# STRUCTURAL AND METAMORPHIC HISTORY OF THE MOINE AND DALRADIAN ROCKS, GLEN ORCHY, ARGYLLSHIRE, SCOTLAND.

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A thesis submitted for the degree
of Master of Science at the
University of Glasgow.

April, 1986.

Dedicated to:

My parents,

My wife (A.Zakiah),

My children (Aaron and Ahmad),

My brothers and,

My sisters.

# SUMMARY

The geology of an area of about 27sq.km, lying within Glen Orchy is described. The area consists of rocks belonging to the upper part of the Grampian Division of the Moine succession and parts of the Appin and Argyll Groups of the Dalradian Supergroup. A lithostratigraphic sequence has been established using way-up evidence from cross-lamination and graded bedding. Moine psammite and semipelite occur at the base and pass up through a passage zone into Dalradian quartzite followed by pelite (with thin calcareous beds) and pebbly quartzite. A tectonic break, the Iltay Boundary Slide occurs between the pelite and the pebbly quartzite.

Field and microscopic examination of the rocks in the area, have revealed the existence of a polyphase deformational history and has enabled four stages of folding (F1 to F4) to be recognised. The earliest deformation (D1) led to the formation of two major isoclinal recumbent folds, the Beinn Chuirn Anticline and Beinn Udlaidh Syncline. Both folds face to the south-east and plunge at a low to moderate angles to the south-west, and have curvilinear hinges. This interpretation of the Beinn Chuirn Anticline as a D1 structure disagrees with its current interpretation by other workers as a D2 synform. The Iltay Boundary

Slide probably developed during D1 and was reactivated locally during the D2 deformation. No F2 major fold has been recognised in the area but F3 minor folding is associated with the development of a major late fold, the Glen Orchy Antiform. This antiform plunges to the SW-SSW or NE-NNE, and folds the Beinn Chuirn Anticline and Beinn Udlaidh Syncline. F4 folding is only locally developed and no major fold related to this phase of folding is seen.

The rocks of the area lie within the garnet zone of the epidote-amphibolite facies. No other higher grade index minerals were found. Periods of mineral growth have been related to the major deformational episodes on micro-textural evidence. The peak metamorphism of the area occurred during the D1 deformation, with the development of the garnet porphyroblasts. No MS2 garnet has been recognised in the area. Later retrogression resulted in the widespread alteration of biotite and garnet to chlorite.

## ACKNOWLEDGEMENTS

I would like to thank Dr. P.W.G. Tanner for his supervision of this research, involving several days in the field, many periods of discussion and reading the manuscript.

Professor B.E. Leake provided the facilities in the Department of Geology and Professor D.R. Bowes gave help and guidance before the course of the research.

I would like to thank Mr. D. Maclean for photographic work; Mr. M. Murray and Mr. R. McDonald for the thin-sections; and Mr. R. Morrison for providing technical facilities. Mr. P. Bradshaw gave considerable assistance in computing work and I thank Mrs. Roslinda M.Asri for typing this thesis.

Finally I would like to thank my wife and my parents for their encouragement throughout the study.

The research was supported by the Sabah State Government and National University of Malaysia.

# DECLARATION

The material presented in this thesis summaries the results of two and half years research work carried out in the Department of Geology, University of Glasgow between August 1983 and April 1986 under the supervision of Dr. P.W.G. Tanner. This study is based on my own independent research and any previously published or unpublished results of other investigators used in this thesis have been given full acknowledgement in the text.

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# CHAPTER 1

# INTRODUCTION

## 1.1. Location of study area

The location of the area studied is shown in Fig. 1-1. It is situated approximately 70 miles north-west of Glasgow and about 30 miles east of Oban.

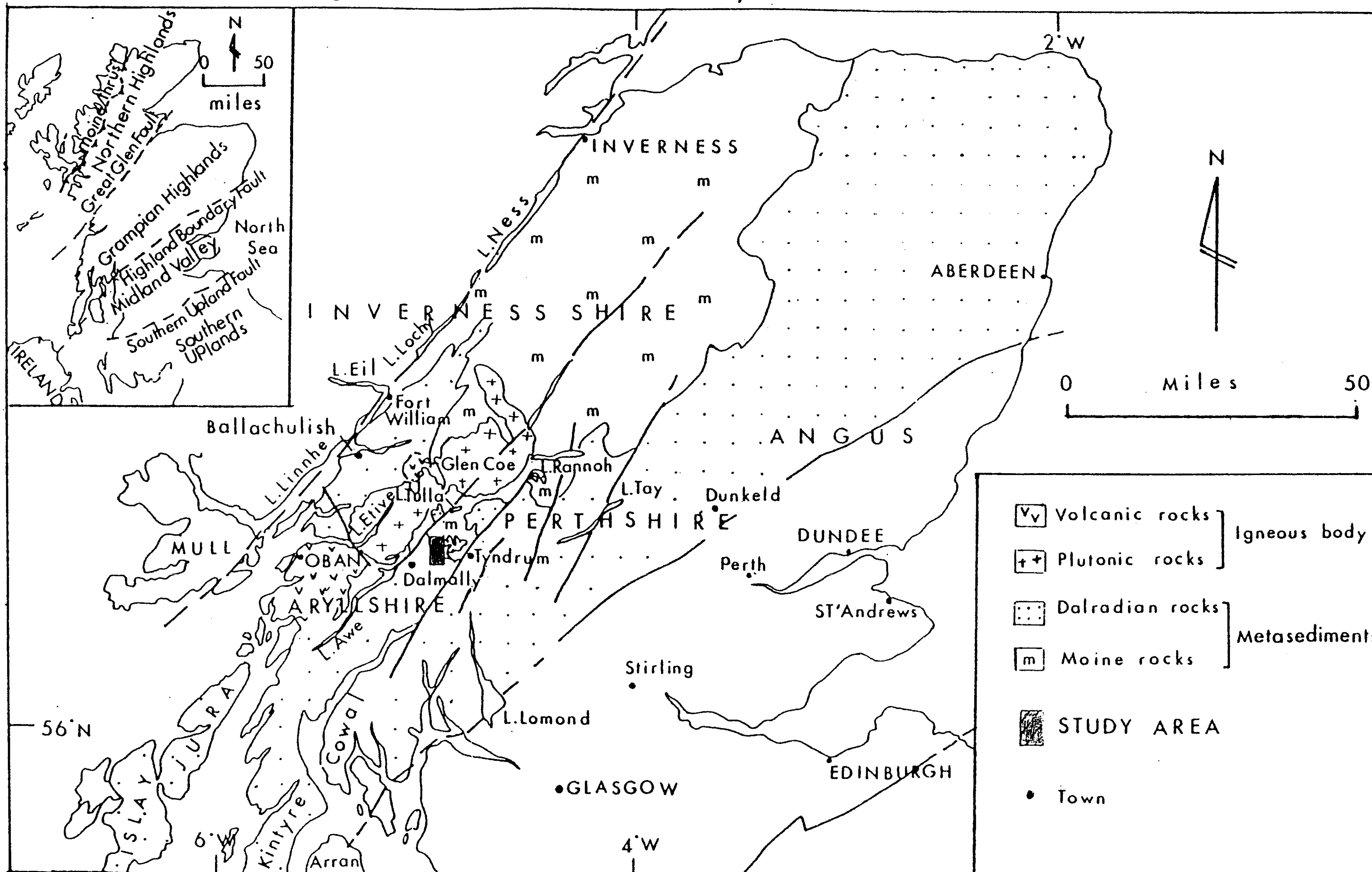
In the regional setting, the area lies between Ballachulish and Loch Eil to the north, Schiehallion and Central Perthshire to the east and Cowal, Loch Awe and Islay to the south-west.

Public transport terminates at Tyndrum and Dalmally. Accommodation is generally easy to find in both of these two towns.

## 1.2. The aims of the study

This work sets out to achieve five main objectives:

Fig.1-1: Location of study area



(1) To make a precise lithological map of the area and test existing stratigraphy using way-up evidence.

(2) To study the geometry and relative ages of the minor structural elements of the rocks in the present area.

(3) To determine the geometry and orientation of major structures from (1).

(4) To investigate the relative structural age of the Beinn Chuirn Fold and determine whether it is an ANTICLINE or an SYNCLINE.

(5) To correlate the structures in the present area with those of adjacent areas.

## 1.3. Method and Terminology

In order to carry out the aims of the study, an area approximately of 27 sq kilometres has been mapped. The area lies on Ordnance Survey sheets 22 and 23 (1:10,000 and 1:10,560 respectively). These two maps were used as a base map and aerial photographs, at an approximate scale of 1:4,600 were used, where possible,for the field mapping.

Particular attention was paid to the minor folds, planar structures (axial planes of folds, bedding, schistosity and cleavage); linear structures (fold hinges and various types of lineations); fold vergence and younging direction.

Rock samples were collected and examined under microscope. Approximately 70 samples from the Moine rocks, 50 samples from the Dalradian rocks and 10 igneous rocks were studied. Most of the rock samples have been cut at right angles to the fabric in the rocks and also at right angles to the fold hinges.

Samples numbers and location, with grid references, are given in Fig. 1-2, and are prefixed by the letters SO (Appendix 1).

Field mapping was carried out in two consecutive field seasons in June-September, 1984 and May-August, 1985. Approximately 20 weeks spent in the field.

This study has employed the techniques of structural analysis in regions of polyphase ductile deformation (cf Ramsay, 1967). This is based on the recognition that the deformation history of the rock mass can be conveniently divided into a number of discrete events which occur in chronological order.

As an example, the first deformation event (DI) is associated with structural elements such as folds (F1), cleavage (S1) and lineations (L1). The next phase (D2) produces F2, S2 and L2 and so on. Bedding is designated, SS. Cleavages and folds are considered to belong to the same phase of deformation if the cleavage is axial planar to the fold.

In this account the terminology used to describe the period of mineral growth (Chapter 6) is that of Sturt and Harris (1961). MSI denotes syn-tectonic metamorphic growth during the development of F1 structures. MP2 denotes static growth after F2 etc. It may sometimes be possible to equate M1 to F1 but in some areas the first metamorphism (M1) occurred during the second tectonic event (Spry, 1969). Si and Se denote fabrics internal and external to a porphyroblast respectively. Suffixes 1, 2, 3, etc., refer to the deformation sequence.

The strike convertion used in this thesis considers all planes as members of a family dipping clockwise away from true north. Thus the strike recorded is the angle swept out from true north.

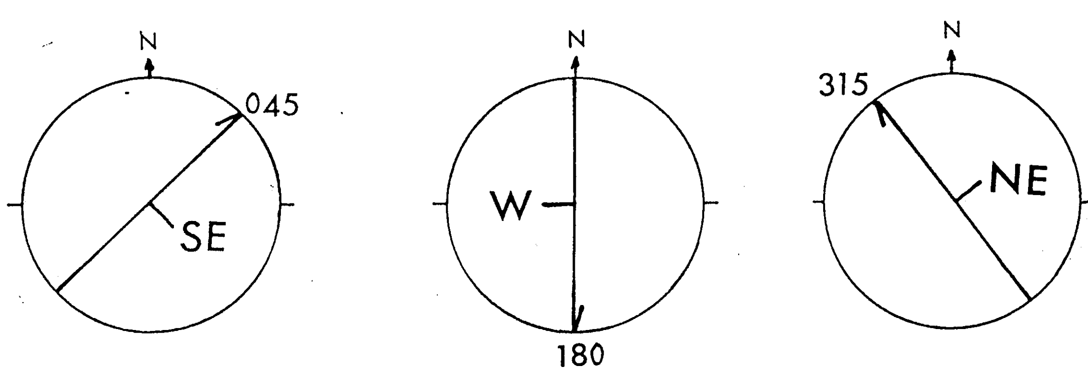
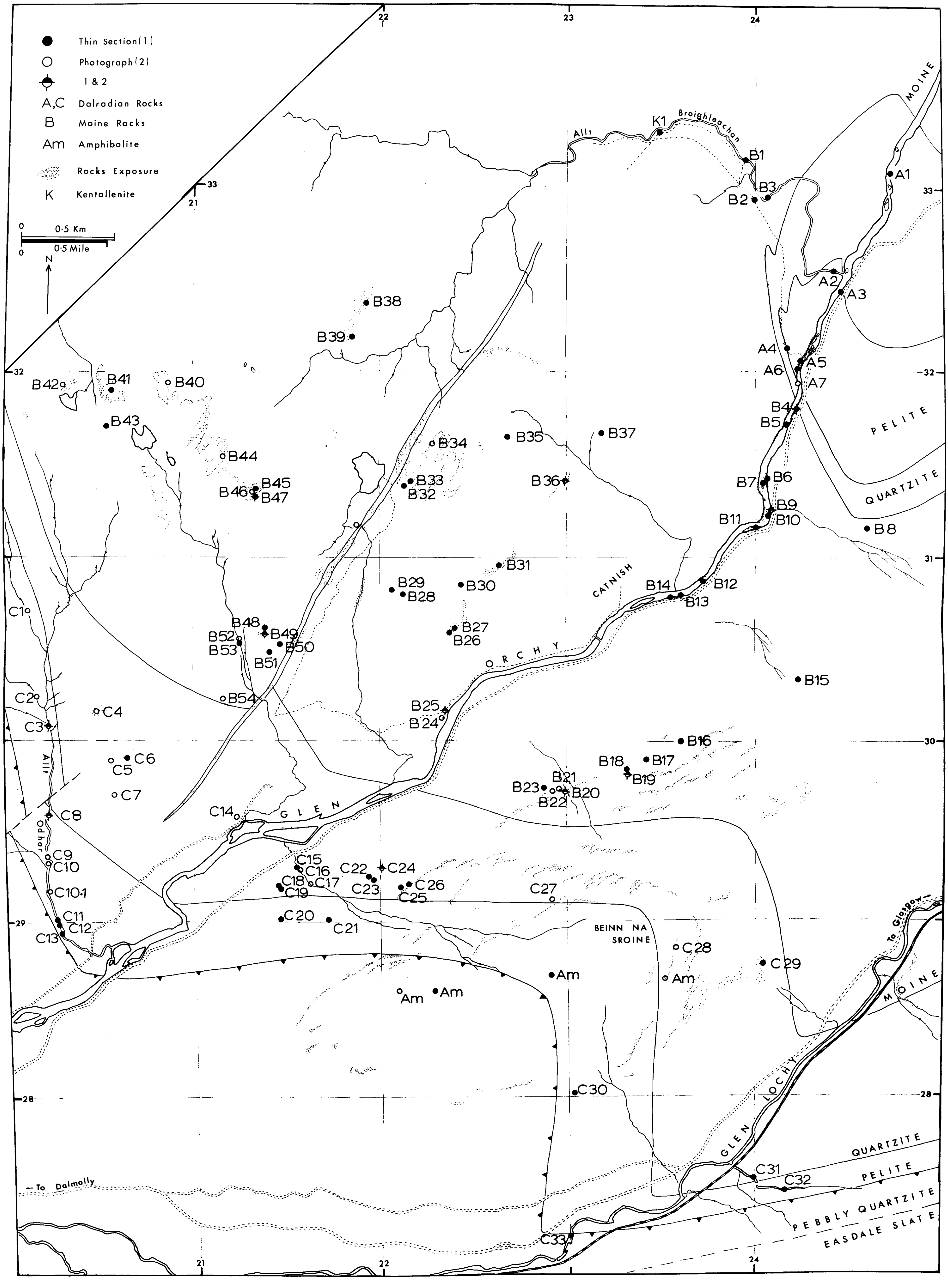


Fig.I-2 : SAMPLE LOCATION



# CHAPTER 2

# BACKGROUND GEOLOGY OF THE GRAMPIAN HIGHLANDS

## 2.1. The Moine Succession

The Moine succession lies east or south-east of the Caledonian Front thrust belt ( The Moine thrust ), unconformably overlies the Lewisian complex and is older than the Dalradian Supergroup ( Harris and Pitcher,1975). These successions typically comprise metamorphosed arenaceous and argillaceous sedimentary rocks which contain a very minor proportion of calcareous or dolomitic beds.

The age of the deposition of the Moine assemblage is still under debate. However, field and isotopic studies show that the Moine rocks from the Central Highland Division of the Scottish Caledonides were affected by the Grenville orogeny ( c.1000 Ma ) and the c.750 Ma events ( Piasecki and van Breemen, 1983 ). So that, the deposition of part of the Moine succession in the Scottish Caledonides was earlier than the Grenville event.

The Moine succession in the Scottish Caledonides can be divided into two groups: ´Old Moines´ and ´Young Moines´. The ´old Moines´ crop out in the Northern Highlands of Scotland, and are divided into three divisions - 1 ) Morar Division, 2) Glen finnan Division, and 3) Loch Eil Division. They occur as the Central Highlands Division in the Grampian Highlands. The ´Young Moines´ which crop out in the Grampian Highlands of Scotland and are named the Grampian Division , structurally overlie the ´Old Moines´ and have a transitional boundary with the overlying Dalradian Supergroup.

The Moine rocks in the studied area is part from the Grampian Division. (Fig. 2.1).

## 2.2. The Dalradian Supergroup

The Dalradian Supergroup consists of late Proterozoic and Cambrian metasediments and meta-igneous deposits ( Harris *et al*. 1978 ), and on a regional scale overlies ( ? with a structural or a sedimentary contact ) the older deformed metasediments ( the Moine Succession ). The Supergroup with an aggregate thickness of approximately 25km ( Harris, *et al*. 1978 ) was deformed and metamorphosed in the Grampian orogeny, which had its peak in the late Cambrian and early Ordovician ( Legget *et al*. 1982 ).

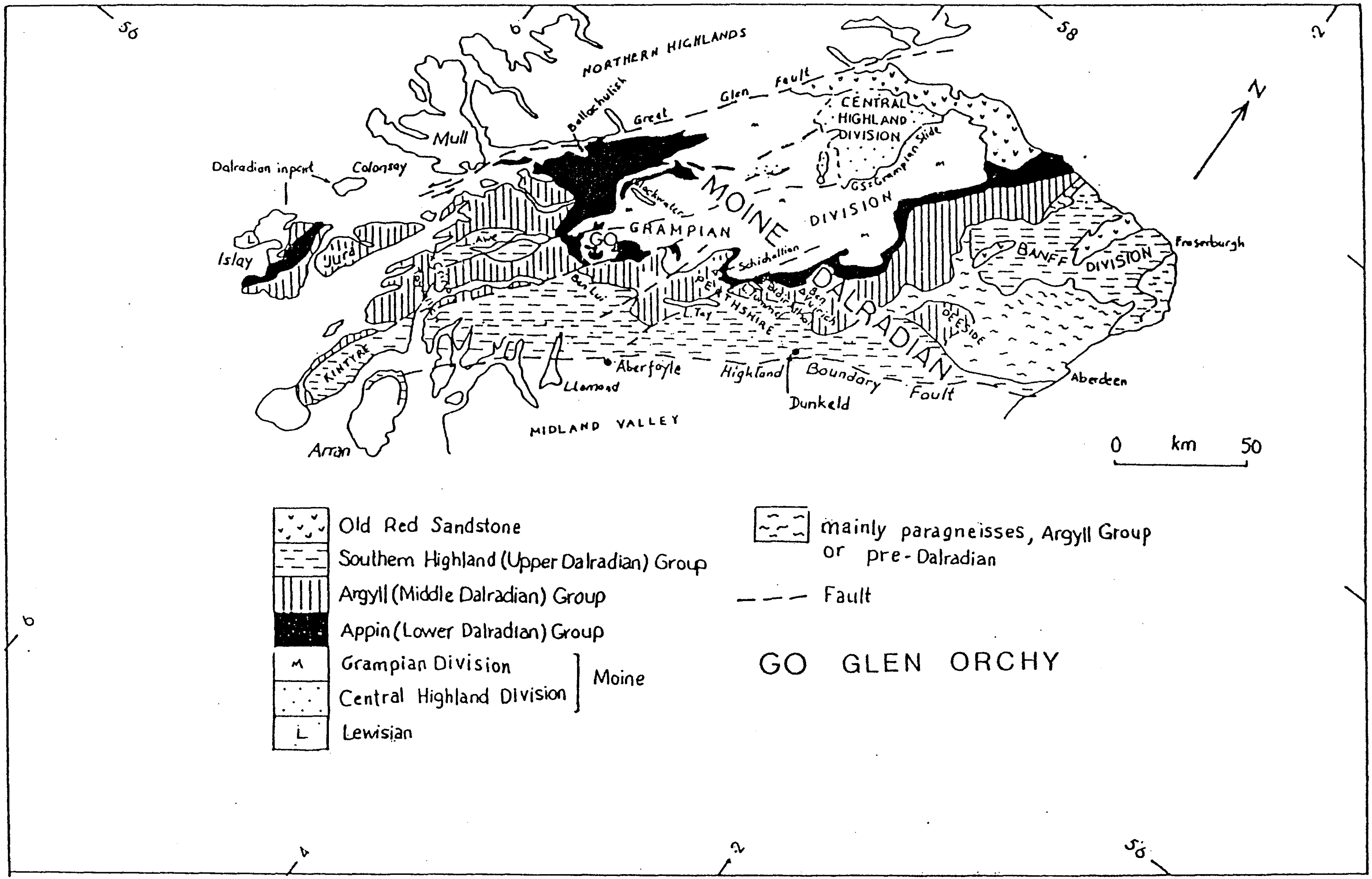



Fig. 2-1: Simplified distribution of Moine and Dalradian rocks in the Grampian Highlands of Scotland. Igneous rocks are omitted (after Harris and Pitcher, 1975; van Breemen and Piasecki, 1983).

This Supergroup crops out over most the Grampian Highlands in Scotland, extends from the Banffshire coast of north-eastern of Scotland through the Central and south-western Highlands of Scotland and from Donegal to Connemara in Western Ireland. The date of initiation of some 25 km of Dalradian sedimentation probably commenced between c.750 and c.700 Ma ago ( Piasecki and van Breemen, 1983 ). The minimum age for the termination of Dalradian sedimentation is provided by a dating of the early stages of the metamorphism at 509 $\pm$ 30 Ma ( Leggo and Pidgeon, 1970 ).

The subdivision of the Dalradian Supergroup prepared by Harris and Pitcher ( 1975; p. 52-57 ), in which the Dalradian Supergroup was divided into three groups,is shown in Table 2 - 1.

The studied area consists of the Lochaber (Transition) and Easdale subgroups of the Appin and the Argyll groups, respectively. The distribution of these groups in the Scottish Caledonides is shown in Fig. 2-1.

| GROUP | SUBGROUP |
|---|---|
| Upper Dalradian (Southern Highland) | not proposed |
| Middle Dalradian (Argyll) | Tayvallich<br>Crinan<br>Easdale<br>Islay |
| Lower Dalradian (Appin) | Blair Atholl<br>Ballachulish<br>Lochaber<br>(Transition) |
| Moine Succession | |

Table 2-1: The stratigraphical succession for the Dalradian Supergroup (after Harris and Pitcher, 1975)

## 2.3. Outline of the deposition of Moine and Dalradian rocks in the Grampian ( Central ) Highlands.

The Grampian Highlands of Scotland comprise metasedimentary rocks which represent part of a thick accumulation of sediment deposited in a complex trough elongated generally NE - SW.

The early episode of sedimentation has resulted in lithologically monotonous rocks, mainly poorly - sorted psammites and pelites ( Watson, 1975 ), which form the Moine Succession. The upper part of the succession in the basin is the Dalradian Supergroup with a characteristic diversity in rock types.

The sedimentation began with deposits of shelf to marginal marine environments ( Harris *et al*. 1978 ) and ended with deep water turbidite and basinal facies ( Anderton, 1982 ).

## 2.4. Outline of the geological history of the Grampian Highlands.

The geological history of the Grampian Highlands began with the deposition of the Moine assemblage ( 'Young Moines' ), followed by the conformable overlying Dalradian Supergroup.

The 'Young' Moine ( Grampian Division ) and the Dalradian rocks of the Grampian Highlands were strongly deformed and metamorphosed during the Grampian orogeny ( early Ordovician, 520 - 510 Ma ) and the Caledonian ( s.s. ) orogeny (Ordovician to middle Devonian, 500 - 400 Ma ). The 'old' Moine from the Central Highland Division was affected by both the Grenville orogeny ( c. 1000 Ma ) and a c. 750 Ma event ( Piasecki and van Breemen, 1983 ).

Due to the effects of the Grampian orogeny ( 520 - 510 Ma ) the Moine and Dalradian rocks in the Grampian Highlands have been folded into huge recumbent primary folds ( D1 fold nappes ), tens of kilometres in amplitude, which are postulated to face north-west and south-east away from a central steep belt or root zone ( cf. Rast, 1963 and Thomas, 1979 ). These D1 fold nappes are associated with slides of both thrust and lag type, and it has been generally assumed that these slides developed during the main metamorphism. However, a recent interpretation ( Soper and Anderton, 1984 ) suggests that these slides were initiated as syndepositional extensional faults which were only modified, and not formed, during the Grampian orogeny. These major structures ( D1 fold nappes and ? slides ) were folded by a second closely related phase of primary folding, D2, on similar axes, under conditions of increasing metamorphic activity ( Thomas, 1979;p.208 ). Further deformation ( late Grampian orogeny and Caledonian orogeny ) which modified the earlier structures ( D1 and D2 structures ) produced major open folds ( D3 ) and more brittle structures (D4).

The structural synthesis of the Moine and Dalradian rocks in these regions is still under debate. At the moment there are at least two possible structural interpretations for the development of these structures in the Grampian Highlands. One of these interpretations is by Thomas ( 1979 ) and other one is by Roberts and Treagus ( 1977 ). The possible structural synthesis of the Grampian Highlands is shown in Fig. 2-2. Bradbury (1985, Fig. 2-3 ), based on a synthesis of previous work, has argued that the tectonic history of the Grampian orogeny is characterized by a tripartite division into an early nappe phase ( ENP ), late nappe phase (LNP ) and Dome-Uplift phase ( DUP ).

