre-Caledonian) rocks, virtually unaffected by the major Caledonian events. It is anticipated that above the MTZ north of Glen Carron and into Sutherland, significant areas of Moine unaffected by Caledonian reworking will not be found.

Table 6.1. MOINE STRATIGRAPHY. Based on the regional work of the Institute of Geological Sciences (Harris and Rathbone, 1980), showing the equivalents south-east of Glen Carron (Enclosure 2).

IGS	Significant features and names employed in Glen Carron area	
GLENFINNAN DIVISION Glenfinnan Striped Schist	Characteristically striped; psammitic to pelitic; some cross-bedding, probably indicating younging away from pelite (below); some possible Lewisian	Monar Banded Psammite
Lochailort Pelite	Coarse to fine, pelitic to semipelitic gneiss; central sheet with irregular occurrence of Lewisian gneiss	Beinn Dronaig Pelite
SGURR BEAG SLIDE	Zone of flagginess; some feldspathisation	GLENUIG SLIDE
MORAR DIVISION Upper Morar Psammite	Commonly cross-bedded; striped assemblage	Achnashellach Banded Psammite
(see below)	BENDRONAIG SLIDE	Attadale Psammite
Morar Schist	Pelitic and semipelitic schist	Creag a' Chaorainn Semipelite
Lower Morar Psammite	Generally pale psammite; heavy mineral bands found surrounding Creag a' Chaorainn Semipelite; contains thin strips of Lewisian in west	Attadale Psammite
Basal Pelite	Pelite, semipelite and psammite; finely banded assemblage; contains thin strips of Lewisian	Dughaill Semipelite
	Lateral equivalent of Dughaill Semipelite, but less micaceous; contains thin strips of Lewisian	Strathcarron Banded Psammite
Lewisian	Only seen as inliers in the Moine succession; probably entirely associated with shear belts	

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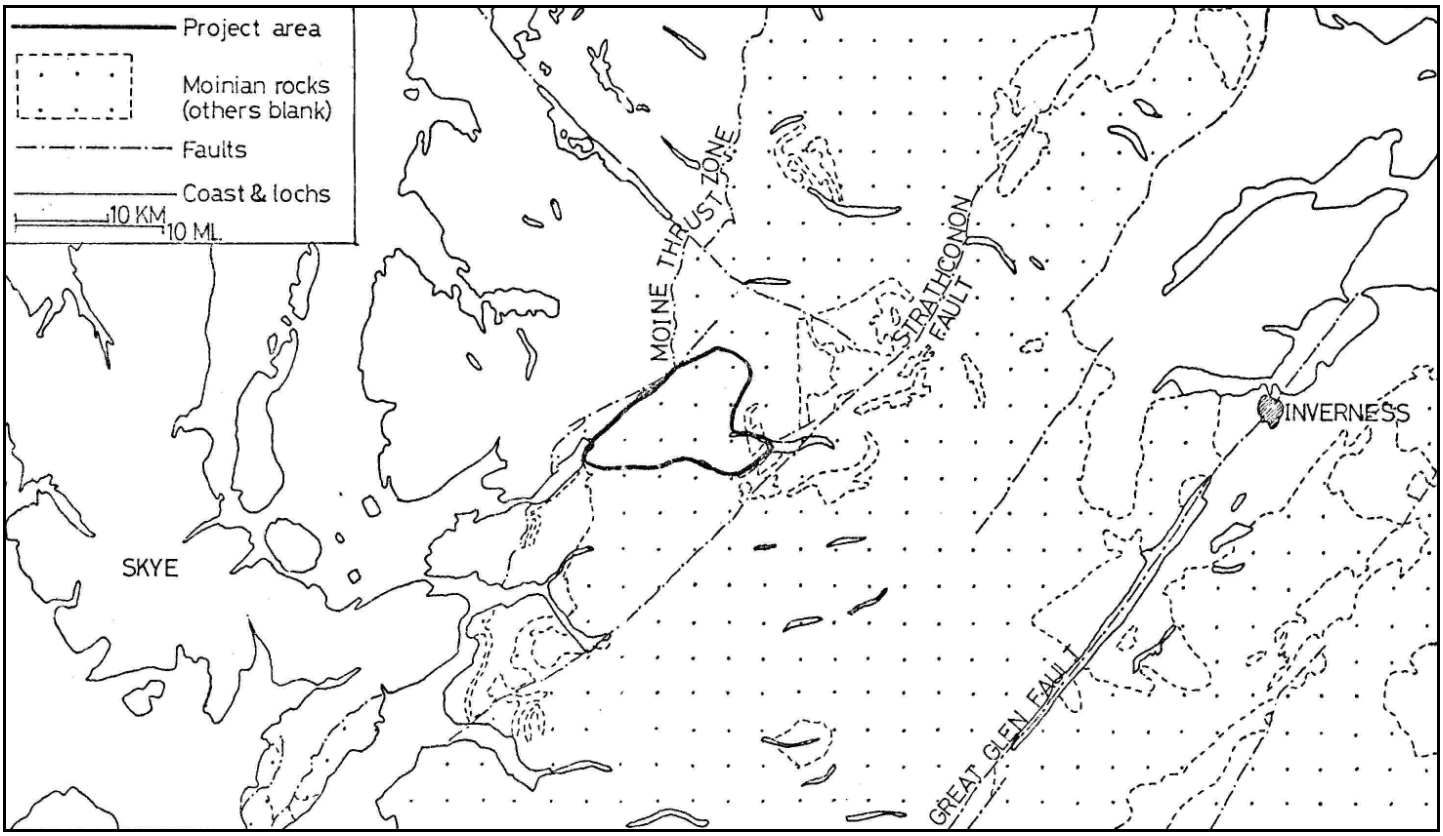


Figure 1.1 Position of the project area in north-west Scotland. Based on “Ten-mile” geological map.

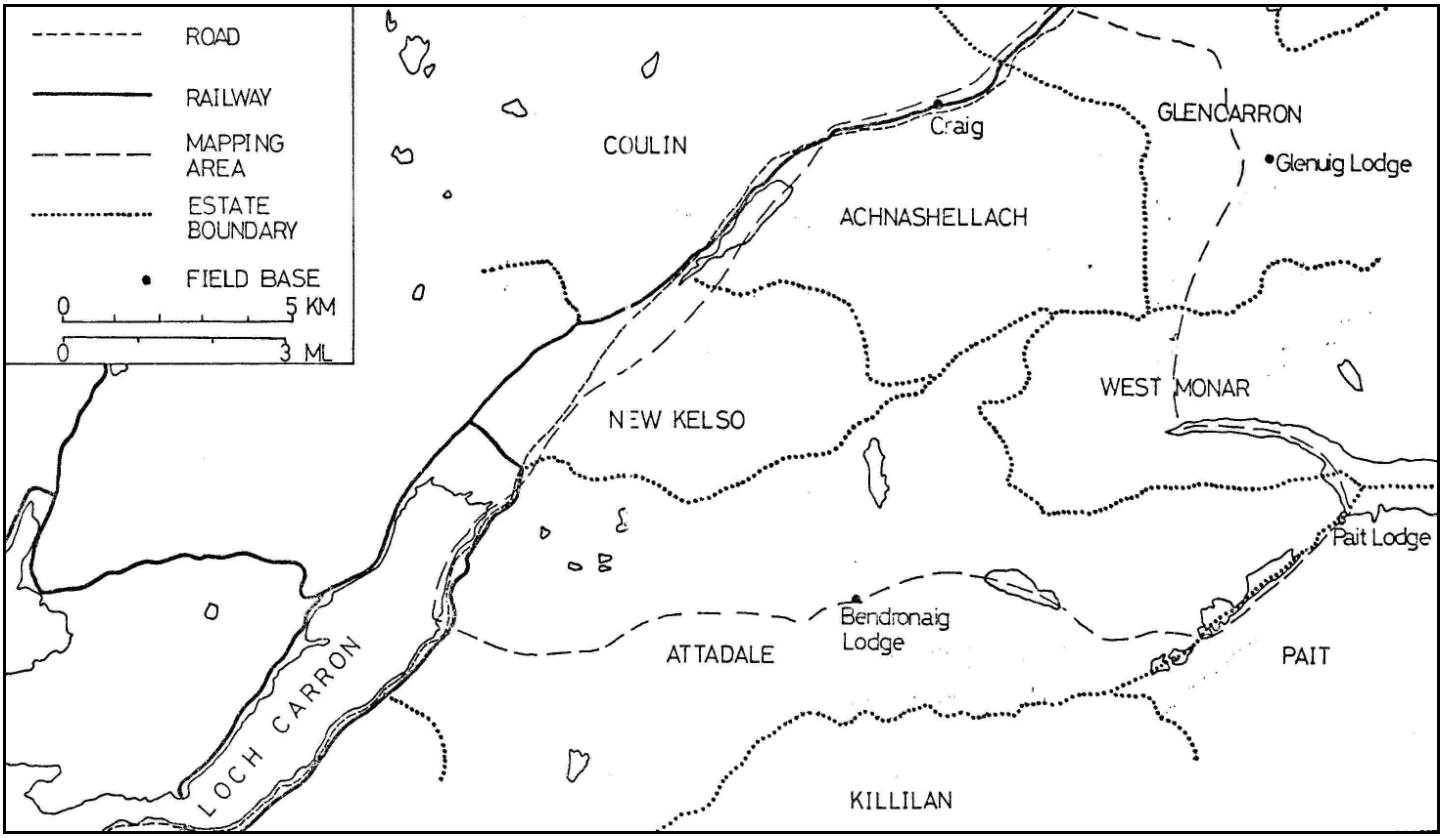


Figure 1.2 Location of the project area, Ross & Cromarty District, Highland Region.

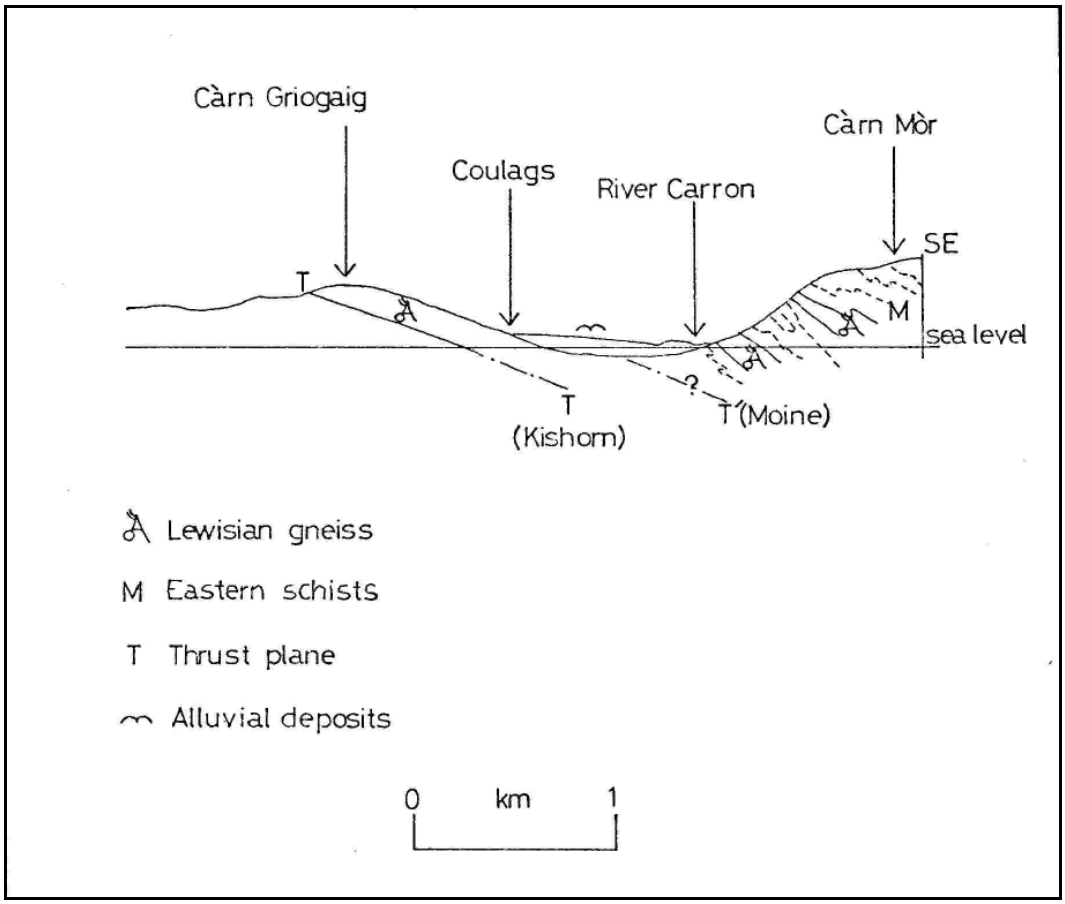


Figure 1.3 Diagrammatic cross-section of Glen Carron. After Peach & others, 1907, Figure 53.

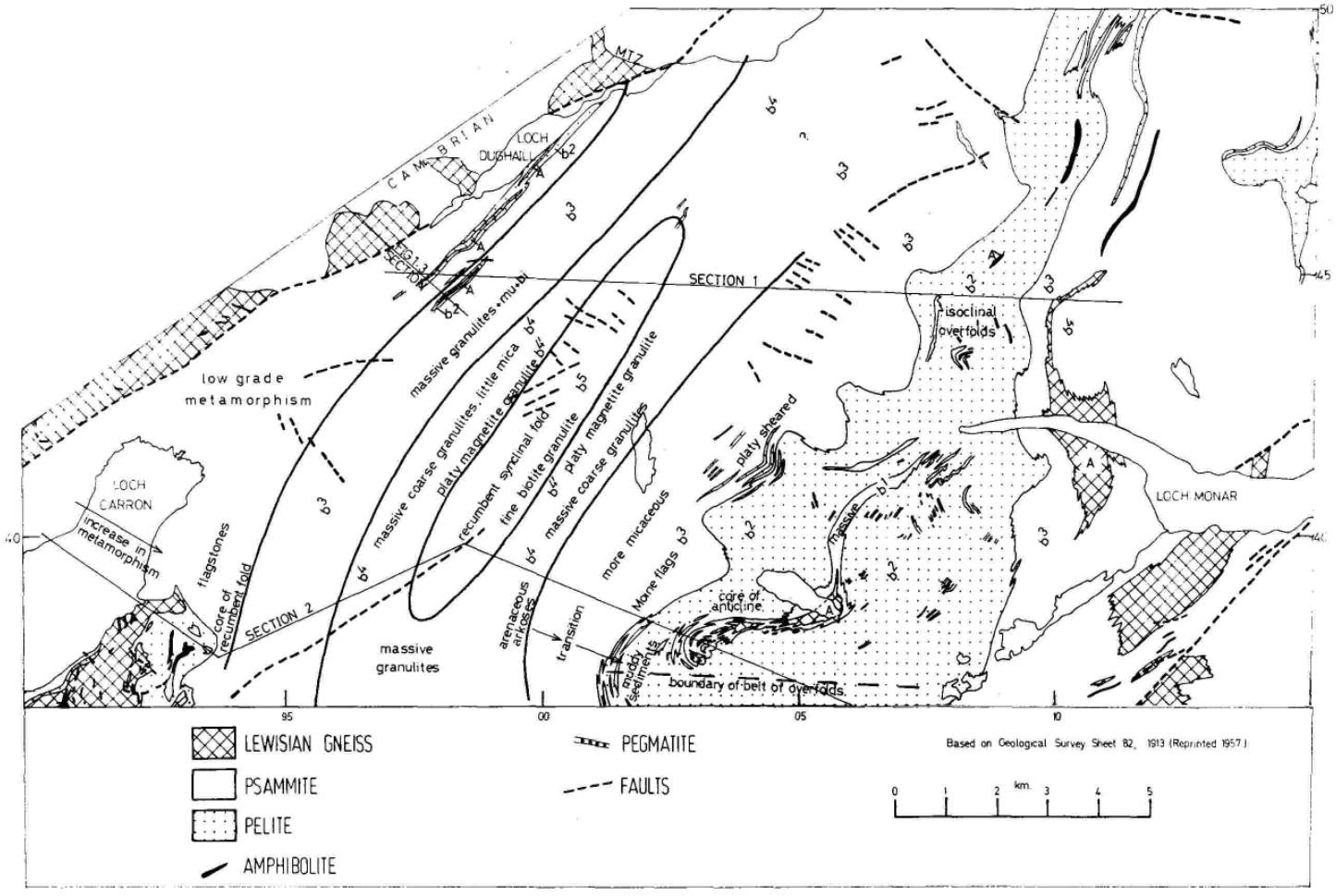


Figure 1.4 Outline geological interpretation, based on G.S. Sheet 82 & Peach et al, 1913

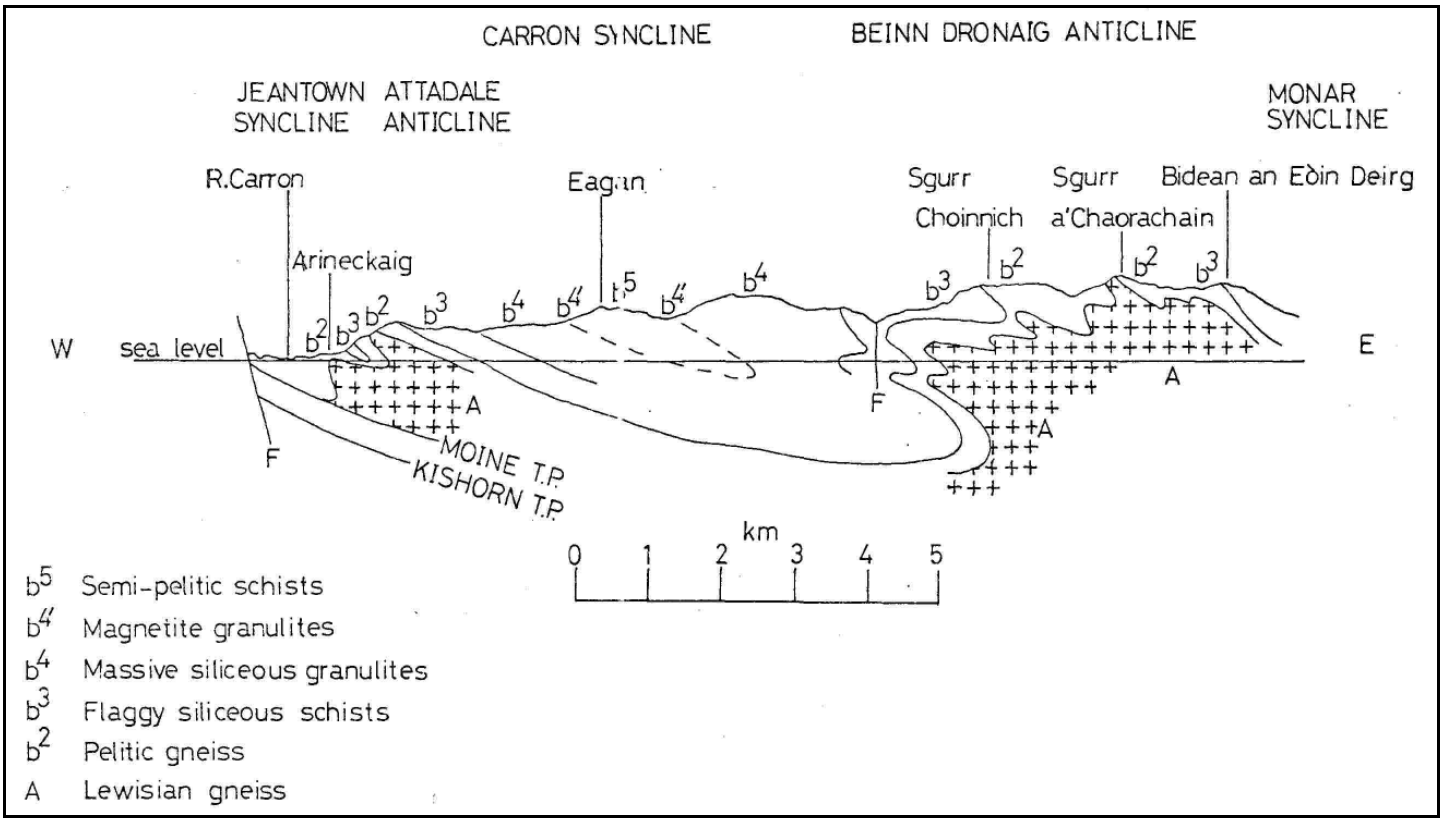


Figure 1.5 Section 1. Diagrammatic section from Arineckaig to Bidean an Eoin Deirg. After Peach & others, 1913.

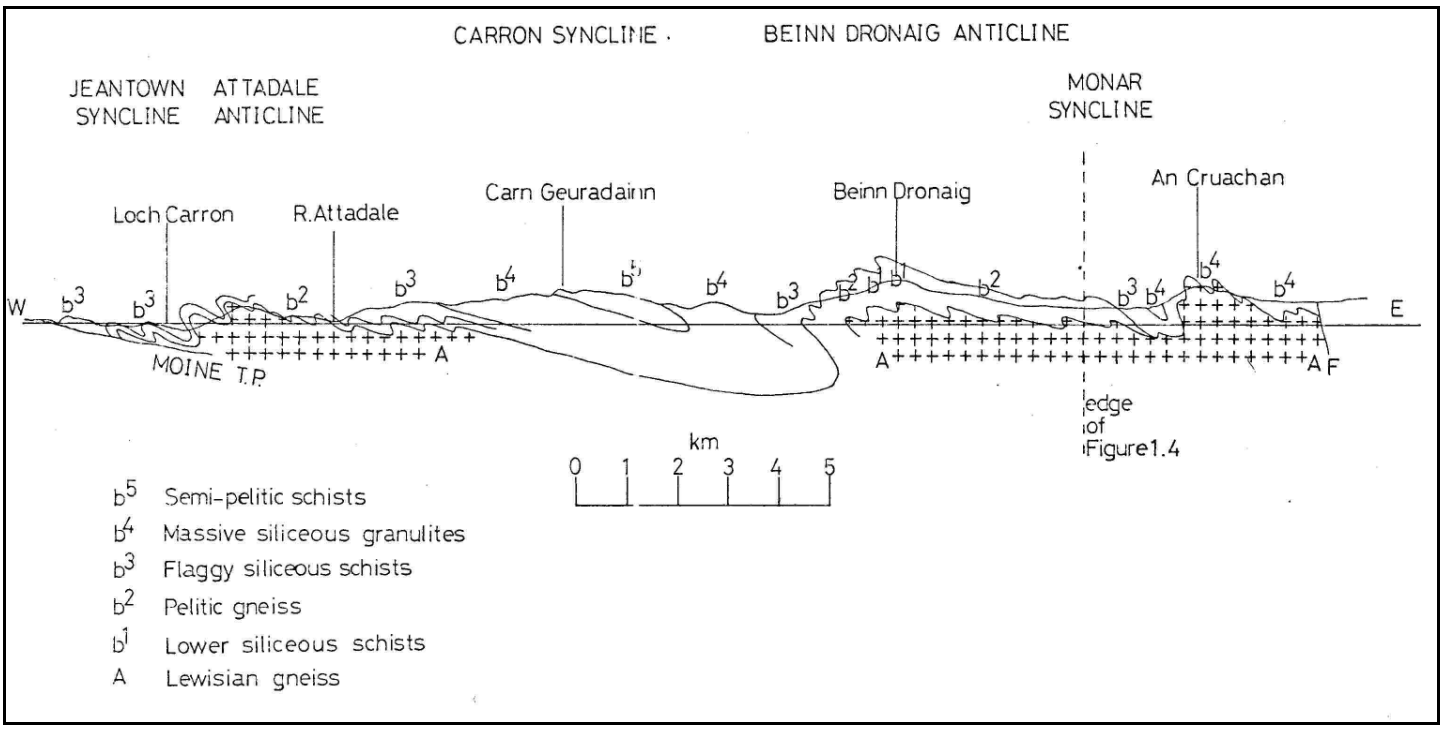


Figure 1.6 Section 2. Diagrammatic section from Loch Carron to An Cruachan. After Peach & others, 1913, Figure 8.