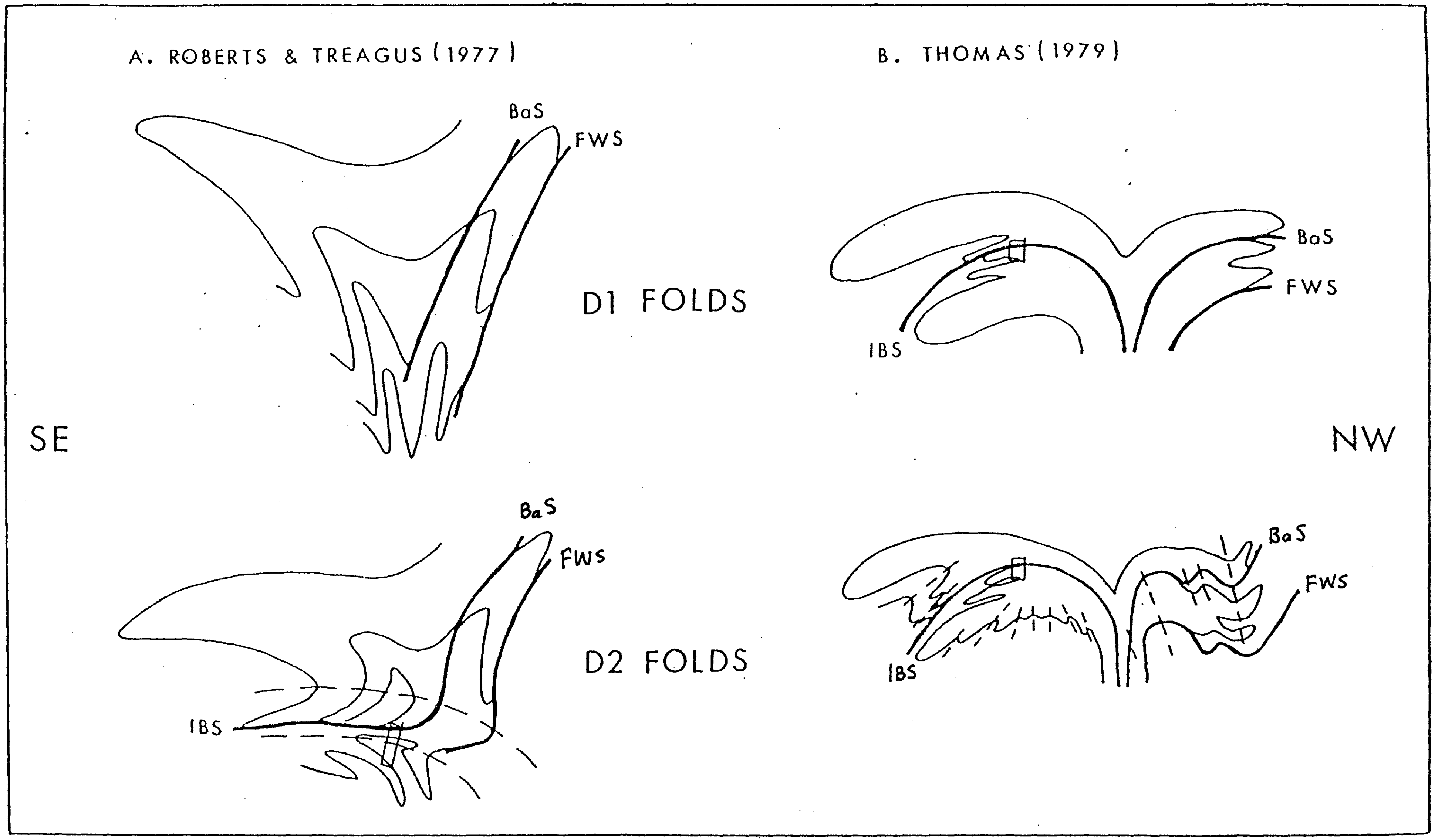



Fig. 2-2: Cartoons showing possible structural synthesis for the SW Highlands. Box insert shows the study area. BaS, Ballachulish Slide; FWS, Fort William Slide and IBS, Iltay Boundary Slide.

Fig. 2-3: Highland duplex interpretive geological cross-section of region between Highland Boundary Fault and Great Glen Fault. (after Bradbury, 1985).

Stratigraphy

1, Southern Highland Group; 2, Easdale and Crinan Subgroups of Argyll Group; 3, Islay Subgroup of Argyll Group; 4, Ballachulish and Blair Atholl subgroups of Appin Group; 5, Lochaber Subgroup of Appin Group; 6, Younger Grampian Group; 7, Older Grampian Group.

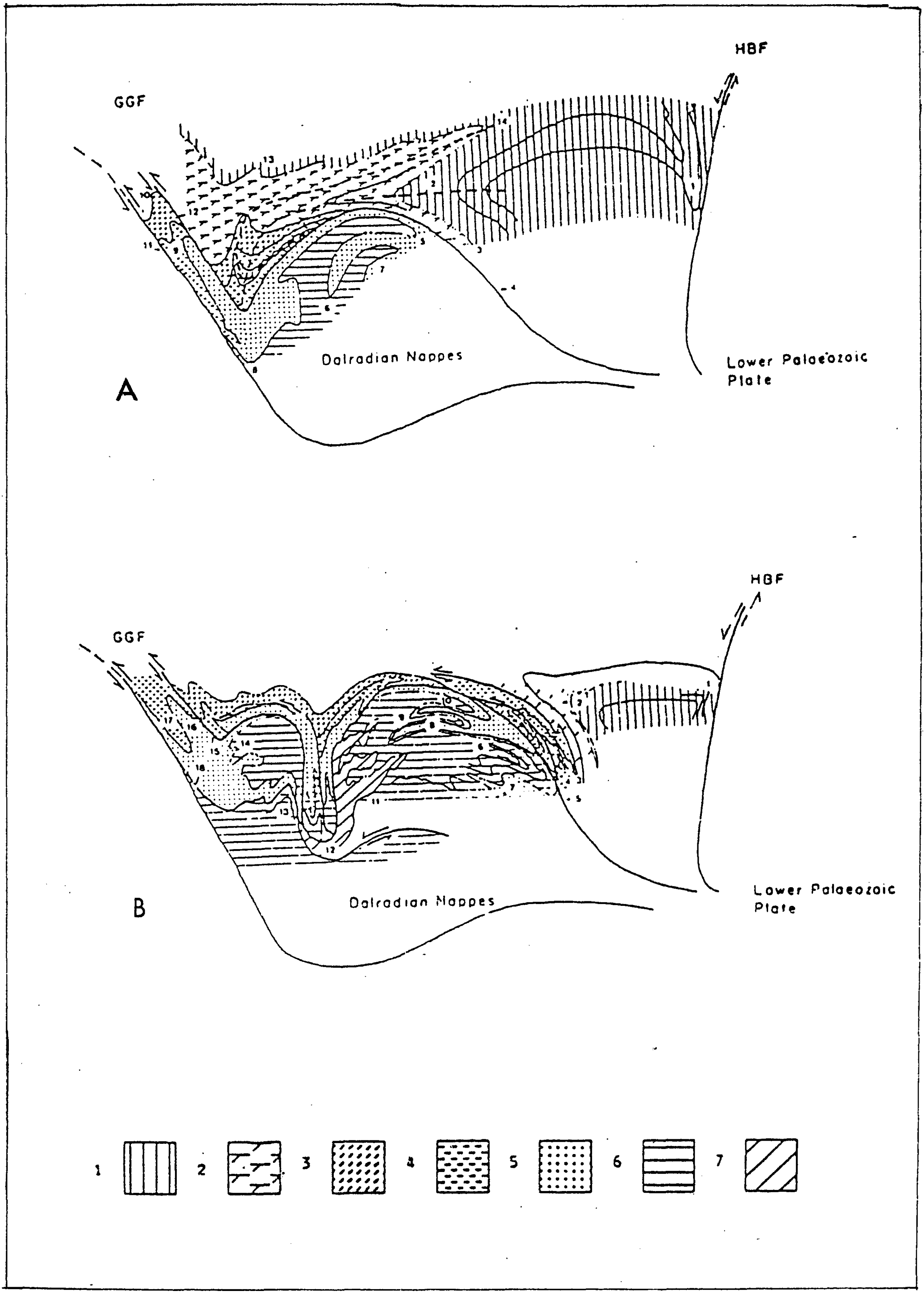
Structures: A

1, Aberfoyle Synform (ENP); 2, Ben Lui Nappe (LNP); 3, Tummel (Knapdale) Belt (LNP and DUP); 4, Boundary Thrust (LNP); 5, Beinn Chuirn Synform (LNP); 6, Beinn Udlaidh Fold (ENP); 7, Lochy Synform (ENP?); 8, Stob Bhan Synform (ENP); 9, Appin Syncline (ENP); 10, Islay Anticline (ENP); 11, Fort William Thrust (LNP); 13, Loch Awe Synclinorium (ENP); 14, Ardrishaig Anticline (Tay Nappe) (ENP).

Structures: B

1, Dunkeld Downbend and Highland Border Steep Belt (DUP); 2, hinge of Ben Lui Nappe (LNP); 3, Killiecrankie Thrust (LNP); 4, Tummel Belt (LNP & DUP); 5, Boundary Thrust (LNP); 6, Atholl Nappe (?ENP); 7, Clunes Antiform (?LNP); 8, Dochard Synform: 9, Core of Drumochter Dome (DUP; 10, Beinn Chuirn Synform (LNP); 11, Ben Alder folds (DUP); 12, Geal Carn-Ossian Steep Belt (DUP); 13, Beinn na Lap Dome (DUP); 14, Kinlochleven 'Anticline' (ENP); 15, Ballachulish Thrust (LNP); 16, Airds Hill Anticline (ENP); 17, Appin Syncline (ENP); 18, Skerrols-Fort William Thrust (LNP).

Fig. 2-3


HBF
GGF
Dalradian Nappes
Lower Palaeozoic Plate
A
HBF
GGF
Dalradian Nappes
Lower Palaeozoic Plate
B
1
2
3
4
5
6
7

Dewey ( 1969 ), Lambert & McKerrow ( 1976 ), Phillips *et al*. ( 1976 ), Watson ( 1984 ) and Bradbury ( 1985; in press ) considered that the main deformation, including possibly the first two phases of major folding ( D1 & D2 ) developed as a result of crustal thickening during the Grampian orogeny, due to north-westerly directed subduction of Iapetus oceanic crust beneath the Grampian rocks.

The early metamorphism (M1) in the Grampian Highlands accompanied the early phases deformation (D1 and D2). These events pre-date the intrusion of the Ben Vurich granite at 519 ± 8 Ma (Aftalion *et al*. 1984 )

The Caledonian orogeny which took place between 500 - 400 Ma (Aftalion *et al*. 1984 ) at c. 420 Ma is the last orogeny to affect the Moine and Dalradian rocks in the Grampian Highlands. This orogeny was responsible for the formation of the D3 and D4 structures. D3 peak metamorphism is associated with the intrusion of gabbros in NE Scotland at 489 ± 17 Ma (Fettes *et al*. 1985 ). The D4 deformation pre-dated the intrusion of the Strichen granite which was intruded at 462 ± 22 Ma ( Aftalion *et al*. 1984 ).

The large post-Caledonian granites ( ´Newer granites´ ) and post-Caledonian faults have obscured the original relationships of the structures in Grampian Highlands.

The outline of the geological history of the Grampian Highlands of Scotland is summarised in Table 2-2.

| Time (Ma) | SEDIMENTATION | OROGENY/EVENTS | STRUCTURE | METAMORPHISM | IGNEOUS ACTIVITY |
|---|---|---|---|---|---|
| Pre c. 1150 | Central Highland Division (Moine rocks) | | | | |
| c. 1150-c. 1000 | | Grenville orogeny affecting the Central Highlands Division (Moine rocks) | Polyphase folding | Amphibolite facies (Northern Highland rocks) | |
| Pre c. 750 | Grampian Division (Moine rocks) | | | | |
| c. 750 | | c. 750 event affecting the Central Highland Division and base of Grampian Division | Deformation of Moine rocks of the Grampian and Central Highland Divisions and development of slides. | ? Amphibolite facies | |
| late Proterozoic-cambrian | Dalradian Supergroup | | | | |

| | | | | |
|---|---|---|---|---|
| Early Ordovician (520-510) | Grampian Orogeny | D1 and D2 (nappes and slides) | Barrovian and Buchan (NE Scotland) metamorphism | i.e. Ben Vurich Granite (514$\pm$7Ma) |
| 500 - 400 | Caledonian Orogeny | D3 and D4 | Peak Metamorphism (close to D3) | NE Gabbros (487$\pm$17Ma) Caledonian granites i.e. Strichen Granite( 462$\pm$22Ma) |
| 415 - 410 | | Post-Caledonian structures | Post-Caledonian metamorphism | 'Newer' granites i.e. Etive,Rannoch Moor |

Table 2-2: Outline of the geological history in the Grampian Higlands of Scotland. (after Piasecki and van Breemen, 1983; Aftalion *et al.* 1984 and Fettes *et al.*, 1985)

# CHAPTER 3

# PREVIOUS WORK

The earliest work in the area adjacent to, and including, the study area was carried out by the Geological Survey of Scotland (Kynaston, 1908). This work considered only the distribution of the rock types and no stratigraphical succession was described from the Glen Orchy area.

Bailey and Macgregor (1912) first mapped the lithostratigraphic succession and structures around the Glen Orchy area in detail (Fig. 3-1). Their lithological boundaries are essentially the same as those of Kynaston (1908); the stratigraphic succession recognised by them in the Glen Orchy area is given in Table 3-1.

This stratigraphic succession was correlated by them with rocks in the Ballachulish area. Bailey and Macgregor (1912) and Bailey (1922) showed that the Leven Schists and the Glen Coe quartzite were part of Ballachulish succession and that the Eilde Flags resembled the Moine rocks of the Central Highlands. Later Bailey (1930) first used way-up structures to show that the Eilde Flags were the oldest rocks in the Glen Orchy area.

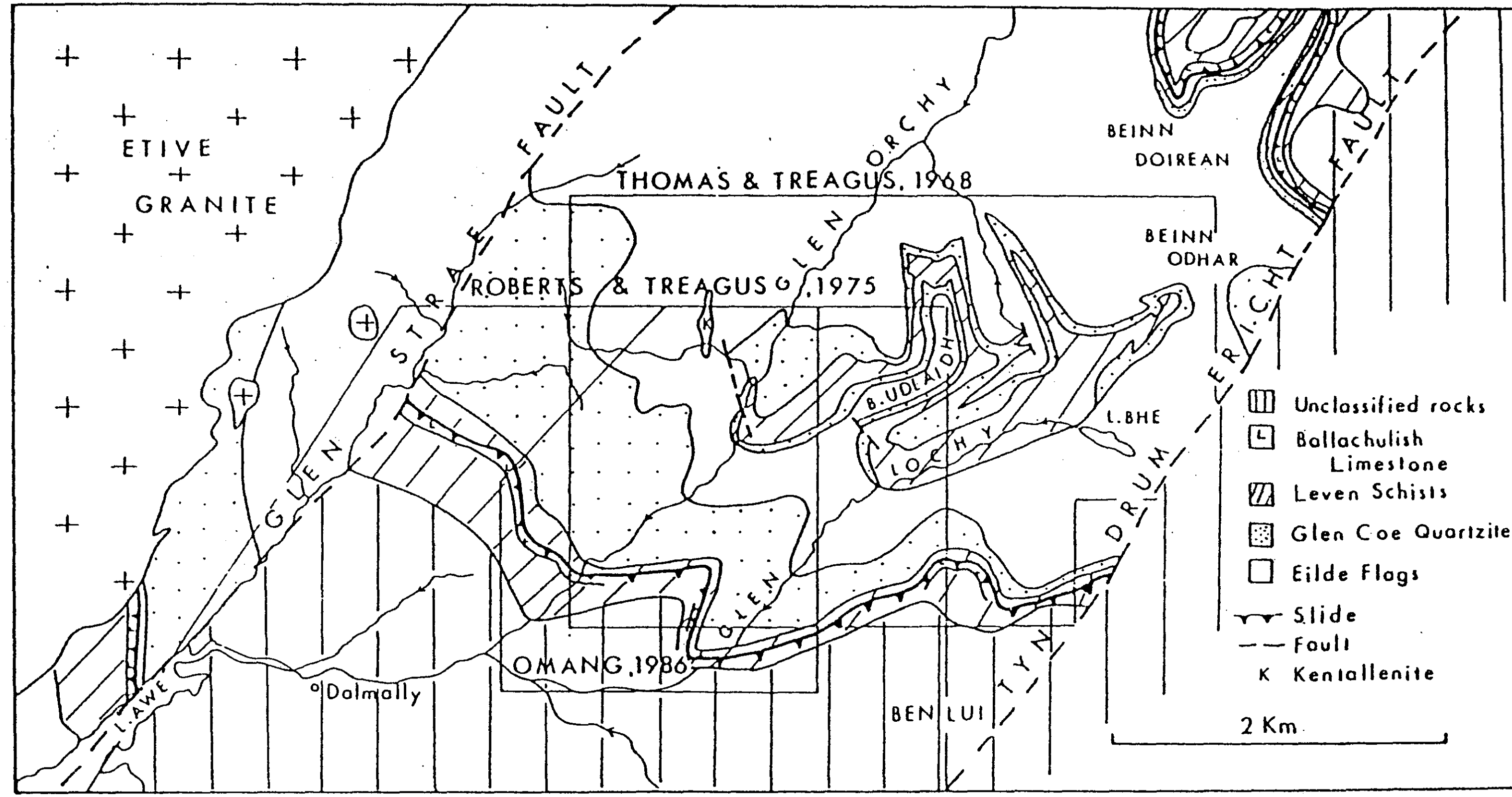



Fig. 3-1: The geology around Glen Orchy area (after Bailey and MacGregor, 1912). Box inserts to show the areas of previous work and of the present study.

Table 3-1: Stratigraphical sequences in the Glen Orchy area.

| Bailey and MacGregor (1912) | Thomas and Treagus (1968) | Roberts and Treagus (1975) |
| --- | --- | --- |
| Unclassified rocks | Black Schist | Easdale Slate |
| Leven Schists | | Pebbly quartzite |
| Ballachulish limestone | | |
| —— Ballachulish slide —— | Iltay Boundary Slide —— | Iltay Boundary Slide — |
| Leven Schists | Leven Schists (with impersistent bands of calcareous rocks) | Leven Schists |
| Glen Coe quartzite | Glen Coe quartzite | Glen Coe quartzite |
| Eilde Flags (Moine rocks) | Granulite (Micaceous feldspathic Moine Psammites) | Eilde Flags (Moine) |

In their 1912 paper, Bailey and Macgregor showed that the Leven Schists and the Glen Coe quartzite have been folded in the heart of the Eilde Flags and form a recumbent syncline which closes towards the north-west, which they named the Beinn Udlaidh syncline (Fig. 3-2A). Also, they correlated the Glen Coe quartzite and Leven Schists below the Eilde Flags to the north of Beinn Chuirn with the Glen Coe quartzite and Leven Schists above, indicating the presence of a synform closing to the south-east with the Eilde Flags in its core (Fig.3 - 2 A), but they did not comment upon this fold in their paper. Beneath the Ballachulish limestone, Bailey and Macgregor (1912) placed a thrust (Ballachulish slide), inferred from the Ballachulish area, and considered that the rocks above were in inverted order on the upper limb of a recumbent synform.

In subsequent papers, Bailey (1922, 1930) discarded the correlation of the Glen Coe quartzite and Leven Schists with the Glen Coe quartzite and Leven Schists above the Eilde Flags, and thereby discarded the fold which was based on this correlation (Figs. 3-2B). The Glen Coe quartzite and Leven Schists of the Glen Orchy area were called ´sub-Eilde´ complex and regarded as being of uncertain stratigraphic position. Bailey also considered the Leven Schists above and below the Ballachulish limestone to represent the two limbs of a recumbent north-westerly facing syncline (Fig. 3 - 2B).

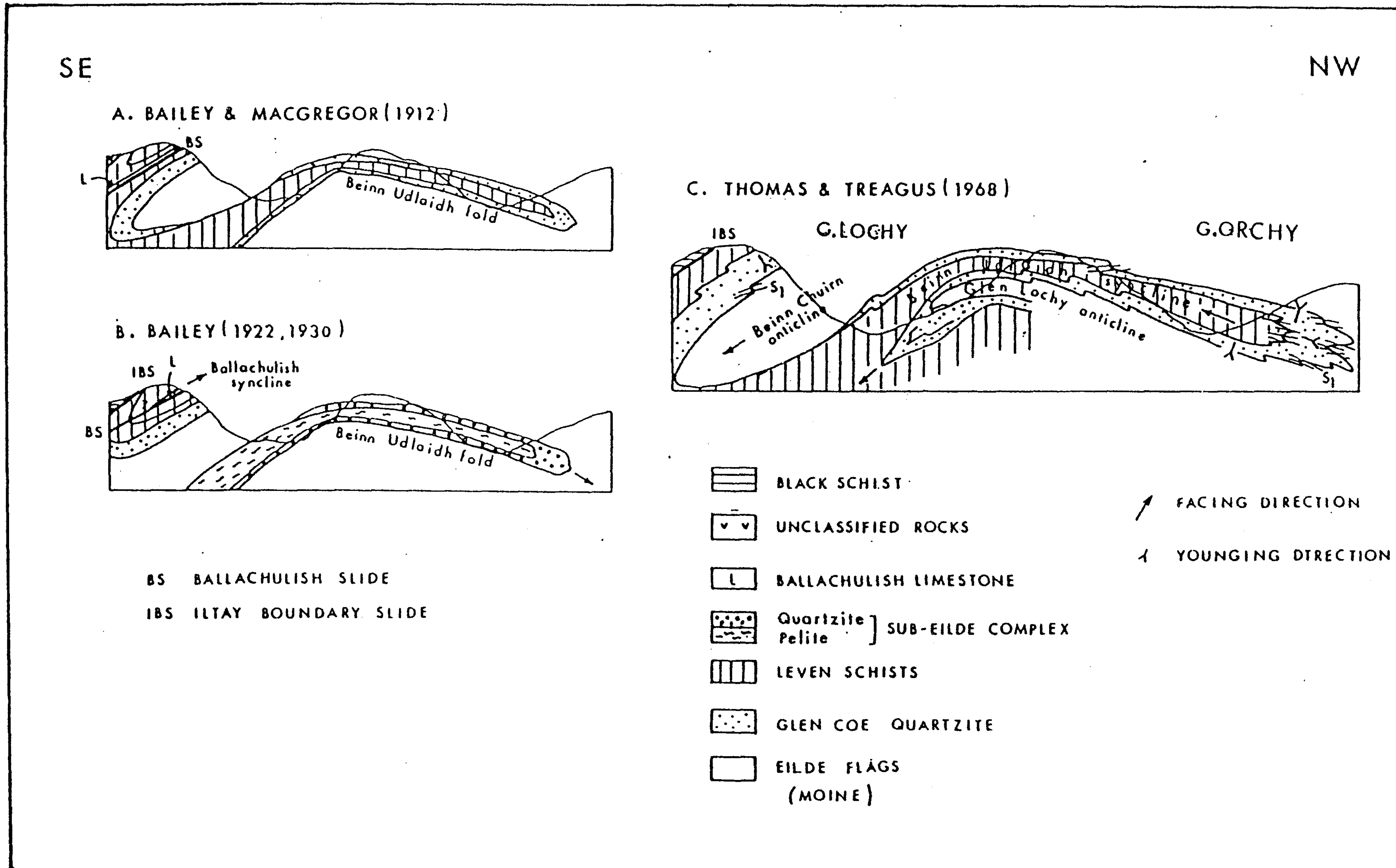



Fig. 3-2: Comparison of the structural interpretations of the Glen Orchy area by the previous workers (after Thomas and Treagus, 1968).

Below this limestone, a thrust (Ballachulish slide) was considered to attenuate the lower limb of this fold. Accordingly, Bailey argued that the limestone occupies the core of a fold (Ballachulish syncline) and that a slide cuts out the lower limb of this fold. Regional considerations indicated that these structures were the Ballachulish fold and Ballachulish slide respectively. He also concluded that the rocks above the Iltay Boundary slide belonged to the Iltay succession and showed the major primary fold (Beinn Udlaidh Syncline) in the rocks beneath the Iltay Boundary slide faced toward to north-west (Fig. 3 - 2B), and that there was no fold in the present position of the Beinn Chuirn Fold.

Cummins and Shackleton (1955, Fig. 3 - 3A), in their study of the structure of the Ben Lui fold above the Iltay Boundary slide, showed that the Beinn Udlaidh Fold is a D1 syncline facing toward the south-east. They considered also that the Ben Lui fold is a D1 structure and recognised the existence of the Beinn Chuirn Fold but did not name it.

In 1964, Roberts and Treagus (Fig. 3 - 3B) showed that the Ben Lui Fold is a D2 structure which faces towards south-east and confirmed that the primary structure (Beinn Udlaidh syncline) below the Iltay Boundary slide also faces towards the south-east.

Fig. 3-3: Simplified interpretaion of structures above and below the Iltay Boundary Slide in the south-west Highlands of Scotland by the previous workers.

A Cummins and Shackleton (1955)

B Roberts and Treagus (1964)

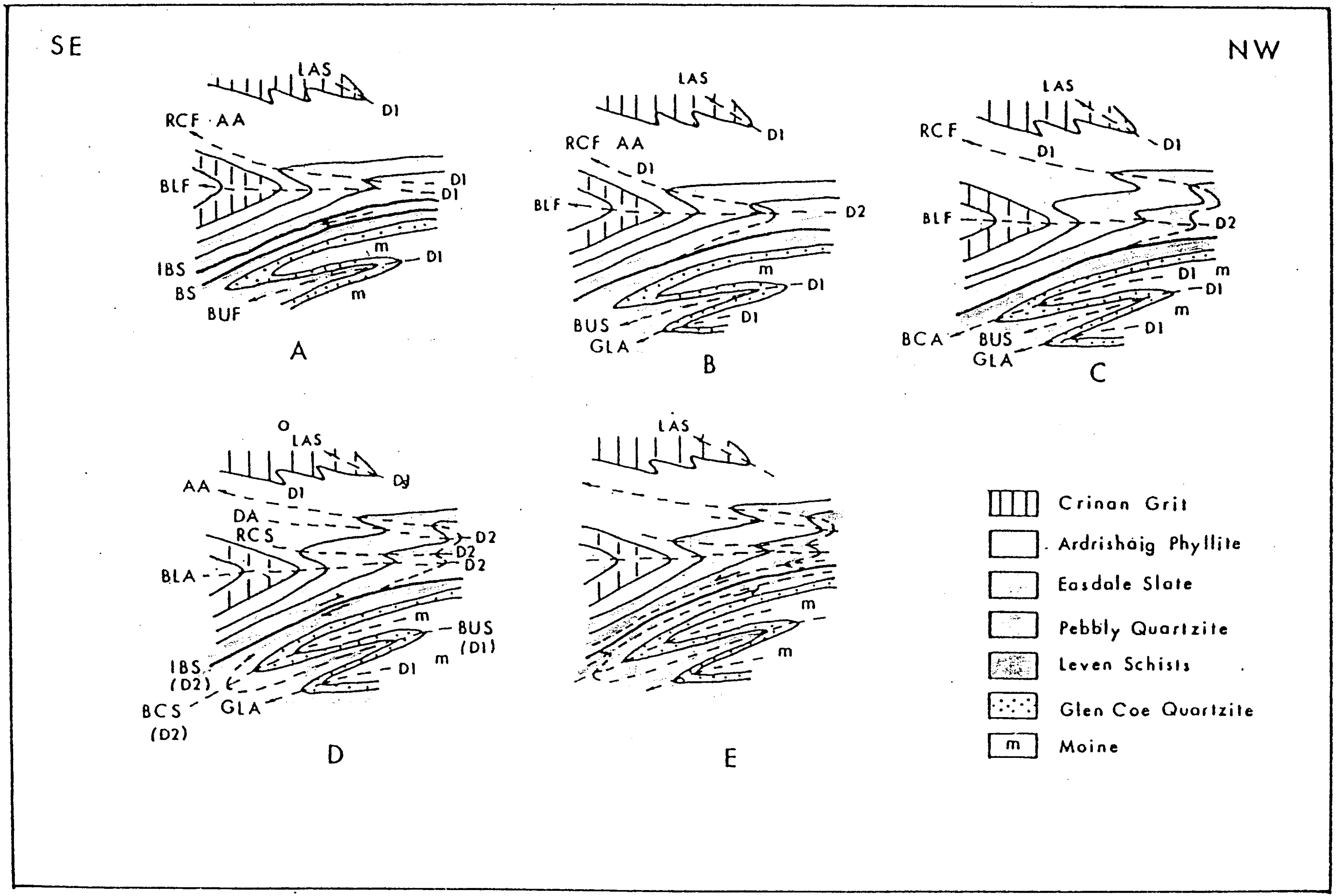
C Thomas and Treagus (1968)

D&E Roberts and Treagus (1975)

(Alternative)

AA, Ardrishaig Anticline; BCA, Beinn Chuirn Anticline; BCS, Beinn Chuirn Synform; BLA, Ben Lui Antiform; BLF, Beinn Udlaidh Fold; BUS, Beinn Udlaidh Syncline; DA, Dalmally Antiform; GLA, Glen Lochy Anticline; LAS, Loch Awe Syncline; RCF, Ra Chreag Fold; RCS, Ra Chreag Synform; BS, Ballachulish Slide and IBS, Iltay Boundary Slide

Fig. 3-3


SE
NW
LAS
RCF AA
BLF
IBS
BS
BUF
D1
m
A
BUS
GLA
D2
B
BCA
C
O
AA
DA
RCS
BLA
IBS (D2)
BCS (D2)
BUS (D1)
D
E
Crinan Grit
Ardrishaig Phyllite
Easdale Slate
Pebbly Quartzite
Leven Schists
Glen Coe Quartzite
Moine

The first detailed structural mapping in the Glen Orchy and Glen Lochy region was carried out by Thomas and Treagus (1968, Fig. 3 - 4). They showed that the stratigraphic succession in the Glen Orchy area was that given in Table 3 - 1. Also, they pointed out that the primary folds (Beinn Udlaidh syncline, Beinn Chuirn anticline and Glen Lochy anticline) in the Moine and Dalradian rocks beneath the Iltay Boundary slide in the Glen Orchy and Glen Lochy areas faced to the south-east (Figs.3-2C and 3-3C)). The name of the Beinn Chuirn Fold was first proposed by Thomas and Treagus (1968), who concluded that it belonged to the D1 deformation. This fold faces towards south-east and forms an anticline (Thomas and Treagus, 1968; Thomas, 1979).

Roberts and Treagus (1975, Fig. 3 - 5) first recognised that the rocks in the Glen Orchy area had undergone at least three phases of deformation. They also investigated the stratigraphic succession and structure above the Iltay Boundary slide and studied the nature of this slide (Figs. 3 - 3D & E). According to them, this slide developed in response to the D2 deformation. Also, they considered the Glen Coe quartzite and Leven Schists in the core of the Beinn Udlaidh fold lay at a deeper structural level than the rocks above the Iltay Boundary slide. They showed that the first cleavage (S1) for the rocks in the deeper structural level is a ´medium grained´ penetrative

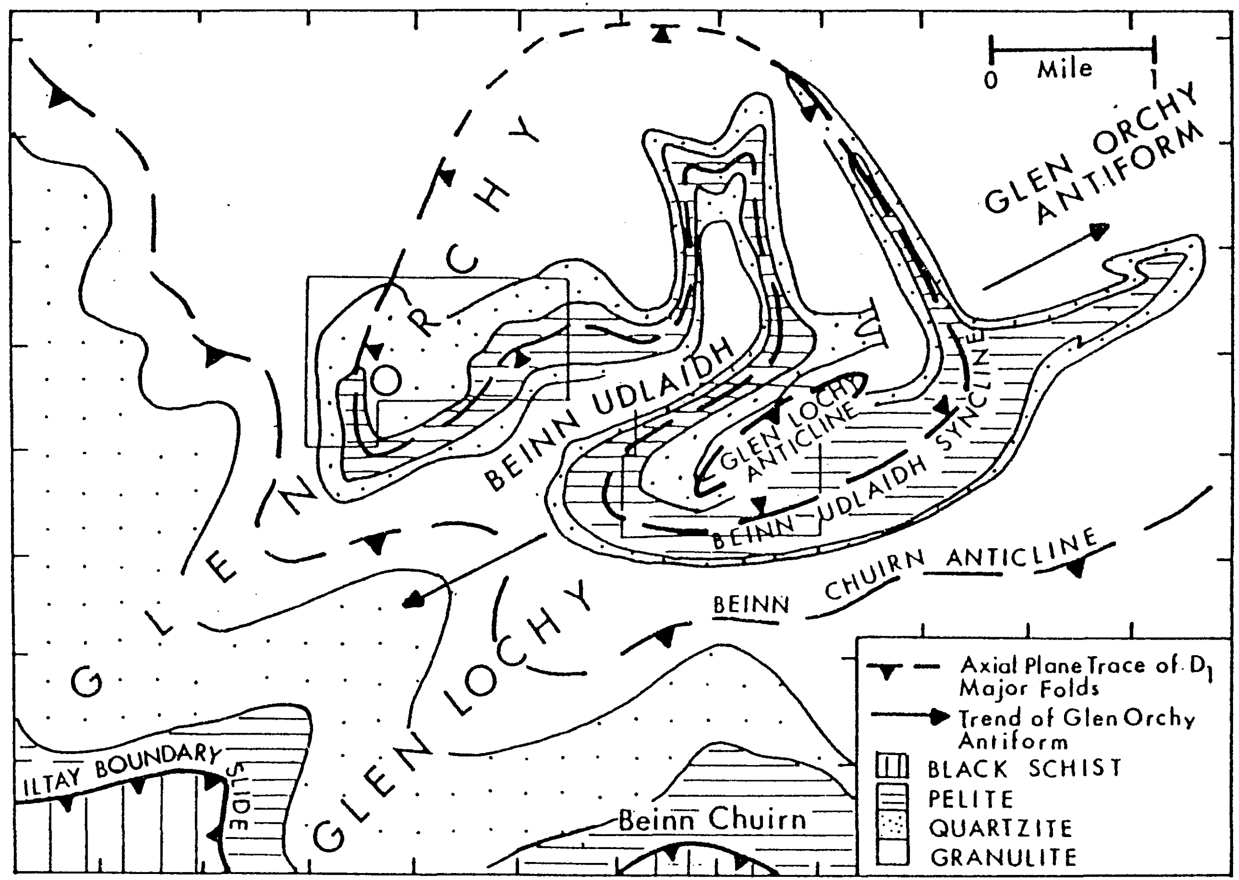



Fig. 3-4: Geological map of the area around Glen Orchy (Thomas and Treagus, 1968). Box inserts show the detailed areas studied by them.

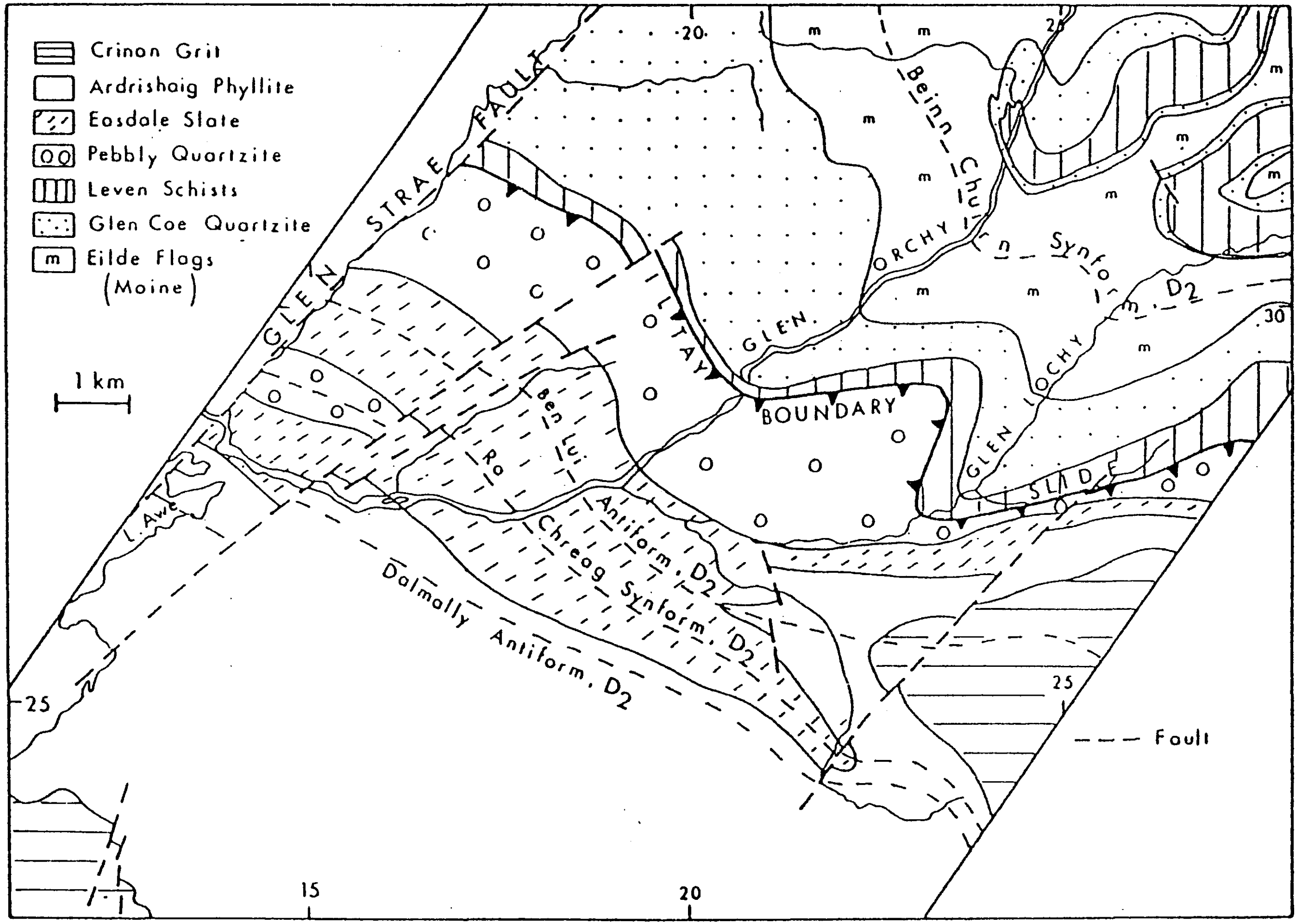



Fig. 3-5: Geological map around Glen Orchy (after Roberts and Treagus, 1975).

cleavage defined by the parallelism of biotite and muscovite flakes. This S1 cleavage is axial planar to folds which appear to affect no earlier structures apart from bedding (SS), such a fabric is best developed in the banded part of Leven Schists adjacent to the outcrop of the Glen Coe quartzite. According to them, the second cleavages (S2) developed in the Ben Lui Schists, and in the Leven Schists which lie immediately below the Iltay Boundary slide, are similar to one another, and associated with recrystallisation and the growth of porphyroblasts such as garnet and feldspar. Therefore Roberts and Treagus (1975, 1977 and 1979) concluded that the Beinn Chuirn Fold belonged to the D2 deformation and is a synform. Field evidence was supported by an examination of the microfabrics.

According to the previous studies the Ben Lui Fold, Iltay Boundary slide, Beinn Chuirn Fold, Beinn Udlaidh fold and Glen Lochy Fold were folded by a major structure, the Glen Orchy antiform.

The climax of regional metamorphism in the Glen Orchy area has a close connection with the D2 deformation (Roberts and Treagus, 1975) and occurrence of the garnet porphyroblasts in the Glen Orchy area is indicative of a medium grade of metamorphism within the garnet zone of the Barrovian metamorphism (Fig. 3 - 6).

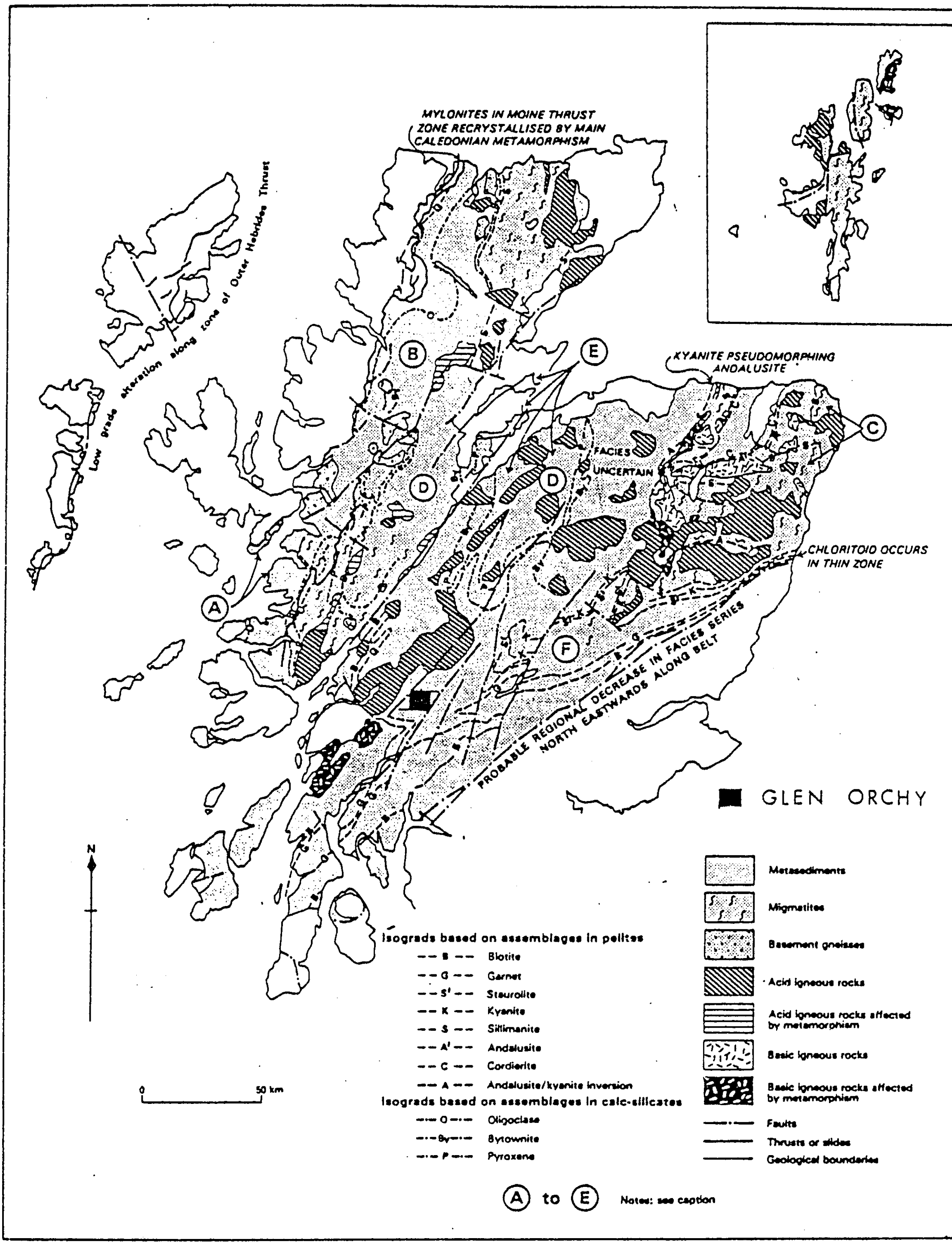



Fig. 3-6: Metamorphic map of Scottish Highlands showing distributions of isograds (after Fettes, 1979). Box (dark) insert shows the Glen Orchy area.

# CHAPTER 4

# LITHOSTRATIGRAPHY AND IGNEOUS INTRUSIONS

## 4.1. Introduction

A lithostratigraphic sequence for the area is presented in Table 4-1. This stratigraphic sequence has been defined by using the evidence from the way-up structures.

The lithological boundaries are essentially similar to that of the previous work, with minor alterations. All the lithological boundaries are stratigraphic contacts, except the contact between underlain pelite and overlain pebbly quartzite, where the contact marked by the tectonic break, Iltay Boundary Slide. The lithological map of the area is presented on a map ( Fig. 4 - 1 ).

Here, the field occurrence and petrography of the rocks are briefly described, starting with the oldest rocks.

Table 4-1: Lithostratigraphical sequence in the Glen Orchy Area.

| | | |
|---|---|---|
| Pebbly quartzite | Easdale subgroup | Argyll Group |
| —Iltay Boundary Slide— | | |
| Pelite (with thin limestone)<br>Quartzite | Lochaber subgroup (Transition) | Appin Group |
| Moine rocks | Grampian Division | |

Passage Zone

## 4.2. Moine rocks

These rocks are exposed in the centre of the area ( Fig. 4 - 1 ). They are generally uniformly flaggy, with a characteristic variation in thickness from 10 - 20 cm, and are sometimes up to 60cm thick.

The rocks vary in colour from pale-grey or pink to dark-grey, the darkness of the shade depending on the amount of biotite present. The pinkish colours are apparently due to the large amount of K-feldspar grains present in the rocks ( Locality 1, NN 23903012 ).

In the Glen Orchy area the Moine rocks may be divided into three units - Psammite, Semipelite and Passage zone rocks.

### 4.2.1. Psammite

The Psammite is a quartzose psammite, which is in part rather coarse - grained and occasionally pebbly or gritty, containing grains up to 0.65cm in diameter ( Localites 3, NN 21883056; 4, NN 21223066 and 5, NN 21143144 ). However, in places the psammite is finely banded and consists of an alternation of thin psammitic ( up to 0.5cm ), micaceous and quartzo-feldspathic units.

The rocks are uniformly flaggy with variation in thickness ( 10 -20 cm intervals ). Occasionally the rocks are found interbedded with semiplite bands ( 2cm to 10cm thick ) and semipelite/pelite bands ( 4cm to 6cm thick ).

The most striking characteristic of these rocks is the remarkable presence of pebbly or gritty units which are up to 1/2m thick, and consist of quartz and white/pink feldspar grains in a matrix. The grains are poorly flattened in the foliation and elongated to lengths up to 0.4cm ( Plate 4 - 1 ). The location for the pebbly or gritty units is shown in Fig 4 - 1. The distinct pebbly/gritty units occur in the junction of psammite and quartzite on the upper limb of the Beinn Chuirn fold.

Generally the psammite rocks occur close to the quartzite. Away from the quartzite outcrop the psammite changes to the semipelite with intervening thin ( 4cm to 10cm thick ) semipelite/pelite bands. An altenation of thin semipelite/pelite and psammite bands often gives the rock a ribbed appearence. The extent of the psammite in the area is shown in Fig. 4 - 1. The limit of the exposures has been determined only approximately in the field.

In thin-section the rocks are seen to consist of

Plate 4-1: Grains of quartz and feldspar are poorly flattened in the foliation in the psammitic Moine rocks. Locality 4 (Fig.4-1). Plan view.
The pencil is pointing towards N160E.

quartz, K-feldspar, oligoclase ( An 15-25 ), biotite, muscovite and opaque minerals.

Sedimentary structure such as trough lamination are well preserved in the psammite ( Plate 4 - 2 ), indicating that the rocks are younging towards the south-west. Bedding planes are also well developed in this rock.

4.2.2. Semipelite

This rock has a dark grey colour and showed a strong foliation. The latter is due to the common occurrence of micas ( biotite and muscovite ) and sometimes chlorite. Pebbly or gritty units are also seen at locality 6 ( NN24063142 ). The grains are mainly of white feldspar with some quartz. Here, most of the grains are not seen to be elongated or flattened. The grains have an average length up to 0.5mm in diameter.

The semipelite consists essentially of porphyroblast garnet, K-feldspar, albite/oligoclase, quartz, biotite, muscovite, chlorite and opaque minerals.

No sedimentary structure were found in the semipelite.

Plate 4-2: (A) Current-bedding in the psammitic Moine rocks.
Younging to right.
Locality 2(Fig.4-1,NN22982971).
Looking towards N164E.

(B) Subvertical cross - bedding preserved in the Moine rocks,
Younging to right.
Light coloured beds are psammite and grey beds are semipelite.
Locality 2(Fig.4-1,NN22982971)
Looking towards N164E.

A

B

4.2.3. Passage Zone

The rock has variable character consisting of striped pelites and semipelites always with calcareous beds, and ribs of quartzite, but is generally graphitic. The rocks appear pale-grey to dark-grey in colour and consist of quartz, feldspar, garnet, biotite, muscovite, calcite and chlorite with sphene, zircon and opaque mineral occurring as accessories.

At locality 7 ( NN21193171 ), on the upper limb of the Beinn Udlaidh syncline, there are approximately 100m of mixed psammites, semipelite and pelite ( with some graphitic and calcareous beds ) between the Moine rocks and the quartzite ( Fig. 4 - 1 ).

In Allt Broighleachan, locality 8 ( NN24203304 ), the same passage group is reduced to a few metres ( 4 - 5m ) thick. In the River Orchy at locality 9 (NN24893337) on the lower limb of this fold ( Beinn Udlaidh syncline ) the passage zone only represented by a few metres ( 5 to 7m ) of impure psammite.

Bedding planes, can be seen in the passage zone; no way-up structures were found. The passage zone is probably best considered as part of the Dalradian sequence ( Table 4 - 1 ).

## 4.3. Dalradian rocks

### 4.3.1. Quartzite

The quartzite occurs in the north of the area, forming an envelope to the Beinn Udlaidh Fold ( Fig. 4 - 1 ), and in the south of the area on the upper limb of the Beinn Chuirn Fold. It is $\sim$ 1500m thick on the lower limb of the Beinn Udlaidh Fold but only $\sim$100m thick on the upper limb.

Bedding is well developed in the quartzite. Sedimentary structure such as cross-lamination are also well preserved in both limbs and show that the quartzite, which forms an envelope to the Beinn Udlaidh Fold, youngs toward the pelite.

The same quartzite which lies on the upper limb of the Beinn Chuirn Fold shows variable thickness, especially the quartzite in the south of the River Orchy. This is partly due to the effect of faulting ( Fig. 5 - 11 ). No way-up structures have been found in this quartzite. However, cross-lamination found in the Moine psammite on the upper limb of the Beinn Chuirn Fold indicates that these rocks young towards the quartzite. This suggests that the quartzite probably youngs toward the pelite found further to the south-west.

The quartzite in the whole area is pure and white, sometimes pink-brownish in colour, due to the present of feldspar grains. The rocks are well bedded, with a variation in thickness from 20cm to 40cm in the parting interval. The occurrence of cross-laminations, suggests that they were deposited in shallow water, possibly under the influence of tidal currents.

In the field the quartzite can be distinguished from the flaggy psammite ( quartzose rocks ) as it has a glassy texture, is relatively ´clean´ and shows little development of a tectonic fabric.

### 4.3.2. Pelite

The rocks occur in the core of the Beinn Udlaidh Fold in the north of the area. In the south of the area these rocks form part of the limb of the Beinn Chuirn Fold. In hand specimen the rocks appear pale to dark brownish in colour, with a well developed schistosity. This schistosity is due to the common preferred orientation of biotite and muscovite flakes.

In the field the rocks are easy to recognise, because they show in places a remarkable development of red garnet porphyroblasts scattered randomly throughout the rock. In size garnets range from 1mm to 5mm in diametre. The garnet porphyroblasts are commonly partially or completely altered to green chlorite, and this gives the rocks a greenish colouration.

The pelite is a fine to medium-grained garnet-mica schist. It is dominated by a penetrative schistosity and shows the later development of crenulation cleavages. No bedding is recognised in the pelite on the limbs of the major fold.

The pelite consists of garnet porphyroblasts, biotite, muscovite, K-feldspar, albite/oligoclase, quartz, in varying proportions, together with the following minerals: sphene, zircon, calcite and opaque minerals.

Occasionally bands of graphitic and calcareous rock a few centimetres are found interbanded with the pelite.

### 4.3.3. Limestone

The outcrop of the limestone in the area is shown in Fig. 4 - 1. Generally these rocks are exposed in the south-west of the area, and extend along strike from north to south. On the upper limb of the Beinn Chuirn fold ( locality C2, NN20183022; Fig. 1 - 2 ) the limestone is found interbedded with pelite and is up to 70cm thick.