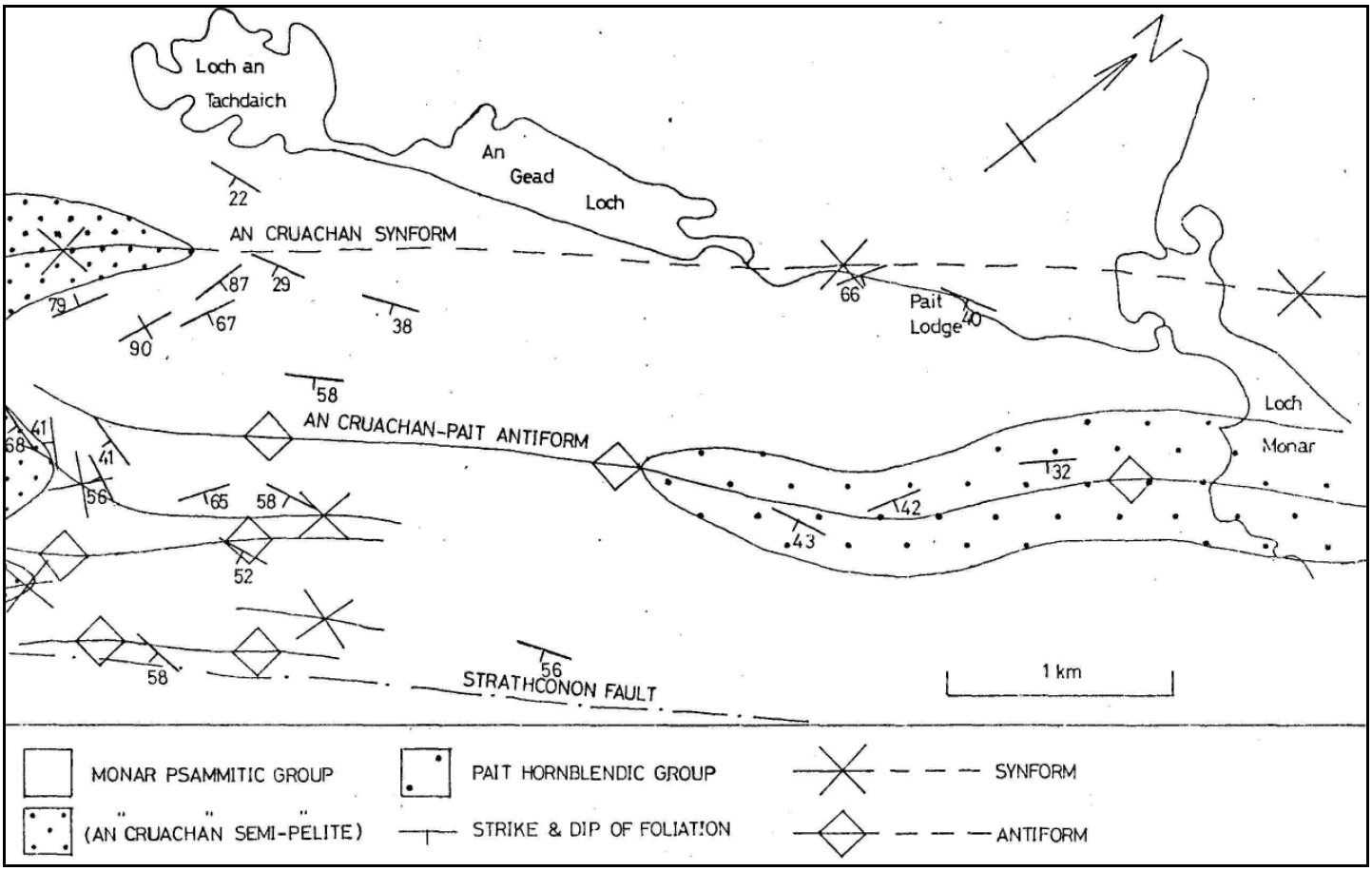


Figure 1.7 Sketch of geology and structure of Pait. After Ramsay, 1954

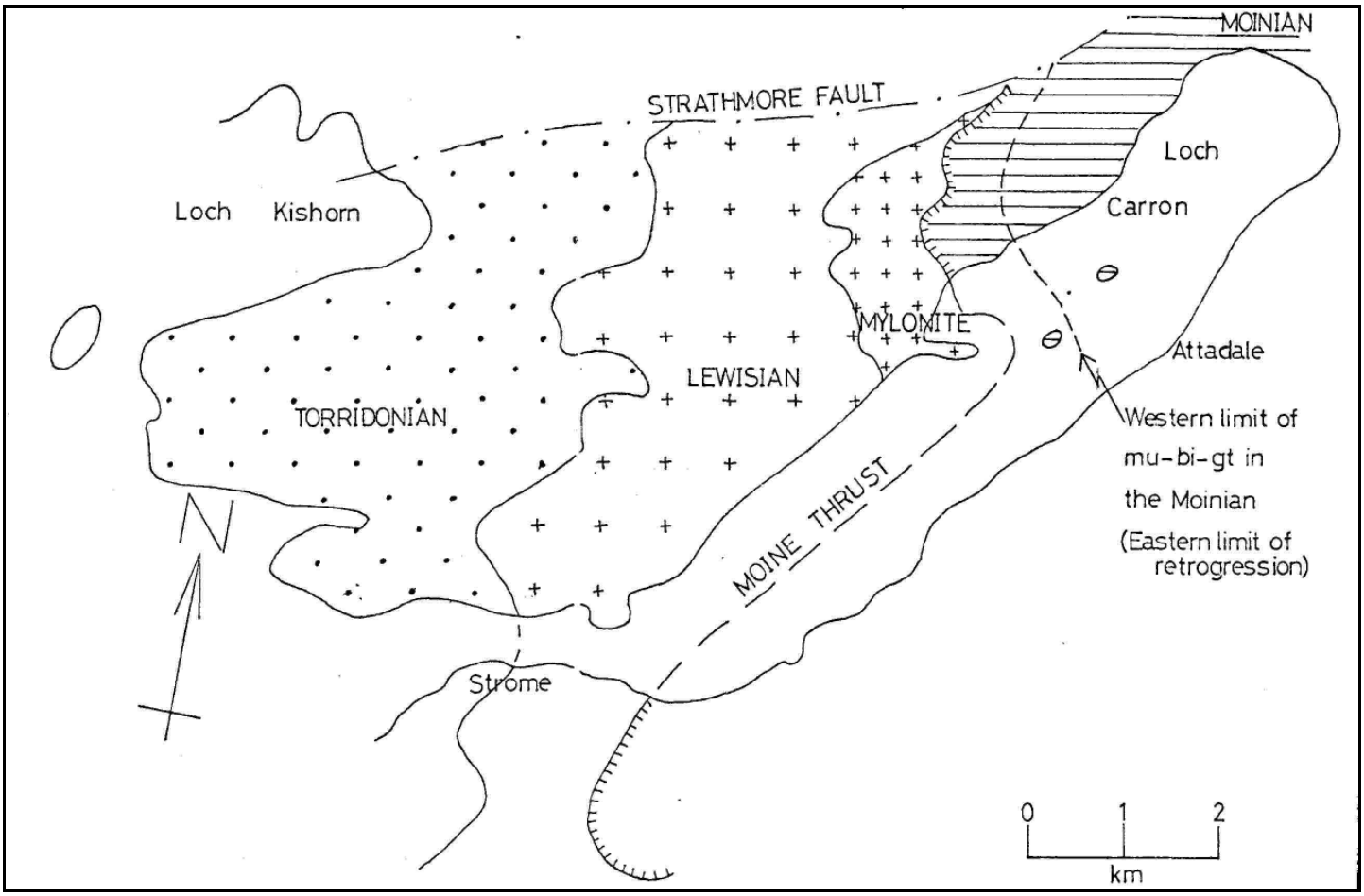


Figure 1.8 Interpretation of Lochcarron area. After Johnson, 1955.

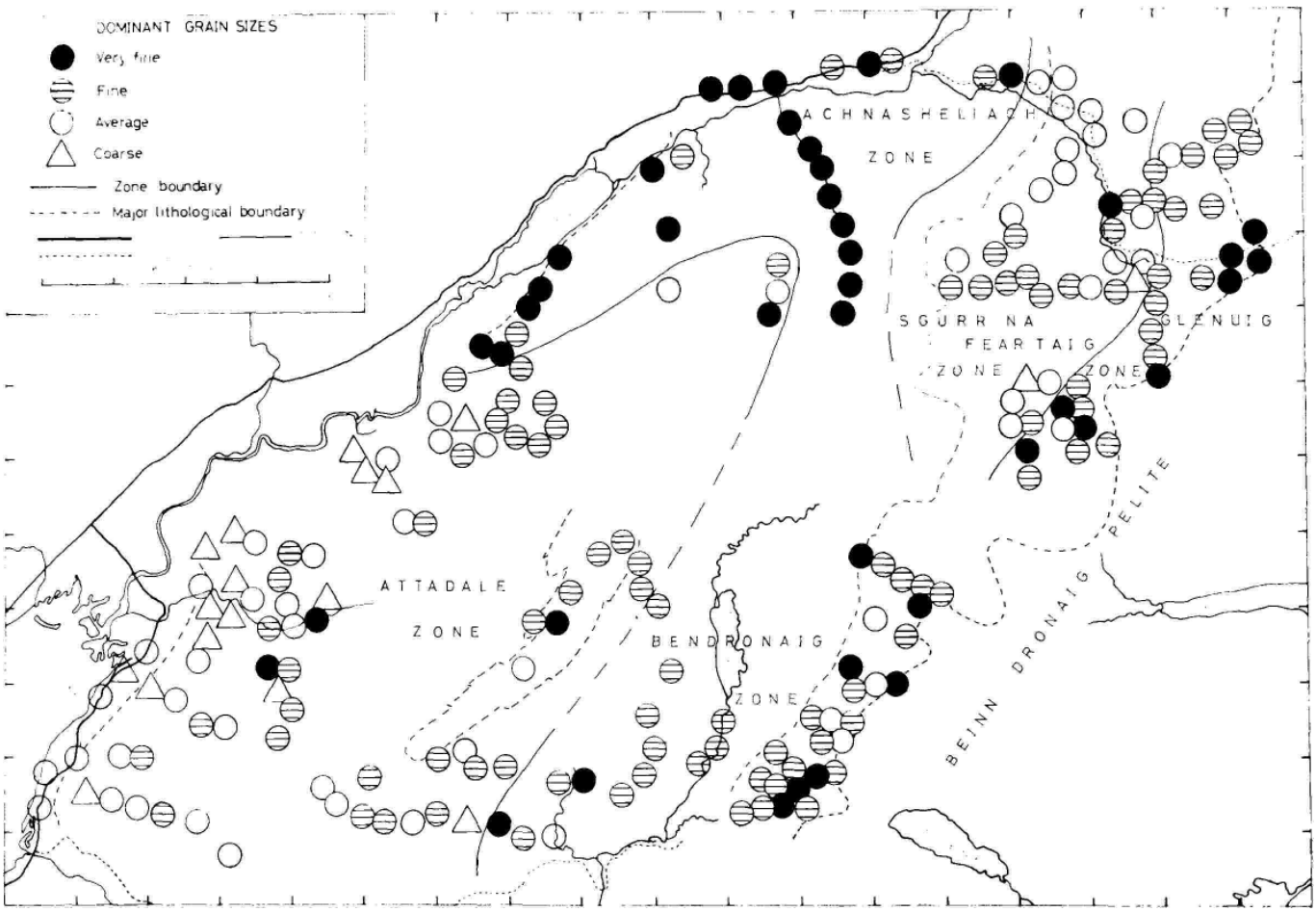


Figure 2.1 Zones of variations in grain size west of Beinn Dronaig Pelite.

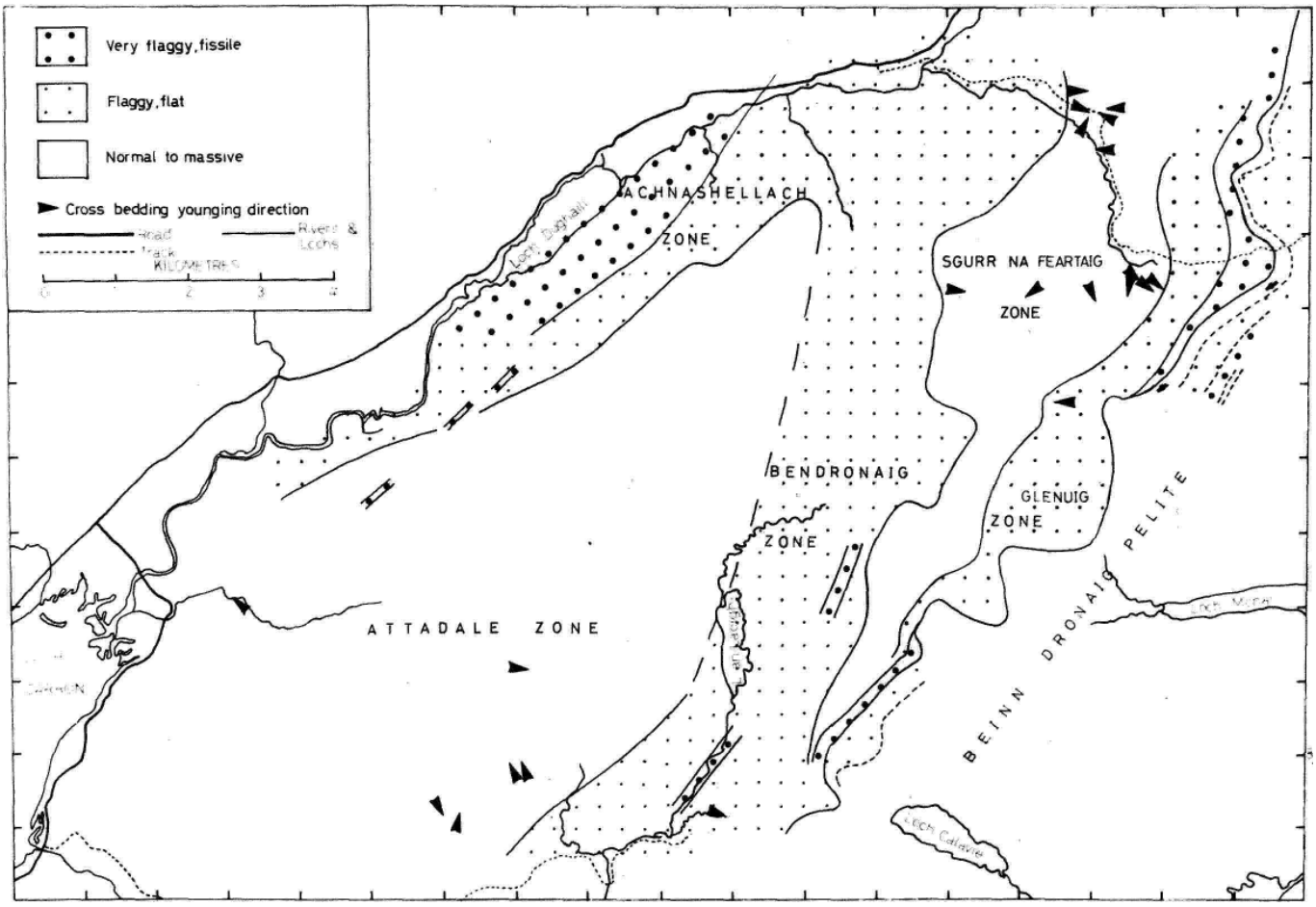


Figure 2.2 Zones of variations in flagginess west of Beinn Dronaig Pelite.

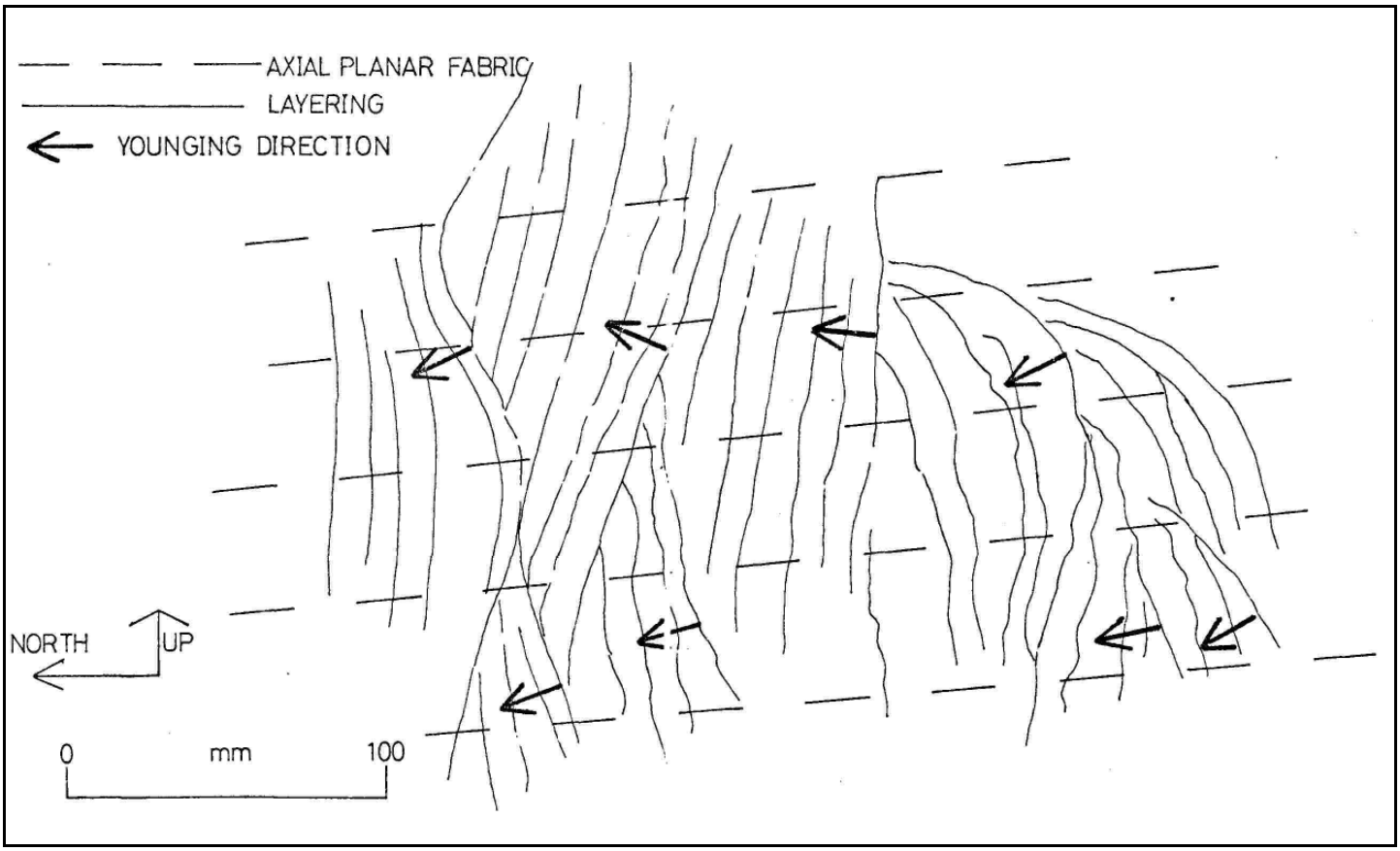


Figure 2.3 Deformed cross-bedding in psammite, Bealach Alltan Ruaridh. NG 9823 3888

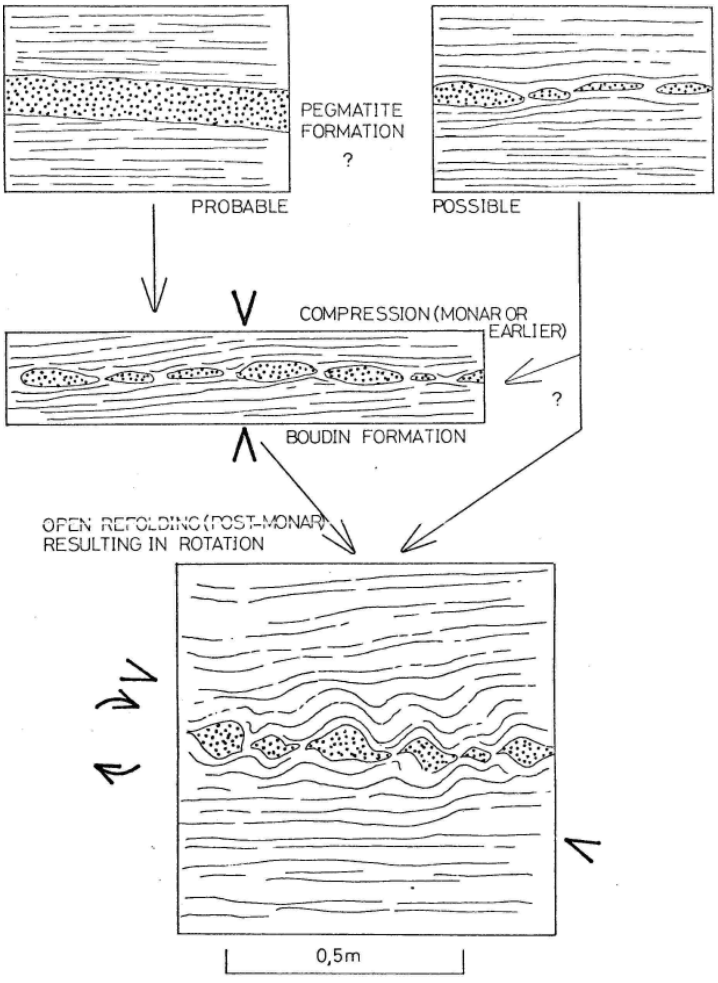


Figure 2.4 Possible stages in the formation of the highly deformed pegmatites in the Monar Banded Psammite, cf Ramsay (1967) p109.

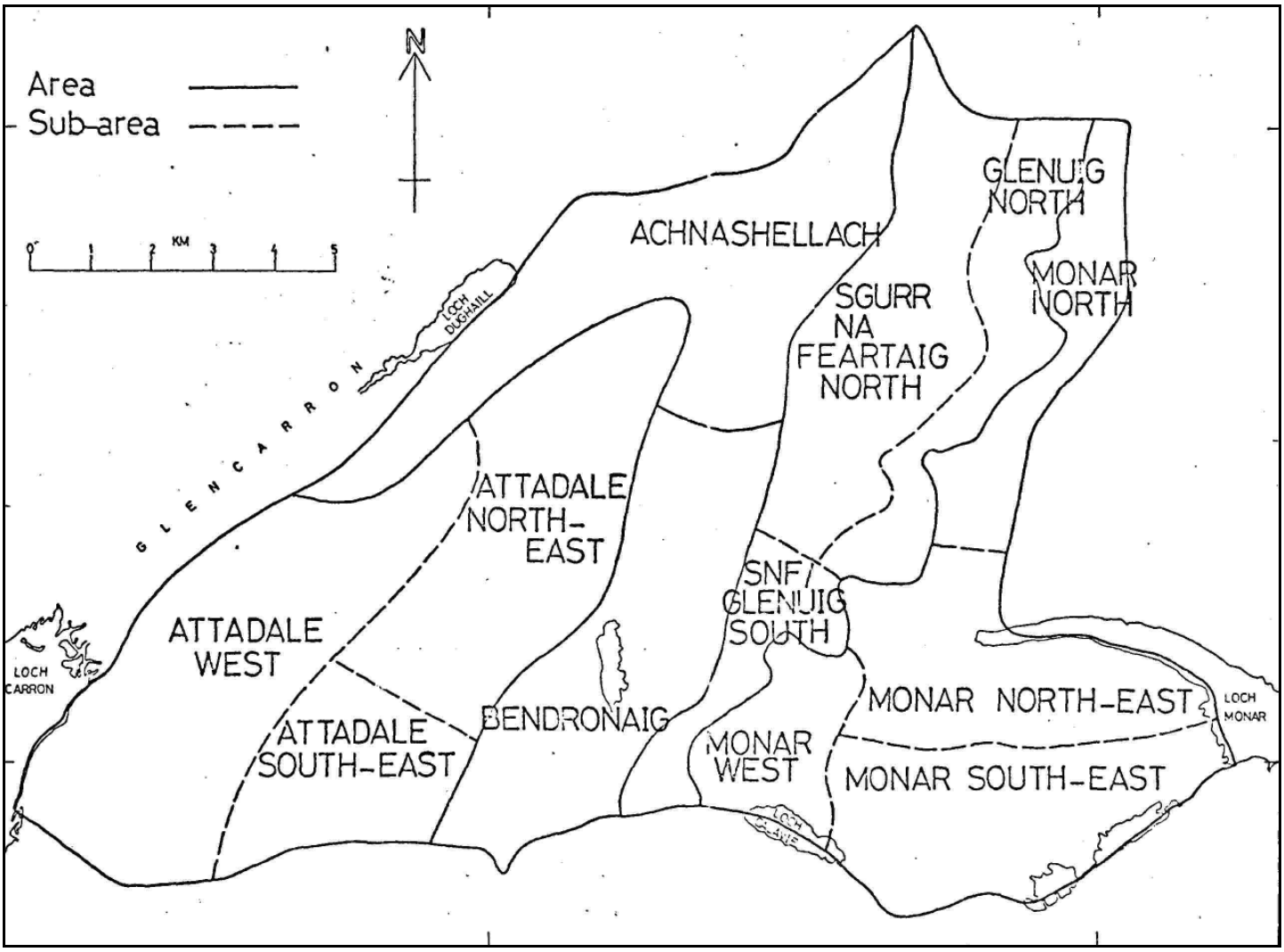


Figure 3.1 Area & sub-area boundaries used in the structural analysis.

Key to Figures 3.2 – 3.25

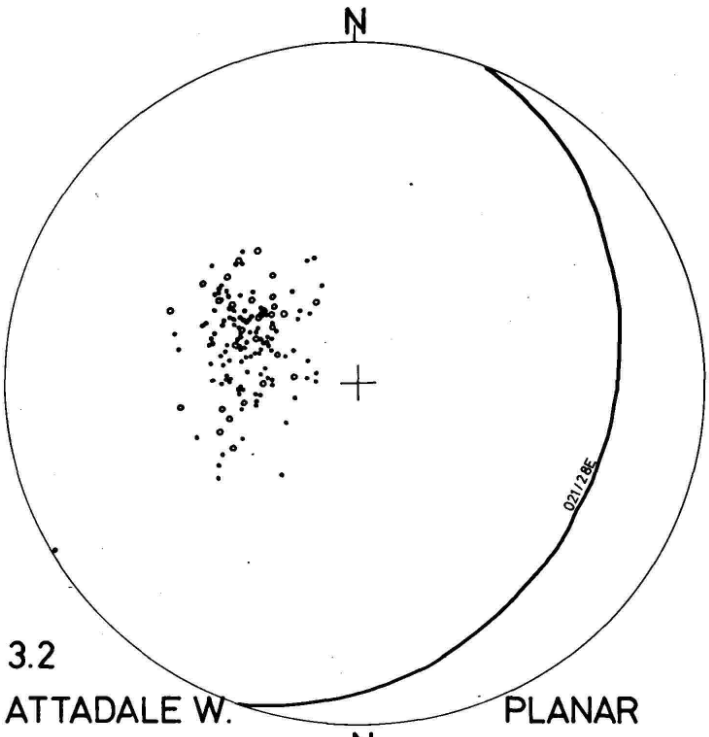
Lambert equal-area lower hemisphere projection. N = Grid North. Even figure numbers = planar (= poles to planes). Odd figure numbers = linear.

Planar
• = SS = layering. o = S = axial planar platy fabric where distinct from layering. Δ = F = axial plane of minor fold.

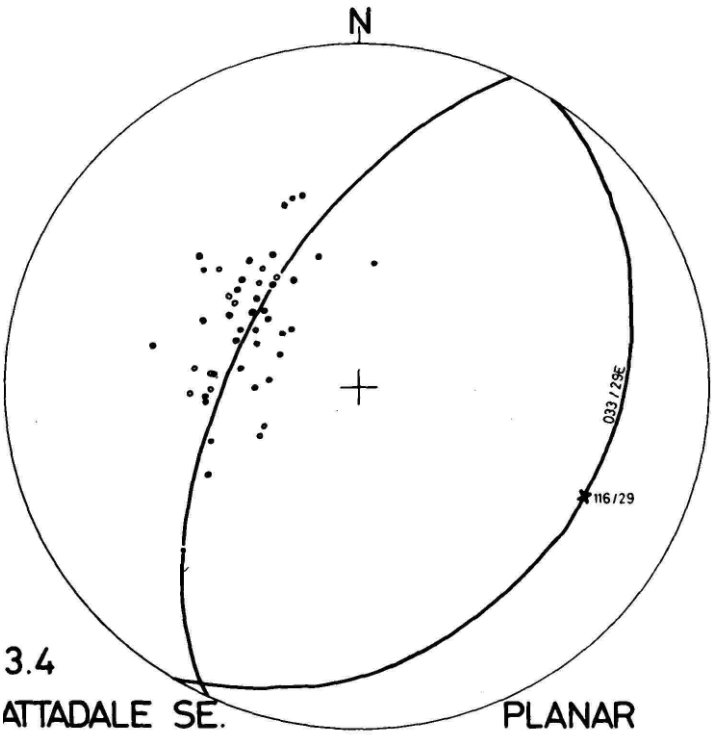
Linear
• = L = all linear features except QVL and F. o = QVL = quartz aggregate lineation in quartz veins. Δ = F = axis of minor fold.

3.2 – 3	=	Attadale W	=	Attadale West sub-area.
3.4 – 5	=	Attadale SE	=	Attadale South-East sub--area.
3.6 – 7	=	Attadale NE	=	Attadale North-East sub-area.
3.8 – 9	=	Bendronaig	=	Bendronaig area.
3.10 – 11	=	Achna	=	Achnashellach area.
3.12 – 13	=	S.N.F.N	=	Sgurr na Feartaig North sub-area.
3.14 – 15	=	Glenuig N	=	Glenuig North sub-area.
3.16 – 17	=	S.N.F/GL.S	=	Sgurr na Feartaig/Glenuig South sub-area.
3.18 – 19	=	Monar N	=	Monar North sub-area.
3.20 – 21	=	Monar W	=	Monar West sub-area.
3.22 – 23	=	Monar SE	=	Monar South-East sub-area.
3.24 – 25	=	Monar NE	=	Monar North-East sub-area.