This limestone has a white to cream colour and is generally medium-grained. It consists of abundant calcite and dolomite with some quartz, plagioclase-feldspar, micas and opaque minerals.

Bailey and Macgregor ( 1912 ) considered that the limestone in the Glen Orchy area may be correlated with the Ballachulish limestone but Thomas and Treagus (1968) considered this limestone occurs as a stratigraphic intercalation.

### 4.3.4. Pebbly quartzite

The pebbly quartzite is the youngest rock exposed in the area, cropping out in the southern part, and overlain by the Easdale slate ( Roberts and Treagus, 1975 ). The pebbly quartzite is separated from the underlying pelite by a tectonic break, the Iltay Boundary slide.

This rock appears pale-brown in colour, with well preserved detrital grains ( Plate 4 - 3 ). Bedding is also well developed in the pebbly quartzite. The rocks are of 0.1 - 1.0cm grain size with best preserved

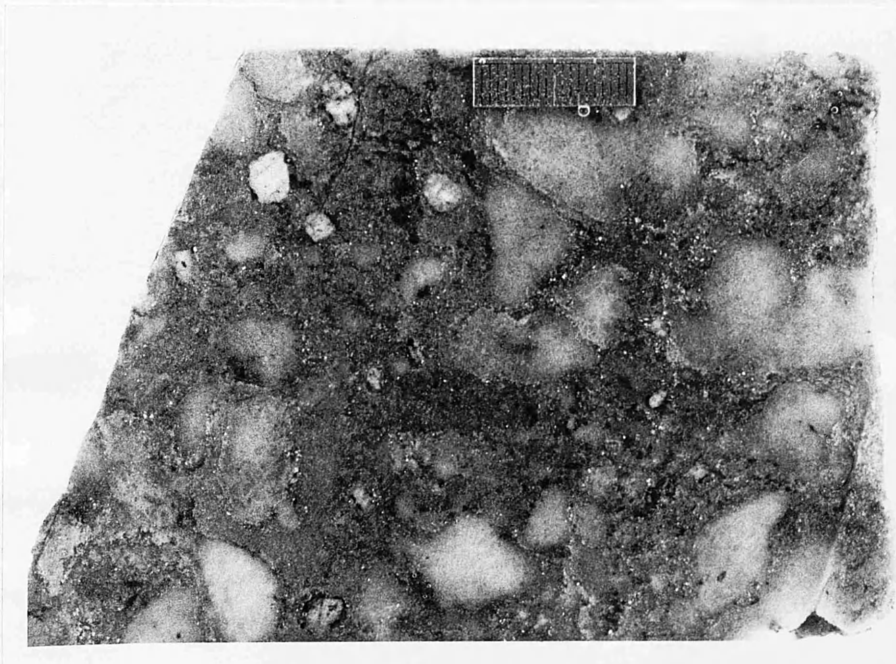


Plate 4-3: Preservation of detrital grains in the pebbly quartzite.
Locality 10(Fig.4-1,NN22912813)

pebbly horizons. The pebbly horizons consist of abundant pebbles of quartz and with some white feldspar. The pebbles are tectonically flattened in the bedding plane and elongated to length up to 0.7cm ( Plate 4 - 4 ). The pebbly beds are best seen at localities 10, 11 and 12 ( Fig. 4 - 1 ). At locality 10 ( NN22912813 ) which is close to the base of the pebbly quartzite, sedimentary grading is well preserved, and indicates that the rocks are younging towards south-west.

The pebbly quartzite usually shows variation in bedding thickness of 10 - 30cm parting interval, sometimes up to 70cm thick. Occasionally the rocks are found interbedded with thin ( 5 - 10cm ) pelite beds.

The pebbly quartzite is consists mainly of quartz, with some K-feldspar, albite/oligoclase, biotite, muscovite and opaque minerals.

## 4.4. Relationship of Moine and Dalradian rocks

Having demonstrated that two rock sequences are recognizable within the Glen Orchy area, the relationship between them is now examined. It is concluded that the stratigrapic sequence in the Glen Orchy area starts with the Moine rocks ( psammite, semipelite and passage zone ) which are followed by

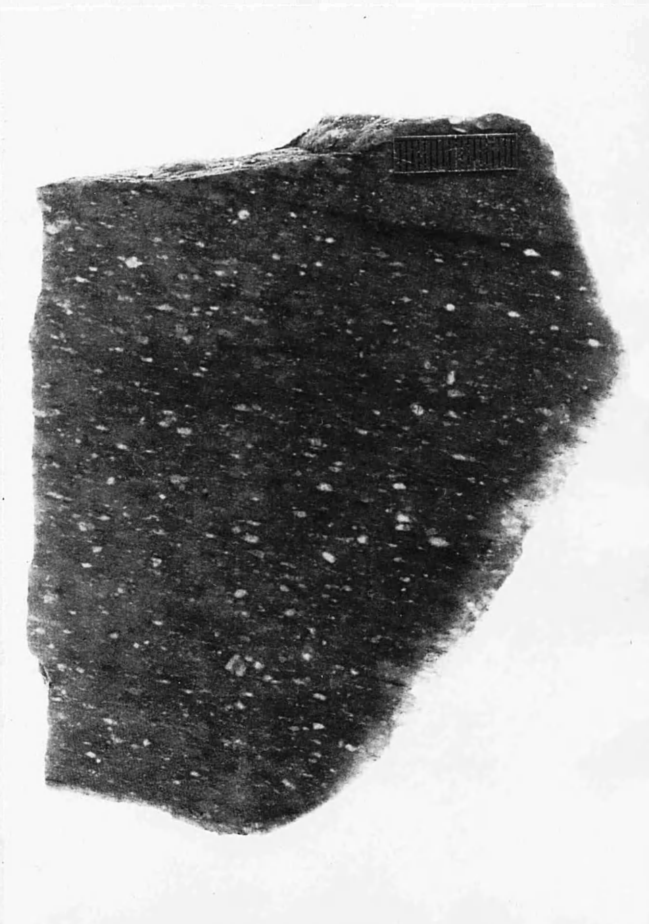


Plate 4-4 : Grains of quartz and feldspar are flattened in the bedding planes in the pebbly quartzite. Locality 10 (Fig.4-1, NN22912813). Photograph from a cut surface rock. The ruler scale is 2cm long.

younger Dalradian rocks ( quartzite - pelite - pebbly quartzite). Evidence from the way-up structures ( cross-lamination ) confirms that this sequence is upwards younging ( Table 4 - 1 ).

Both Moine and Dalradian rocks of the area have been deformed and folded into two major folds - the Beinn Udlaidh Fold which occurs in the north and Beinn Chuirn Fold which lies in the south and structurally above the Beinn Udlaidh Fold.

The quartzite which lies on the lower limb and upper limb of the Beinn Udlaidh Fold forms an envelope to this fold and has pelite in its core. The quartzite becomes thinner as it is traced from the lower limb around to the upper limb of the fold. This variation in thickness may be due to stronger deformation of the upper limb of the fold as evidence from thin-section clearly shows that the fabrics in pelite which are found close to the quartzite on the upper limb are possibly high-strain fabrics, and sometimes appear mylonitic. Way-up structures such as cross-lamination found in the quartzite on the lower limb of this fold confirm that the quartzite youngs towards the pelite.

Further, both the quartzite and the pelite are exposed in the south of the area and occur on the upper limb of the Beinn Chuirn Fold, which also has Moine rocks in its core. Again, the way-up structures ( cross-lamination ) which are well preserved in the psammitic Moine rocks on the upper limb and near the hinge zone of the Beinn Chuirn Fold confirm that the sequence youngs to the south-west away from the Moine rocks.

All the lithological contacts between Moine and Dalradian rocks are marked by the transition zone ( a mixed zone a few metres wide ). There appears to be a lithological transition between Moine-like and Dalradian-like rocks with no evidence of an unconformity or depositional break between them. The contact between the pelite and overlying pebbly quartzite, is marked by a tectonic break, Iltay Boundary slide, as described in Chapter 5.

## 4.5 Igneous Rocks

### 4.5.1. Basic dykes

Dykes in the studied area may be divided into two groups, according to their trend, either NNE-SSW or E-W.

#### NNE-SSW dykes

A few dykes with a NNE-SSW trend are found in the area. Most of these dykes crop out in the western part of the area, and have an average width of about 2 - 3 metres. The dykes are often nearly vertical ( 80 - 90 dip ) and were intruded into the metasediments at right angles to the bedding planes or foliations. In hand specimen the rocks have a greenish colouration and are fine to medium-grained.

One NNE-SSW dyke sectioned consists mainly of olivine, pyroxene, amphibole, plagioclase-feldspar, micas, quartz and opaque mineral in varying proportions.

E-W dykes

The E-W dykes are medium to coarse-grained igneous rocks. Dykes of this trend are exposed mainly in the south of the area, with some in the north. They have a variable width, up to 30m maximum width as seen at locality 13 ( NN23142910, Fig. 4 - 1 ). However, these dykes are generally of the order of 5 to 20m in width.

The chilled margins which formed during the intrusion of these dykes are always found. As an example, at locality 14 ( NN21363022 ) a thin 15 - 10cm ) chilled margin is seen, which is dark-brownish in colour. At the same locality, one of the E-W dykes (

( approximately 25m wide ) cuts the NNE-SSW quartz breccia ( 20-30m width ) which is described later. This indicates that the E-W dyke is younger than the quartz breccia. Assuming, that the NNE-SSW quartz breccia formed at the same time as the NNE-SSW dykes, because both have a similar trends, it would be possible to infer that the E-W dykes are also younger that the NNE-SSW dykes.

In thin-section the E-W dyke is seen to consist of olivine, pyroxene, amphibole, plagioclase-feldspar, micas and quartz.

Kynaston (1908) considered that the E-W dykes are of Tertiary age and of doleritic composition.

### 4.5.2. Basic sills

These intrusions occur in both Moine and Dalradian rocks and are generally concordant with the bedding planes or main schistosity of the host rock.

They are green to dark green in colour and have a fine to medium grain size. Usually these rocks are less than 1 meter thick.

At least two types of sill can be recognised in the area. One of them is a greenish in colour and it is seen to consists of olivine , pyroxene, amphibole, micas, feldspar, quartz, and opaque mineral. The other one is a little bit darker, suggesting that it contains more ferromagnesium minerals. They appear to be late igneous intrusions, possible of the same generation age as the dykes.

4.5.3. <u>Kentallenite</u>

This igneous basic mass occurs in the northern area, on the west side of Glen Orchy, about 2 kilometres north of Catnish. The rocks are almost black in colour, but appear greenish when weathered.

The limited exposure of these rocks in the present study are located only approximately in the field. The rock has formed an elongated shape, approximately 1 kilometre in length and a 1/4 kilometre in breadth.

In thin-section , it is seen to be a medium to coarse-grained rock which consists of olivine, augite, biotite and feldspar.

The similar type of rock to that exposed here was originally described from Kentallen, near Ballachulish and has been described in detail by Bowes and Wright (1967 ).

## 4.5.4. Amphibolite

Rocks of this type are always found with concordant relations to bedding planes and schistosity, also sometimes found as a boudins or lenses ( with up to 20 - 30cm in diametre ). The rocks are dark greenish, and show a strong foliation. The foliation is due to the preferred orientation of minerals mainly amphibole, plagioclase-feldspar and with some micas.

The rocks are mostly exposed in the south of the area ( Fig. 4 - 1 ). At localities 15 ( NN23522867 ) and 16 ( NN23022802 ) the rocks have a variable thickness ( 20 - 50cm ) and are sometimes up to 1 metre thick. Here, the rock shows a poorly developed mineral lineation on the foliation plane. The mineral lineation is defined by amphibole and micas, has SW - NE to WSW - ENE trends and 10 - 20 plunge. These orientations are similar to the orientations of the local F1 minor folds (S - shape fold).

Evidence such as a well developed foliation and a linear fabric suggests that these rocks were probably deformed during the main deformation of the Dalradian metasediments.

## 4.6. Iltay Boundary Slide

The recognition of the slide in the area is based on stratigraphic correlations (cf. Bailey, 1922).

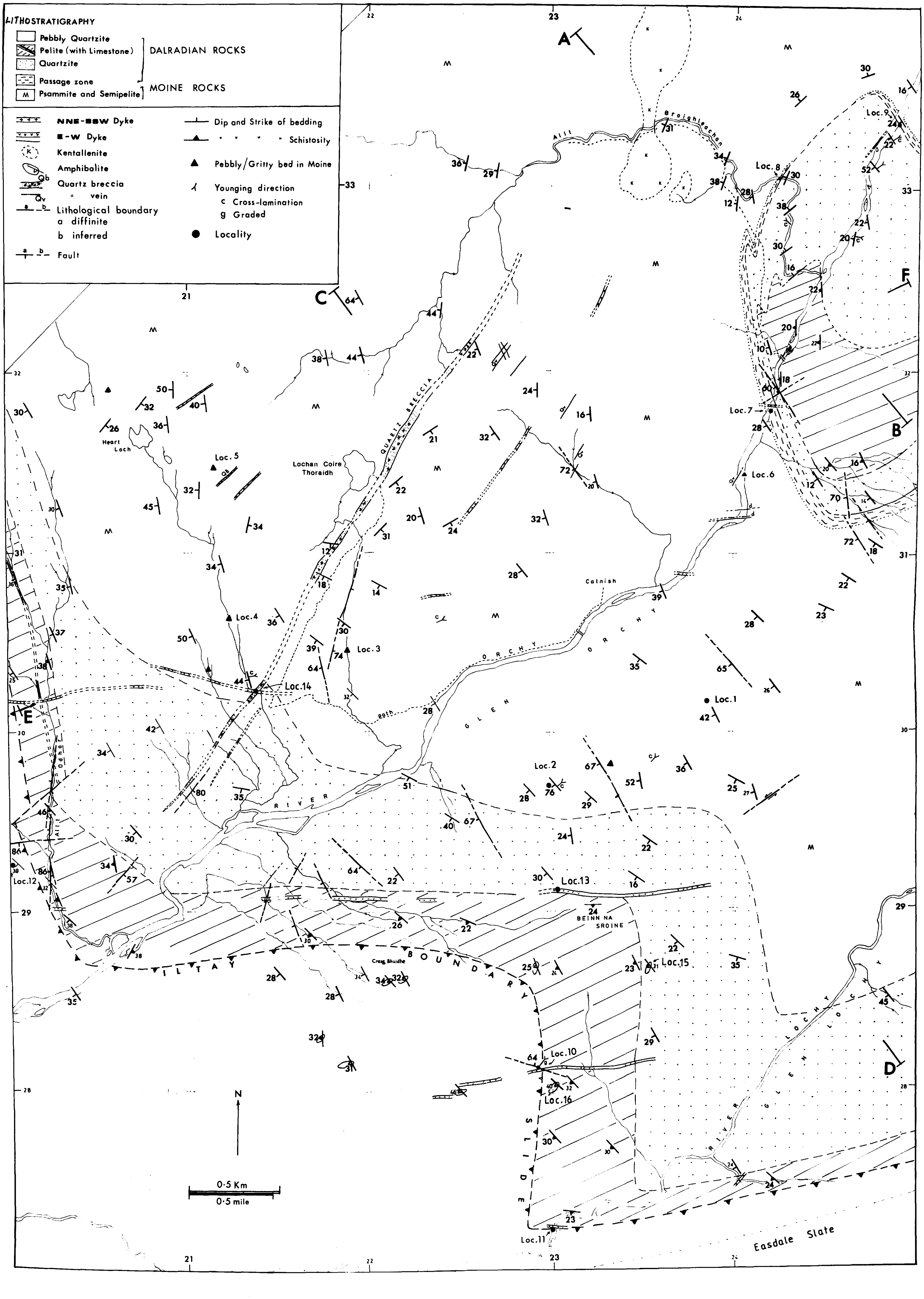
The slide is located between pelite and the pebbly quartzite (Fig. 4-1). If the stratigraphic correlation (Harris and Pitcher, 1975) is correct then the sequence between pebbly quartzite and pelite is missing at the slide contact in the area.

In the present mapping, no definite outcrop of the slide plane has been found. Evidence for its presence is based on microscopic studies.

Bailey (1922), Rast (1963) and Roberts and Treagus (1977) considered that the Iltay Boundary Slide is primary structure closely related to the D1 deformation.

However, Roberts and Treagus (1975, 1979) and Bradbury (1985) concluded that the slide developed in response to the D2 deformation.

# Fig.4-1 : LITHOLOGICAL MAP



# CHAPTER 5
# STRUCTURE

## 5.1. Introduction

The rocks of the Glen Orchy area show evidence of polyphase deformation and at least four phases of deformation ( D1-D4 ) are recognised. The D1 and D2 deformations have each developed minor folds, and S- and L- fabrics. D3 and D4 deformations are also associated with the minor folds but, no S3 and S4 fabrics were recognised. An extensional crenulation cleavage is observed in the pelite on the upper limb of the Beinn Chuirn Fold.

As a result of the extensive deformation, bedding planes (SS) are recognised only in the quartzite and the pebbly quartzite, and in the Moine psammite. Banding in the semipelite or pelite beds defined as a composite foliation (Sc=SS/S1), subparallel or parallel to the S1 cleavage on the limbs of the major folds.

The structural sequence of the rocks in the area is described based on field relationships and microscopic studies. The structural data are presented on maps and equal area lower hemisphere projections and computed means of the structural elements ( planar structures ) are shown in Figs. 5-7 , 5-8 and 5-9. Structural cross-sections ( true-scale ) are presented at the end of this chapter (Figs. 5-10).

## 5.2. D1 deformation

Structures formed during the first phase of deformation are widespread in the Moine psammite, semipelite and passage zone and in the Dalradian rocks ( quartzite and pelite ) of the area. Evidence of this deformation, which produced regionally dominant first generation structures, is found especially in those areas that have suffered low finite strains as indicated by the preservation of sedimentary structures such as cross-lamination.

This deformation is responsible for the development of two important major D1 folds, the Beinn Udlaidh Fold and Beinn Chuirn Fold.

The structural data for the D1 deformation are presented on maps ( Figs. 5-1 and 5-3 ) and stereographic projections ( Figs. 5-7, 5-8 and 5-9 ).

### 5.2.1. D1 minor structures

Minor folds belonging to the first phase of folding are strongly developed in the area and D1 fabric may be used as a convenient structural marker. They control the attitude of the bedding (SS) in individual outcrops. Minor F1 folds are found on both limbs and on the hinge zone of major D1 folds.

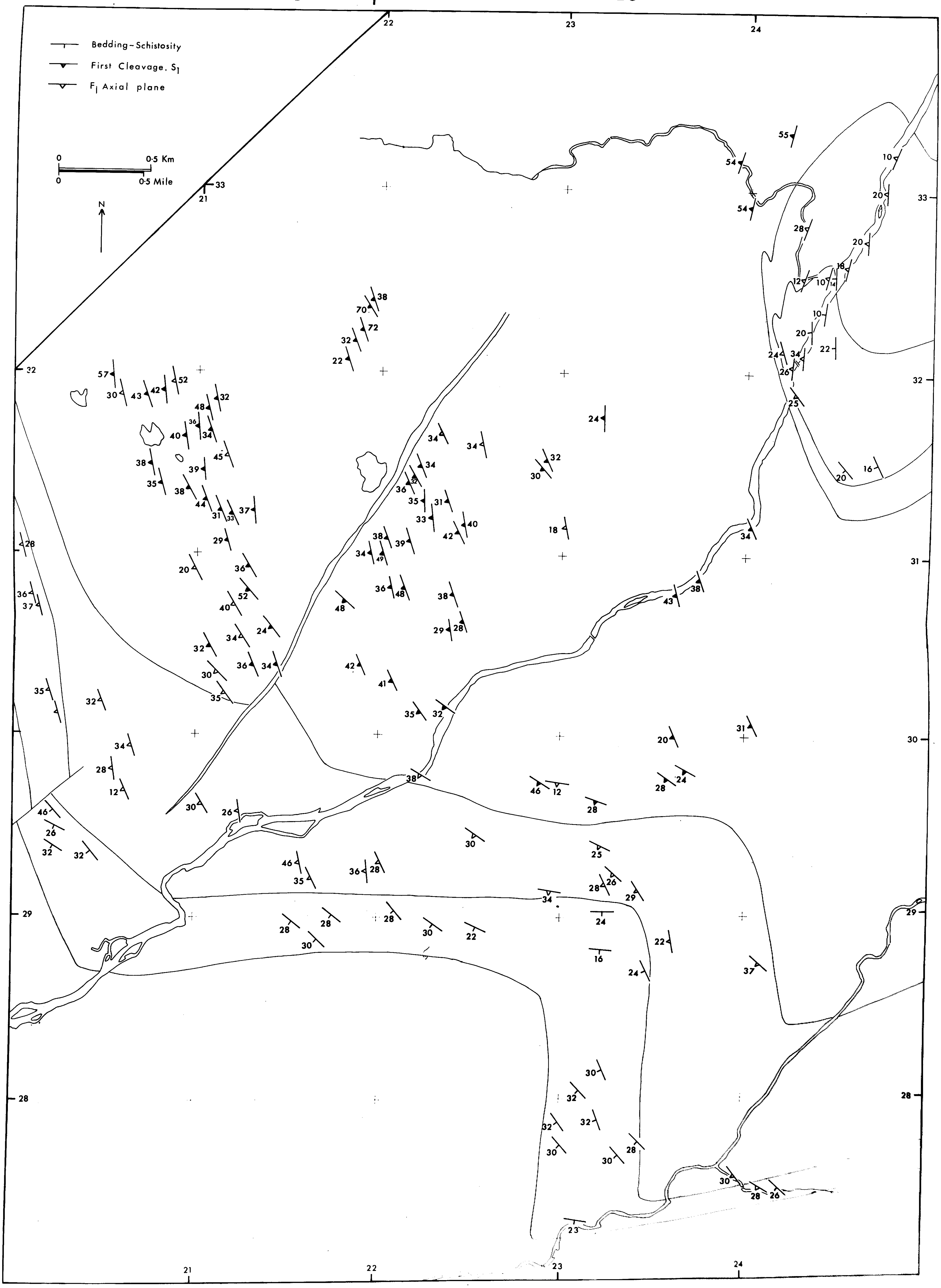
The early cleavage (S1) is best developed in the Moine outcrops.

#### S1 cleavage

The S1 cleavage is a dominant fabric in the area ( Fig. 5-1 ). The intensity of this planar fabric depends on the lithology of the rock in which it develops and also on the intensity of the deformation. In the quartzose rocks ( bedded psammite ) it is defined by a closely spaced cleavage ( 0.1-0.2mm ), whereas in the pelitic or semipelitic units the S1 cleavage is defined as a penetrative cleavage ( 0.05-0.1mm ).

This S1 cleavage is strongly developed in the flaggy Moine psammite and clearly seen in the field. However in the pelitic beds the S1 cleavage forms as a composite foliation ( Sc = SS/S1 ), parallel or

Fig.5-1: D$_1$ PLANAR STRUCTURES



subparallel to that of bedding (SS), especially on major fold limbs. In the fold hinge zones the S1 cleavage is at a high angle to bedding (SS).

The S1 planar fabric is axial planar to minor folds (F1) which appear to affect no earlier structures apart from bedding. In thin-section the S1 cleavage is defined essentially by the product of the strong preferred alignment of muscovite and biotite flakes and of the quartz and feldspar grains between them ( Plate 5-1 ).

The attitude of the S1 cleavage, together with that of bedding (SS) has been recorded wherever possible. Selected, but typical, readings are shown on a map ( Fig. 5-1 ). Where the S1 cleavage is not deformed by later structures, it has a N-S strike in the north of the area which swings to SSE-NNW or SE-NW in the south. This deflection in strike of the S1 cleavage is due to later deformation.

On the lower limb of the Beinn Chuirn Fold, S1 cleavage is steeper than bedding or lithological layering ( Fig. 5-2 ). But, on the upper limb of Beinn Chuirn Fold ( south of study area ) the S1 cleavage is less steep than bedding ( Fig. 5-2 ).

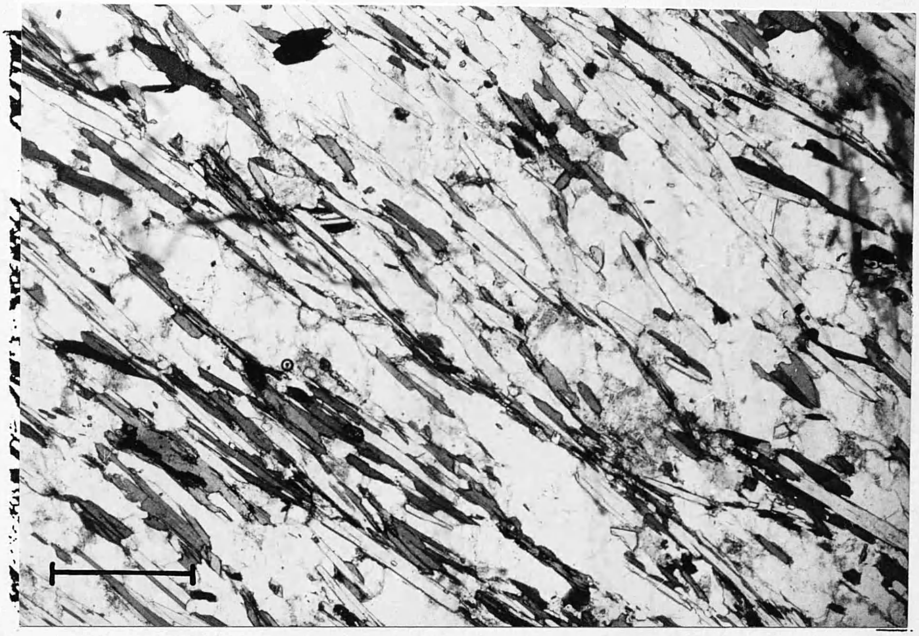


Plate 5-1 : The S1 mica fabric in the semipelitic Moine rocks Locality B45(NN21333133) The bar scale is 0.5mm long.

Fig. 5-2: F1 fold vergence and S1-SS relationships.

SS Bedding

S1 First cleavage

Z - fold ] down plunge viewed

S - fold ]

'M' or 'W' - fold

Cleavage (S1) steeper than bedding (SS)

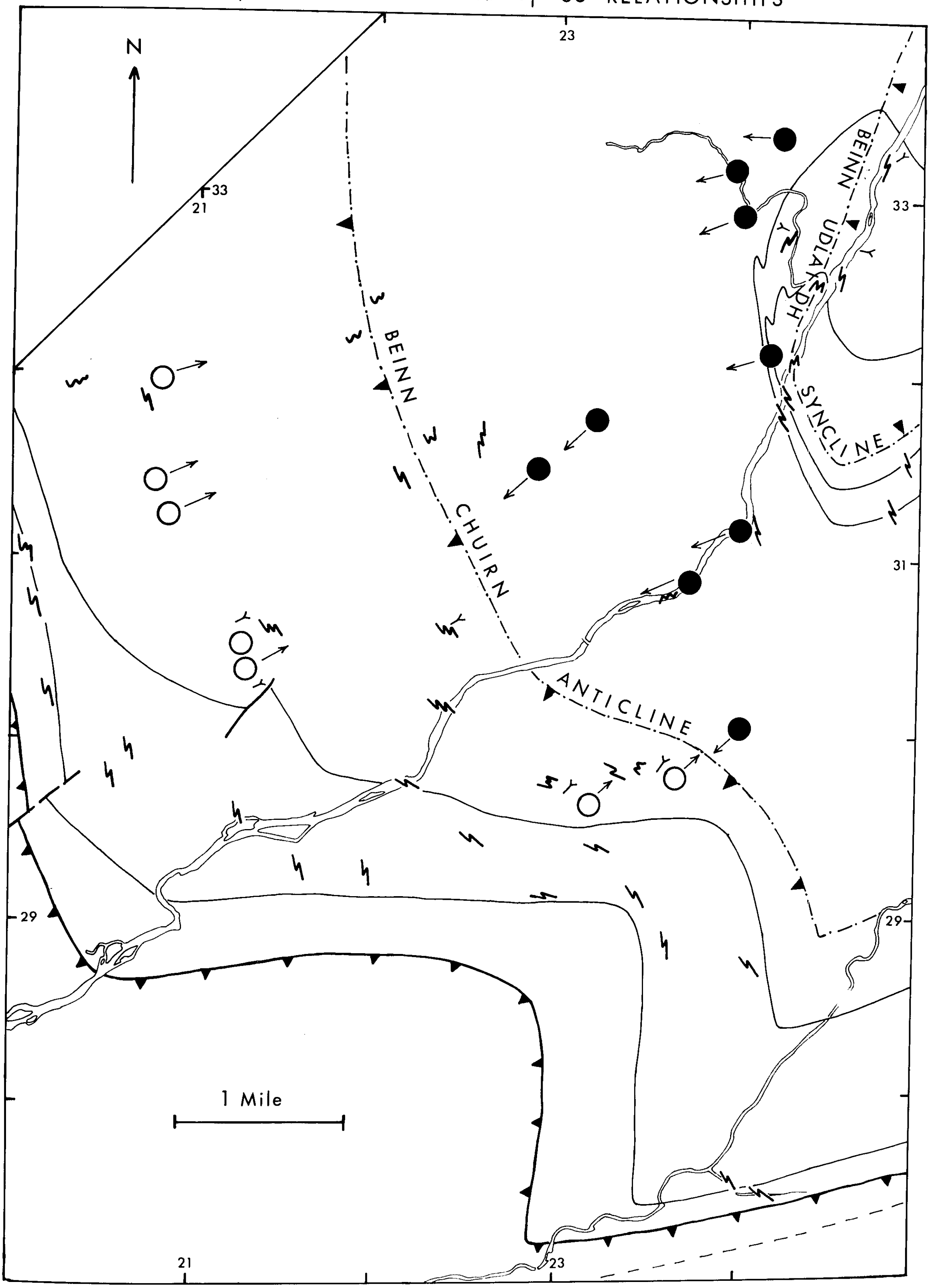
Cleavage (S1) less steep than bedding (SS)

Arrow indicates toward Anticline

Younging direction

Axial traces of major fold

Fig. 5-2: $F_1$ FOLD VERGENCE and $S_1$ – SS RELATIONSHIPS



The relationship between S1 cleavage and bedding is most clearly seen in the Moine rocks ( Plates 5-2 and 5-3 ). This relationship has been used to determine the geometry of the Beinn Chuirn Fold.

At several localities where the S1 cleavage forms a composite foliation ( Sc=SS/S1 ) with bedding, it has been deformed by the S2 cleavage ( Plate 5-4 ) and locally both SS and S1 have been crenulated during the D2 deformation.

F1 minor folds

Minor F1 folds of bedding are common and vary in amplitude and wavelength from a few millimeters to several meters with the interlimb angles at about 30-50 degrees. F1 minor folds also vary in style, depending on lithology and position in multilayered sequences.

An important characteristic of the F1 axes ( hinges ) and of the SS-S1 intersection lineation is their extreme variability in angle of plunge ( Fig. 5-3 ). Although some of this variation is due to later deformation, where it is observed over a distance of a few meters it must be an original feature of the D1 deformation ( Voll, 1960; pp.555 ). In some places minor F1 folds have strongly curvilinear hinges ( Plate

Plate 5-2 : Subvertical bedding (SS) cut by a moderate dipping (30-40 degrees) S1 cleavage in Moine psammite.

Plate 5-3 : Horizontal bedding (SS) cut by a steeply dipping (60 or 70 degrees) cleavage (S1) in the psammitic Moine rocks. Locality B42 (NN20373195). Viewed to N170E.
The head of the hammer is 16.5cm long.

Plate 5-4 : Composite fabric (SS/S1) crenulated by S2 spaced crenulation cleavage in the semipelitic Moine rocks. Upper limb of the Beinn Chuirn Fold.
Locality B43(NN20553170).
Viewed to N035E.
The scale is in inches.

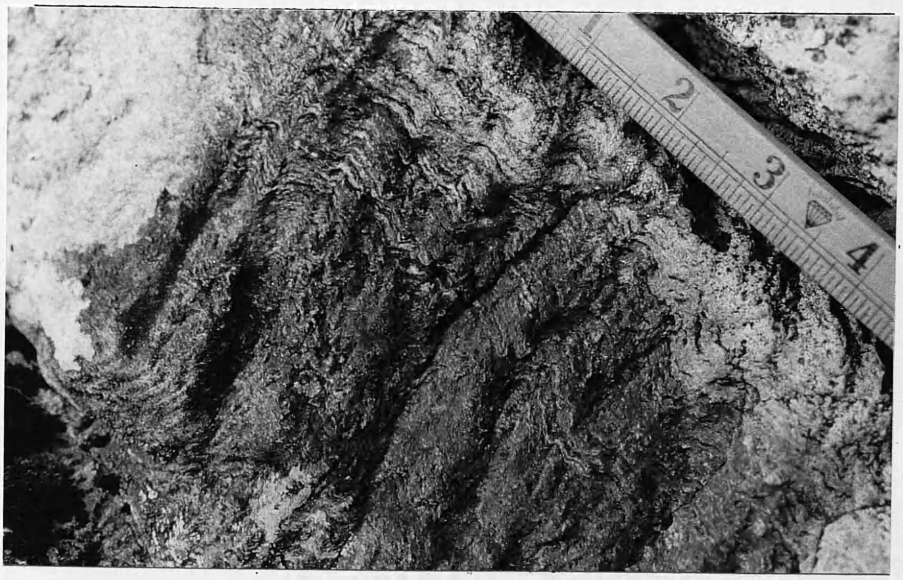
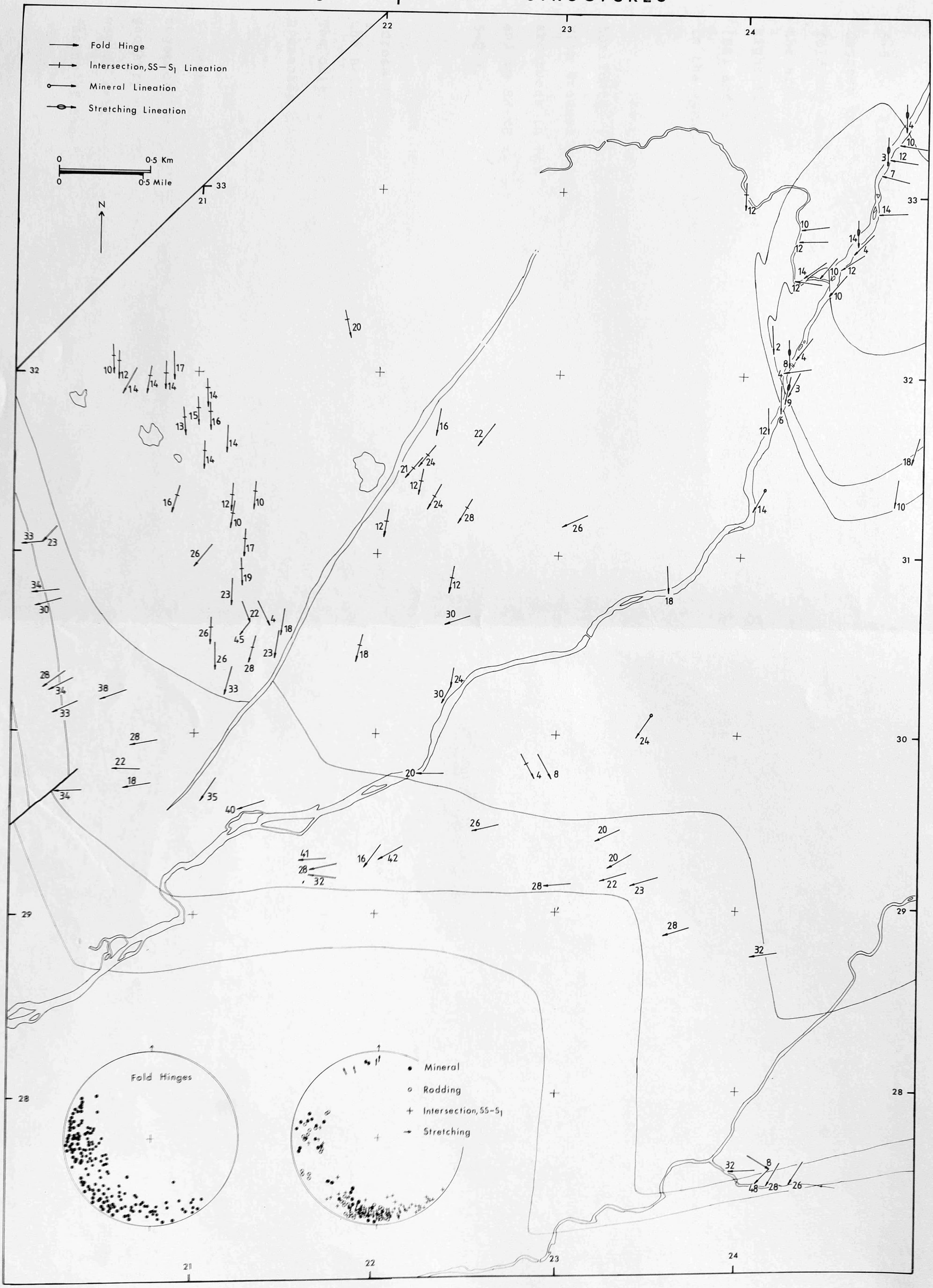

1
2
3
4

Fig.5-3 : $D_1$ LINEAR STRUCTURES



5-5 ). Here, the fold hinge curves through about 90 degrees in 2-3 metres. It is suggested that the major fold may also have a curvilinear hinge. In the south of the area, near the hinge zone of the Beinn Chuirn Fold, a tight F1 minor fold ( s-vergence ) which affects bedding (SS) and shows a slightly curvilinear fold hinge, occurs in the semipelite-psammite rocks ( Plate 5-6 ).

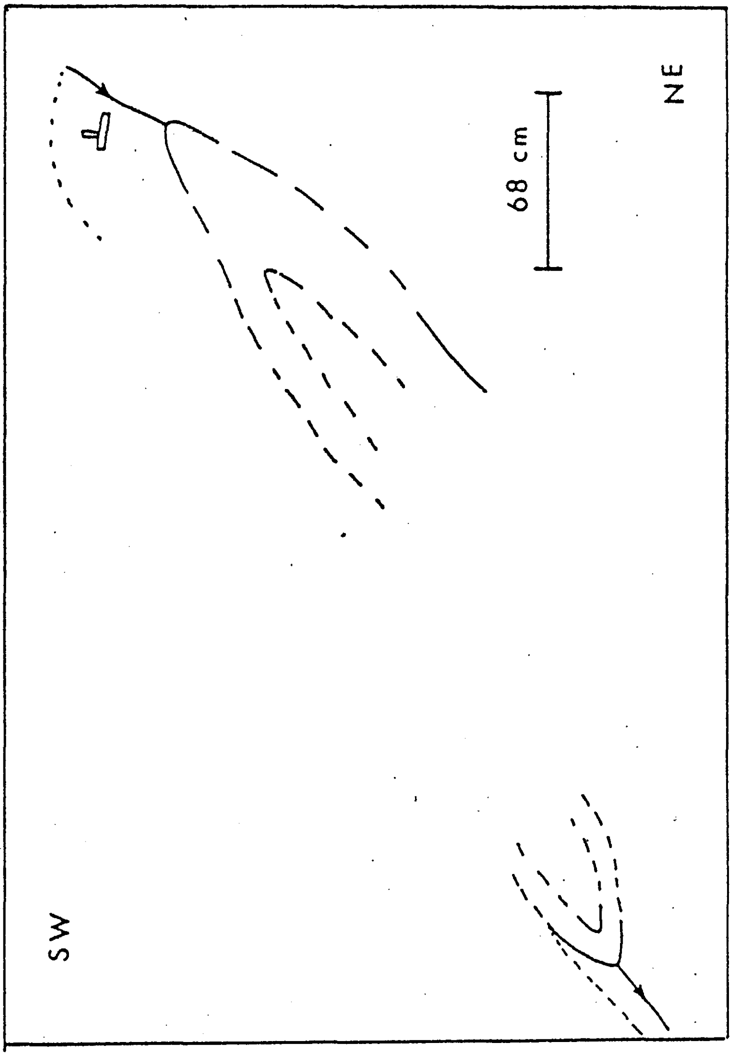
The plunge of the minor F1 folds varies from near horizontal ( 5-20 degrees ) to moderate ( 20-40 degrees ) with gradual swing in trend, generally from E-W in the exposures in the north of the area, to S-N in the centre, and to SW-NE or SSW-NNE in the south of the area ( Fig. 5-3 ).

These variations in plunge of the minor folds across the area suggest that the major fold hinges both the Beinn Chuirn Fold and Beinn Udlaidh Fold are curved. The orientation and geometry of the minor folds is presented on the equal area projection ( Fig. 5-8 ).

The asymmetry or vergence of minor folds ( S- and Z- pattern as viewed down plunge ) has been used, together with SS-S1 relationship, to confirm the geometry of the major D1 folds. In conjuction with way-up criteria these have been used to determine the facing of the major D1 folds. There are numerous minor

Plate 5-5 : D1 minor fold showing a strongly curvilinear hinge in the psammitic Moine rocks. Upper limb of the Beinn Chuirn Fold Locality B52 (NN21243053).
Viewed to N310E.
The head of the hammer is 16.5cm long.

Plate 5.6 : D1 minor fold showing a slightly curvilinear hinge in semipelitic psammitic, moine rocks. Near the hinge zone of the Beinn Chuirn Fold. Locality B24 (NN22423023).
Viewed to N230E.
The pencil is 140cm long.




Redrawn from Plate 5 - 5

folds ( Plate 5-7 ) associated with the Beinn Chuirn Fold and Beinn Udlaidh fold, and their S-, M-/W- or Z-pattern depends upon their position on the major D1 folds. Table 5-1 shows the patterns and position of the minor folds with respect to the major folds.

Minor folds which shows only a single fold nose are commonly seen. These minor folds noses cannot used to determined the geometry of the major folds. However, their attitude has been recorded, wherever possible.

The minor F1 folds which developed in the quartzite have a poorly developed axial planar fabric. However, the minor folds which developed by the folding of quartzite beds within the pelites show a strong axial planar fabric in the pelite layers.

Near the hinge zone of the Beinn Chuirn Fold, minor F1 folds ( Z-vergence ) which deform bedding occur in the psammitic rocks ( Plate 5-8 ). Here, in the outer arc of these minor folds, cross-lamination can be seen which is defined by a planes of dark heavy minerals ( magnetite ). In the inner arcs strongly developed grading is preserved, and fine penetrative S1 cleavage ( 1-2mm ) is clearly seen.

Both cross-lamination and grading in a single unit/bed, possibly suggest deposition from a turbidite

Plate 5-7 : (A) Dl minor folds (S-vergence) in the quartzite on the lower limb of the Beinn Udlaidh Fold. The folds plunge out from the photograph (right to left). Locality Al(NN24763314). Viewed to N060E.

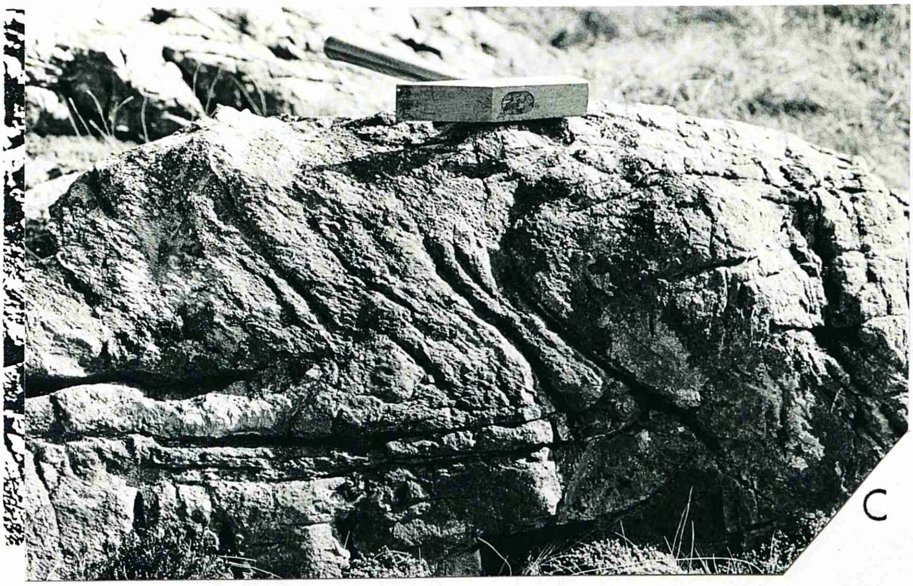
(B) Dl minor folds (S-vergence) in the quartzite on the upper limb of the Beinn Chuirn Fold plunging towards N260 - 265E. Locality NN20123069. Viewed to N320E.

(C) Dl minor folds in the psammitic Moine rocks on the upper limb of the Beinn Chuirn Fold. The fold plunge towards N220-230E, and have a strongly developed axial planar fabric. Locality B41(NN20603191).Viewed to N210E.

The head of the hammer is 16.5cm long.

A

B



C

Table 5-1: The Patterns and position of the minor folds on the major D1 folds

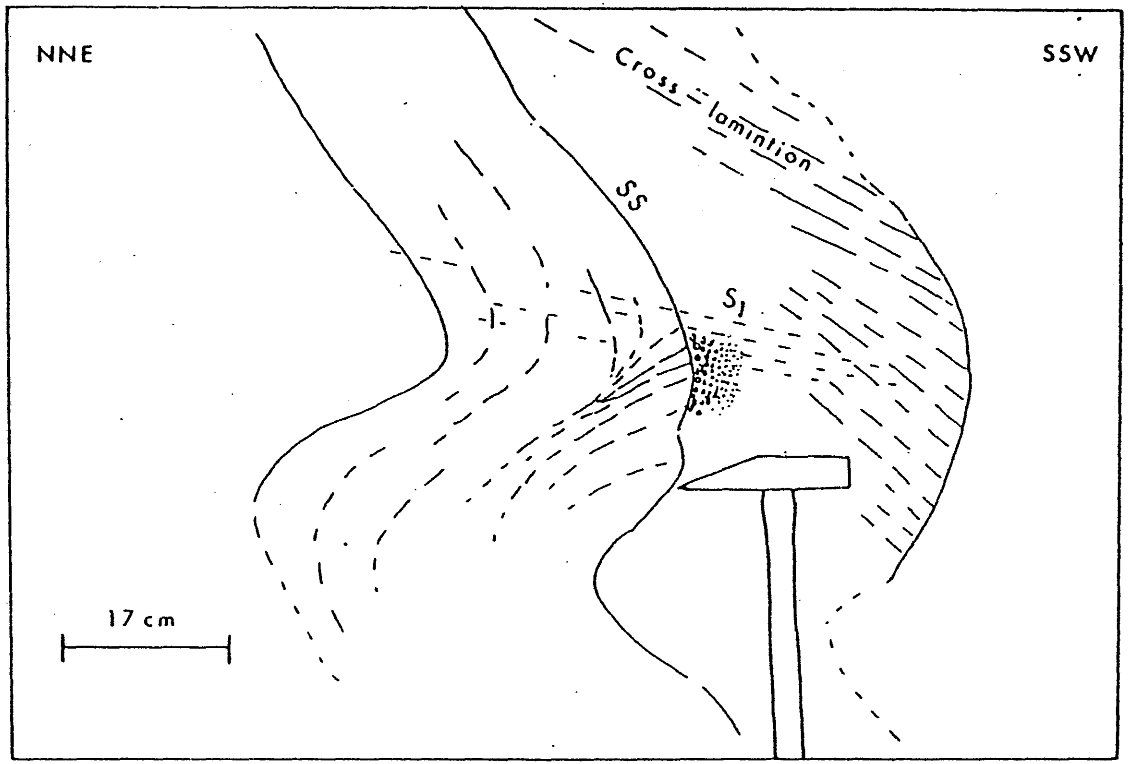
| Major Folds | Pattern | Position |
|---|---|---|
| 1. Beinn Udlaidh Fold | S-folds | lower limb |
| | Z-folds | upper limb |
| 2. Beinn Chuirn Fold | Z-folds | lower limb |
| | S-folds | upper limb |

´M´/´W´-folds are found in the hinge zones.

Plate 5-8

(A) D1 minor fold of bedding with well preserved cross-lamination and graded structure. Near the hinge zone of the Beinn Chuirn Fold. Locality B19(NN23332980). Viewed to N180E.

(B) Close-up of (A) to show that the cross-laminae are defined by Fe-ore minerals (magnetite). The head of the hammer is 16.5cm long.




Redrawn from Plate 5 - 8A

flows, but the rocks may have been deposited in either deep or shallow water.

F1 minor folds which have symmetrical profile (w-pattern) occur in a mixed quartzite and pelite on the upper limb of the Beinn Chuirn Fold (Plate 5-9), and show much thickening in noses and thinning of limbs, indicative of flow folding or buckle folds modified by pure shear.

Minor F1 folds also are well developed in the limestone. These folds have an S-shaped in profile (Plate 5-10).

<u>L1 lineation</u>

The lineation is seen as a mineral lineation marked by alignment of muscovite and biotite (Plate 5-11); by rodding (Plate 5-12) and by the SS-S1 intersection lineation (Plate 5-13). Other linear fabrics in the area are stretching lineations (Plate 5-14).

The L1 mineral lineation is generally very poorly or weakly developed. However, there are several localities where it is strongly developed especially on the semipelite surfaces ( e.g. NN24073125 ).

An L1 rodding lineation is strongly developed on psammitic surfaces and poorly or rarely developed in

Plate 5-9 : D1 minor folds ('m'- or 'w'- folds) in the mixed quartzite and pelite. Plunge from left to right towards N265E. Viewed to N220E. Locality 16(NN21782914). The tape scale is 7cm long.

Plate 5-10: D1 minor fold (S-vergence) in the limestone on the upper limb of the Beinn Chuirn Fold.Viewed down plunge towards N250E.
Locality C2(NN20183022).
The pencil is 14cm long.

Plate 5-11: L1 mica lineation on the semipelite surface in the Moine. Locality B9(NN24033143). Pencil points in the N202E direction. The pencil is 14 cm long.

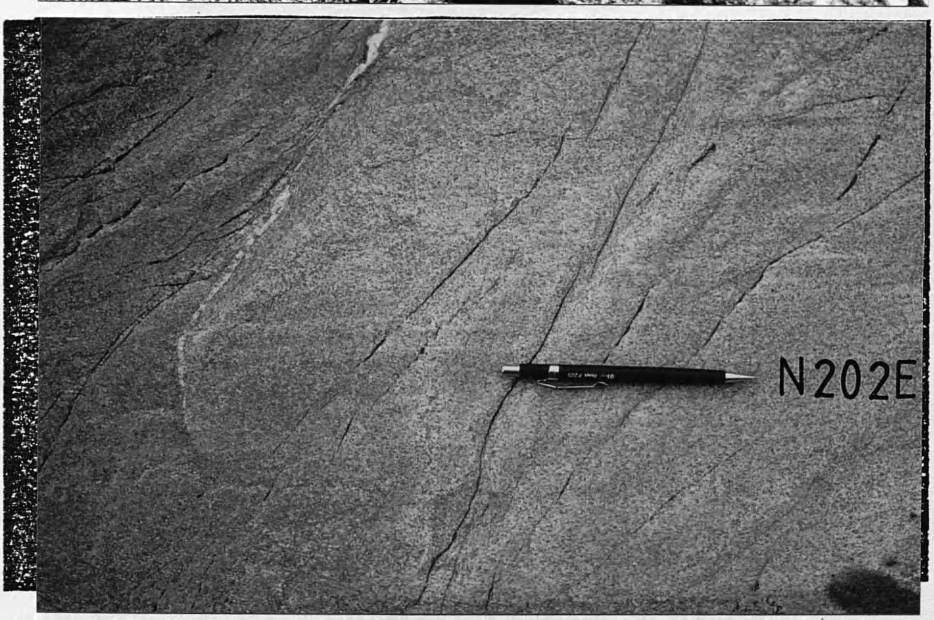
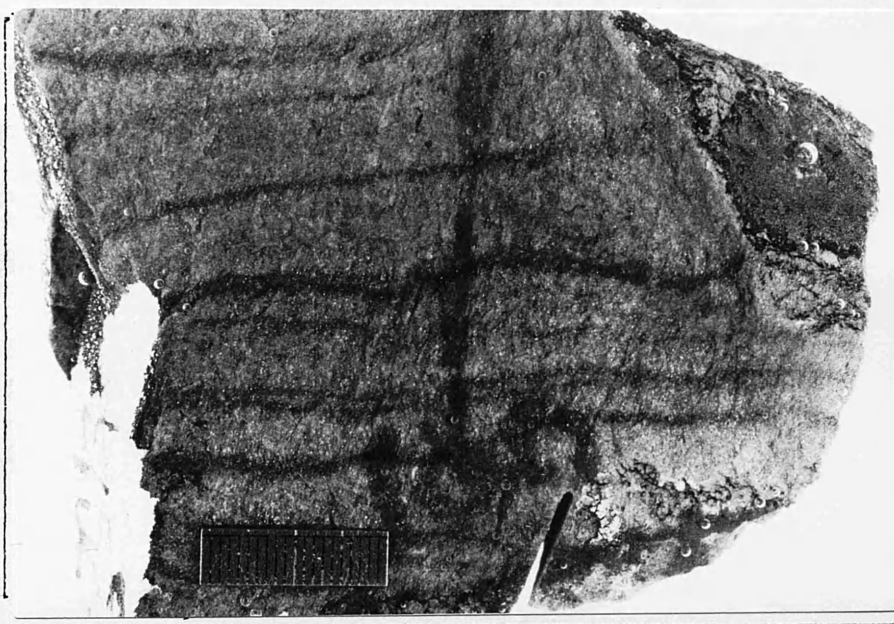

N202E

Plate 5-12: L1 rodding lineation overprinted by an L2 intersection lineation (S2-SS/S1) in the semipelitic Moine rocks. Locality B4(NN21193171). The coin is 2.7cm across.