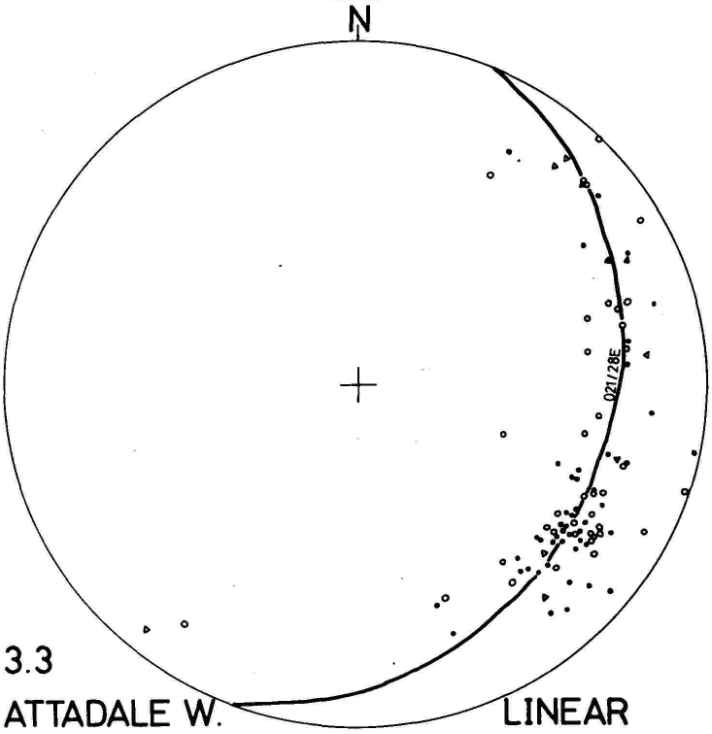
Mean layering plane and planar pole distribution girdles indicated.
Figure 3.24 also shows open fold limbs (022°/40°E, 148°/82°W) and axial plane (108°/42°S).



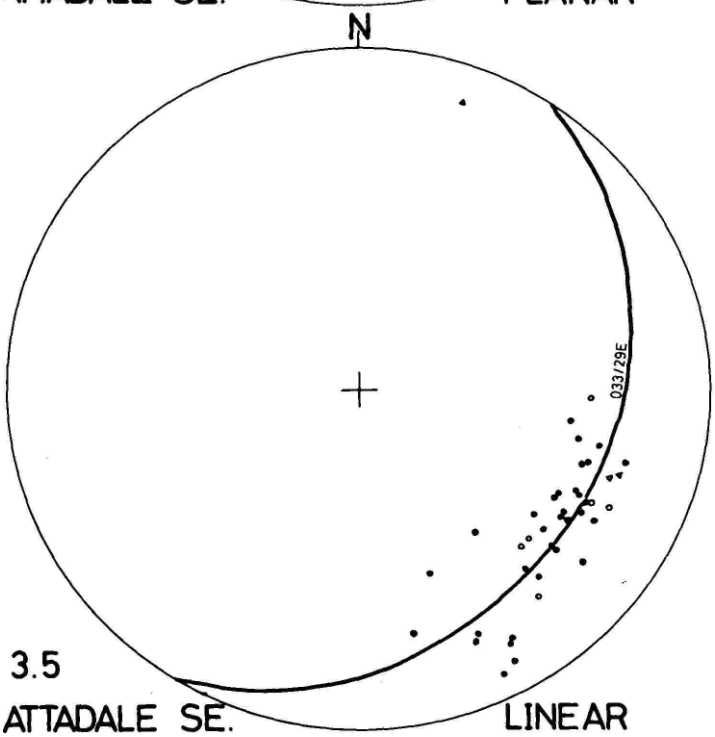
3.2
ATTADALE W. PLANAR



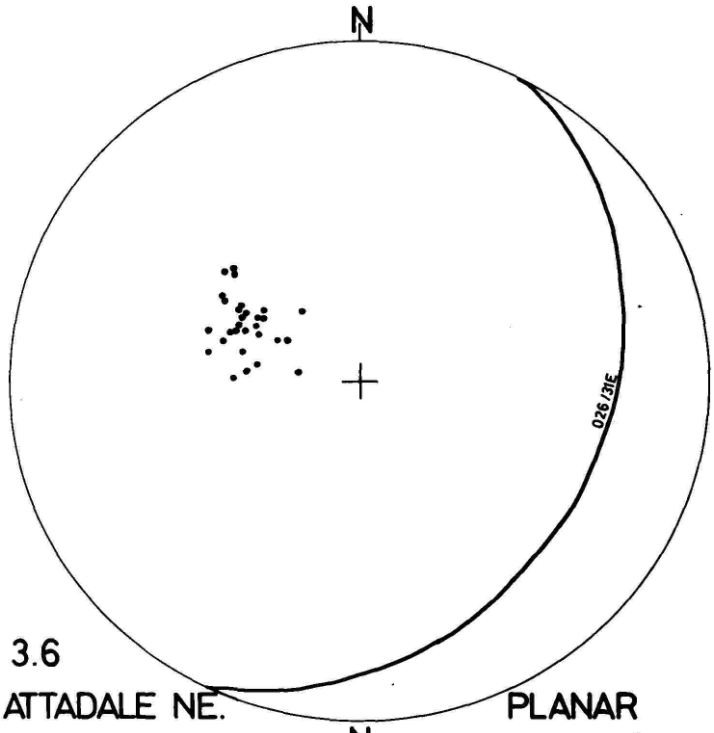
3.4
ATTADALE SE. PLANAR



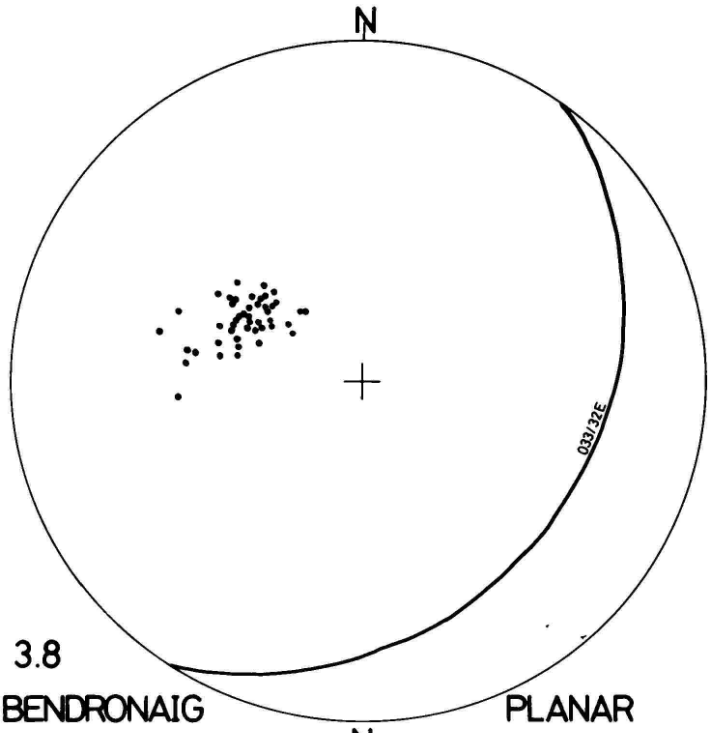
3.3
ATTADALE W. LINEAR



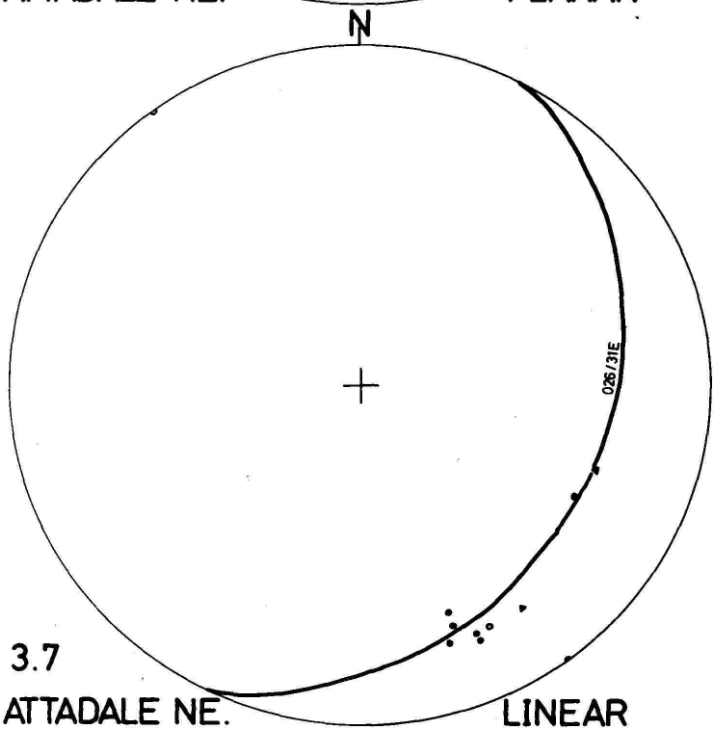
3.5
ATTADALE SE. LINEAR



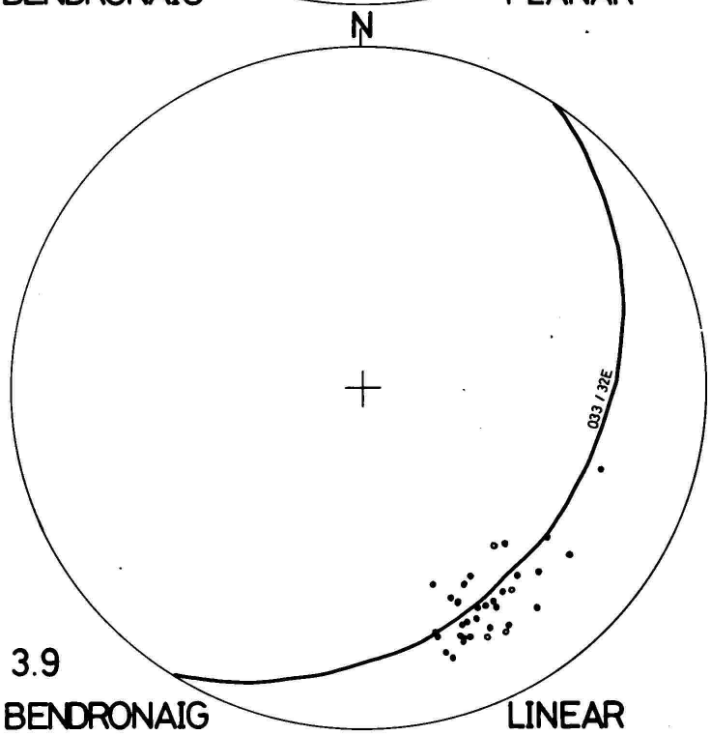
3.6
ATTADALE NE. PLANAR



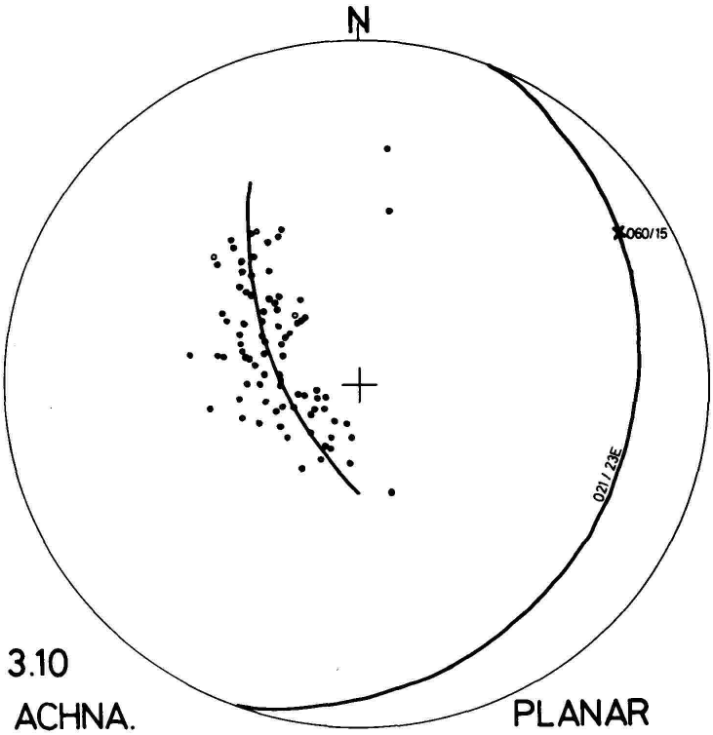
3.8
BENDRONAIG PLANAR



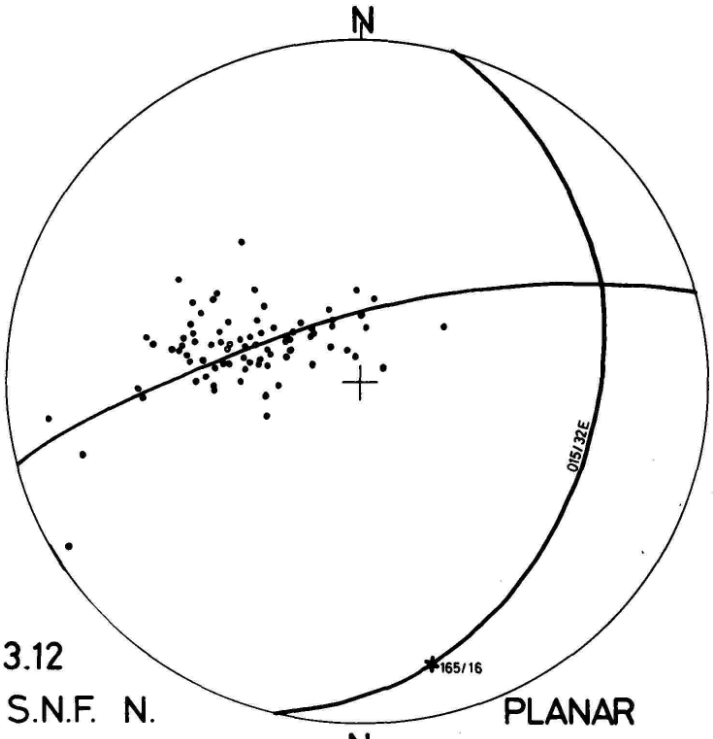
3.7
ATTADALE NE. LINEAR



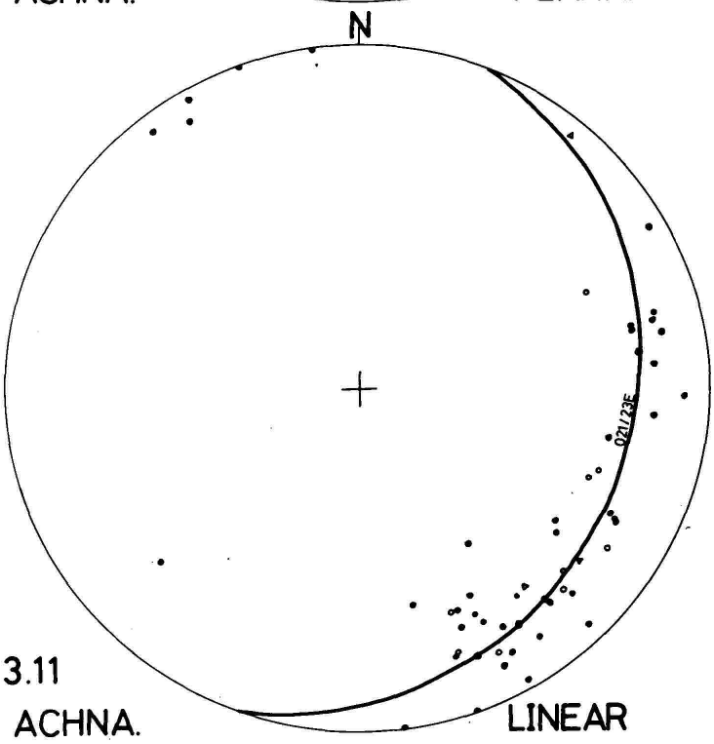
3.9
BENDRONAIG LINEAR



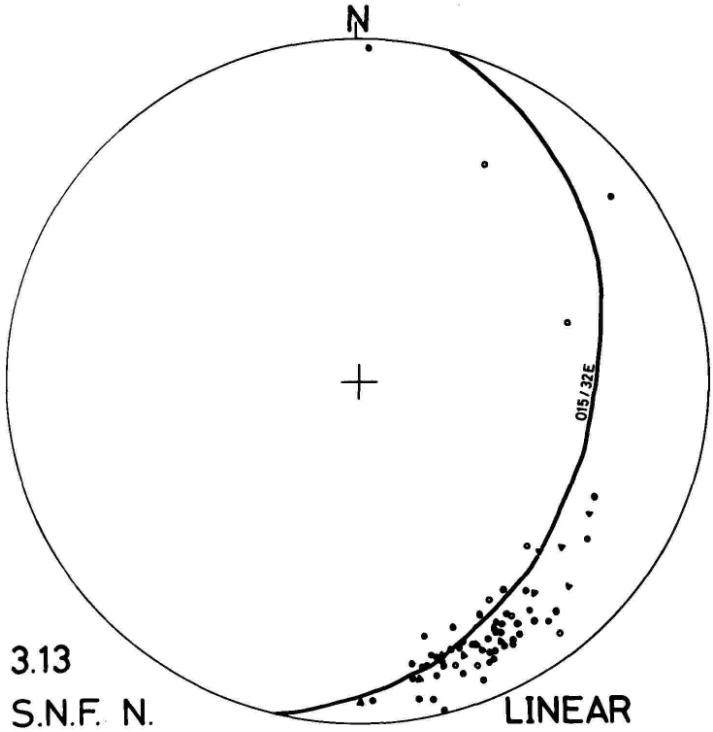
3.10
ACHNA. PLANAR



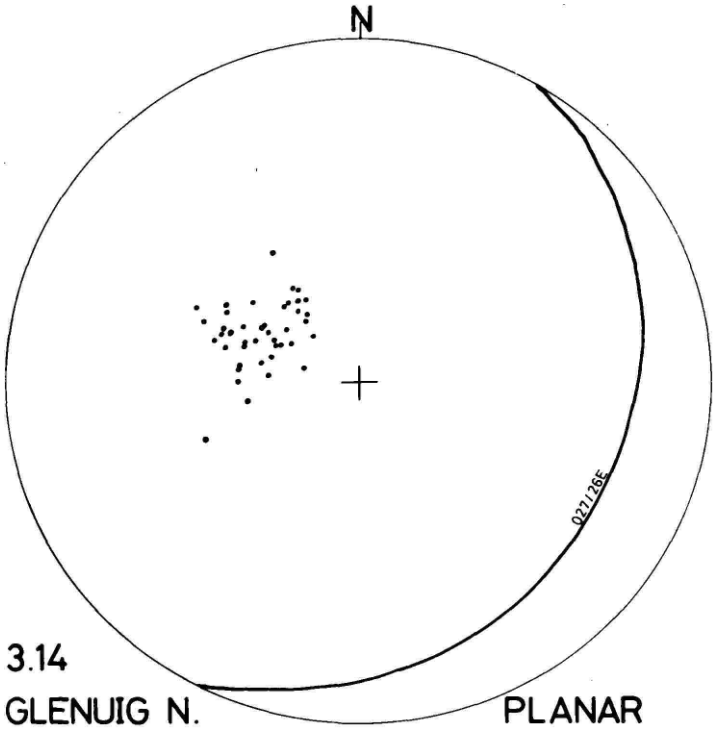
3.12
S.N.F. N. PLANAR



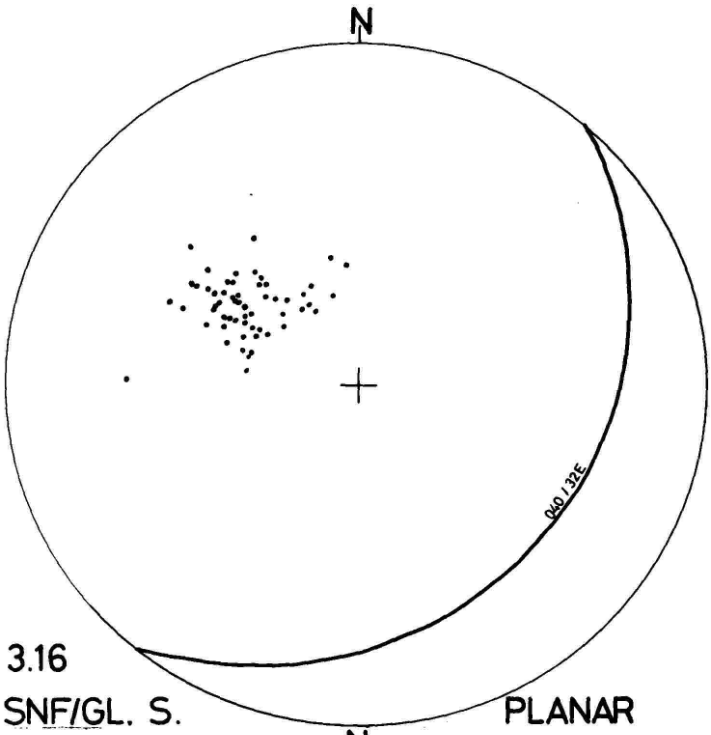
3.11
ACHNA. LINEAR



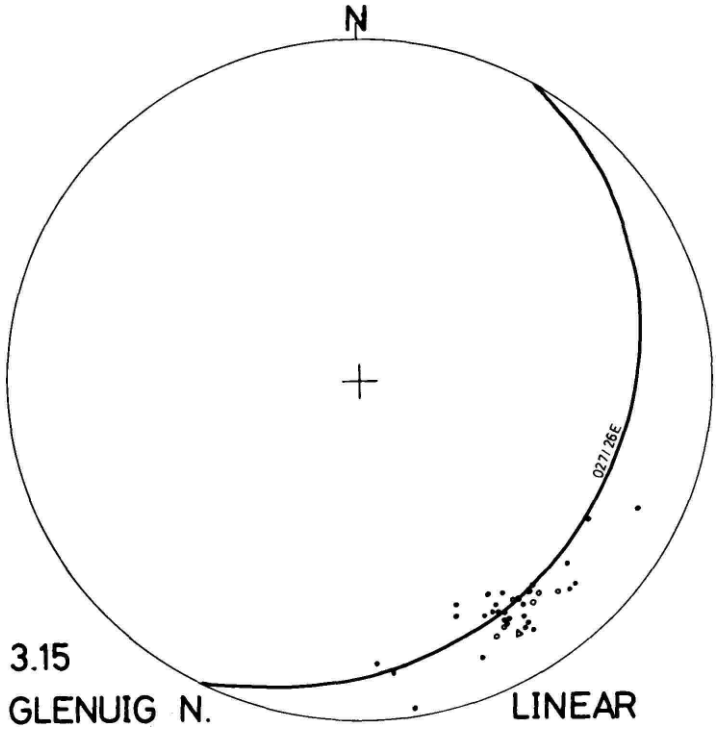
3.13
S.N.F. N. LINEAR



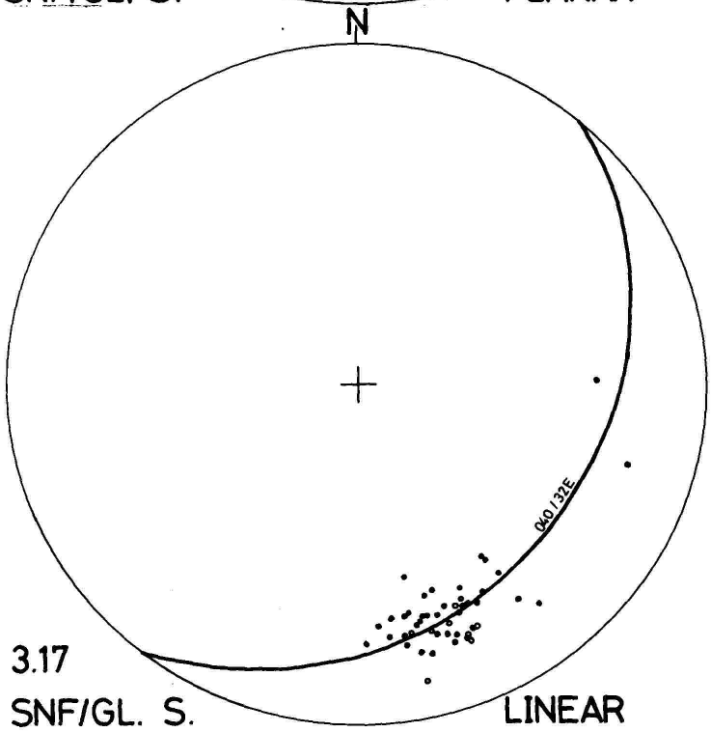
3.14
GLENUIG N. PLANAR



3.16
SNF/GL. S. PLANAR



3.15
GLENUIG N. LINEAR



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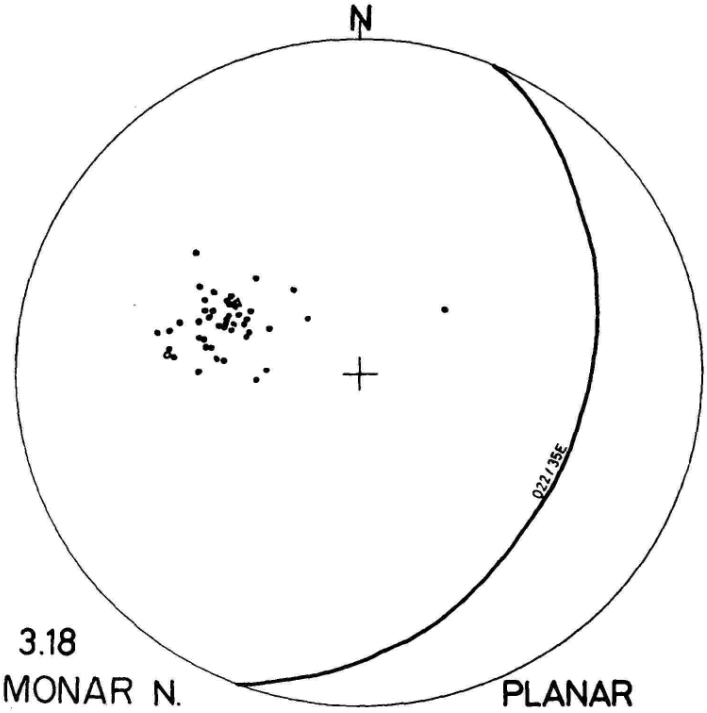
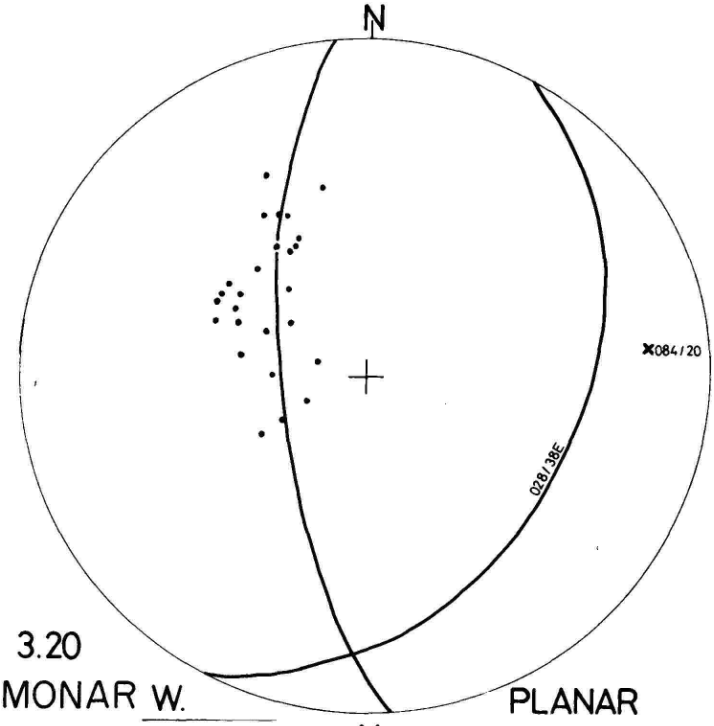
SNF/GL. S. LINEAR