Plate 5-13: L1 intersection lineation (SS-S1) on the cleavage (S1) plane in the semi-pelitic Moine rocks. Upper limb of the Beinn Chuirn Fold. Locality B53 (NN21253052).
The bar scale is 2cm long.

Plate 5-14: L1 stretching lineation on the quartzite surface.
Locality A1(NN24783318).
The bar scale is 3.0cm long.


L1=N178E
L2=N160E




N186E

semipelite or pelite.

The L1 intersection lineations are the dominant linear fabrics in the Moine psammite and semipelite.

These lineations are mostly seen near the hinge Beinn Chuirn Fold. This linear fabric is developed on the S1 cleavage plane ( NN21303040 ) and on bedding ( NN 20373195 ).

The stretching or extension lineation resulting from elongate pebbles of quartz or feldspar is best developed on the quartzite surface of the lower limb of Beinn Udlaidh Fold ( Plate 5-14 ).

The orientation of L1 lineations in the area is shown in Figs. 5-3 and 5-9.

5.2.2. <u>D1 major folds</u>

As shown in Fig 5-2, two major F1 folds, the Beinn Udlaidh Fold and the Beinn Chuirn Fold are found in the Glen Orchy area. Both of these major folds are associated with minor folds, and S- and L- fabrics.

## Beinn Udlaidh Fold (F1)

This major fold is situated in the north of the area. It is a syncline facing up to the south-east. Its axial-trace is shown in Fig 5-2. Its core lies in the pelite outcrop and its envelope forms by the quartzite.

The closure of the Beinn Udlaidh Fold can be demonstrated in the Allt Broighleachar river ( Locality A2, NN24423256 ) as noted by Bailey and Macgregor (1912) and Thomas and Treagus (1968). The hinge zone of this fold is composite, comprising of two synclines with an intervening anticline, which plunge towards the south-west ( Thomas and Treagus 1968, pp.128 ).

The upper limb of this fold is much reduced in thickness in comparison with the lower limb. As the closure of the fold lies within the quartzite, it is possible to demonstrate the axial-planar relationship of S1 at the fold hinge. However, where the closure of the fold lies within the pelite, S1 ( confirmed in thin-section ) is an axial-planar to the syncline, which plunges about 5-20 degrees to the south-west ( Fig. 5-8A ). However, there is plentiful evidence on the limbs of this fold, from F1 minor fold vergence, S1 fabric evidence and way-up criteria to confirm its D1 syncline.

Beinn Chuirn Fold (F1)

As shown in Fig. 5-2, the Beinn Chuirn Fold occurs structurally above, and to the south of the Beinn Udlaidh Fold. Its axial trace lies within the Moine outcrop. The fold closure and hinge zone are determined from the bedding-cleavage ( SS-S1 ) relationship and by congruous patterns of S- and Z- folds of D1 age.

Evidence from the geometry of the minor F1 folds and bedding-cleavage relationship, together with way-up structure indicate that the Beinn Chuirn Fold closes to the E.

Sedimentary structures such as cross-lamination are best preserved in the Moine rocks (psammite) on the upper limb and near the hinge zone of the Beinn Chuirn Fold but no way-up criteria are found in the Moine rocks (psammite) on the lower limb.

However, by using the way-up criteria which are found in the quartzite on the upper limb of the Beinn Udlaidh Fold and the repetition the quartzite and pelite on the upper limb of the Beinn Chuirn Fold ( Thomas and Treagus 1968; Roberts and Treagus 1975 ), together with the minor structures, it can be demonstrated that the Beinn Chuirn Fold is an anticline of D1 age.

## 5.3. D2 Deformation

This deformation is only of local importance and the minor structures are not related to any major fold within the area. The D2 structures are most evident in the pelitic or semipelitic lithologies, especially in the pelite on the upper limb of the Beinn Chuirn Fold. This deformation produces a strong crenulation cleavage (S2) and spaced cleavage (S2) deforming composite foliation ( SS/S1=Sc ) and cross-cutting minor F1 folds. S2 crosses SS and S1 at a small angle in an anticlockwise sense giving an intersection ( SS/S1-S2 ) generally plunging to the SE.

The geometry of the structures which are associated with the D2 deformation is shown in Fig. 5-4.

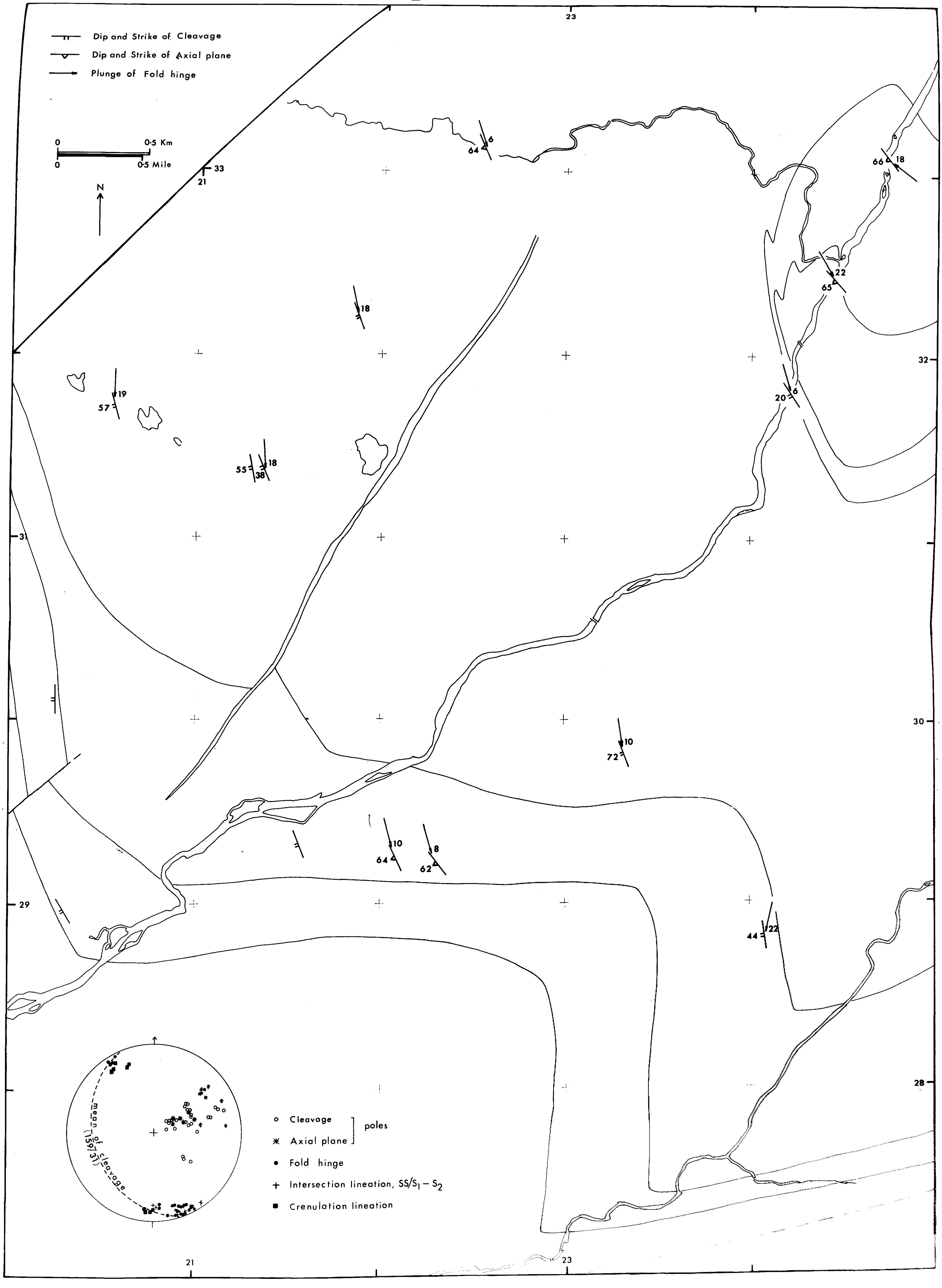
### 5.3.1. D2 minor structures

#### S2 cleavage

Like the early fabric (S1) the type of cleavage developed during the D2 deformation depends not only on the lithology which is affected but also on the intensity of the deformation.

In the psammitic Moine rocks the S2 fabric

Fig. 5-4 : $D_2$ STRUCTURES



defined by the spaced cleavage and the S2 fabric that develops in the semipelite or pelite beds is formed as a crenulation cleavage. This S2 cleavage is axial planar to the minor F2 folds.

In thin section S2 is always seen to deform the composite foliation ( SS/S1=Sc ) giving an intense crenulation with recrystallization of mica on the limbsof the F2 microfolds.

However, there are only a few localities where the S2 fabric can be seen in the field.

At locality B4 ( NN24193176 ), on the upper limb of the Beinn Udlaidh Fold, in the River Orchy, the S2 spaced cleavage which is axial planar fabric to the F2 minor folds is found in the transition passage zone of Moine rocks. The S2 fabric consistently cuts across the composite foliation ( SS/S1=Sc ) and the F1 minor folds at a small angle in an anticlockwise sense, dipping shallowly to the SW ( Plate 5-15 ).

In thin-section the S2 cleavage occurs as closely spaced (0.5 to 1.0mm ) microlithons, in which the relict S1 fabric can be seen in places ( Plate 5 - 16 ).

About 4-5m upstream of this locality B4 ( NN24193176 ) isoclinal D1 minor folds verging west are overprinted by S2 related to D2 minor folds verging

Plate 5-15: D1 minor folds (Z-vergence) folded by D2 minor folds (S-vergence)in the Moine semipelite - psammite on the upper limb of the Beinn Udlaidh Fold. D2 cleavage, which is axial planar to the D2 minor folds, is strongly developed.

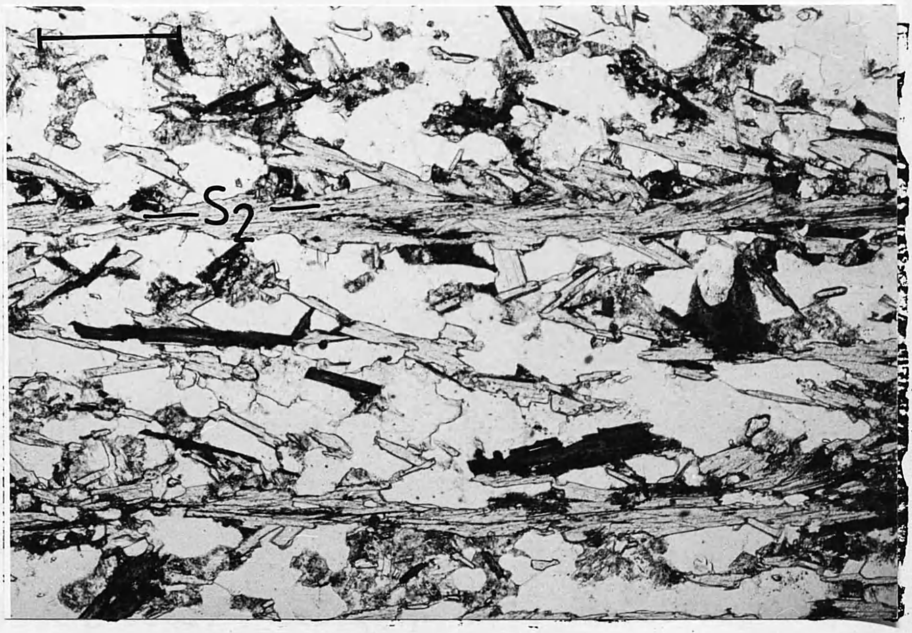
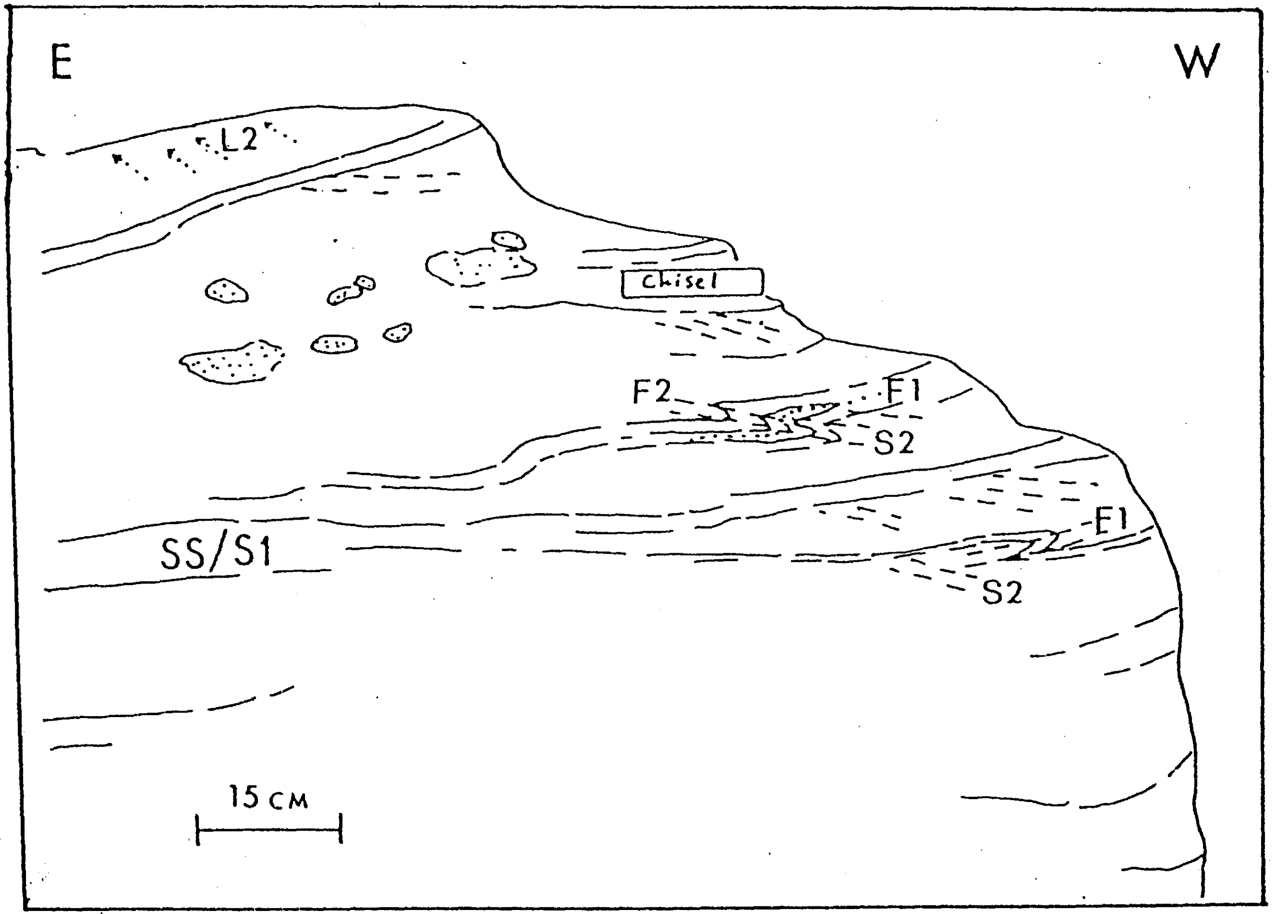



Plate 5-16: S2 close spaced cleavage with the relict S1 mica fabric preserved in the microlithons.
Locality B4(NN24193176).
The bar scale is 0.5mm long.




Redrawn from Plate 5 - 15

east. Under the microscope the S2 fabric is defined by a crenulation cleavage, but it does not develop a differentiated layering on the limbs of the F2 microfolds. About 5-6m downstream from locality B4 ( NN24193176 ) the S2 spaced cleavage strongly cuts across the composite foliation ( SS/S1=Sc ) in the flaggy Moine semipelite ( Plate 5-17 ). This ( SS/S1-S2 ) relationship indicates a D2 synform to the SW or W.

At locality B45 ( NN21333133 ), in the semipelite rocks, near hinge zone of the Beinn Chuirn Fold, the D2 deformation has produced a strong crenulation of the S1 fabric and as well as of bedding. In thin-section the S1 fabric is defined mainly by aligned flakes of brown biotite and muscovite.

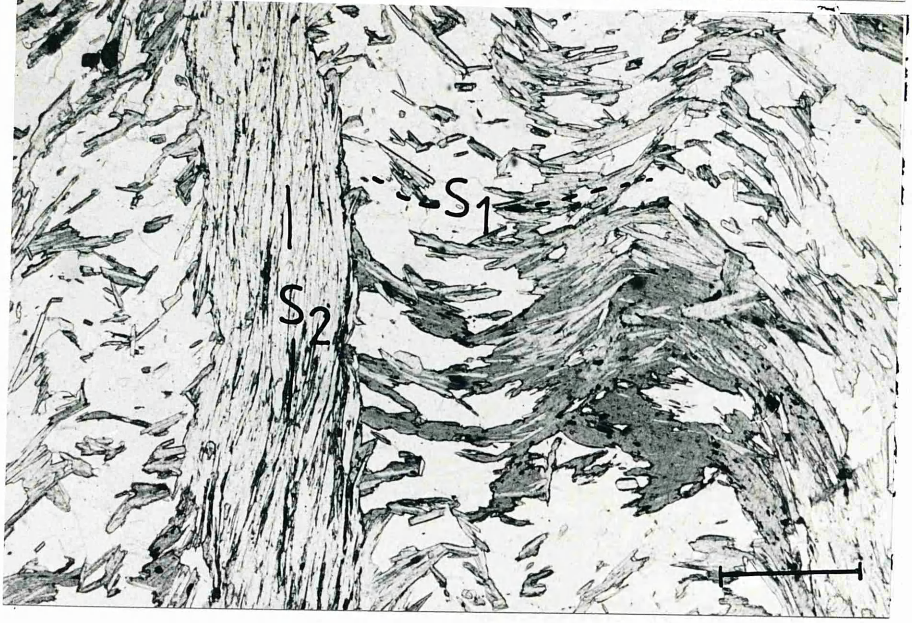
At locality B43 ( NN20553170 ), on the upper limb of Beinn Chuirn Fold, the S2 fabric is defined by a crenulation cleavage ( Plate 5-4 ). Here it can be seen that the composite foliation ( SS/S1=Sc ) and F1 minor folds ( Z- vergence ) have been deformed during the D2 deformation. The lineation is marked by a crenulation lineation. In thin-section the S2 fabric is made-up by a differentiated fabric of mainly muscovite and chlorite flakes which lie along the limbs of the F2 microfolds ( Plates 5-18 and 5-19 ).

Plate 5-17: Composite fabric (SS/S1) cut by S2 spaced cleavage. About 5-7m down -stream from locality B4(NN24193176). The handle of the hammer is 34cm long. Viewed towards N160E.

Plate 5-18: F2 microfold associated with the MS2 micas on the limbs in the semipelite Moine rocks. Locality B43(NN20553170). The bar scale is 0.5mm long.

Plate 5-19: MS2 differentiated layering along the limb of an F2 microfold. Locality B43(NN20553170). The bar scale is 0.5mm long.


$S_2$
$S_1$


$S_1$
$S_2$

About 4-5m south of locality B47 ( NN21333133 ) on the limb of a parasitic F1 minor fold, the spaced D2 fabric is strongly superimposed on the S1 fabric ( Plate 5-20 ). At locality B46 ( NN21303130 ) the S2 fabric is formed by spaced microlithons ( 0.1 to 0.3inch ) in which the composite foliation ( SS/S1=Sc ) forms a sigmoidal pattern ( Plate 5-21 ).

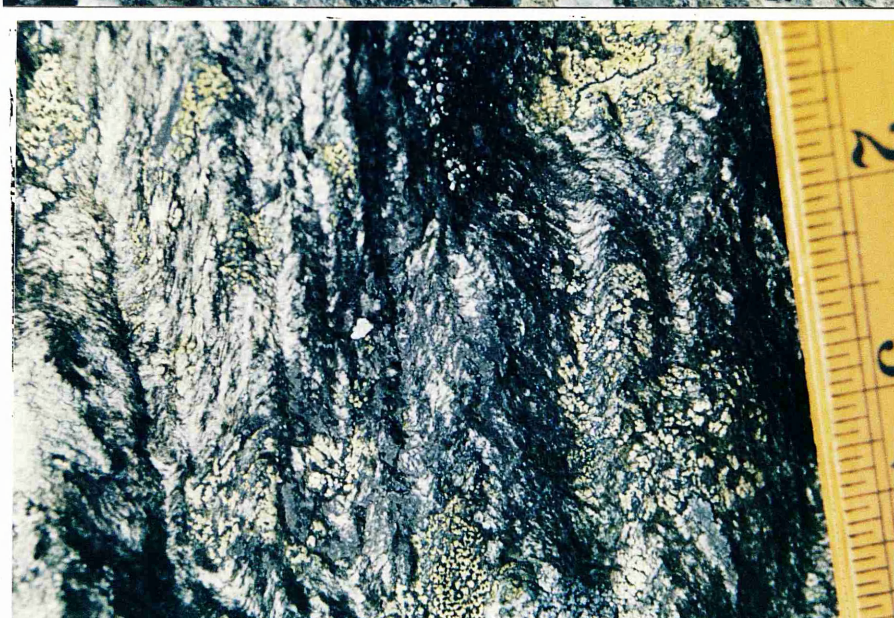
In some places the S2 fabric can also be traced using the growth of porphyroblasts ( feldspar and garnet ) which contain inclusion fabrics as a marker. At locality B6 ( NN24063142 ) the medium-grained ( S2 =Se ) fabric is deflected around plagioclase / K-feldspar porphyroblasts, that contain fine grained inclusion trails (Si) of quartz, feldspar, mica and ore. In the plagioclase crystals these inclusion trails (Si) are usually straight or slightly curved and always discordant with respect to the MS2 mica fabric.

At locality C15 ( NN21552930 ), garnet porphyroblasts contain inclusion trails ( SS/S1=Si ) which are strongly curved ( S-pattern ); the external fabric ( MS2 fabric ) is wrapped around the garnet. These textures are interpreted as indicating a MP1 or pre- D2 growth of the plagioclase and a syntectonic D1 but pre- D2 growth of the garnet. The geometry of the D2 planar fabrics is presented on a Fig. 5-4.

Plate 5-20: D2 cleavage defined by a somewhat spaced crenulation cleavage which deforms the composite fabric (SS/S1) in the psammite - semipelit Moine rocks.
Locality B47(NN21333133).
Viewed towards N010E.

Plate 5-21: (A) D2 cleavage defined by the spaced microlithons (0.2-0.8cm) deforms the composite fabric (SS/S1) in the semipelitic Moine rocks.
Locality B46(NN21293137).
Viewed towards N190E.
The head of the hammer is 16.5cm long.

(B) Close-up of (A).
The ruler scale is in inches.



F2 minor folds

Few minor folds were developed during the D2 deformation in the area. However, minor F2 folds (S-shaped) with a strongly developed axial planar fabric (S2) are found on the lower limb of the Beinn Chuirn Fold in the transition zone of Moine rocks ( Plate 5-15 ). Minor D2 folds ( S-shaped ) which are not associated with the development of the axial planar fabric (S2) can also be seen in the flaggy Moine psammite, especially in the north of the area, on the lower limb of the Beinn Chuirn Fold. These folds are considered to belong to the D2 generation as they have the same geometry as the minor D2 folds and fabrics elsewhere in the area.

At locality B9 ( NN24083125 ), F2 minor folds ( S-shaped ) with a weak axial planar fracture cleavage are found in the semipelite Moine rocks ( Plate 5-22 ).

In some places ( NN23342980; NN21863216 ) the minor D2 folds are defined by upright plunging folds which have an axial planar crenulation cleavage (S2).

The orientation of the minor D2 folds is shown in Figs. 5-4 and 5-8.

Plate 5-22: D2 minor folds (S-shaped) associated with a weak axial planar fracture cleavage in the semipelitic Moine rocks.
Locality B9(NN24083125).
Viewed down plunge to the N160E.
The handle of the hammer is 35cm long.

L2 lineations

The L2 lineations in the area are mainly marked by a crenulation lineation, by F2 hinges and by an ( SS/S1-S2 ) intersection lineation ( Plates 5-12 and 5-17 ), which mainly develops in the Moine rocks.

The orientation of the L2 lineation is shown in Fig. 5-9. The L2 lineation plunges at a low to moderate angles towards the SE-SSE or NW-NNW.