3.18
MONAR N. PLANAR



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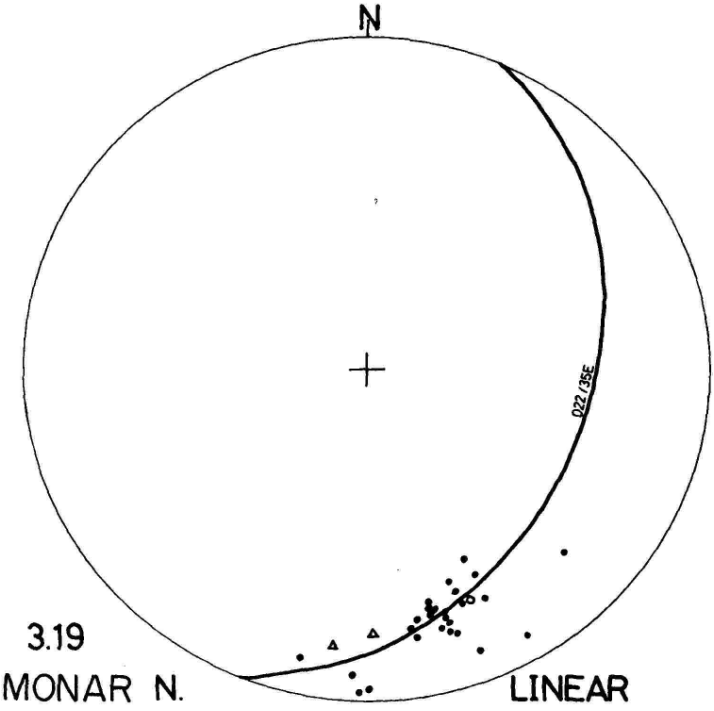

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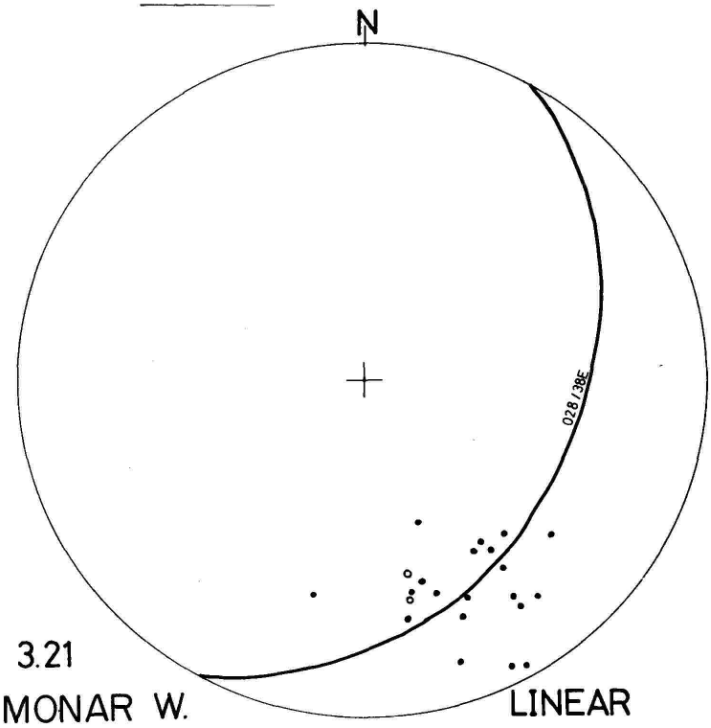
MONAR N. LINEAR



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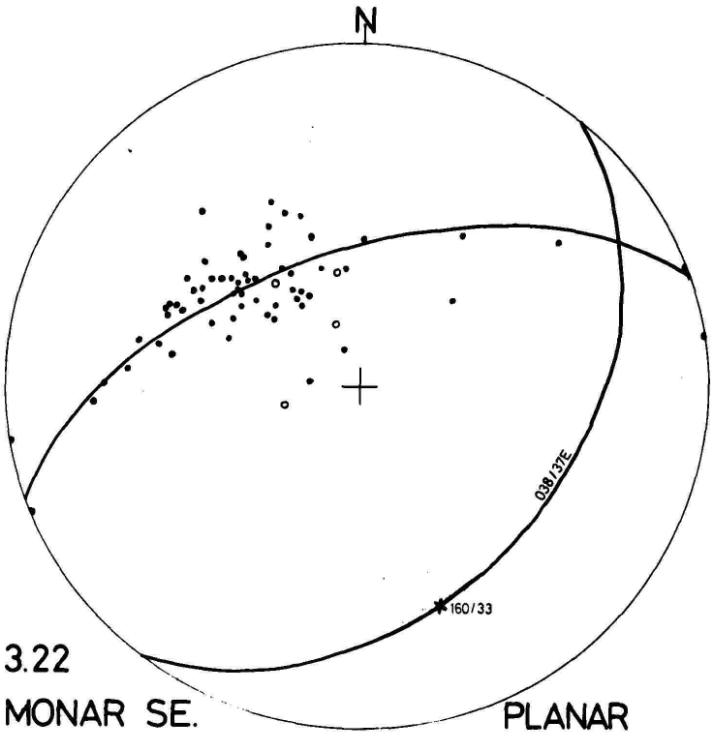
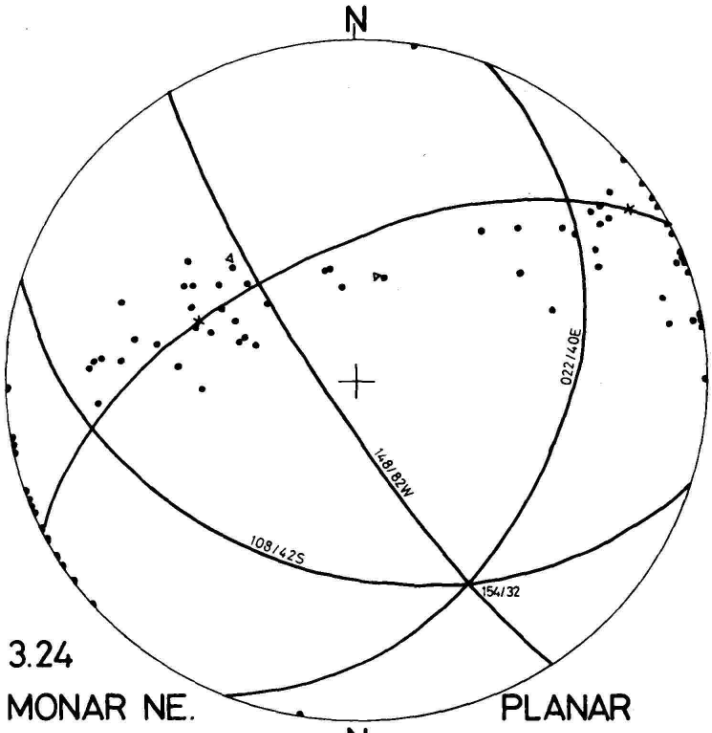
MONAR W. LINEAR



3.22
MONAR SE. PLANAR



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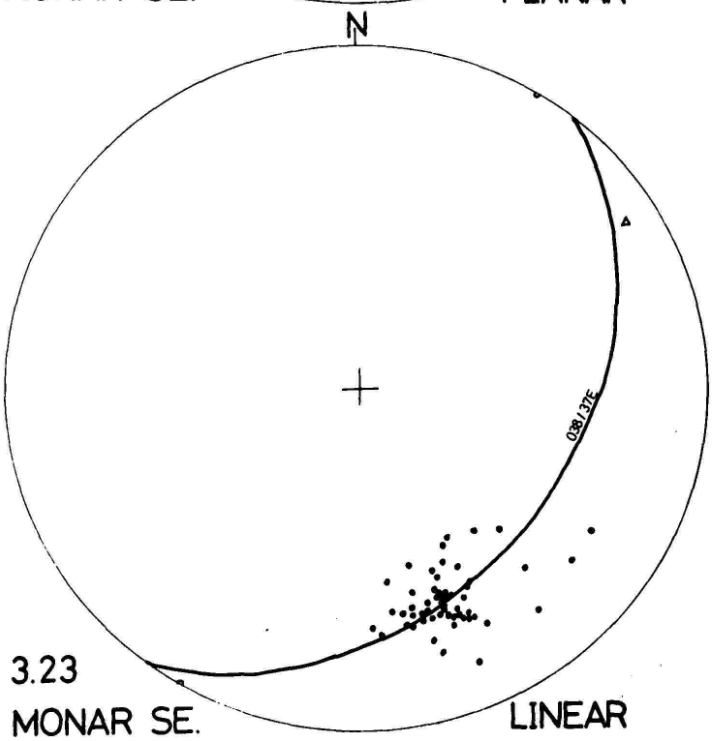
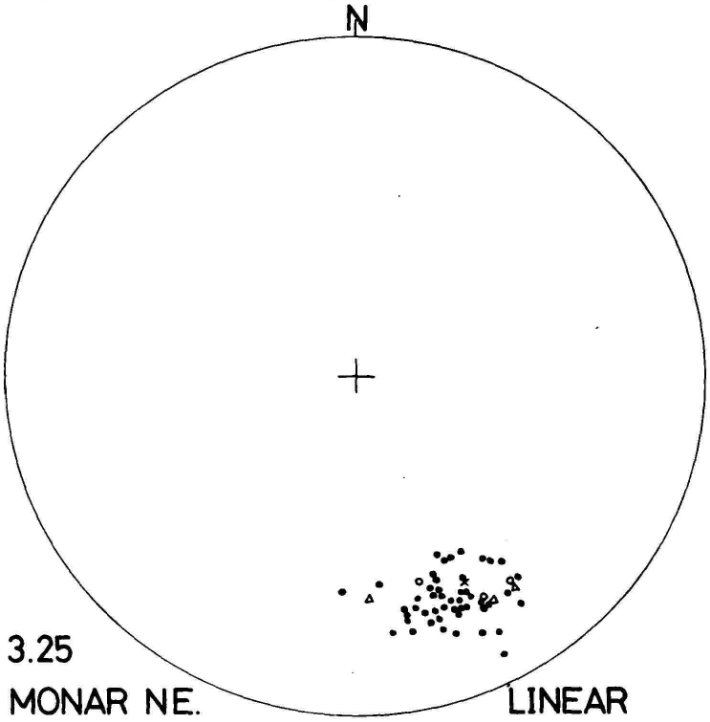
MONAR NE. PLANAR



3.23
MONAR SE. LINEAR



3.25
MONAR NE. LINEAR

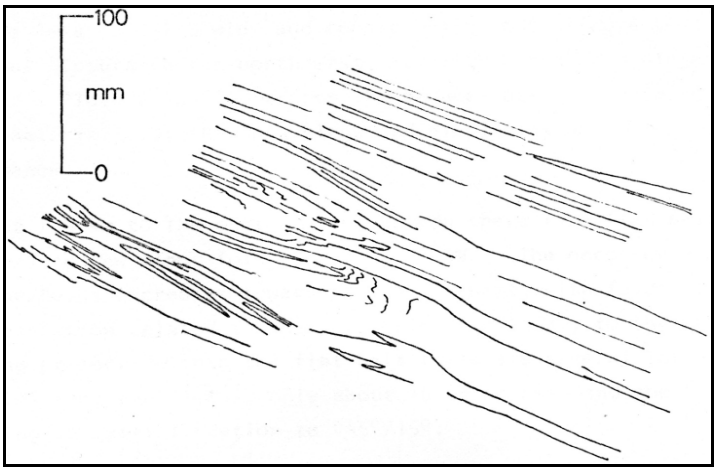


Figure 3.26. ATTADALE WEST SUB-AREA. Isoclinal fold interference pattern in psammite with micaceous bands. Above Arineckaig NG 9918 4419. Looking north-east.

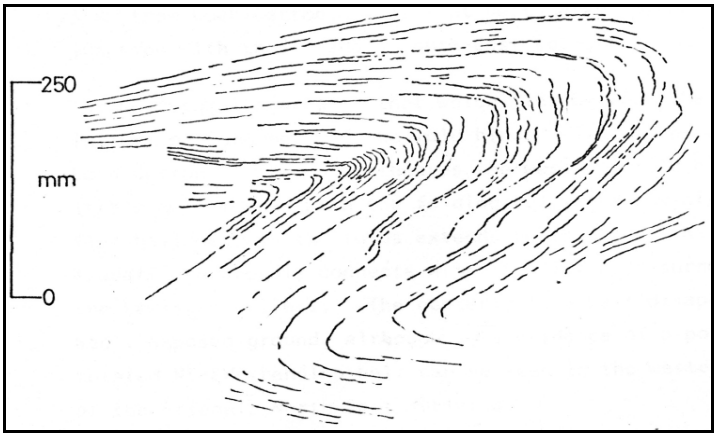


Figure 3.27. ATTADALE WEST SUB-AREA. Class 1C tight to open fold style characteristic of the sub-area. Good axial planar fabric. 1.2 km south-east of Strathcarron. NG 9482 4104. Looking 140 °, down hinge.

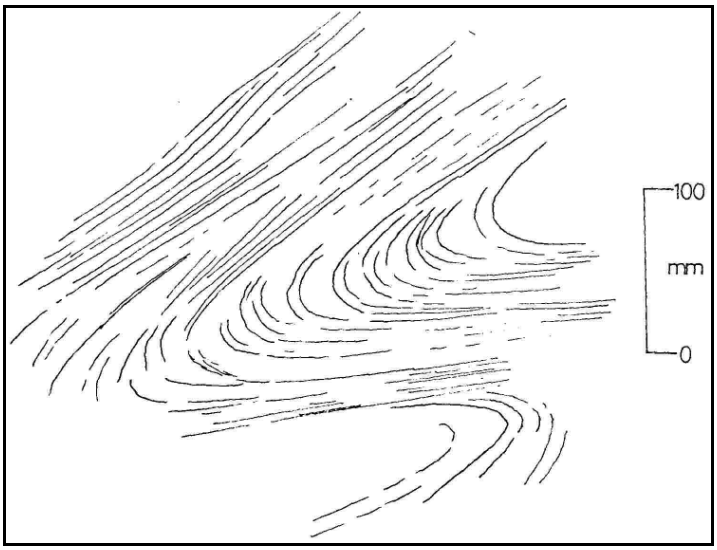


Figure 3.28. ATTADALE WEST SUB-AREA. Class 2 tight fold pair in psammite. Good axial planar fabric. 1.3 km east of Attadale House. NH 9390 3926. Looking 120°, down hinge.

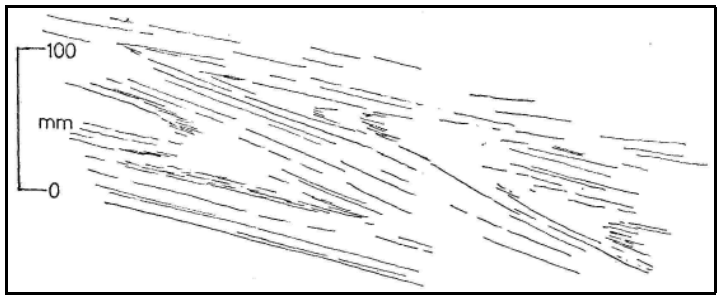


Figure 3.29. ATTADALE SOUTH-EAST SUB-AREA. Class 2 tight fold pair in psammite. Good axial planar fabric. West of Bealach Alltan Ruaridh. NG 9642 3950. Looking 080°, fold axis about 020°/low plunge.

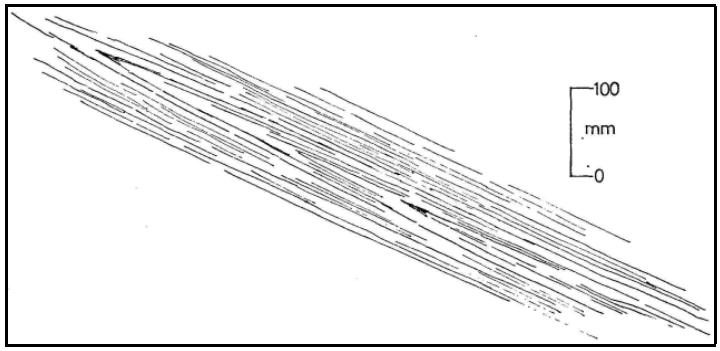


Figure 3.30. BENDRONAIG SUB-AREA. Class 2 intrafolial isoclinal fold. Near Allt Feithe Chaillich. NG 9971 3975. Looking 045°. Axis indeterminate.

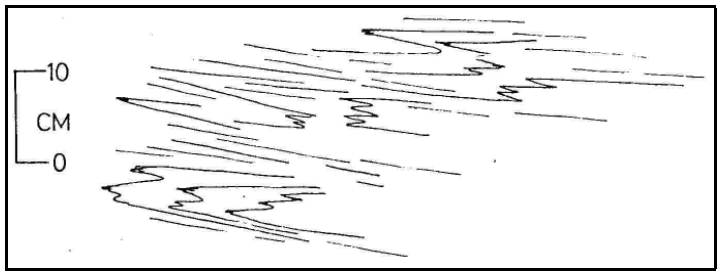


Figure 3.31. ACHNASHELLACH AREA. Class 2 tight-isoclinal folding in psammite. Near Arineckaig. NG 9858 4547. Looking 110° . Fold axis indeterminate.

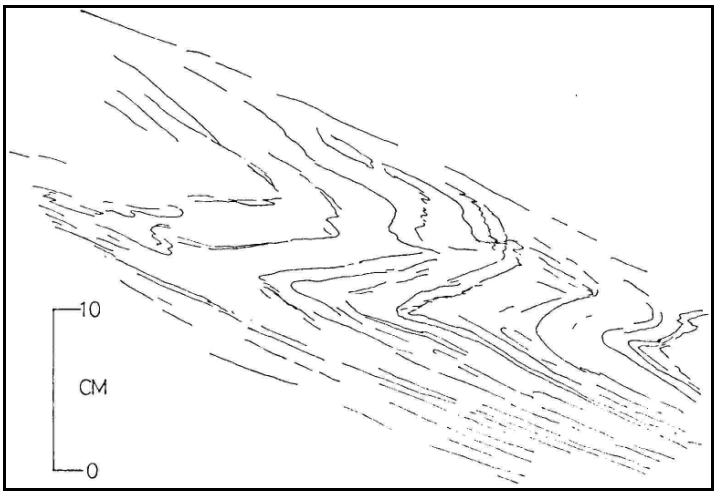


Figure 3.32. SGURR NA FEARTAIG/GLENUIG SOUTH SUB-AREA. Class 1C intrafolial tight minor fold pair in striped psammite. Close to Allt Coire na Sorna. NH 0294 3923. Looking 075°. Fold axis indeterminate.

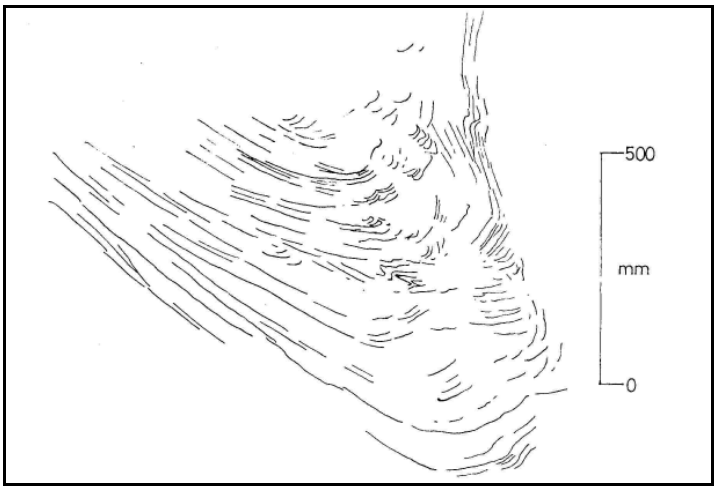


Figure 3.33. SGURR NA FEARTAIG/GLENUIG SOUTH SUB-AREA. Class 1C – 2 open to tight folding in hinge of major fold. Good axial planar platy fabric. South-west of Beinn Tharsuinn. NH 0422 4246. Looking north, approx. parallel to fold hinge.

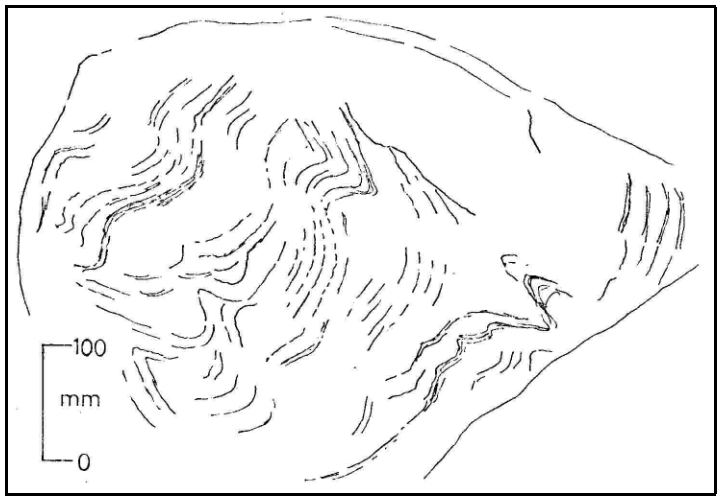


Figure 3.34. MONAR SOUTH-EAST SUB-AREA. Open folding with strong axial planar platy fabric and poorly preserved banding. Near Pait Lodge. NH 1225 3998. Looking 045°. Fold axes approx. 160°.

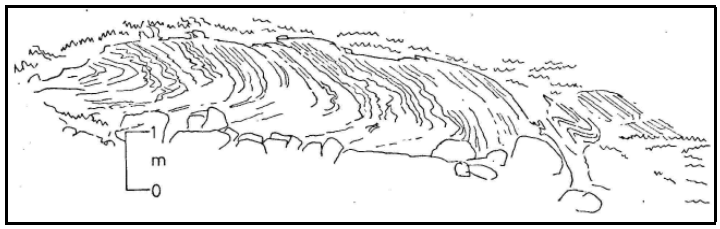


Figure 3.35. MONAR-NORTH EAST SUB-AREA. Class 1B. Second-order open folds refolding early fold pair (to right). South of Loch Monar. NH 1016 4182. Looking 160°, down fold hinge.

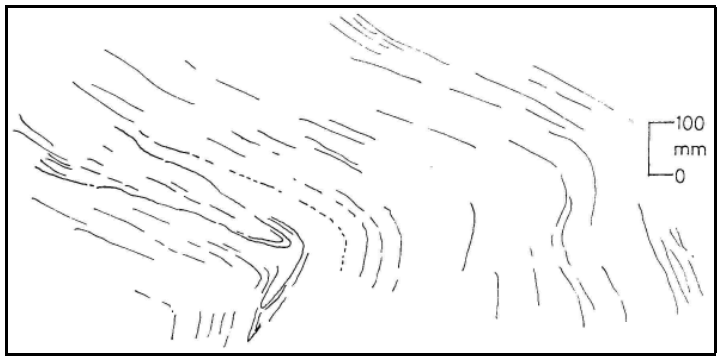


Figure 3.36. MONAR NORTH-EAST SUB-AREA. Class 1B open refold of earlier Class 2 isoclinal fold. Early axial planar fabric also refolded. South of Loch Monar. NH 1082 4092. Looking 190°; axis of early fold and refold about 160°.

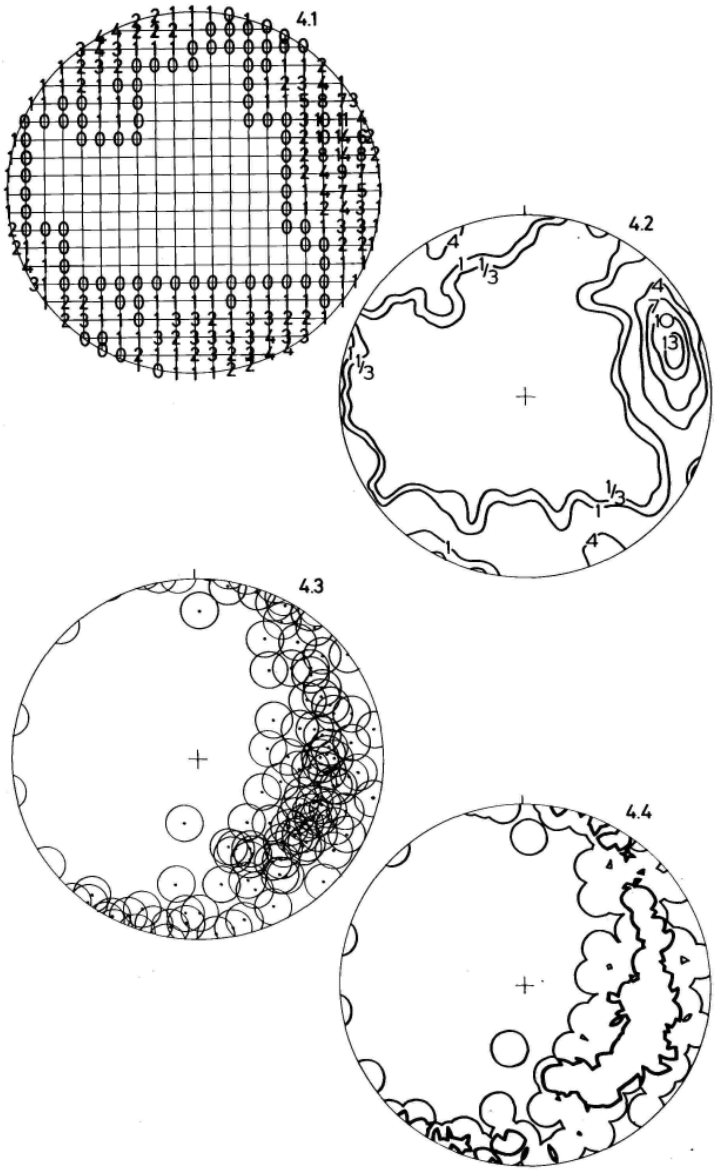


Figure 4.1 Schmidt method. 300 points on analysed diagram, counted out as per cent per 1 per cent area using a 1 cm^2 grid. After Turner and Weiss (1963), Figure 3-10(a).

Figure 4.2. Schmidt method. Contours on 300 point diagram. Contours at 13, 10, 7, 4, 1 and 14%. After Turner and Weiss (1963), Figure 3-10(b).

Figure 4.3. Circle method (Mellis method). 100 points with 20 mm diameter circles (1 per cent area). After Turner and Weiss (1963), Figure 3-12(a).

Figure 4.4. Circle method (Mellis method). Contours on 100 point diagram. Thin line = 1 per cent contour (limit of circles). Thick line = 3 per cent contour (overlap of 3 or more circles). After Turner and Weiss (1963), Figure 3-12(b).

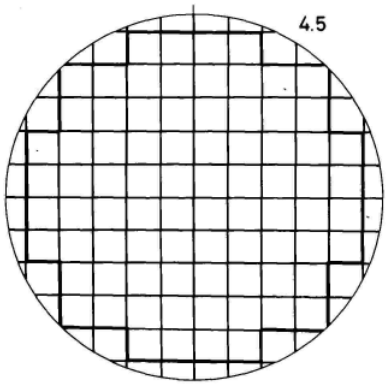


Figure 4.5. Square-grid method. 100 cell squared-grid counter. Opposing partial cells are added together. After Stauffer (1966), Figure 1.