### 5.3.2. The D2 major fold

Evidence from both field and microscopic studies indicates that there is no major F2 fold in the studied area.

## 5.4. D3 deformation

The D3 deformation in the area is associated with the development of minor folds ( both S- and Z- shaped ) which plunge to either the north or south at low to moderate angles. No fabric (S3) has been observed in the area.

The linear fabric (L3) associated with this deformation is marked by the parallel hinges of crumples which do not develop an associated crenulation cleavage, and also by minor F3 folds hinges.

The structural elements related to this deformation are shown in Fig. 5-5, 5-6, 5-8 and 5-9.

### 5.4.1 D3 minor structures

#### S3 cleavage

No S3 cleavage ( field and microscopic evidence ) is recognised in the area.

#### F3 minor folds

F3 minor folds which affect the SS and S1 are strongly developed, particularly at the transition zone ( quartzite-pelite and pelite-pebbly quartzite ) on the upper limb of the Beinn Chuirn Fold ( Plate 5-23 ).

The F3 minor folds have both S- and Z- shaped in profiles ( as viewed down plunge ), suggesting that a major late fold crosses the area. The axial planes of the S-profile F3 minor folds have strikes SW-NE and dips to the NW at about 60 - 70 degrees. Whereas, the

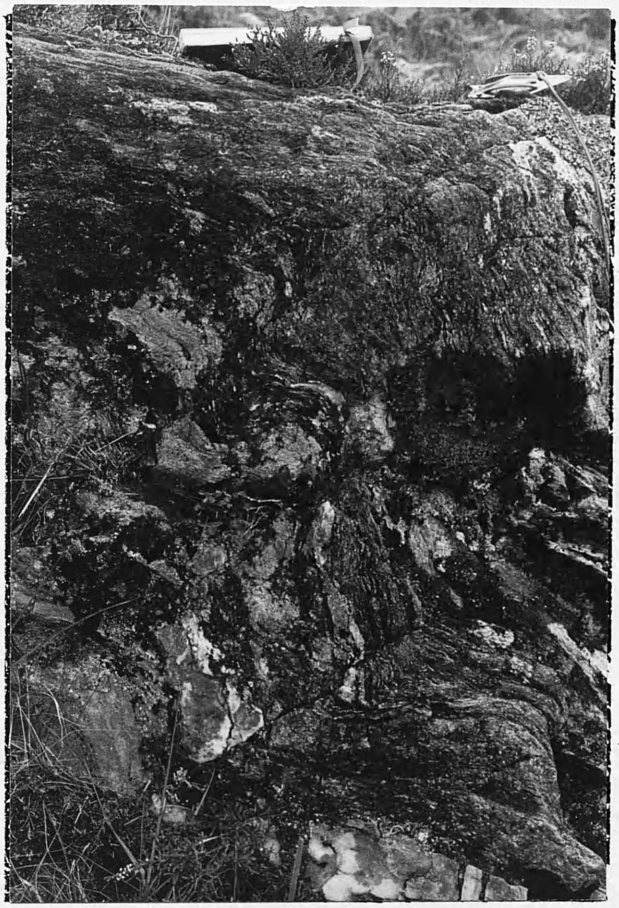


Plate 5-23: D3 minor folds (Z-shaped) in the transition zone (quartzite-pelite) on the upper limb of the Beinn Chuirn Fold. The axial plane is gently dipping (20-30 degrees) to the SE.

Z-profile F3 minor folds have a NE-SW strike and dip at about 50 - 60 degrees to the SE.

The hinges of these folds plunge at a low to moderate angles to the SW-SSW or NE-NNE ( Figs. 5-5 and 5-8 ).

L3 lineation

The L3 lineations are best developed on the pelite surfaces and the plunge and geometry of the L3 lineation is shown in Figs. 5-6 and 5-9.

### 5.4.2. D3 major fold

Glen Orchy Antiform

Bailey and Macgregor (1912) recognised that there is a late major fold in the Glen Orchy area, the Glen Orchy antiform. Their evidence was from the geometry of the bedding planes.

Thomas and Treagus (1968) showed that this antiform plunges at about 30 degrees, generally SW but in places to the NE, and has gentle dips ( up to 10 degrees ) on its NW-limb ( Glen Orchy area ) and relatively steep dips ( up to 40 degrees ) on its SE-limb ( Glen Lochy area ).

A number of D3 minor folds have been found in the area. These minor folds do not have axial planar fabrics when examined under the microscope.

The D3 minor folds at localities C5 ( NN20572979 ) and C19 ( NN21462919 ) show S- and Z- patterns ( as viewed down plunge ) which can be related to a large open D3 fold of bedding and schistosity in this part of Glen Orchy. The axial plane of the minor folds have moderate to steep dips to either the NW or SE and plunge varies from 10 - 30 degrees to the SW-SSW or NE-NNE. The evidence from the minor D3 folds suggests that the effect of the Glen Orchy antiform can be seen in the area and supports the Roberts and Treagus ( 1975, 1977 ) view that the Glen Orchy antiform developed in response to the D3 deformation.

## 5.5. D4 deformation

The D4 deformation is the last ductile event to affect the rocks of the area and is only of local importance. This deformation produces warps to open upright folds. F4 minor folds vary in trend, and plunge at low to moderate angles. No S4 planar fabric ( field or microscopic ) has been recognised.

Kinkband structures which deform bedding (SS) and S1 cleavage are found in pelite.

The L4 lineation in the rocks is only marked by crenulations, kinks and minor F4 fold hinges.

The plunge and geometry of the D4 structural elements in the area is shown in Figs. 5-5, 5-6, 5-8 and 5-9.

5.5.1. <u>D4 minor structures</u>

Broad warps to open upright symmetrical minor folds which deform both F1 and F2 minor folds are found in the Moine rocks ( Plate 5-24 ). The axial planes of these F4 folds are generally subvertical to vertical and the fold hinges plunge at a low angles ( 2-10 degrees ) with varies in trends (Figs. 5-6 and 5-8 )

On the upper limb of the Beinn Chuirn Fold,( locality C3,NN20243008 ), F4 open upright minor folds which fold F1 minor folds ( S-vergence ) are found in the transition zone of quartzite and pelite ( with thin beds of limestone ). This F4 fold has vertical or steeply-dipping axial planes and fold hinges which plunge at low angles to the SW-WSW.

Plate 5-24: D4 upright plunging folds in flaggy Moine psammite.
Locality NN(21883116).
Viewed towards N220E.
The handle of the hammer is 34cm long.

# Fig.5-5 : $F_3$ AND $F_4$ AXIAL PLANES

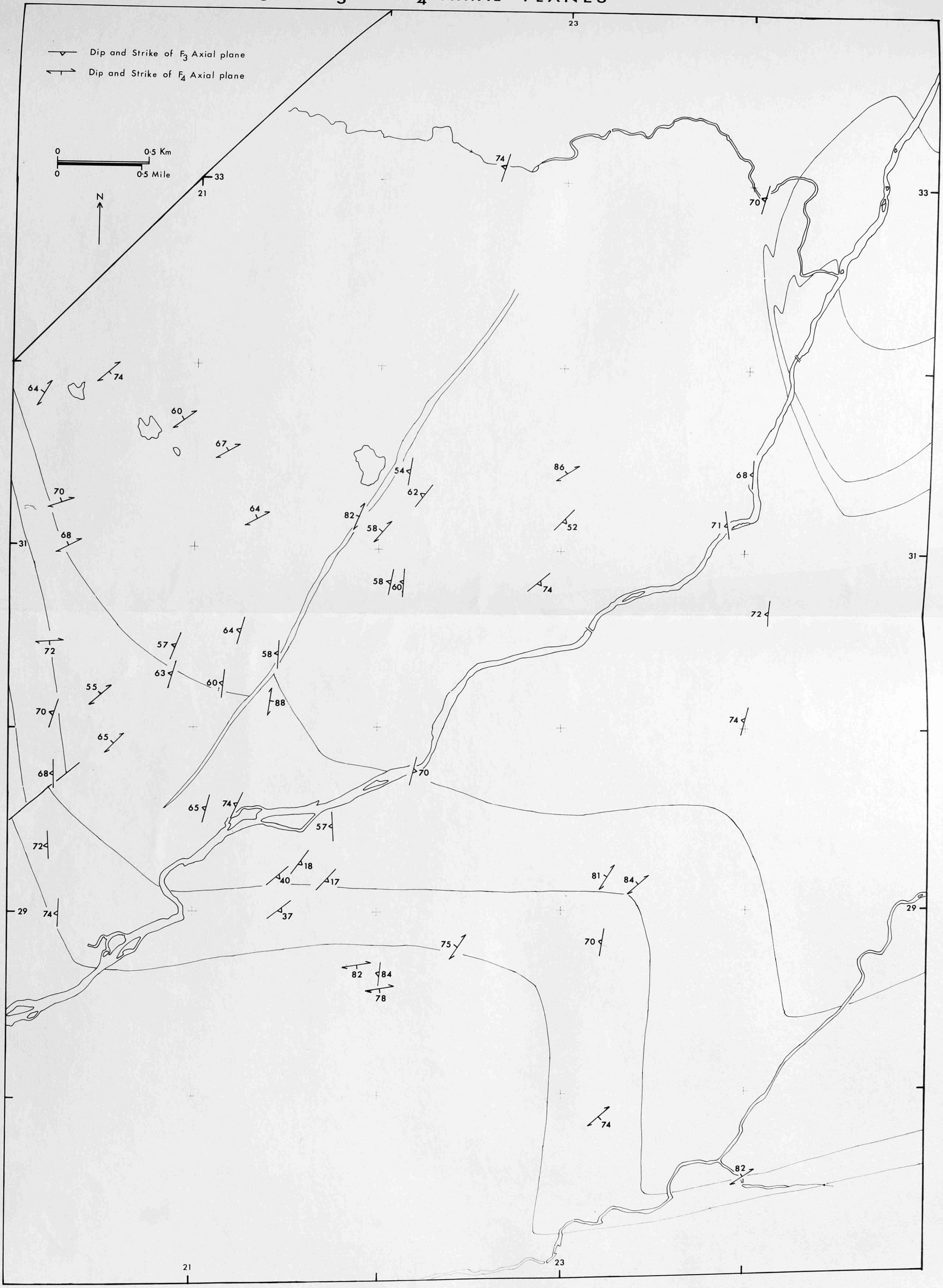
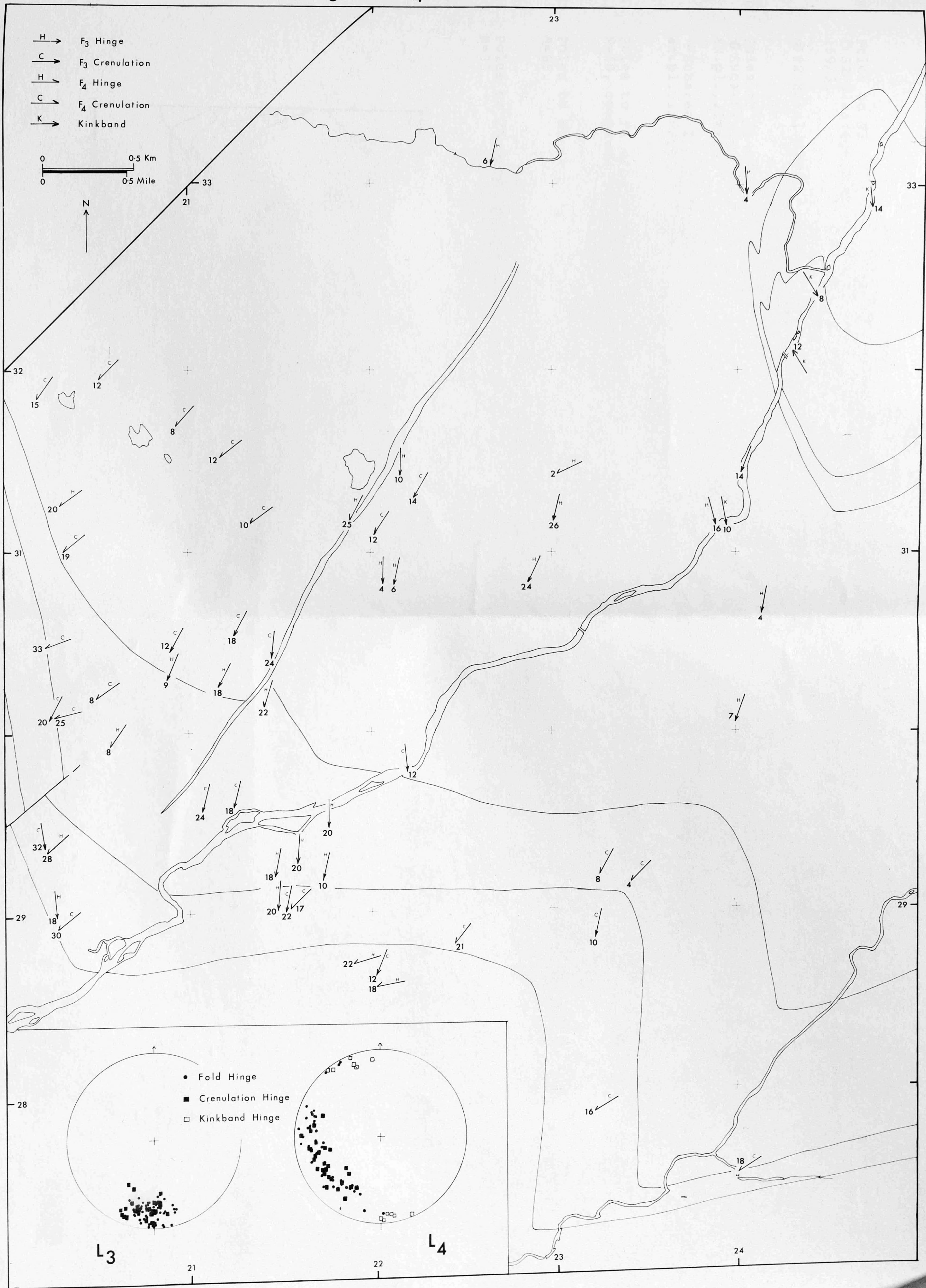


Fig. 5-6: $D_3$ AND $D_4$ LINEATIONS



H: Poles to S2,
○ S2 cleavage, N=47, computed mean, 159/31.

✳ F2 axial planes, N=21.

I: Poles to F1 axial planes,
● Subarea 1, N=30, computed mean of ax.pl., 218/18.

+ Subarea 2, N=21, computed mean of F1 ax.pl., 150/30.

J: Poles to F1 axial planes in quartzite, N=40, computed mean, 164/30, subarea 3.

K: Poles to F3 axial planes in the area, N=65.

L: Poles to F4 axial plane in the area, N=33.

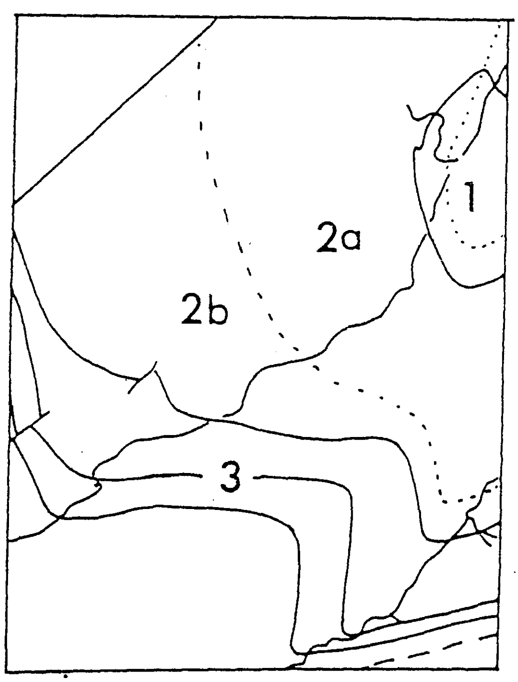


Figure 5-7: Lower hemisphere equal area projections of planar structures of the area. A map given below shows location of subareas.

A: Poles to SS in quartzite, N=140, subarea 1.

B: Poles to SS/Sl in pelite, N=90, subarea 1.

C: Poles to SS in Moine rocks, N=450; computed means of SS,152/25, subarea 2.

D: Poles to SS in Moine rocks.
● Lower limb (L.L) of the Beinn Chuirn Fold,N=97, computed mean of SS,158/32, subarea 2a.

× Upper limb (U.L) of the Beinn Chuirn Fold, N=58,computed mean of SS,160/43, subarea 2b.

E: Poles to SS in quartzite,N=142,computed mean of SS,145/28,subarea 3.

F: Poles to SS/Sl,
\+ Pelite,N=128,computed mean of Sl, 137/30,subarea 3.

● Pebbly quartzite,N=67,computed mean of SS,145/29,subarea 3.

G: Poles to Sl,
○ Lower limb (L.L) of the Beinn Chuirn Fold,N=33,computed mean, 160/38, subarea 2a.

▲ Upper limb (U.L) of the Beinn Chuirn Fold,N=48,computed mean, 158/32, subarea 2b.

Fig. 5-7

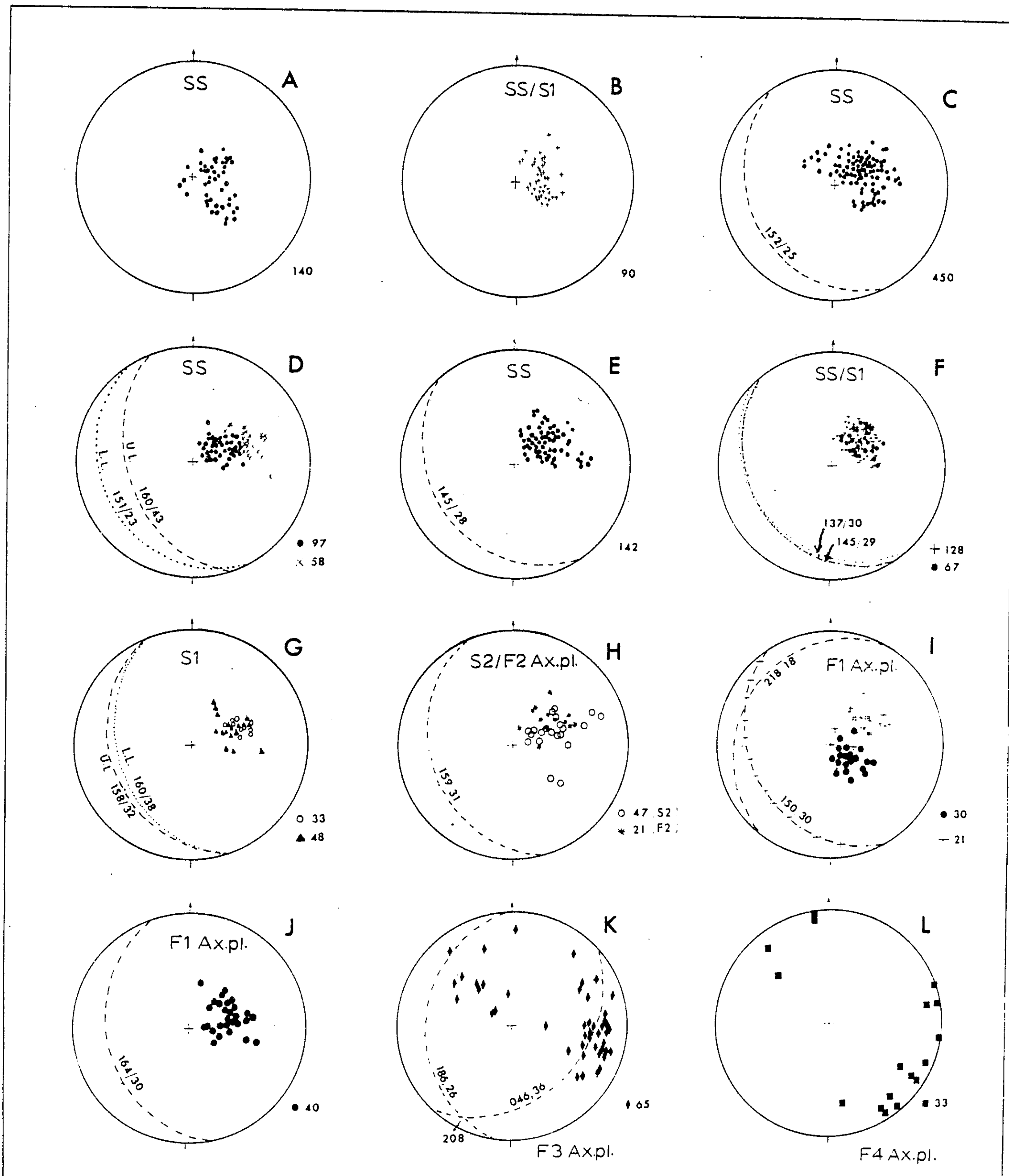

SS
A
140
SS/S1
B
90
SS
C
152/25
450
SS
D
U.L.
L.L.
160/43
151/23
97
58
SS
E
145/28
142
SS/S1
F
137/30
145/29
128
67
S1
G
L.L.
U.L.
160/38
158/32
33
48
S2/F2 Ax.pl.
H
159/31
47 (S2)
21 (F2)
F1 Ax.pl.
I
218/18
150/30
30
21
F1 Ax.pl.
J
164/30
40
K
186/26
046/36
208
65
F3 Ax.pl.
L
33
F4 Ax.pl.

Fig. 5-8: Lower hemisphere equal area projections of fold hinges. A map given below shows the location of sub-areas.

Subarea 1: A,D,G and J
Subarea 2: B,E,H and K
Subarea 3: C,F,I and L

Numbers of observations in brackets:

A (150), B (82), C (71), D (20),
E (26), F (8), G (21), H (13),
I (53), J (0), K (37), L (39).

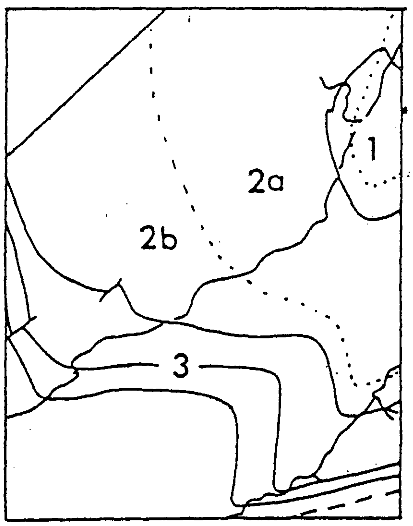


Fig. 5-8

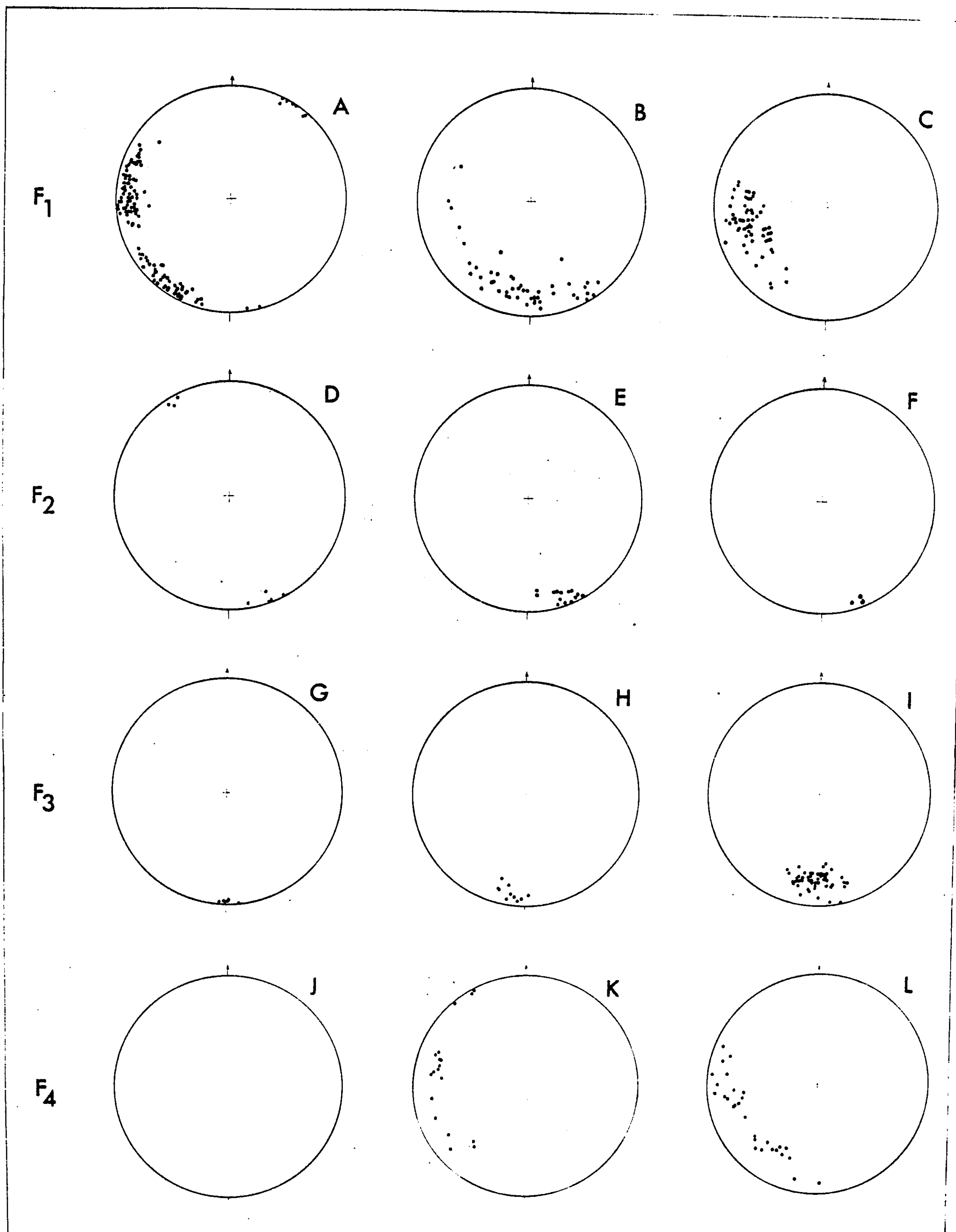


Fig. 5-9: Lower hemisphere equal area projections of linear structures. A map given below shows the location of subareas.