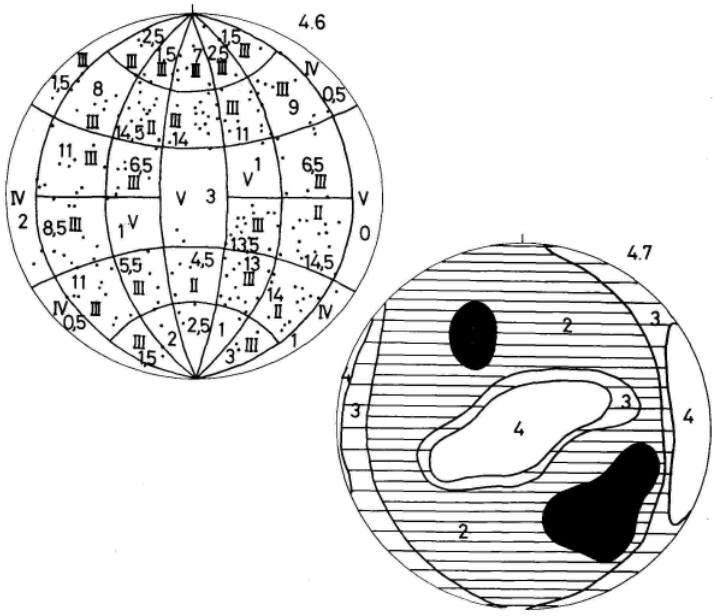
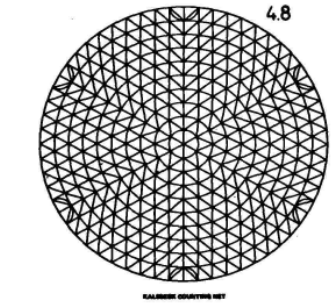
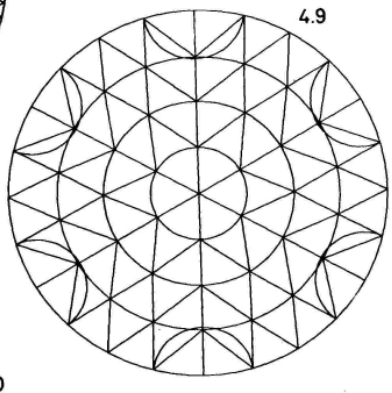


Figure 4.6. Vistelius method. 200 point diagram with counting grid. Roman number = value used for contouring. Arabic number = number of points per counting cell. After Vistelius (1966), Figure 37.

Figure 4.7. Vistelius method. Contours on 200 point diagram. Contour intervals use Roman numbers derived in Figure 4.6. After Vistelius (1966), Figure 38.





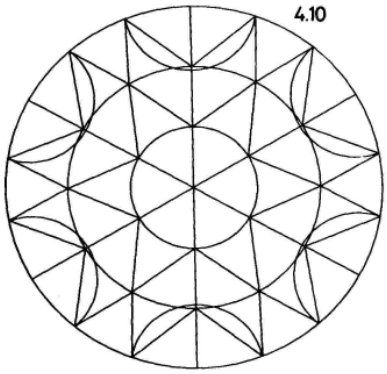
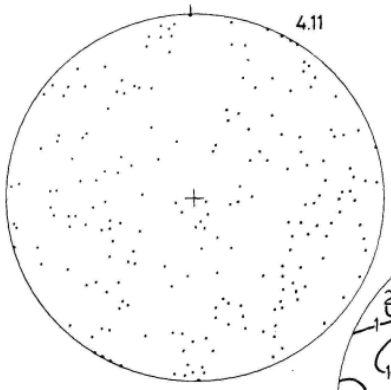


Figure 4.8. Kalsbeek hexagon counting net. 300 counting point net (600 triangles) using semicircles for edge corrections. After Kalsbeek (1963), Figure l.

Figure 4.9. 49 counting point hexagon net. Equal-area counting areas derived from the Kalsbeek net, for use with 196 or more points.

Figure 4.10. 28 counting point hexagon net. Equal-area counting areas derived from the Kalsbeek net, for use with 112 or more points.



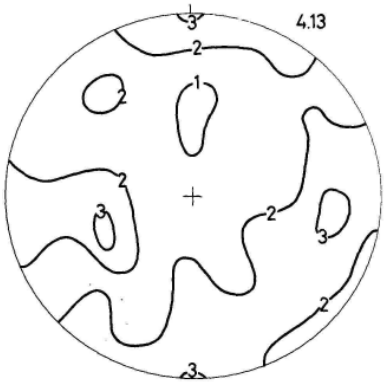
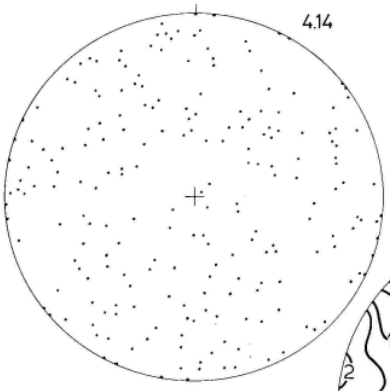


Figure 4.11. 200 point sample from an isotropic parent. After Stauffer (1966), Figure 3C.

Figure 4.12. 200 point sample from an isotropic parent (Figure 4.11) contoured by the squared grid method. Contours 1, 2, 3 and 4% per 1 per cent area. After Stauffer (1966), Figure 3D.

Figure 4.13. 200 point sample from an isotropic parent (Figure 4.11) contoured by 49 counting point hexagon net. $\Sigma = 610.5$, $n_{max} = 19$ (3.1%), $n_{min} = 4$ (0.7%). Contours 1, 2 and 3%.



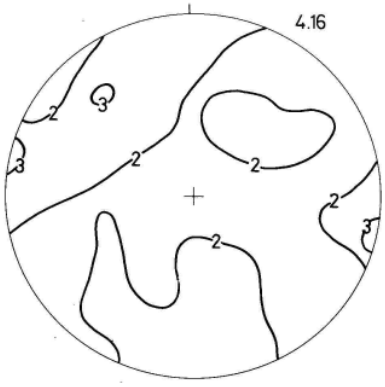


Figure 4.14. 200 point sample from an isotropic parent. After Stauffer (1966), Figure 3E.

Figure 4.15. 200 point sample from an isotropic parent (Figure 4.14) contoured by the squared grid method. Contours 1 and 2% per 1 per cent area. After Stauffer (1966), Figure 3F.

Figure 4.16. 200 point sample from am isotropic parent (Figure 4.14) contoured by 49 counting point hexagon net. $\Sigma = 610$, $n_{max} = 19.5$ (3.2%), $n_{min} = 7$ (1.1%). Contours 2 and 3%.

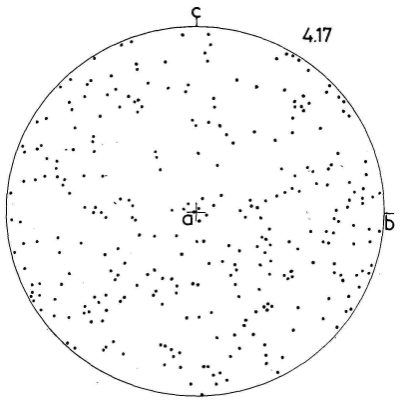


Figure 4.17. 300 quartz c-axes (0001). Basal Cambrian Quartzite, south shore of Loch Glencoul. After Phillips (1937), Figure D27.

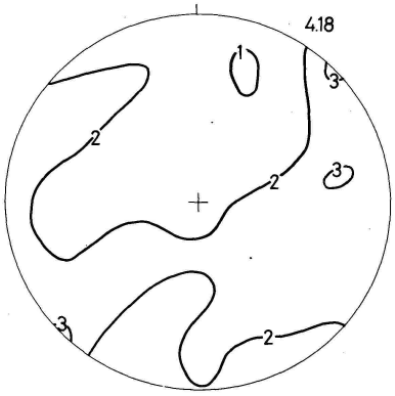
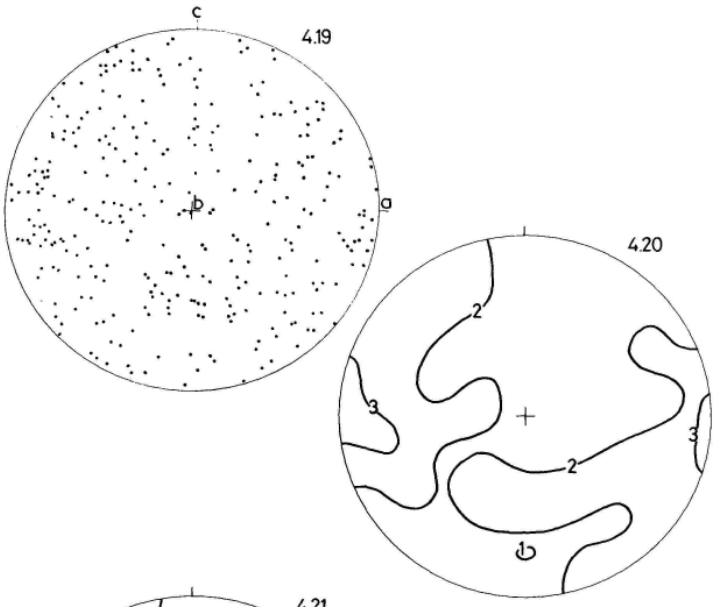


Figure 4.18. 300 quartz c-axes (0001). Basal Cambrian Quartzite, south shore of Loch Glencoul. Contoured by 49 counting point hexagon net. $\Sigma = 902.5$, $n_{max} = 28$ (3.1%), $n_{min} = 7$ (0.8%). Contours 1, 2 and 3%.



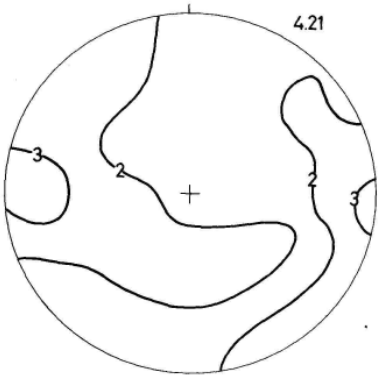
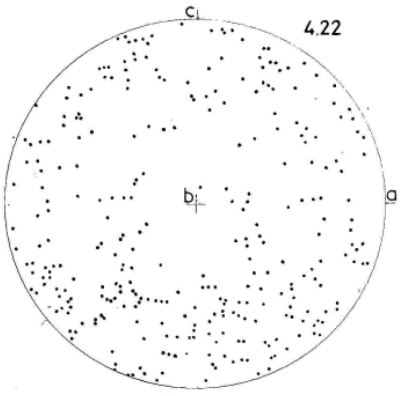
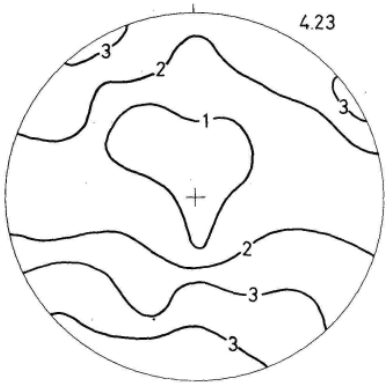


Figure 4.19. 300 quartz c-axes (0001). Undisturbed Serpulite Grit, the Knockan Cliff. After Phillips (1937), Figure D28.

Figure 4.20. 300 quartz c-axes (0001). Undisturbed Serpulite Grit, the Knockan Cliff. Contoured by 49 counting point hexagon net. $\Sigma = 959.5$, n_{max} = 32 (3.3%), n_{min} = 9 (0.9%). Contours 1, 2 and 3%.

Figure 4.21. 200 quartz c-axes (0001). Undisturbed Serpulite Grit, the Knockan Cliff. Contoured by 49 counting point hexagon net with counting net rotated 30° clockwise relative to Figure 4.20. $\Sigma = 944$, n_{max} = 36 (3.8%), n_{min} = 11 (1.2%). Contours 2 and 3%.





Figures 4.22. 300 quartz c -axes (0001). Sheared Torridonian Sandstone, Glen Docherty, Kinlochewe. After Phillips (1937), Figure D29.

Figure 4.23. 300 quartz c-axes (0001). Sheared Torridonian Sandstone, Glen Docherty, Kinlochewe. Contoured by 49 counting point hexagon net. $\Sigma = 922.5$, n_{max} = 35.5 (3.8%), n_{min} = 3 (0.3%). Contours 1, 2 and 3%.

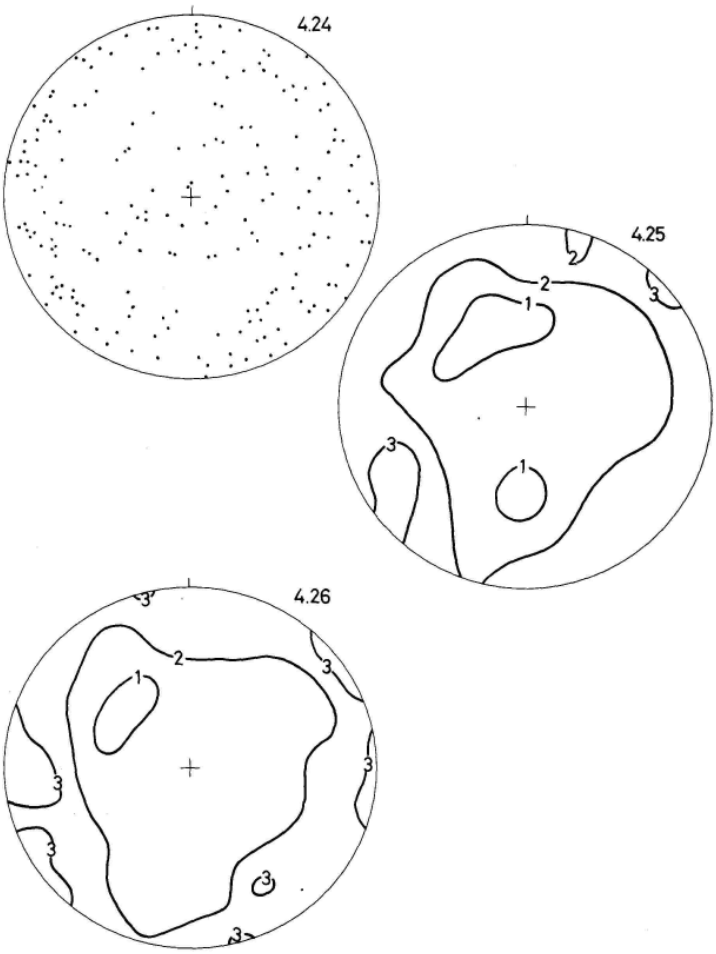


Figure 4.24. 200 quartz c-axes (0001). Hornfels. After Phillips (1944).

Figure 4.25. 200 quartz c-axes (0001). Hornfels. Contoured by 49 counting point hexagon net. E = 638, n_{max} = 24 (3.8%), n_{min} = 4 (0.6%).

Figure 4.26. 200 quartz c-axes (0001). Hornfels. Contoured by 49 counting point hexagon net with cp net rotated 30° anticlockwise relative to Figure 4.25. Σ = 621, n_{max} = 22 (3.5%), n_{min} = 4 (0.6%). Contours 1, 2 and 3%.

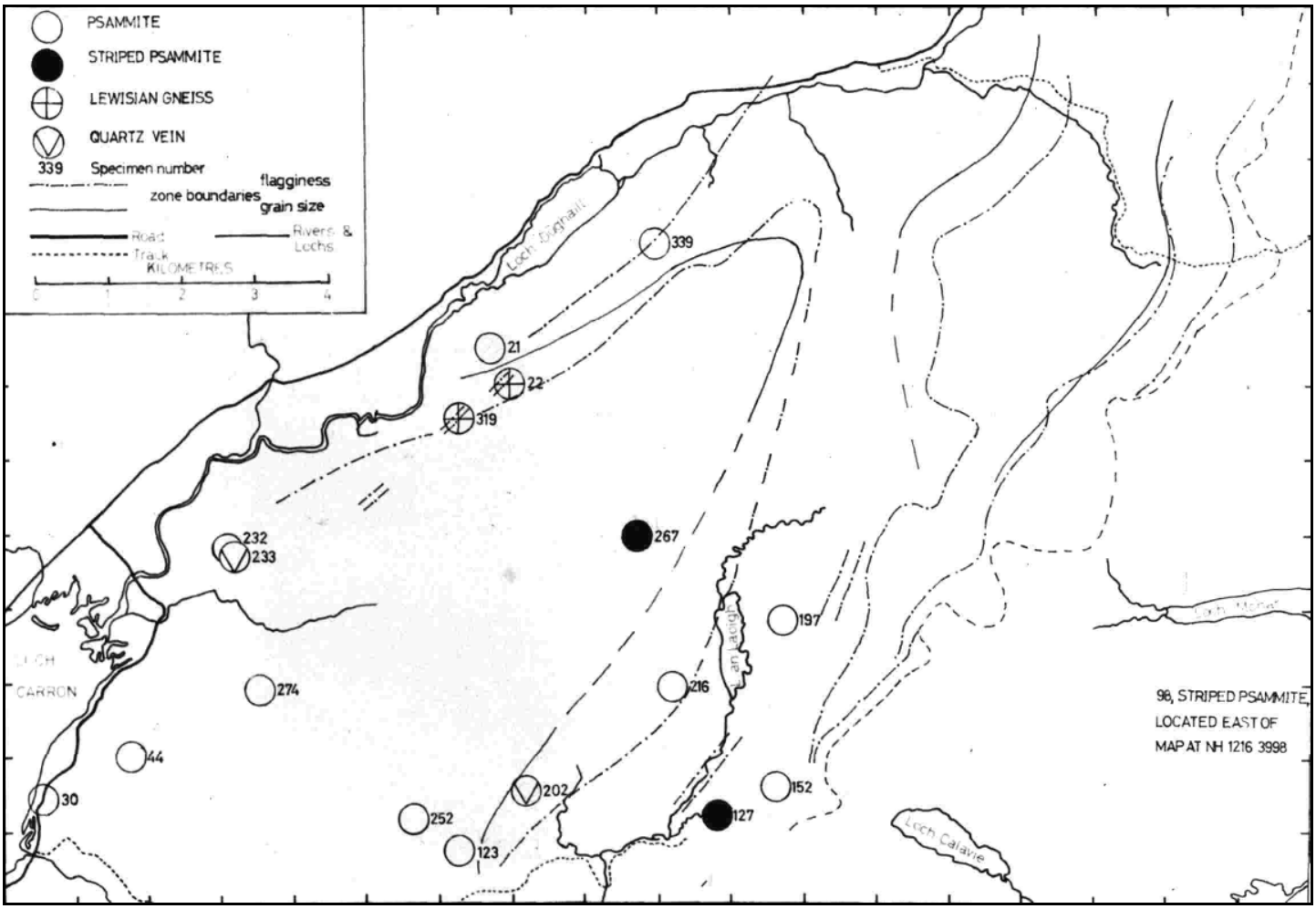
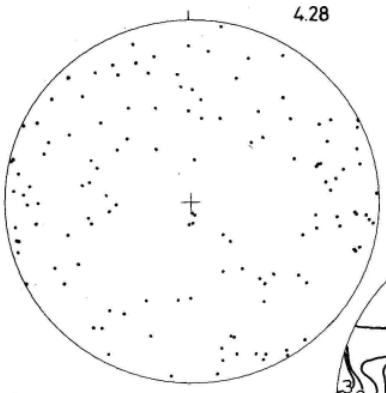
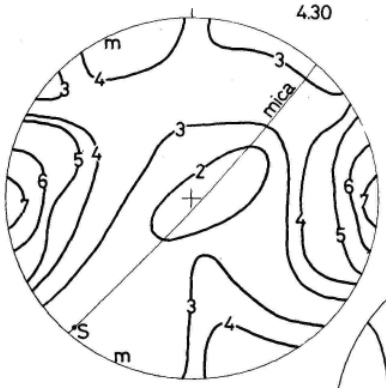


Figure 4.27. Petrofabric sample locations, rock types and numbers.





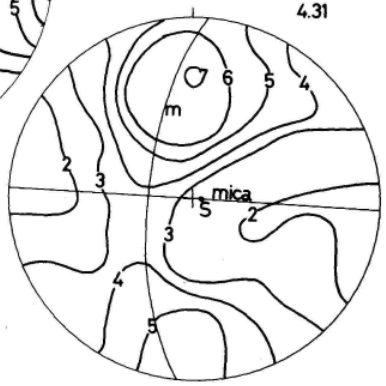
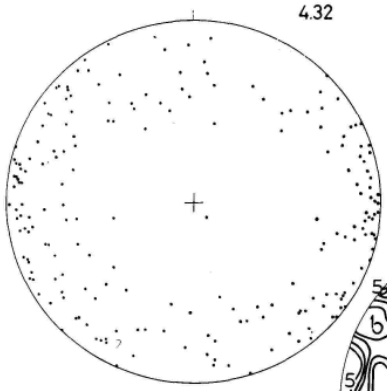


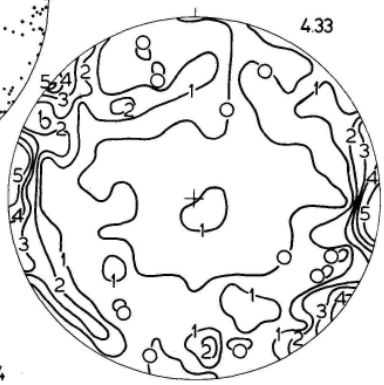
Figure 4.28. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512.

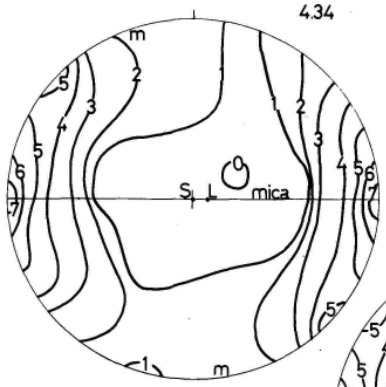
Figure 4.29. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512. Contoured by Schmidt method. Contours 0, 1, 2, 3, 4 and 5% per 1 per cent area.

Figure 4.30. 120 quartz c-axes (0001), 22, Lewisian gneiss. NG 9890 4512. Contoured by 28 counting point hexagon net. $\Sigma = 409$, $n_{max} = 31$ (7.6%). Contours 2, 3, 4, 5, 6 and 7%.

Figure 4.31. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512. Contoured by 28 counting point hexagon net. Centre of net is down dip of mica fabric. Points rotated and contoured. $\Sigma = 407.5$, $n_{max} = 29$ (7.1%), $n_{min} = 6$(1.5%). Contours 2,3.4.5,6 and 7%. m = symmetry plane.







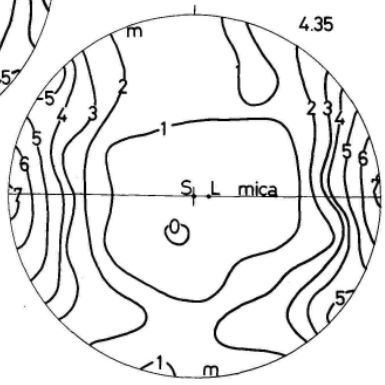


Figure 4.32. 200 quartz c-axes (0001). 21, psammite. NG 9868 4537.

Figure 4.33. 200 quartz c-axes (0001). 21, psammite. NG 9868 4537. Contoured by Schmidt method. Contours 0, 1, 2, 3, 4 and 5% per 1 per cent area.

Figure 4.34. 200 quartz c-axes (0001). 21, psammite. NG 9868 4537. Contoured by 49 counting point hexagon net. $\Sigma = 620.5$, $n_{max} = 45$ (7.25%). Contours 0,1,2,3,4,5, 6 and 7%.

Figure 4.35. 200 quartz c-axes (0001). 21, psammite. NG 9868 4537. Contoured by 49 counting point hexagon net with counting net rotated 30° anticlockwise relative to Figure 4.34. $\Sigma = 614$, $n_{max} = 45$ (7.33%). Contours 0, 1, 2, 3, 4, 5, 6 and 7%.

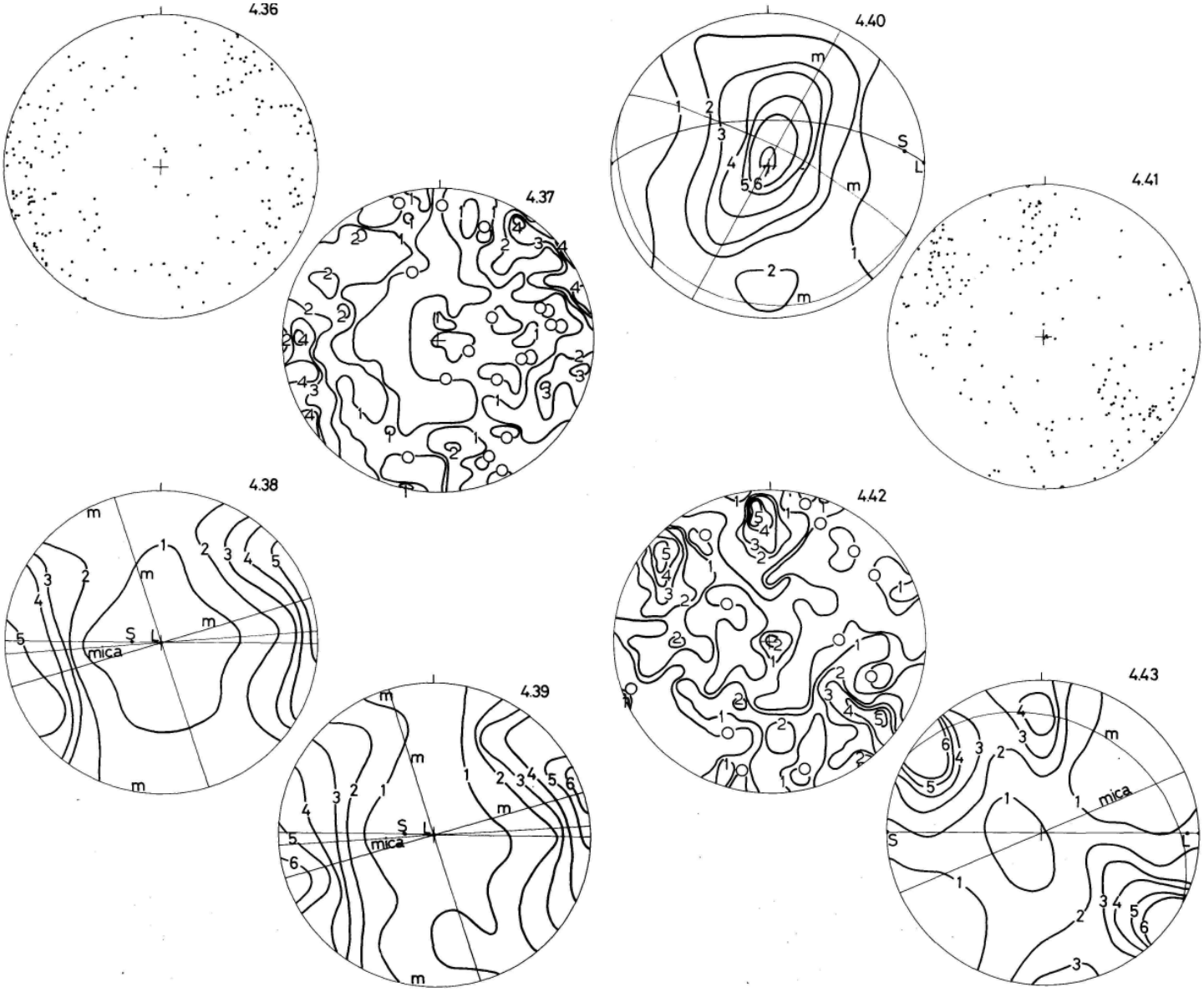


Figure 4.36. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998.

Figure 4.37. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998. Contoured by Schmidt method. Contours 0,1,2,3,4 and 5%.

Figure 4.38. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998. Contoured by 49 counting point hexagon net. Σ =601.5, n_{max} =35 (58%). Contours 1, 2, 3, 4 and 5%.

Figure 4.39. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998. Contoured by 49 counting point hexagon net with counting net rotated 10° anticlockwise relative to Figure 4.38. Σ = 605, n_{max} = 415 (6.9%). Contours 1,2,3,4, 5 and 6%.

Figure 4.40. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998. Points from Figure 4.36 rotated so that maximum defined in Figures 4.38 and 4.39 is in the centre of the net. Contoured by 49 counting point hexagon net. Σ = 595.5, n_{max} = 42 (7.2%). Contours 1, 2, 3, 4, 5, 6 and 7%.

Figure 4.41. 200 quartz c-axes (0001). 44, psammite. NG 9370 3997.

Figure 4.42. 200 quartz c-axes (0001). 44, psammite. NG 9370 3997. Contoured by Schmidt method. Contours 0, 1, 2, 3, 4 and 5% per 1 per cent area.

Figure 4.43. 200 quartz c-axes (0001). 44, psammite. NG 9370 3997. Contoured by 49 counting point hexagon net. Σ = 615, n_{max} = 41.5 (6.7%). Contours 1, 2, 3, 4, 5 and 6%.

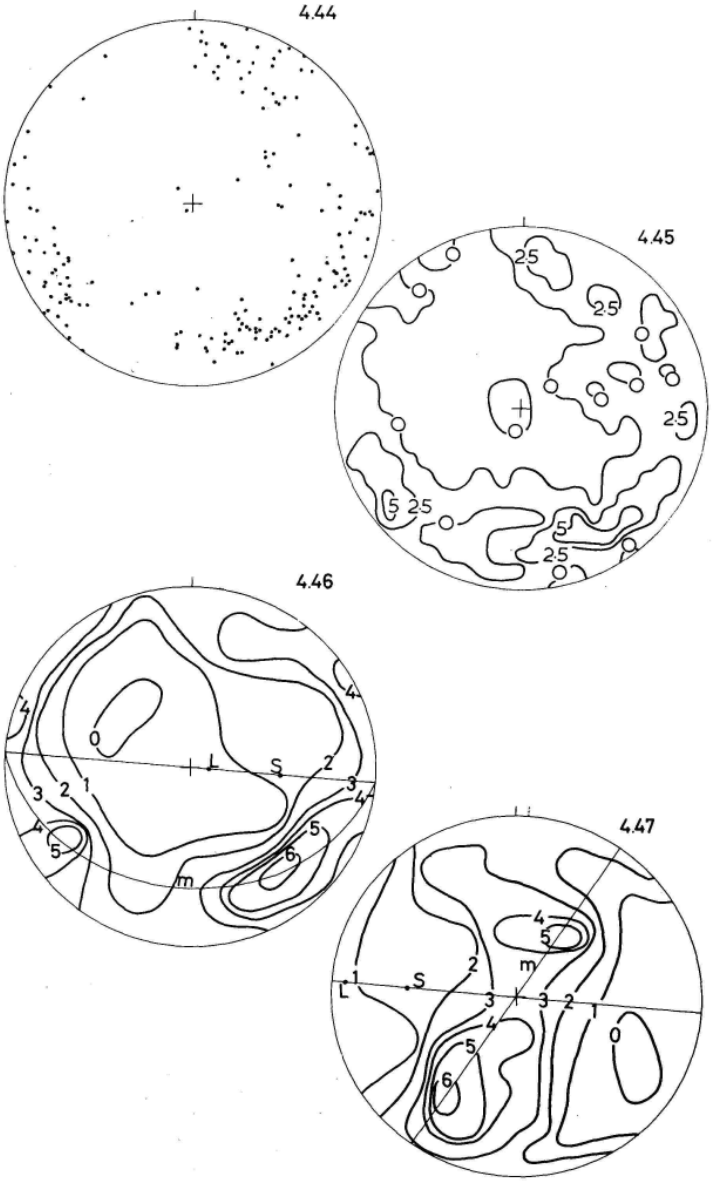


Figure 4.44. 180 quartz c-axes (0001). 233, quartz vein in psammite. NG 9530 4287.

Figure 4.45. 180 quartz c-axes (0001). 233, quartz vein in psammite. NG 9530 4287. Contoured by Schmidt method. Contours 0, 2½ and 5% per 1 per cent area.

Figure 4.46. 180 quartz c-axes (0001). 233, quartz vein in psammite. NG 9530 4387. Contoured by 49 counting point hexagon net. $\Sigma = 551.5$, $n_{max} = 36$ (6.5%). Contours 0, 1,2 , 3, 4, 5 and 6%.

Figure 4.47. 180 quartz c-axes (0001). 233, quartz vein in psammite. NG 9530 4287. Contours from Figure 4.46 rotated 90° clockwise about a N -S axis through the net.

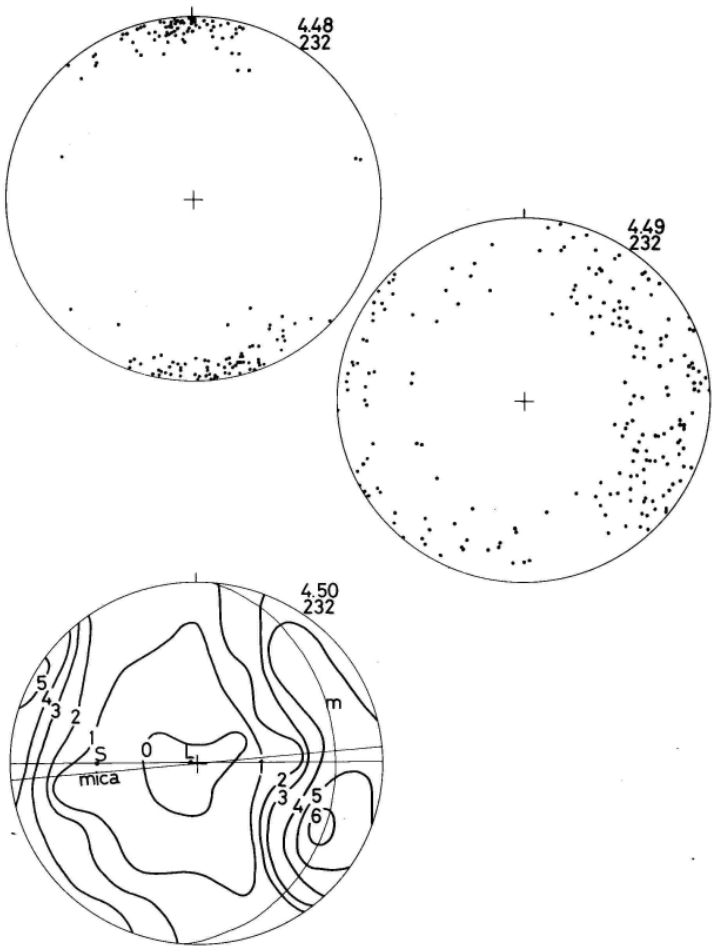
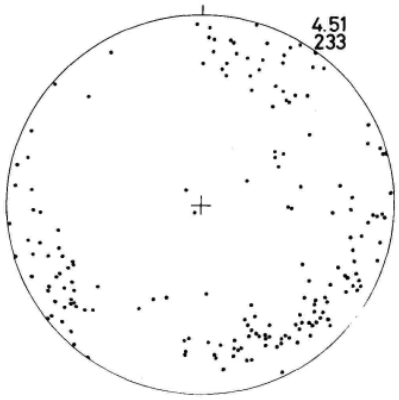


Figure 4.48. 151 mica poles to (001). 232, psammite. NG 9525 4295.

Figure 4.49. 200 quartz c-axes (0001). 232, psammite. NG 9525 4295.

Figure 4.50. 200 quartz c-axes (0001). 232, psammite. NG 9525 4295. Contoured by 49 counting point hexagon net. $\Sigma = 616$, $n_{max} = 40$ (6.50). Contours 0, 1, 2, 3, 4, 5 and 6%. Section perpendicular to lineation 134°/17° plunge. Layering 178°/27° E dip. m = symmetry plane.



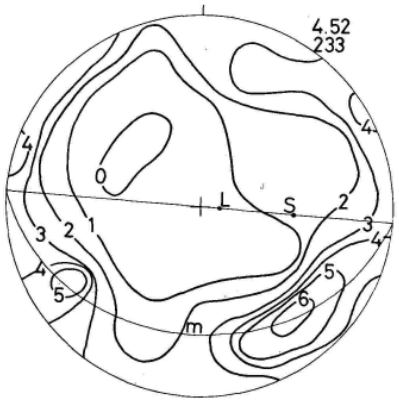


Figure 4.51. 180 quartz c-axes (0001). 233, quartz vein in psammite. NG 9530 4287.

Figure 4.52. 180 quartz c-axes (0001). 233, quartz vein. NG 9530 4287. Contoured by 49 counting point hexagon net. $\Sigma = 551.5$ $n_{max} = 36$ (6.5%). Contours 0, 1, 2, 3, 4, 5 and 6%. Section perpendicular to lineation 082°/34° plunge. Regional planar structure 033°/35°E dip. m = symmetry plane.

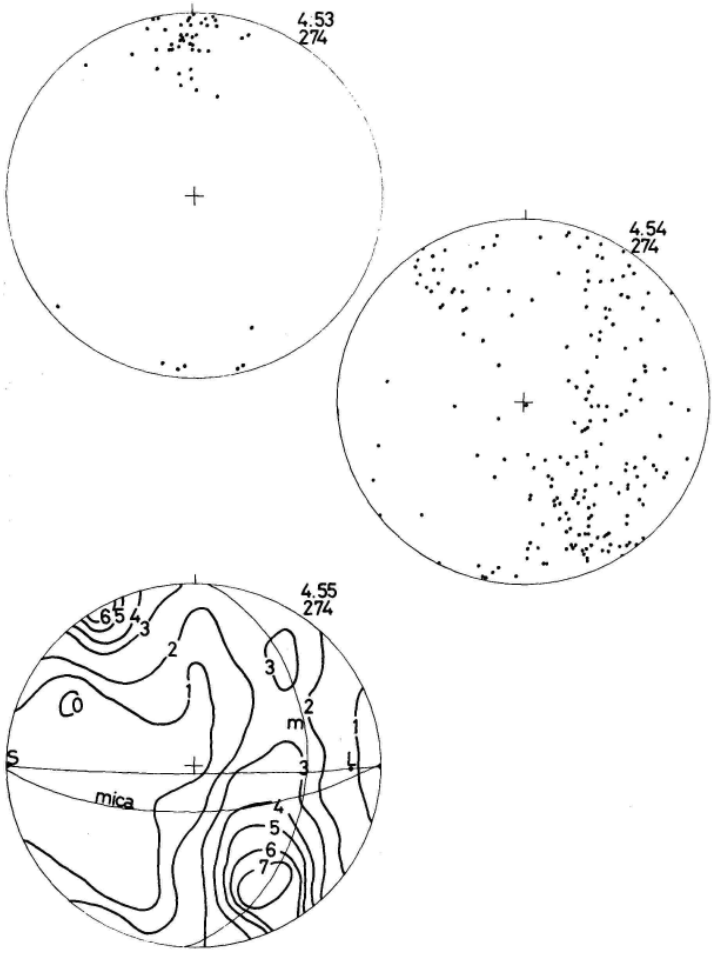


Figure 4.53. 50 mica poles to (001). 274, psammite. NG 9583 4083.

Figure 4.54. 200 quartz c-axes (0001). 274, psammite. NG 9583 4083.

Figure 4.55. 200 quartz c-axes (0001). 274, psammite. NG 9583 4083, contoured by 49 counting point hexagon net. $\Sigma = 613$, $n_{max} = 44$ (7.2%). Contours 0, 1, 2, 3, 4, 5, 6 and 7%. Section perpendicular to layering 018°/24°E dip. m = symmetry plane.

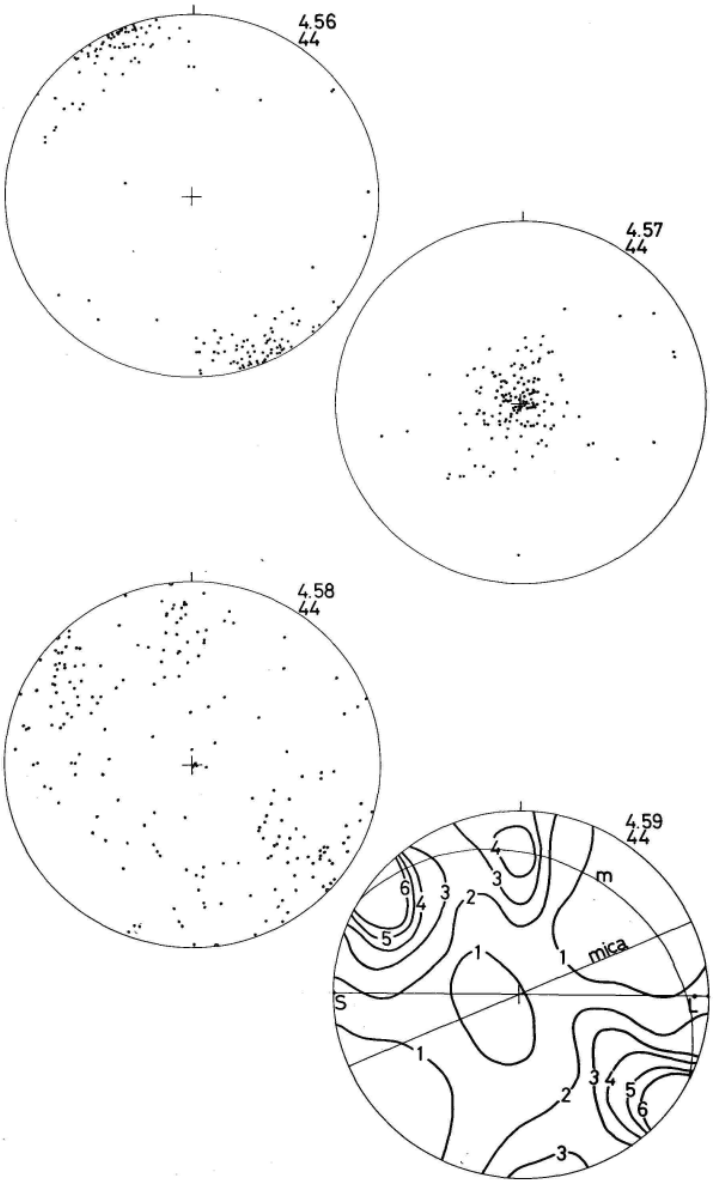


Figure 4.56. 151 mica poles to (001). 44, psammite. NG 9370 3997.

Figure 4.57. 151 mica poles to (001). 44, psammite. NG 9370 3997. Points rotated to centre of net relative to Figure 4.56.

Figure 4.58. 200 quartz c-axes (0001). 44, psammite. NG 9370 3997.

Figure 4.59. 200 quartz c-axes (0001). 44, psammite. NG 9370 3997. Contoured by 49 counting point hexagon net. $\Sigma = 615$, $n_{max} = 41.5$ (6.7%). Contours 1, 2, 3, 4, 5 and 6%. Section perpendicular to layering 036°/10° E dip, and approximately perpendicular to strike. Centre of diagram = 228°. Lineation 132°/12° plunge. m = symmetry plane.

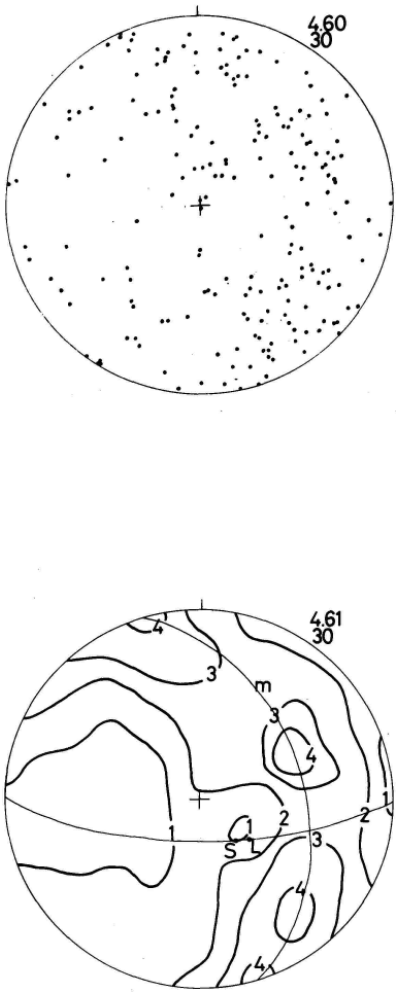
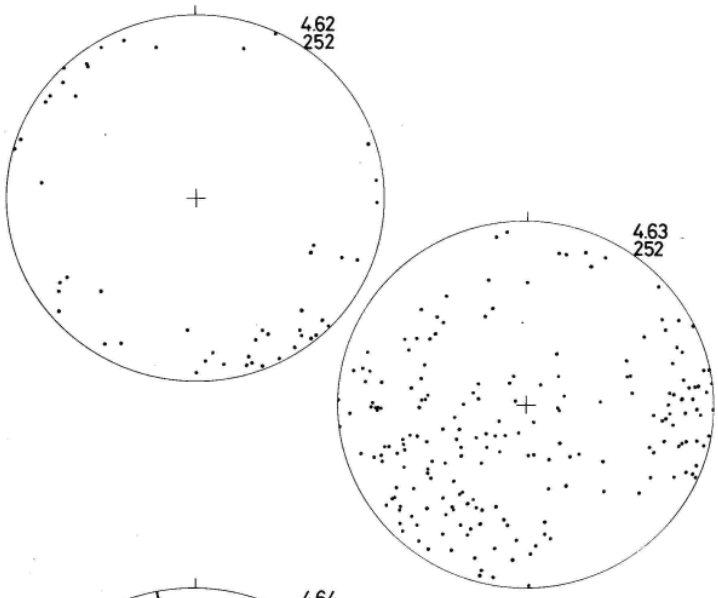


Figure 4.60. 200 Quartz c-axes (0001). 30, psammite. NG 9252 3940.

Figure 4.61. 200 quartz c-axes (0001). 30, psammite. NG 9252 3940. Contoured by 49 counting point hexagon net. $\Sigma = 617$, n_{max} 29 (4.7%). Contours 1, 2, 3 and 4%. Section approximately perpendicular to layering 153°/36° E dip. No regional lineation noted. m = symmetry plane.



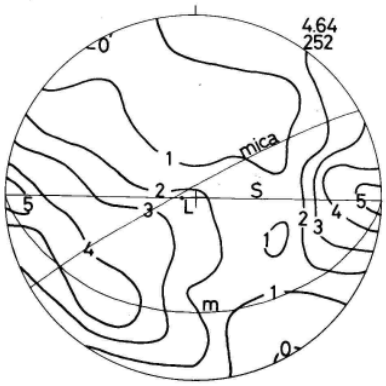
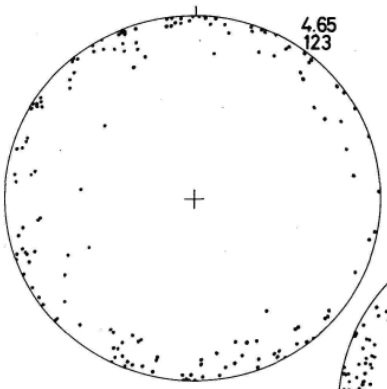
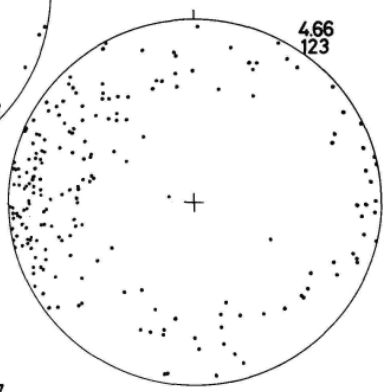


Figure 4.62. 50 mica poles to (001). 252, psammite. NG 9788 3924.

Figure 4.63. 200 quartz c-axes (0001). 252, psammite. NG 9788 3924.

Figure 4.64. 200 quartz c-axes (0001). 252, psammite. NG 9788 3924. Contoured by 49 counting point hexagon net. $\Sigma = 604$, $n_{max} = 35$ (5.8%). Contours 0, 1, 2, 3, 4 and 5%. Section perpendicular to lineation 103°/36° plunge. Layering approximately 074 °/49° S dip. m = symmetry planes.





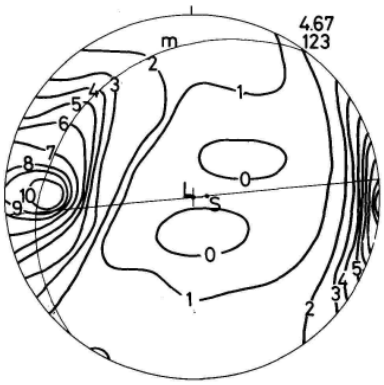
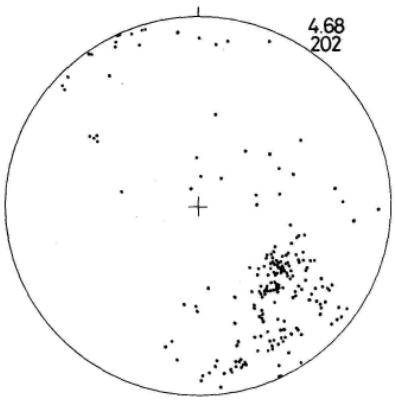


Figure 4.65. 150 mica poles to (001). 123, psammite. NG 9833 3884.

Figure 4.66. 200 quartz c-axes (0001). 123, psammite. NG 9833 3884.

Figure 4.67. 200 quartz c-axes (0001). 123, psammite. NG 9833 3884. Contoured by 49 counting point hexagon net. $\Sigma = 614$, $n_{max} = 641$ (10.5%). Contours 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10%. Section perpendicular to lineation 119°/36° plunge. Planar surface 035°/36°E dip. m = symmetry planes.



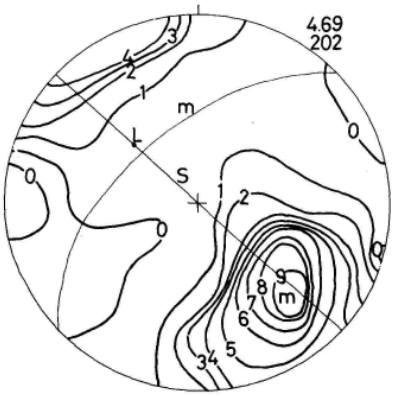
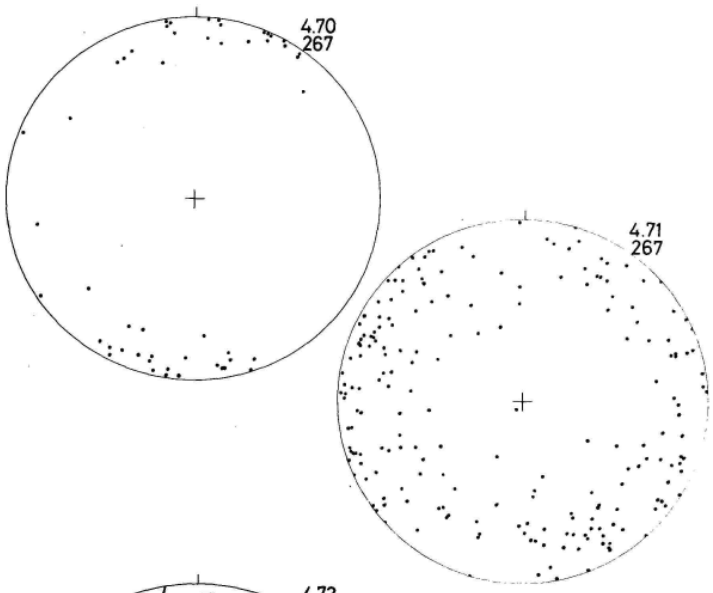


Figure 4.68. 200 quartz c-axes (0001). 202, quartz vein. NG 9910 3965.

Figure 4.69. 200 quartz c-axes (0001). 202, quartz vein. NG 9910 3965. Contoured by 49 counting point hexagon net. $\Sigma = 610$, $n_{max} = 93$ (15.25%). Contours 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10%. Section perpendicular to planar structure in surrounding psammite 030°/28° E dip. Cross = Axis of symmetry.



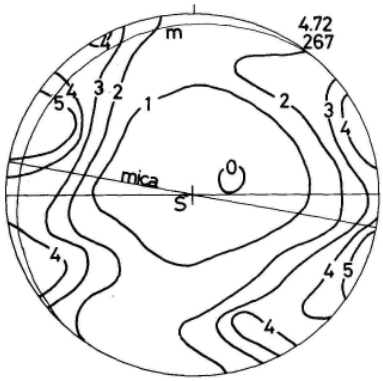
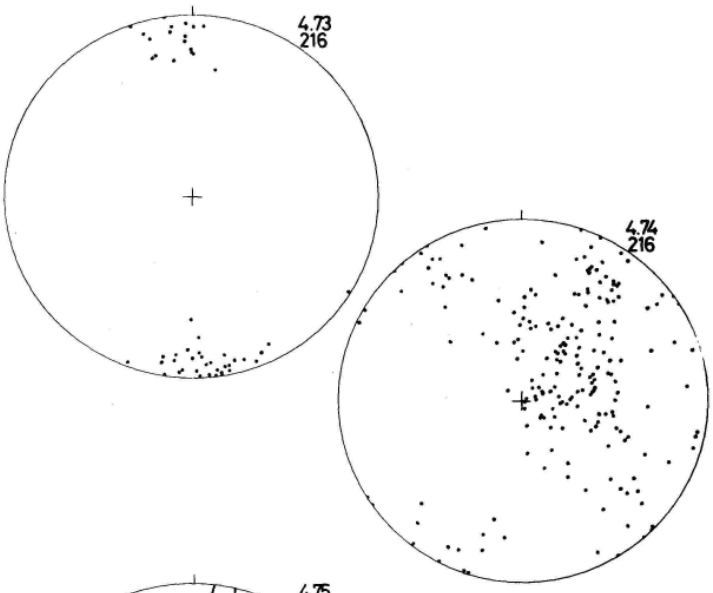


Figure 4.70. 50 mica poles to (001). 267, striped psammite. NH 0322 4286.

Figure 4.71. 200 quartz c-axes (0001). 267, striped psammite. NH 0322 4286.

Figure 4.72. 200 quartz c-axes (0001). 267, striped psammite. NH 0322 4286. Contoured by 49 counting point hexagon net. $\Sigma = 617.5$, $n_{max} = 34$ (5.5%). Contours 0, 1, 2, 3, 4 and 5%. Section perpendicular to dip of layering 042°/20° E dip. No lineation noted. m= symmetry plane.



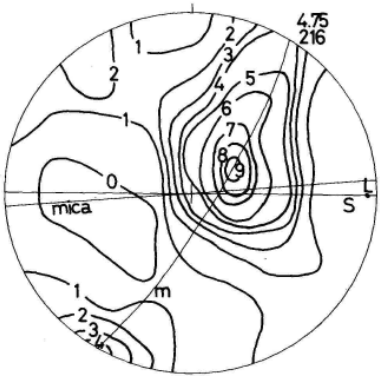
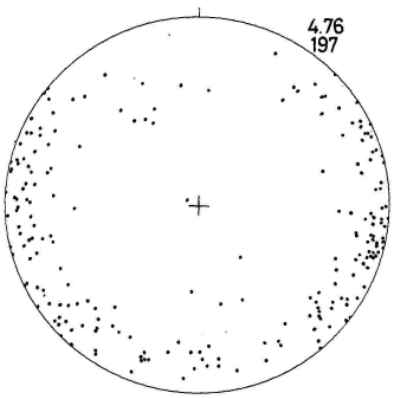


Figure 4.73. 50 mica poles to (001). 216, psammite. NH 0125 4109.

Figure 4.74. 200 quartz c-axes (0001). 216, psammite. NH 0125 4109.

Figure 4.75. 200 quartz c-axes (0001). 216, psammite. NH 0125 4109. Contoured by 49 counting point hexagon net. $\Sigma = 602.5$, $n_{max} = 56$ (9.3%). Contours 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9%. Section perpendicular to layering 045°/33° E. m = symmetry plane.



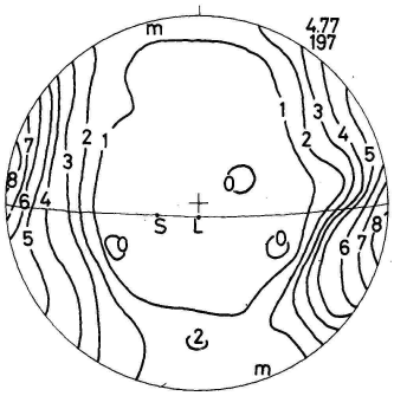


Figure 4.76. 200 quartz c-axes (0001). 197, psammite. NH 0283 4175.

Figure 4.77. 200 quartz c-axes (0001). 197, psammite. NH 0283 4175. Contoured by 49 counting point hexagon net. $\Sigma = 642$, $n_{max} = 56$ (8.7%). Section cut. perpendicular to lineation 154°/22° plunge. Layering 050° /22° S dip. m = symmetry plane.

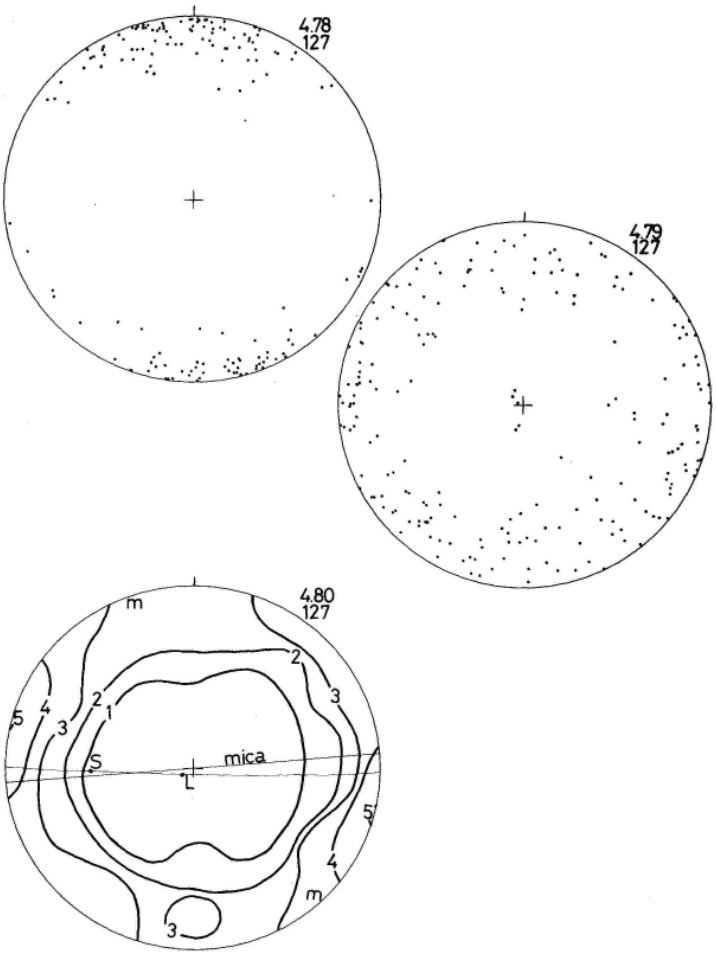


Figure 4.78. 150 mica poles to (001). 127, striped psammite. NH 0178 3913.

Figure 4.79. 200 quartz c-axes (0001). 127, striped psammite. NH 0178 3913.

Figure 4.80. 200 quartz c-axes (0001). 127, striped psammite. NH 0178 3913. Contoured by 49 counting point hexagon net. $\Sigma = 606.5$, $n_{max} = 30.5$ (5.0%). Contours 1, 2, 3, 4 and 5%. Section perpendicular to lineation 158°/22° plunge. Layering 024°/33° E dip. m = symmetry plane.

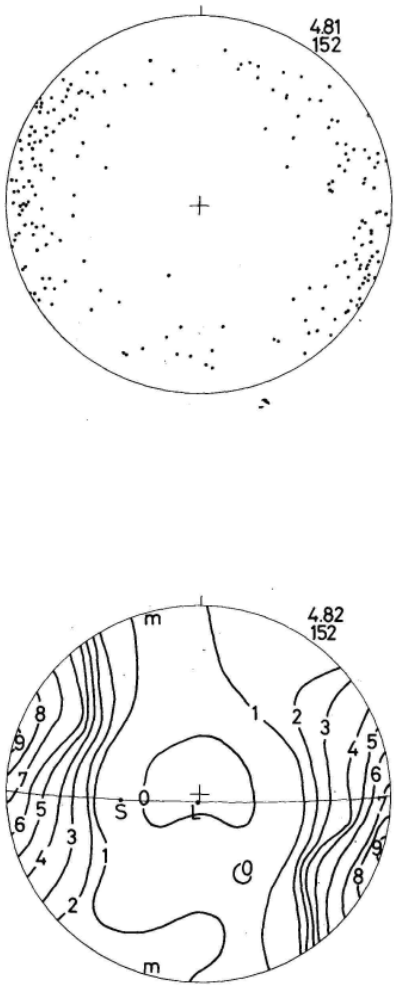
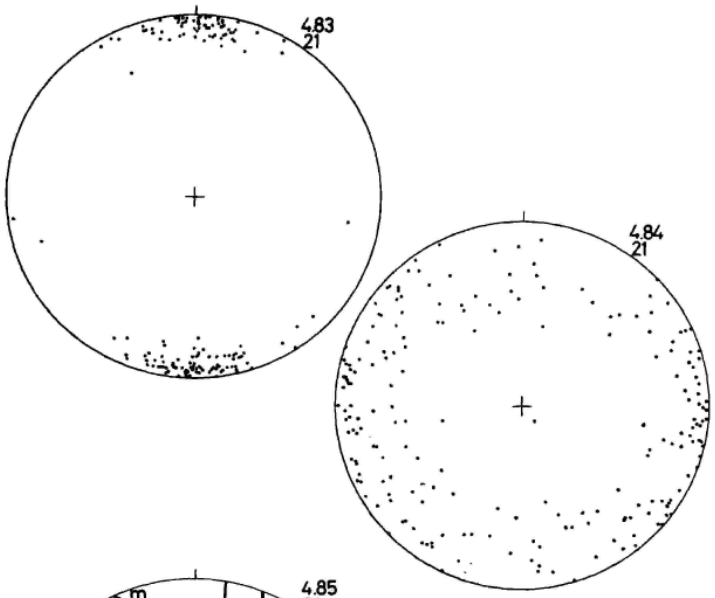


Figure 4.81. 200 quartz c-axes (0001). 152, psammite. NH 0265 3962.

Figure 4.82. 200 quartz c-axes (0001). 152, psammite. NH 0265 3962. Contoured by 49 counting point hexagon net. $\Sigma = 614$, $n_{max} = 56.5$ (9.2%). Contours 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9%. Section perpendicular to lineation 156°/37° plunge. Layering 033°/42° E dip. m = symmetry plane.



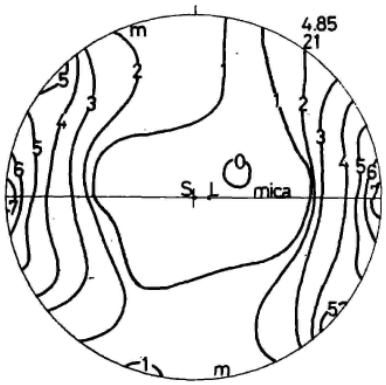
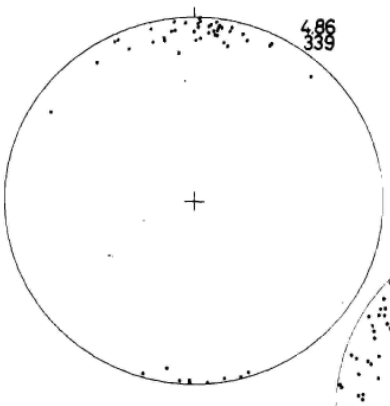
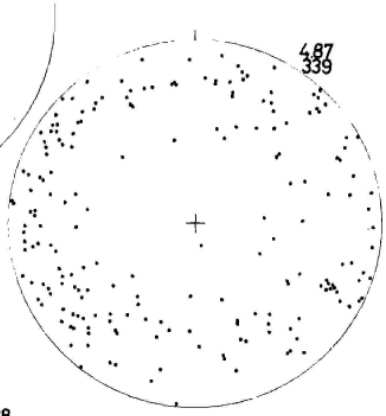


Figure 4.83. 150 mica poles to (001). 21, psammite. NG 9868 4537.

Figure 4.84. 200 quartz c-axes (0001). . 21, psammite. NG 9868 4537.

Figure 4.85. 200 quartz c-axes (0001). 21, psammite. NG 9868 4537. Contoured by 49 counting point hexagon net. $\Sigma = 620.5$, $n_{max} = 45$ (7.25%). Contours 0, 1, 2, 3, 4, 5, 6 and 7%. Section perpendicular to dip 034°/20° E. m = symmetry plane.





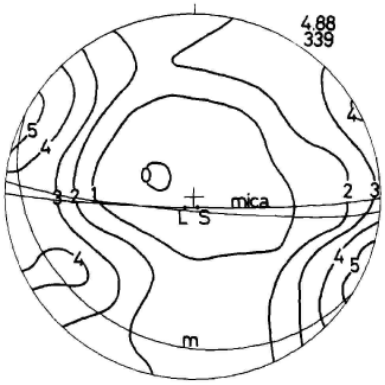
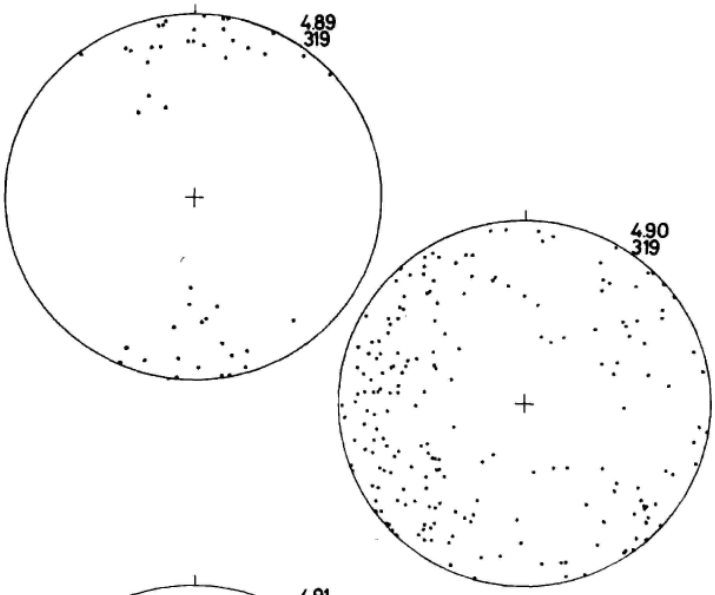


Figure 4.86. 50 mica poles to (001). 339, psammite. NH 0095 4695.

Figure 4.87. 200 quartz c-axes (0001). 339, psammite. NH 0095 4695.

Figure 4.88. 200 quartz c-axes (0001). 339, psammite. NH 0095 4695. Contoured by 49 counting point hexagon net. $\Sigma = 625.5$, $n_{max} = 35$ (5.6%). Contours 0, 1, 2, 3, 4 and 5%. Section perpendicular to layering 023°/30° E dip. m = symmetry plane.



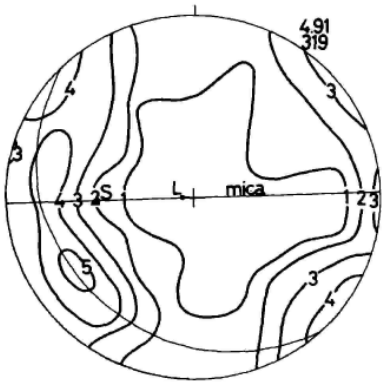
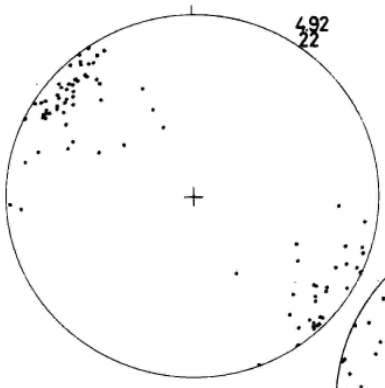
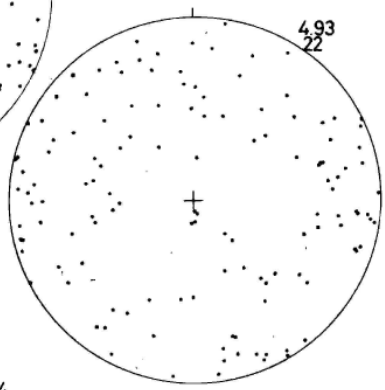


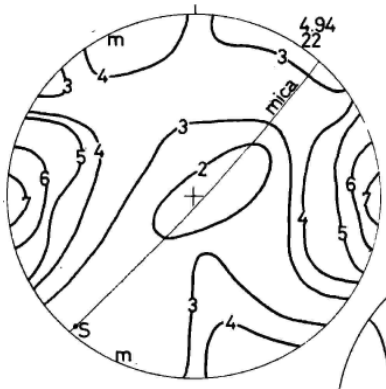
Figure 4.89. 50 mica poles to (001). 319, Lewisian gneiss. NG 9838 4463.

Figure 4.90. 200 quartz c-axes (0001). 319, Lewisian gneiss. NG 9838 4463.

Figure 4.91. 200 quartz c-axes (0001). 319, Lewisian gneiss. NG 9838 4463. Contoured by 49 counting point hexagon net. $\Sigma = 628.5$, $n_{max} = 33.5$ (5.3%). Contours 0, 1, 2, 3, 4 and 5%. Section perpendicular to mica planar surface, 042°/46° E dip. m = symmetry plane.







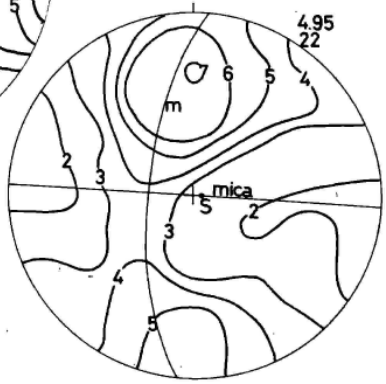


Figure 4.92. 85 biotite mica poles to (001). 22, Lewisian gneiss. NG 9890 4512.

Figure 4.93. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512.

Figure 4.94. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512. Contoured by 28 counting point hexagon net. $\Sigma = 409$, $n_{max} = 31$ (7.6%). Contours 2, 3, 4, 5, 6 and 7%. Section perpendicular to horizontal and to mica planar surface approximately 000°/55° E dip. m = symmetry plane. No lineation noted.

Figure 4.95. 130 quartz c-axes (0001). 22, Lewisian gneiss. NG 9890 4512. Contoured by 28 counting point hexagon net. Centre of net is down dip of mica fabric. Points rotated and contoured. $\Sigma = 407.5$, $n_{max} = 29$ (7.1%), $n_{min} = 6$ (1.5%). Contours 2, 3, 4, 5, 6 and 7%. m = symmetry plane.

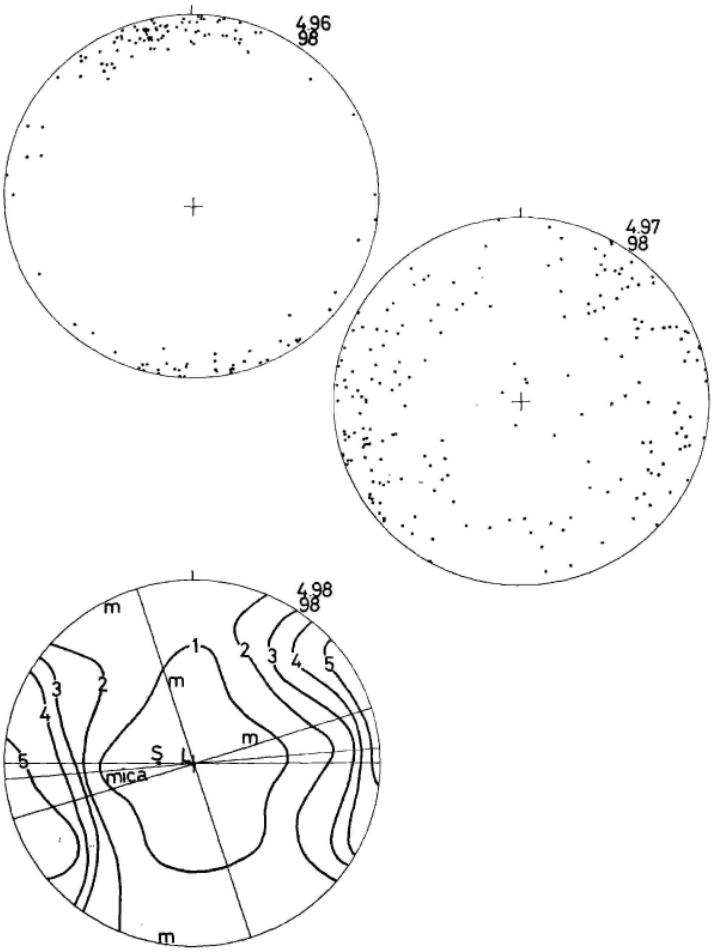


Figure 4.96. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998.

Figure 4.97. 120 biotite mica poles to (001). 98, striped psammite. NH 1216 3998.

Figure 4.98. 197 quartz c-axes (0001). 98, striped psammite. NH 1216 3998. Contoured by 49 counting point hexagon net. $\Sigma = 601.5$, $n_{max} = 35$ (5.8%). Contours 1, 2, 3, 4 and 5%. Section perpendicular to lineation 160°/37° plunge. Layering 040°/40° E dip. m = symmetry plane.

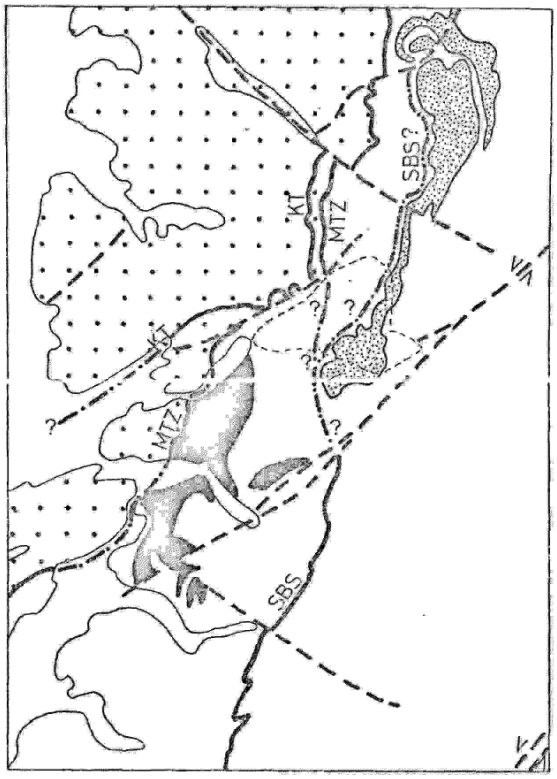


Figure 6.1 Major fractures and slides in part of the western Highlands. Based on Geological Survey 'Ten Mile' map (1979).

Figure 6.1 Major fractures and slides in part of the wester Highlands. Based on Geological Survey 'Ten Mile' map (1970).

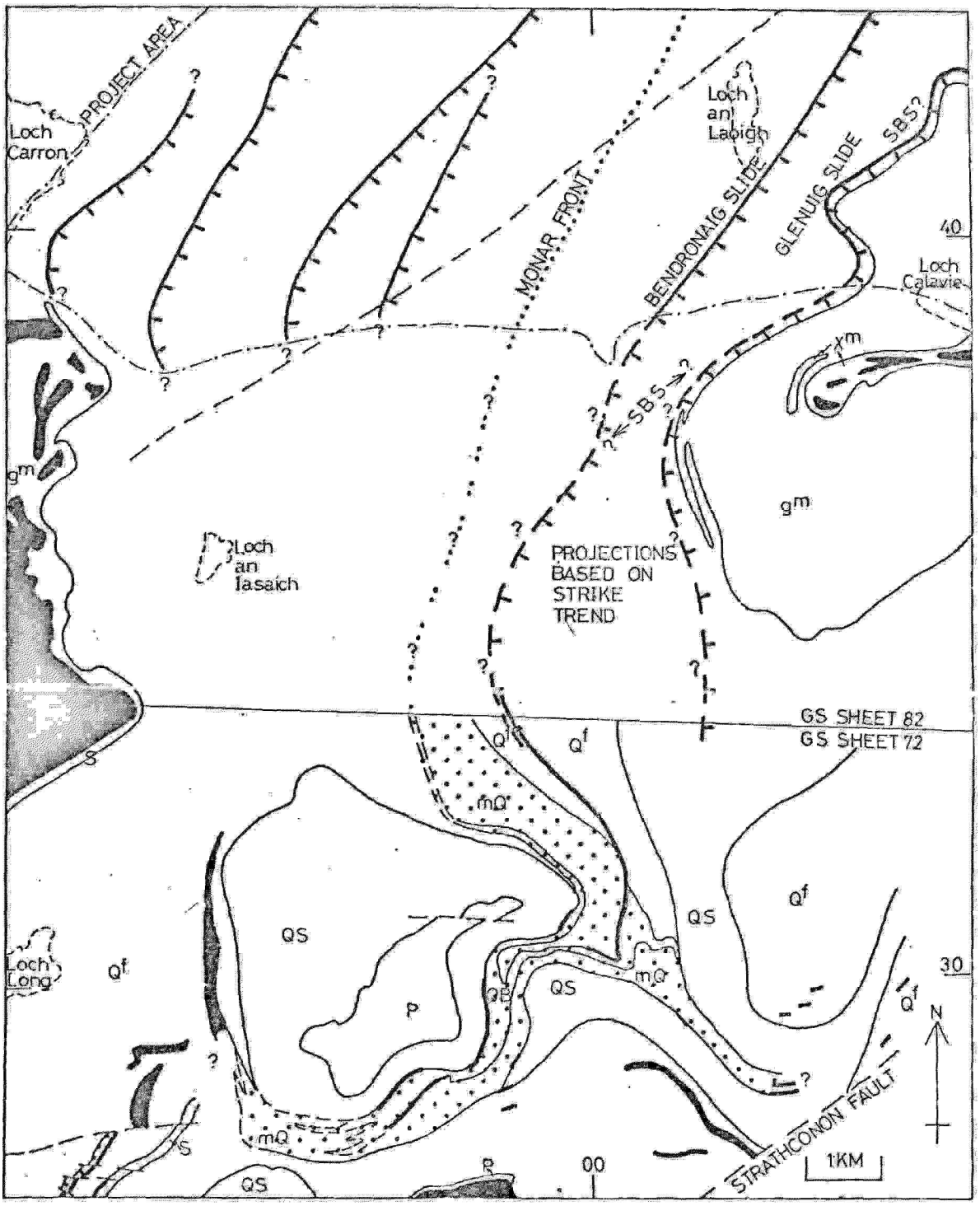


Figure 6.2. Possible structural correlations west of Beinn Dronaig. Based on Enclosure 5, Peach and others (1913) and May (pers. comm.).

P = Pelite
S = Semipelite
QS = Dark psammite
Q^f = Pale psammite
mQ = Gneissose psammite } - associated with sliding.
QB = Quartz-biotite-rock }
= Lewisian hornblende gneiss
g^m = Pelitic gneiss
X^m = Siliceous schist.

Figure 6.2 Possible structural correlations west of Beinn Dronaig. Based on Enclosure 5, Peach and others (1913) and May (pers. comm.).

Plate 2.1. Fine grained dark psammite in the Achnashellach Zone (Figure 2.1). Some relict feldspars 1 – 2 mm across still visible. Forestry track east of Craig. NH 0661 4878. Looking 010°.

Plate 2.2. Coarse grained psammite in the Attadale Zone (Figure 2.1). Large amounts of relict feldspars, up to 5 mm across,visible. East of Strathcarron. NG 9510 4196. Looking 090°.

Plate 2.3. Very fine grained flaggy psammite at the Bendronaig Zone/Sgurr na Feartaig Zone boundary (Figure 2.2). South-west of Beinn Tharsuinn and above Plate 2.4. NH 0382 4274. Looking 050°.

Plate 2.4. Very fine grained very flaggy psammite in the Bendronaig Zone (Figure 2.2). South-west of Beinn Tharsuinn and below Plate 2.3. NH 0380 4283. Looking 070°.

Plate 2.5. Inverted cross-bedding, apparently undeformed, in massive psammite in the Sgurr na Feartaig Zone (Figure 2.2). East of Cona Mheallain. NH 0713 4862. Looking east.

Plate 2.6. Inverted cross-bedding, apparently undeformed, in massive striped psammite in the Sgurr na Feartaig Zone (Figure 2.2). In stream south of Pollan Buidhe. NH 0792 4638. Looking 130°.

Plate 2.7. Deformed, inverted cross-bedding, with angle of rest, increased by deformation, in massive psammite in the Attadale Zone (Figure 2.2). Bealach Alltan Ruaridh. NG 9907 3976. Looking 120°.

Plate 2.10. Lithological boundary between the Monar Banded Psammite (left) and Beinn Dronaig Pelite (right) (Enclosure 2). North-west of Pait Lodge, close to Loch Monar. NH 0958 4152. Looking 146°.

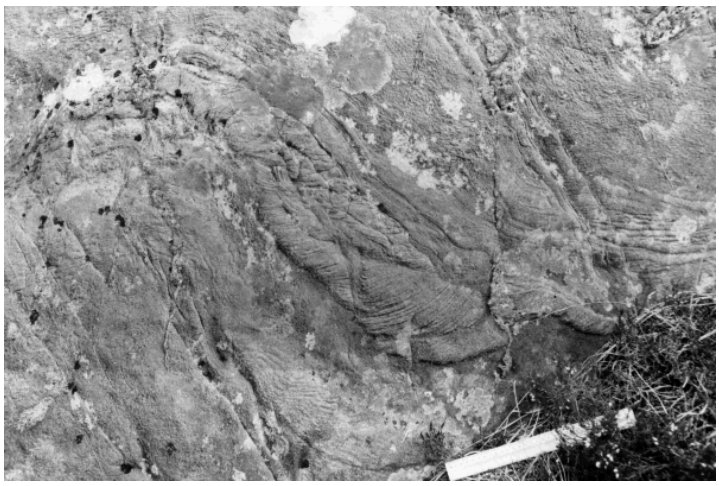


Plate 2.8. Highly deformed upright cross-bedding, with angle of rest greatly increased by deformation, in massive striped psammite of the Monar Banded Psammite (Enclosure 2). North-west of Pait Lodge, by Loch Monar. NH 1055 4103. Looking 165°.

Plate 2.11. Typically strongly banded psammite/dark psammite/ semipelite assemblage of the Monar Banded Psammite. Also shows several deformed cross-cutting pegmatites cf. Figure 2.4. North-west of Pait Lodge, by Loch Monar. NH 0995 4147. Looking 140°.

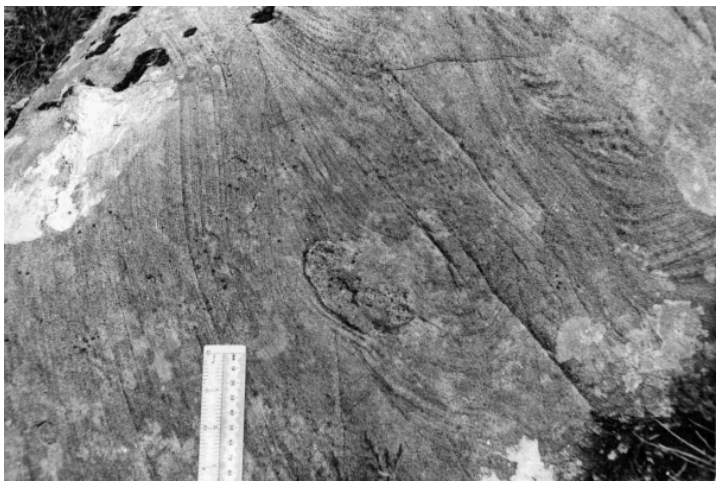


Plate 2.9. Highly deformed upright cross-bedding, with angle of rest greatly increased by deformation, in massive striped psammite of the Monar Banded Psammite (Enclosure 2). North-west of Pait Lodge, by Loch Monar. NH 1055 4103.

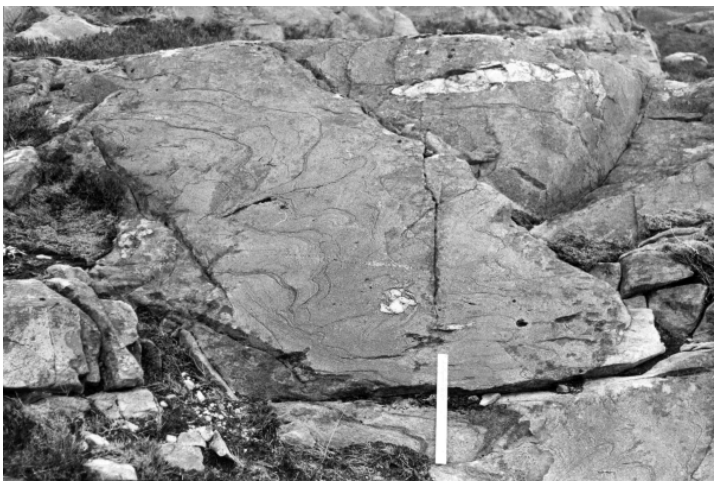


Plate 2.12. Massive quartz-vein development in massive psammite of the Attadale Zone (Figure 2.2). Also illustrates the hinge belt fold style of no preferred vergence (Section 3.6). East of Achintee. NG 9570 4023. Looking 100°.

Plate 2.13. Extensive development of quartz vein psammite of the Attadale Zone (Figure 2.2). South-east of Arineckaig. NG 9890 4431. Looking east.

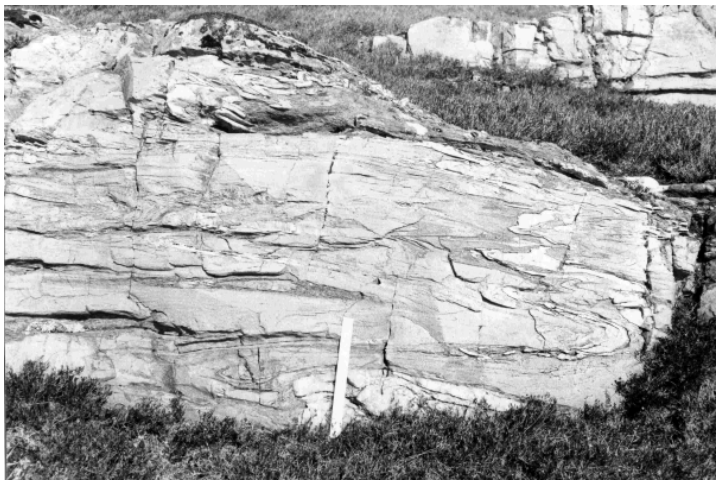


Plate 2.14. Quartz veins preferentially developed in the pelitic bands in a psammite of the Attadale Zone (Figure 2.2). Also illustrates isoclinal folding (class lc – 2) within the hinge zone of the local major fold. East of Attadale House. NG 9449 3893. Looking 060°.

Plate 2.15. 'Lit-par-lit' development of quartzo-feldspathic segregations in a psammitic – pelitic striped assemblage in the Monar Banded Psammite (Enclosure 2). Near Pait Lodge. NH 1216 3998 Looking 120°.

Plate 2.16. Ptygmatic folding in 'lit par-lit' quartzo-feldspathic segregation in open folding, Monar Banded Psammite (Enclosure 2). Between Meall Mor and Pait Lodge. NH 1074 4067. Looking south.

Plate 2.17. Strongly deformed pegmatite parallel to layering in banded semipelite, and thin, straight cross-cutting pegmatite, in Beinn Dronaig Pelite (Enclosure 2). South of Loch Monar. NH 0907 4145. Looking 150º.

Plate 2.18. Highly deformed pegmatites in Monar Banded Psammite (Enclosure 2) cf Figure 2.4. Pegmatite preferentially developed in psammitic parts of assemblage, west of Pait Lodge. NH 1042 1069. Looking 160°.

Plate 2.19. Large boudined pegmatites in Achnashellach Banded Psammite below Beinn Dronaig Pelite (Enclosure 2). At the top of the Glenuig Zone (Figure 2.2) on Sgurr nan Ceannaichean and the probable equivalent of the Sgurr Beag Slide (Chapters 5 and 6). NH 0883 4794. Looking 200°.

Plate 3.1. ATTADALE WEST SUB-AREA. Class 2 tight folding. Looking down plunge; vergence west. South-east of Strathcarron. NG 9375 3997.

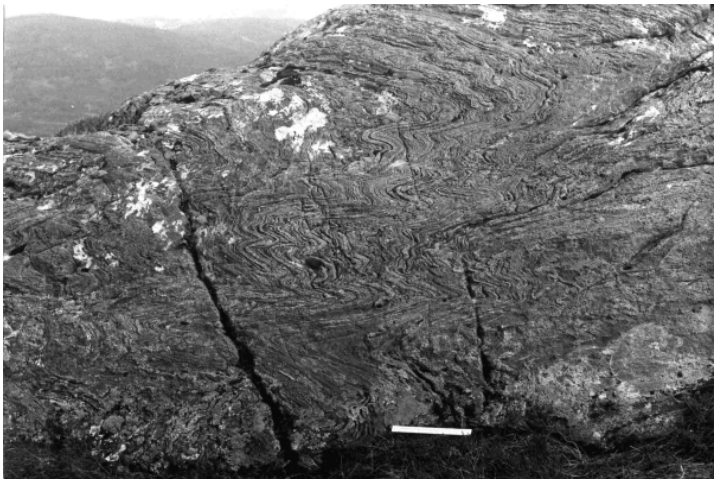


Plate 3.4. MONAR NORTH-EAST SUB-AREA. Class lc – 2 open second-order and open – tight third-order folds in Monar Banded Psammite. West of Pait Lodge. NH 1074 1067. Looking 160°.

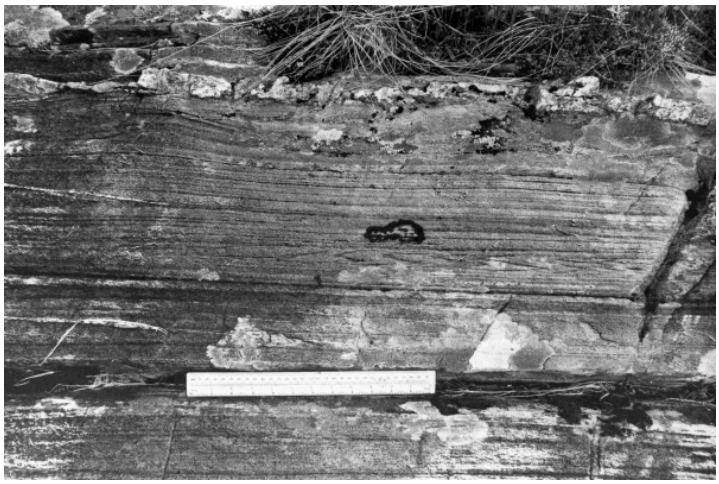


Plate 3.2 SGURR NA FEARTAIG/GLENUIG SOUTH SUB-AREA. Class 2 intrafolial tight – isoclinal fold pair. South-west of Sail Riabhach. NH 0262 3951. Looking 120°.

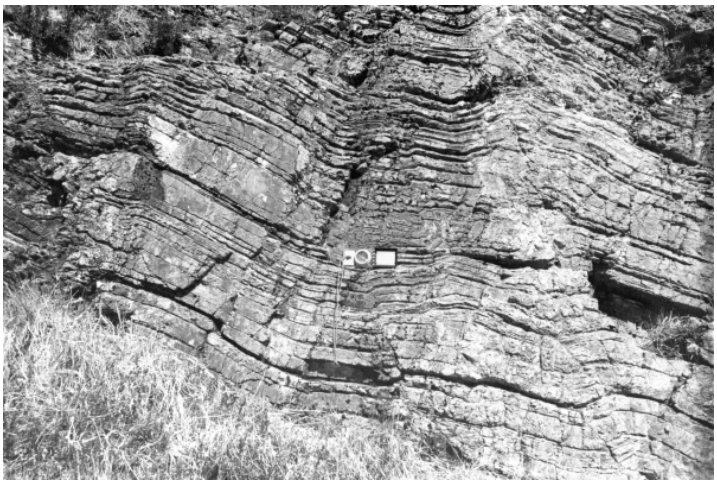


Plate 3.5. SGURR NA FEARTAIG/GLENUIG SOUTH SUB-AREA. Brittle/semi-ductile kink bands in very flaggy psammite. South-west of Sail Riabhach. NH 0265 3962. Looking 035°.

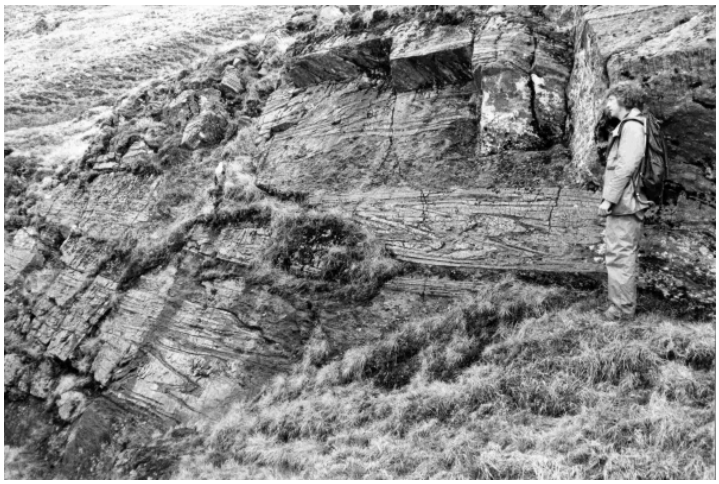


Plate 3.3. MONAR NORTH SUB-AREA. Class lc tight folding intrafolial to semipelitic bands in pelite. Almost at right angles to plunge. South of Glenuig. NH 0810 4512.

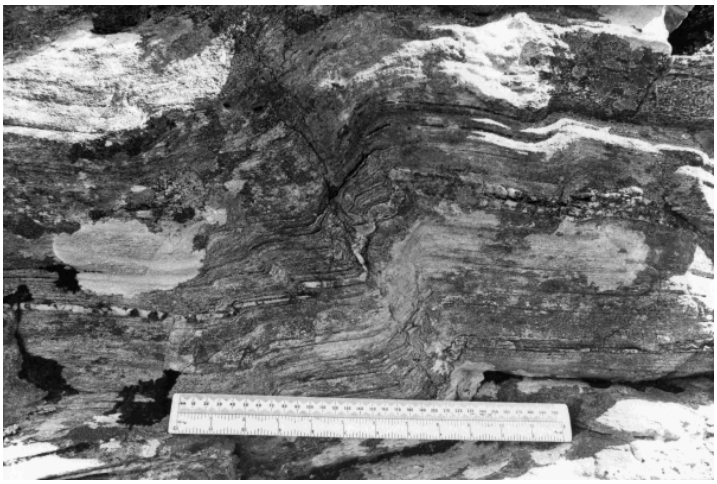
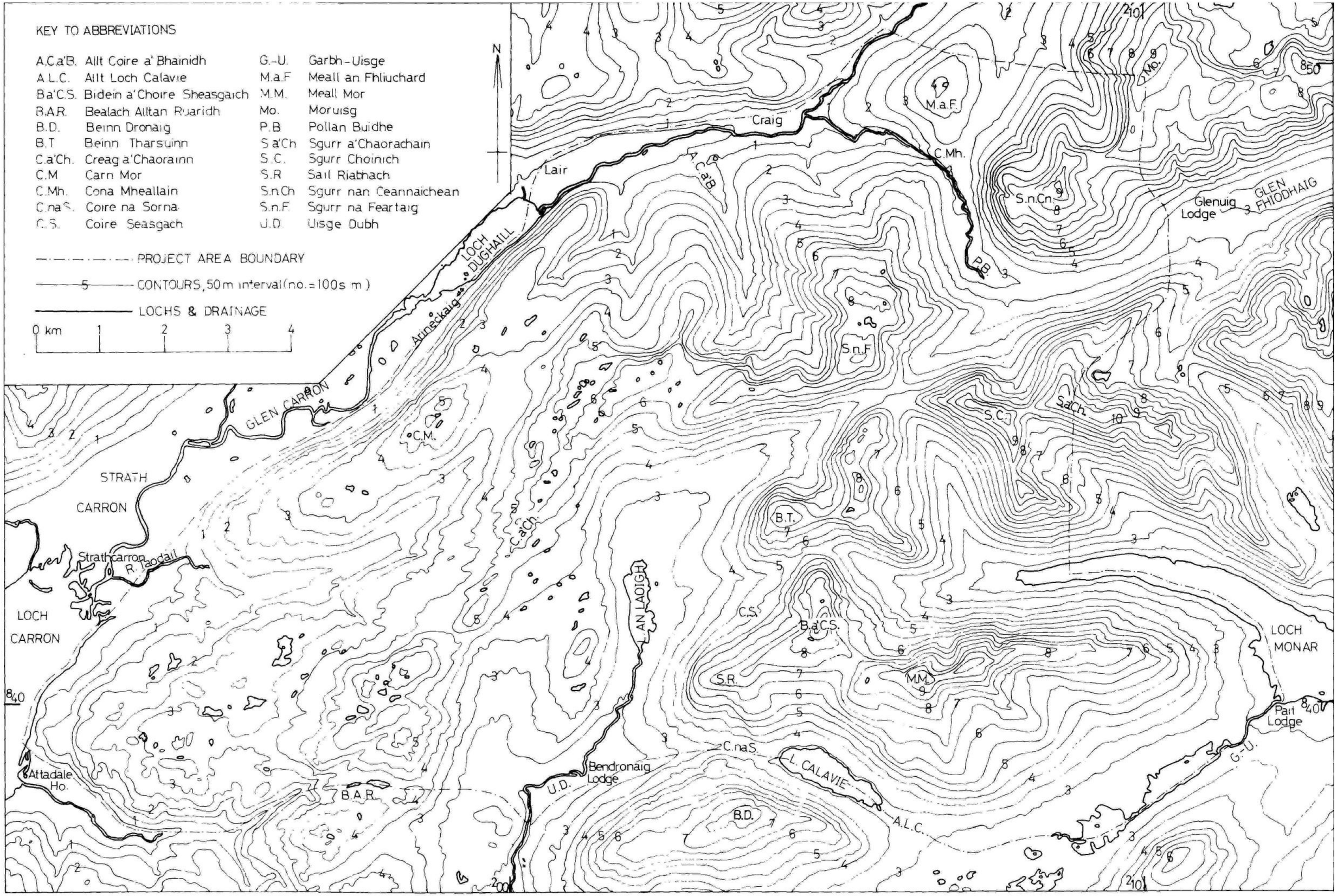
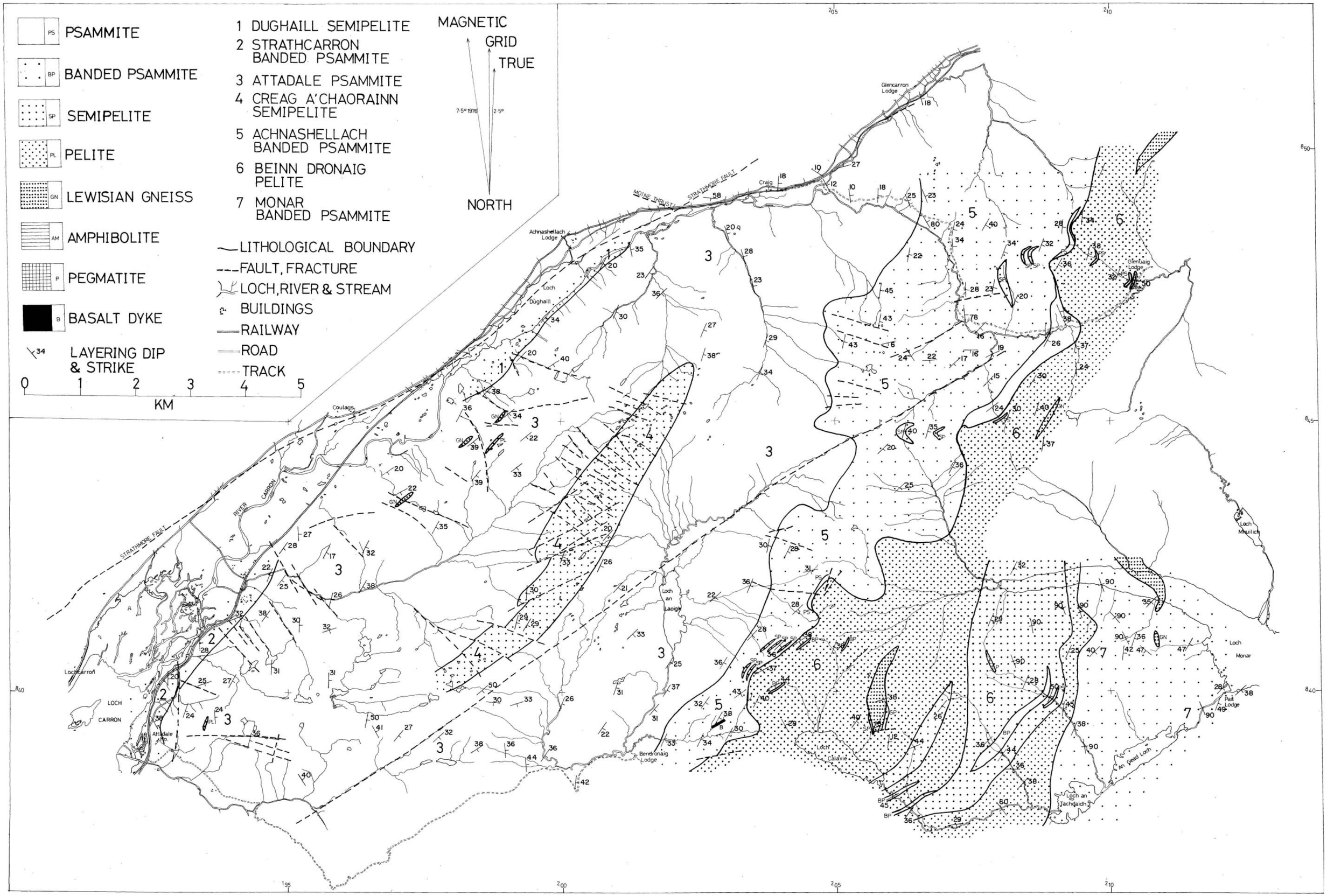


Plate 3.6. SGURR NA FEARTAIG/GLENUIG SOUTH SUB-AREA. Small semi-ductile kink with fracture in very flaggy psammite. South-west of Sail Riabhach. NH 0247 3952. Looking 080º.



Enclosure 1. Topography, drainage & place names.

BASED ON ORDNANCE SURVEY 1:50 000 SHEET NO 25 (1976)


PSAMMITE
BANDED PSAMMITE
SEMIPELITE
PELITE
LEWISIAN GNEISS
AMPHIBOLITE
PEGMATITE
BASALT DYKE
LAYERING DIP & STRIKE
0 1 2 3 4 5
KM
1 DUGHAILL SEMIPELITE
2 STRATHCARRON BANDED PSAMMITE
3 ATTADALE PSAMMITE
4 CREAG A'CHAORAINN SEMIPELITE
5 ACHNASHELLACH BANDED PSAMMITE
6 BEINN DRONAIG PELITE
7 MONAR BANDED PSAMMITE
LITHOLOGICAL BOUNDARY
FAULT, FRACTURE
LOCH, RIVER & STREAM
BUILDINGS
RAILWAY
ROAD
TRACK
MAGNETIC
GRID
TRUE
NORTH
7·5° 1976
2·5°
STRATHMORE FAULT
MOINE THRUST
Glencarron Lodge
Achnashellach Lodge
Craig
Loch Dughaill
Coulags
RIVER CARRON
Lochcarron
LOCH CARRON
Attadale Pt.
Loch an Laoigh
Bendronaig Lodge
Loch Calavie
Loch an Tachdaidh
An Gead Loch
Loch Monar
Loch Mhuilich
Glenuaig Lodge
Pait Lodge

ENCLOSURE 3 TRENDS OF PLANAR STRUCTURES IN THE MOINE OF THE GLEN CARRON REGION

FOLIATION, UNDIFFERENTIATED
CLEAVAGE, "

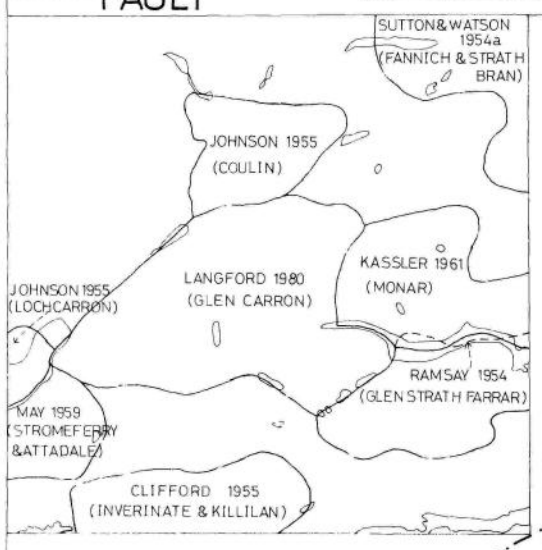
S2 ORRIN) RAMSAY
S1 MONAR) 1954

1st) Axial planar)
2nd) cleavage &) MAY 1959
3rd) axial planes)

1st) Fold) KASSLER
2nd) axial) 1961
3rd) planes)
FAULT

N

0 KM 5



LOCH A'CHROISG
LOCH DUGHAILL
LOCH MONAR
LOCH CARRON
LOCH CALAVIE
LOCH LONG
LOCH MULLARDOCH

ENCLOSURE 4 TRENDS OF LINEAR STRUCTURES IN THE MOINE OF THE GLEN CARRON REGION.

→ LINEATION, UNDIFFERENTIATED

ɜ→ MINOR FOLD AXIS

--→ b1 ORRIN
→ b2 MONAR
} RAMSAY 1954

--→ 1st
→ 2nd
⋯→ 3rd
} MAY 1959

--→ 1st
→ 2nd
⋯→ 3rd
} KASSLER 1961
1=ORRIN 2=MONAR 3=POST-MONAR

→→ 4th

—— FAULT

0 KM 5

N

Loch a' Chraisg

Loch Beghaill

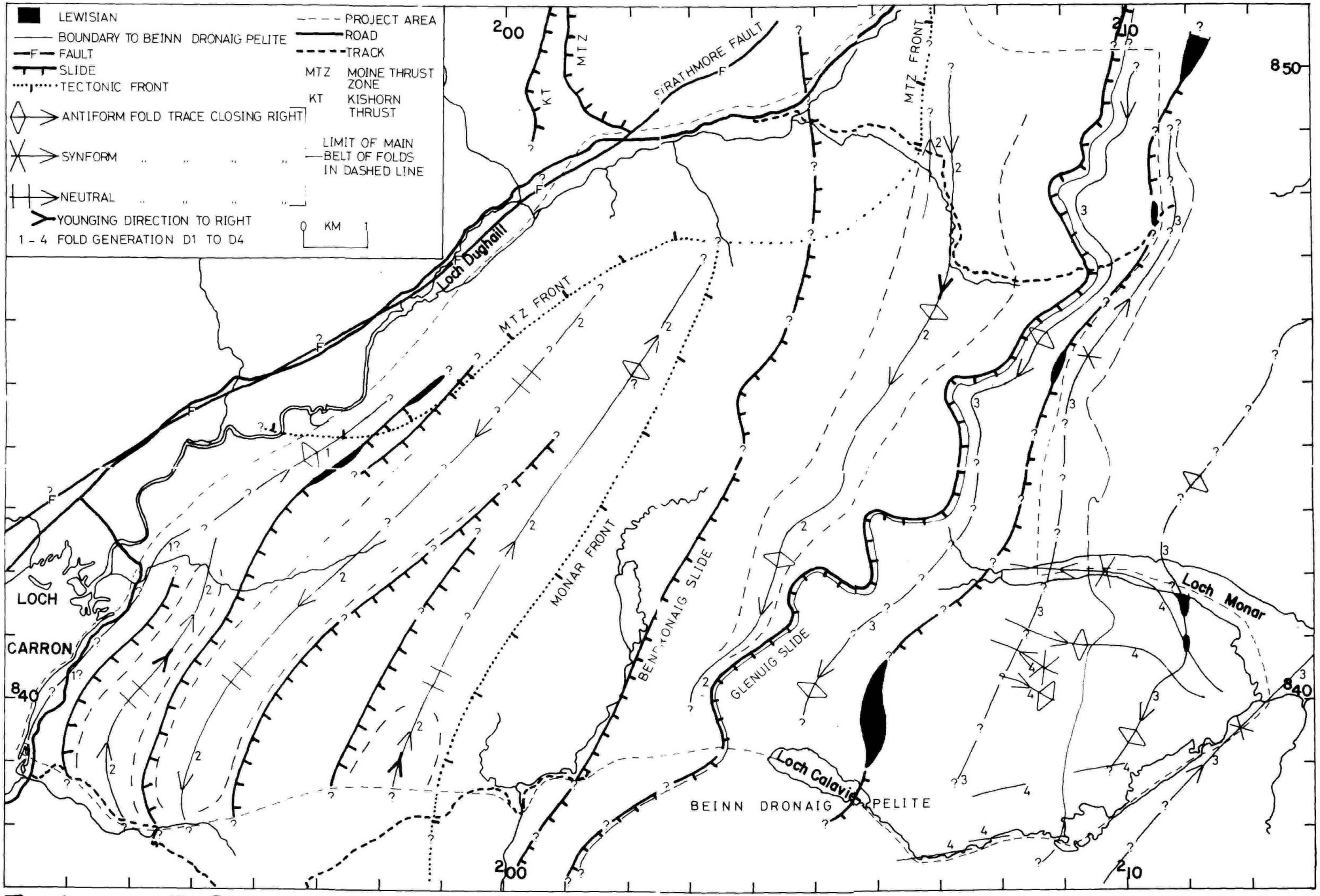
Loch Monar

Loch Calavie

Loch Carron

Loch Long

Loch Mullardoch



Enclosure 5 Structural overlay for the Moine of Glen Carron.