Subarea 1: A,D,G and J
Subarea 2: B,E,H and K
Subarea 3: C,F,I and L

Symbol:

●, mineral lineation; 0, rodding lineation, →, stretching lineation; +, intersection lineation; ■, crenulation lineation and □, kinkband hinges.

Numbers of readings in brackets:

A: ● (20), 0 (18), → (22);
B: ● (16), 0 (32), + (167);
C: ● (14), 0 (12);
D: ■ (15);
E: + (30), ■ (17);
F: ■ (10);
G: ■ (24);
H: ■ (14);
I: ■ (45);
J: □ (9);
K: ■ (27), □ (12) and
L: ■ (30), □ (9).

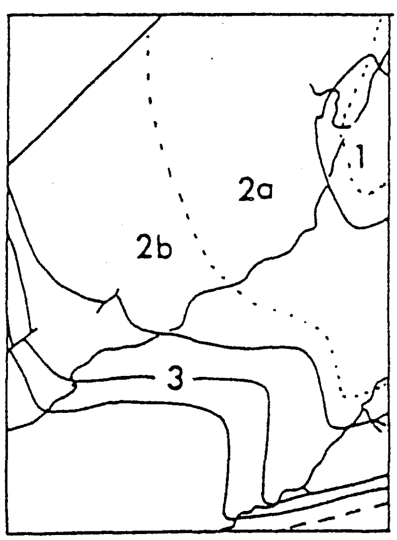
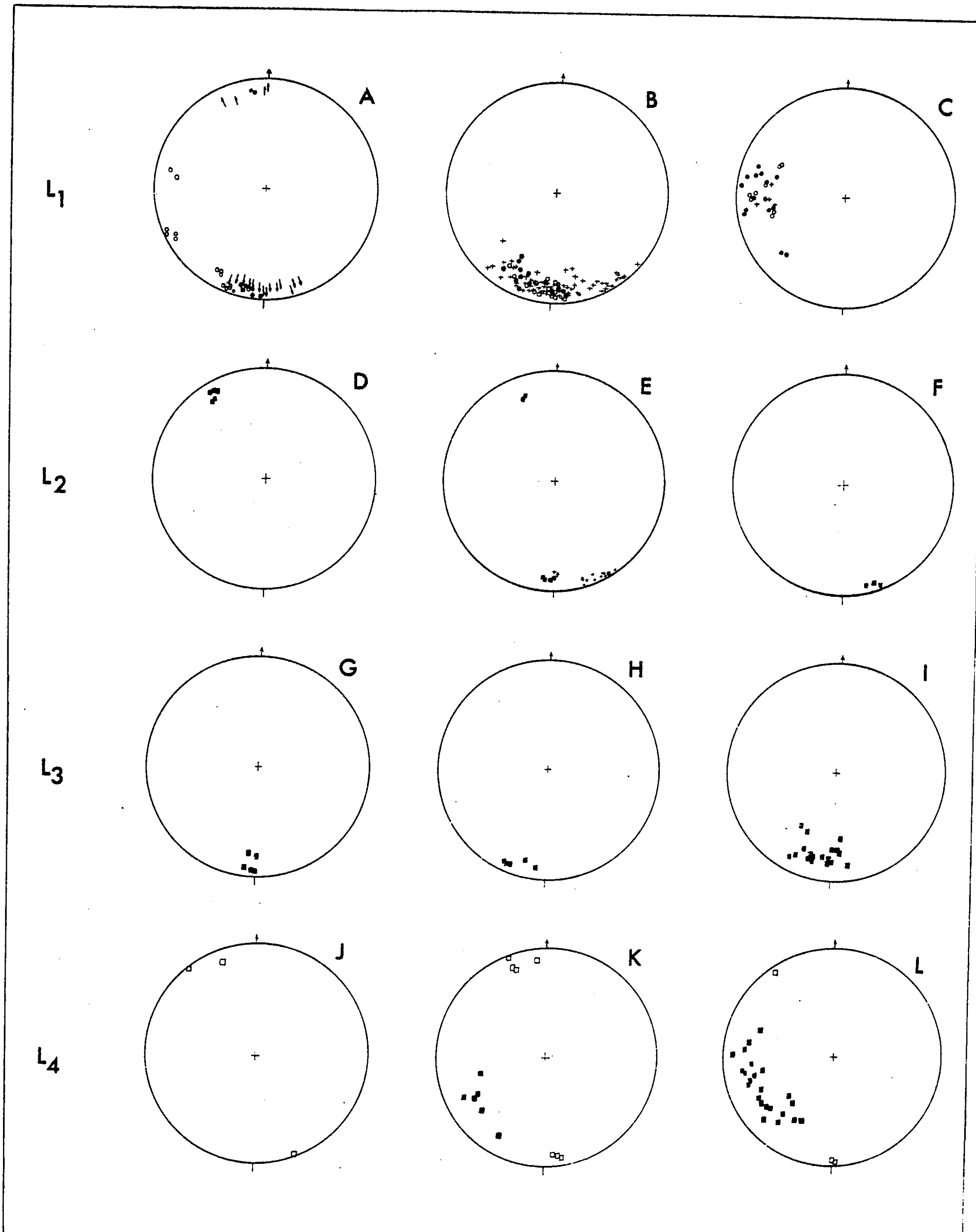


Fig. 5-9



D4 kinks have a variable orientation and have deformed both bedding (SS) and the S1 cleavage seen in the pelite beds. The kink bands commonly occur in a single set. However, in some places conjugate sets are seen.

5.6. Quartz breccia

The outcrop of the quartz breccia is shown in Fig. 4-1. The quartz breccia has a NNE-SSW trend and a variable width ( between 1m to 20m width ). However, up to 30m width has been observed in the largest body.

This rock is steeply dipping ( 80-90 degrees ) to the E. The rocks are brecciated, with angular quartz fragments and shows some cavities a few mm in diametre. In places, euhedral to subhedral quartz crystals are seen inside the cavity.

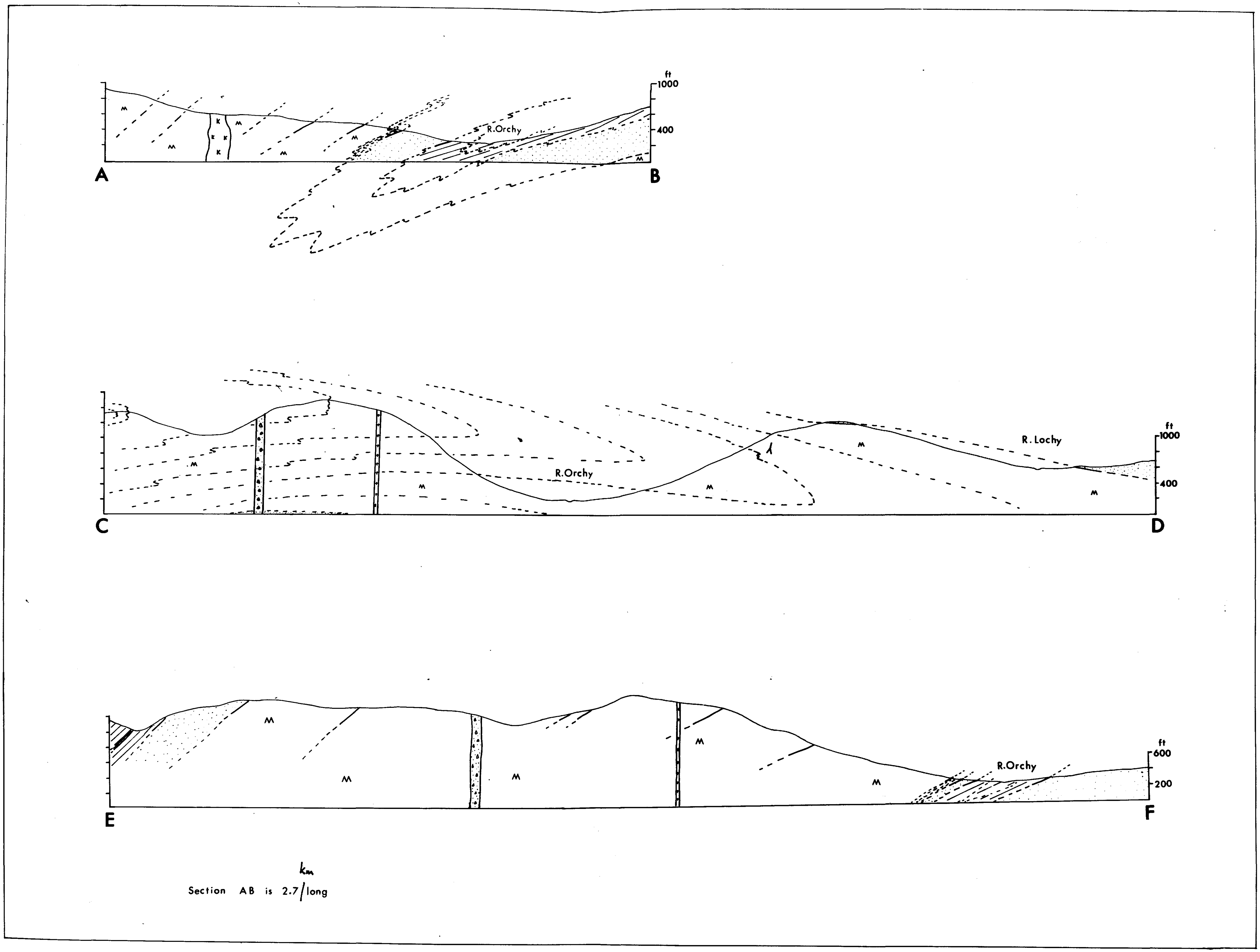
It may be that this quartz 'breccia' formed in the fault zone under extensional stress, where the quartz material from the country rocks moved into the fault zone, crystallized, and was later brecciated due to later movement within the fault zone.

Generally the quartz breccias in the area have a closely similar attitude to the F3 axial plane trends, so they may have developed during D3 deformation.

Fig. 5-10: True scale vertical cross-sections along Iines AB, CD and EF on Fig. 4-1.

Section AB is 2.7km long.

Fig. 5-10 : CROSS- SECTION



There are a few quartz veins which have an E-W trend and do not show brecciation.

At locality 14 ( NN21363022, Fig. 4-1 ) the NNE-SSW quartz breccia ( about 25m width ) is cut by the E-W dyke ( about 20m width ), suggesting that the NNE-SSW quartz breccia is older than the E-W dyke.

## 5.7. Faults and Joints

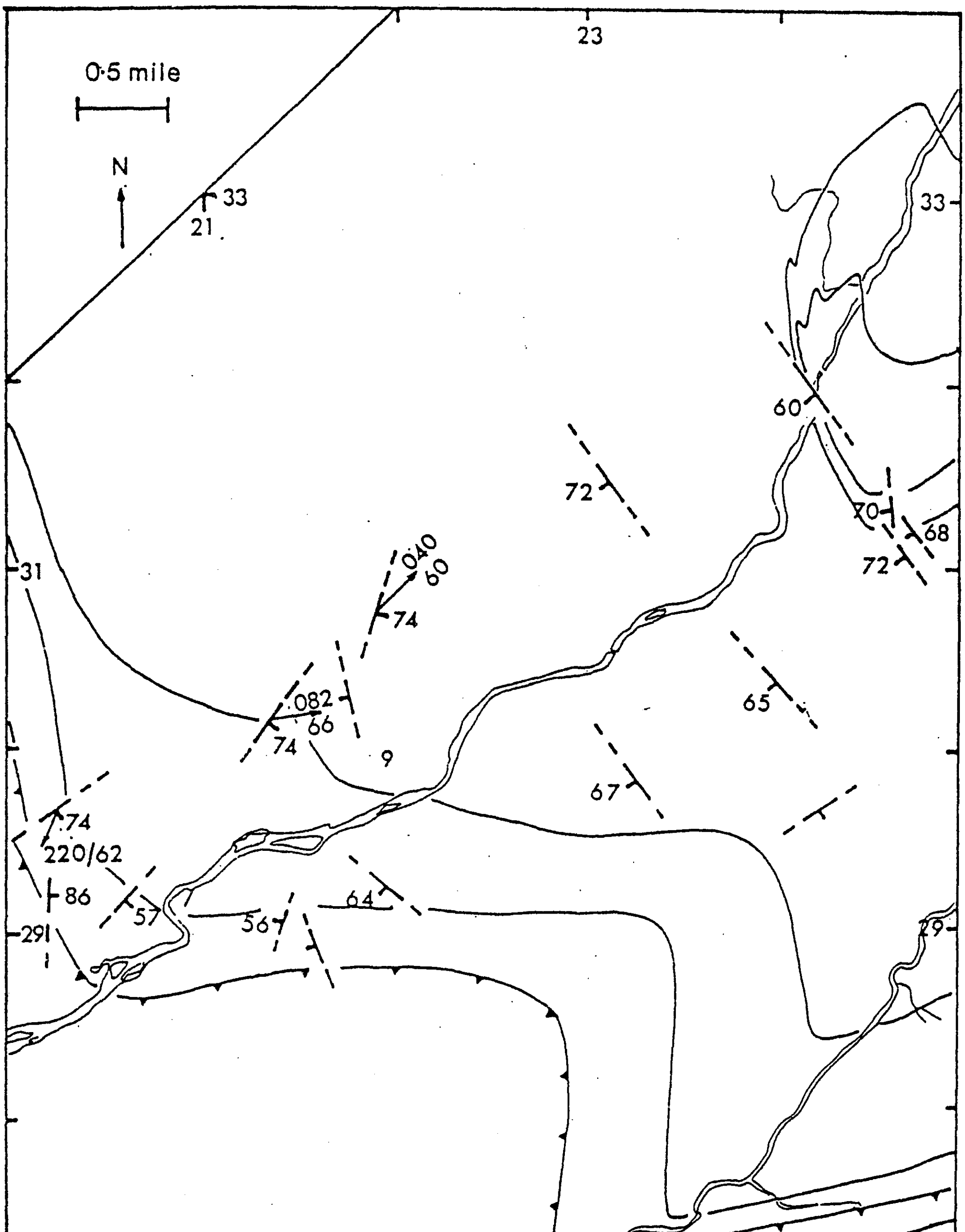
The faults which are found in the area are extensional faults ( Fig. 5-11 ). No strike-slip fault have been recognised but in some places small reverse faults are seen ( NN20222928 ).

At least, three sets of faults can be recognised with reference to their strike direction. These are :

(1) NNE-SSW strike
(2) N-S strike
(3) NW-SE or E-W strike

Most of these faults dip at about 60-80 degrees. The relative sense of movement on some of the faults has been identified using the orientation of the quartz fibres or slickenside lineations on the fault plane. These relative slip movements are presented on map,

Fig. 5-11: The geometry of the faults of the area. A small arrow indicates the relative movement on the fault plane.



marked by the small arrows.

The faults which have a NNE-SSW strike show a similar trend to the quartz breccia, therefore they may be contemporaneous. The N-S faults are well exposed in the river Allt Odhar in the SW of the area. The vertical displacement on this fault (N-S) is approximately 15-25 meters, and the fault has been cut by a NNE-SSW trending fault ( NN20242967 ). The E-W or NW-SE faults generally have a same trend as the E-W or NW-SE dykes ( ? Tertiary age ). Assuming that these faults are of similar age to the Tertiary dykes, they are younger than the NNE-SSW or N-S faults as the NNE-SSW quartz breccia has been cut by the E-W dyke ( NN21363022 ). From the above relationship it can be suggested that the relative ages of the faults going from the older to the younger, is: NNE-SSW fault older than N-S fault and older than E-W/NW-SE fault. However, to determine the relative age of the faults is not simple and the above sequence of events is not necessarily correct.

Joints are also common brittle structures found in the area and they may be divided into four groups with regard to their geometry :

(1) N-S joint

(2) NE-SW joint

(3) E-W joint

(4) NW-SE joint

Conjugate joints are also seen in the area ( NN24783318 ) but no detailed study of joint patterns has been made.

## 5.8. Structures associated with the Iltay Boundary Slide

As mentioned in Chapter 4 ( section 4.6 ), the line of outcrop of the Iltay Boundary Slide is not exposed in the area. Therefore, the slide has been located approximately between the closest exposures of the underlying pelite and of the overlying pebbly quartzite ( Fig. 4-1 ). The slide plane follows the attitude of the schistosity and bedding.

Since the slide zone is not exposed in the area, it is very difficult to decide whether the slide developed during either the D1 or D2 deformations, or later. Evidence which indicates that a slide or zone of ductile thrusting has affected the rocks in the area seen when the rocks are examined under the microscope and some evidence is obtained from exposures which are close to the slide.

### 5.8.1. Tectonic fabrics found close to/within the slide zone

At localities 10 ( NN221912813, Fig. 4-1 ) and 12 ( NN20062928, Fig. 4-1 ) the pebbly quartzite which lies close to or on the top of the slide plane and contains pebbles ( quartz and feldspar ) within it which have been deformed and show an elongate shape ( up to 0.9cm long ). These pebbles are flattened within the composite bedding schistosity plane ( Plate 4-4 ).

At locality C32 ( NN24142746 ), in the river Eas Daimh ( Glen Lochy area ), D1 minor folds ( S-vergence ) are seen in the pelite. These folds show a strongly developed axial planar fabric (S1) of biotite and muscovite flakes when examined in the thin-section. Based on this observation, where the minor fold found in the pelite show this type of fabric and have the same geometry as D1 folds outside the slide zone they are classified as being of D1 age.

At locality C13 ( NN20272894 ) in the river Odhar, the rocks (pelite) are highly deformed and show a mylonite fabric ( Plate 5-25 ). This, indicates that the rocks have been affected by the slide. Pressure shadows around garnet porphyroblasts are also clearly seen and the external fabrics wrap around the garnet

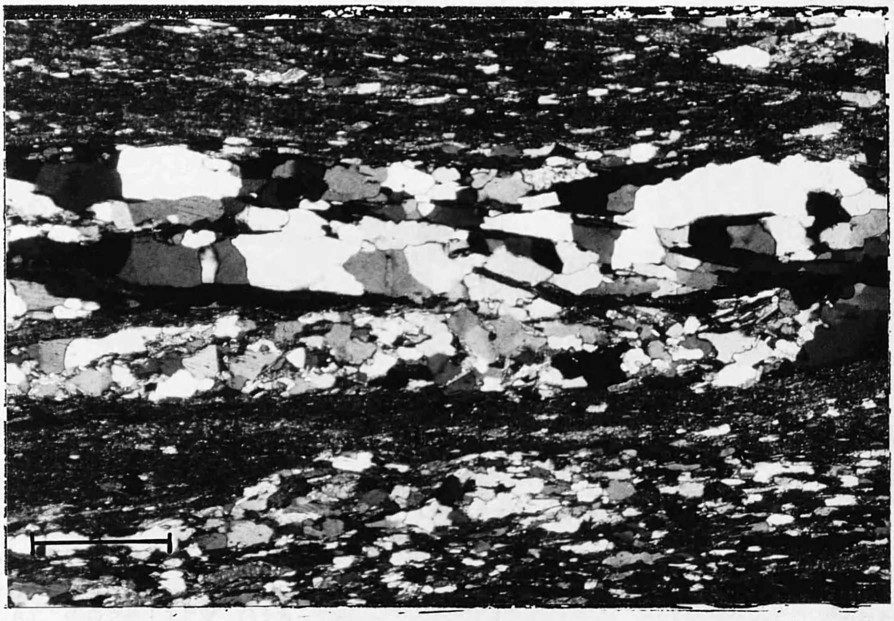


Plate 5-25: The fabric in the pelite-pebbly quartzite transition zone near the slide.

The bar scale is 0.5mm long.

Plate 5-26: The matrix fabric wrapped around the garnet porphyroblasts. Pressure shadows seen at the edge of the garnet.
The bar scale is 0.5mm long.

(Plate 5-26). The garnets lack an internal inclusion fabric.

At locality C12 (NN20262898) a sigmoidal fabric pattern is seen in the pelite in thin-section (Plate 5-27). The dominant fabric in these rocks is an alignment of quartz grains, brownish biotite and muscovite flakes.

At locality C15 (NN21552930) the external fabric is wrapped around the garnet porphyroblasts are seen in the pelite. The garnet contains the inclusions fabric which makes an angle to the external fabric. Recognition of the relative age of the main fabric in the slide zone depends on the age of the garnet.

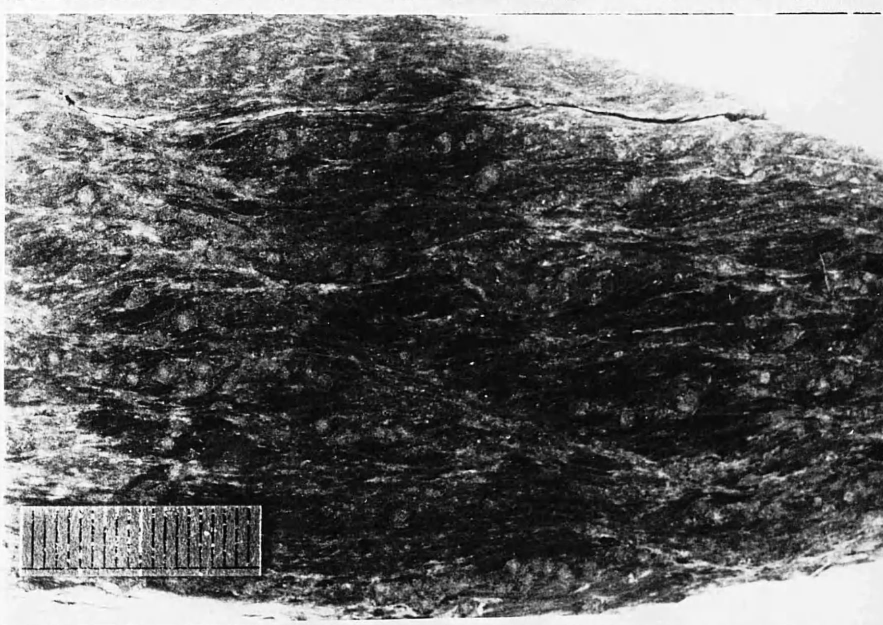
At locality C30 ( NN23112801 ) the extension crenulation cleavage (Plate 5-28) is found in the pelite. The spacing of the cleavage zone varies from 0.5-0.8cm. The cleavage zones are marked by the concentration of muscovite and chlorite ( Plate 5-29 ).

The extensional crenulation cleavage is defined by sets of small-scale ductile shear-bands formed during extension along an earlier foliation, and is common in mylonite zones ( Platt and Vissers, 1980 ).

Plate 5-27: A weak sigmoidal pattern of MS1 fabric in the pelite - pebbly quartzite transition.
The bar scale is 0.5mm long.

Plate 5-28: Extensional crenulation cleavage in the pelitic Dalradian rocks on the upper limb of the Beinn Chuirn Fold.
Locality 30 (NN23112801).
Photograph from a cut surface.
The ruler scale is 2cm long.

Plate 5-29: Muscovite and chlorite flakes concentrated in the extensional cleavage zone.
The bar scale is 0·25mm long.



In general, from this investigation of rocks, occurring close to the slide, it can be suggested that there are possibly D1 and D2 structures associated with the slide. From this evidence, the present study suggests that the Iltay Boundary Slide movement probably took place during D1 deformation and has been reactivated locally during the D2 deformation.

However, such an interpretation is only provisional and may require modification on the basis of further work.

# CHAPTER 6

# MINERAL GROWTH AND DEFORMATION RELATIONSHIPS

## 6.1. Introduction

This chapter presents the result of a microscopic study to investigate timing of deformation and metamorphism events by using microstructural relationships. A number of workers (including Rast; 1958; Sturt and Harris, 1961; Zwart, 1963; Johnson, 1962; Spry, 1969; Vernon, 1977) have developed a well established technique that enables mineral growth to be related to deformation episodes. This approach of textural analysis is obviously a very important one, especially in areas which have undergone a series of metamorphic and deformation episodes. However, depending on the criteria used, there are some ambiguities in the interpretation of these fabrics. For instance, if a fabric in a rock is truncated by a porphyroblasts with no evidence of an internal fabric (Si), then the growth period of the porphyroblasts post-dates the formation of the fabric. However, if the porphyroblasts contains an internal fabric at an angle to the external fabric then the porphyroblasts must pre-date the formation of that external fabric (Se). Following this argument through, there is no reason why the porphyroblasts with no internal fabric should not, also, pre-date the main rock fabric (Ferguson and Harte, 1975).

Another point of disagreement concerns the time relations between a porphyroblasts that has a fabric wrapped around it,and that fabric. Spry (1969) decided that as it was ´impossible´ for a growing grain to deform its matrix the porphyroblast must pre-date the external fabric. Other workers, however, (Harvey and Ferguson, 1973; Yardley, 1974 ) have questioned this assumption, and Yardley showed that by a process involving the pressure solution of soluble phases in the matrix (e.g. quartz) a growing porphyroblast could deform the enclosing matrix without doing any work against the load pressure.

Obviously ambiguities and disagreement on fundamental points, such as the two given above, lead to the possibility of two different workers producing different histories of mineral growth within the same area. Consequently the application of this technique is difficult to make entirely objective. It is important consider the bulk composition of the rock, so that periods of mineral growth that are inconsistent with normal chemical processes are not postulated (Vernon, 1975; p.224). In other words it is important that if a mineral is suggested as growing during a certain phase that there is another mineral or set of minerals breaking down at the same time which are suitable chemical composition for it to grow.

## 6.2. S1 fabric

As described in the chapter 5 the S1 fabric is the dominant fabric which developed in the rocks of the area. The development of this fabric throughout the area, especially in the Moine makes it a useful reference time horizon (assuming no diachroneity across the area) in the recognition of metamorphic growth phases.

The S1 fabric is a closely penetrative cleavage (0.01 to 0.1mm) of quartzo-feldspathic layers and micaceous layers. It consists of aligned micas (muscovite and biotite) and quartz grains. Both mucsovite and biotite which have a similar grain size and shape (generally 2.0-0.5mm long) and show a very strong preferred orientation (Plates 5-1 , 6-1 and 6-2). In an area such as this where the F1 folds are tight to isoclinal the S1 fabric away from the fold hinges, will be parallel or subparallel to bedding (SS).

This fabric is of MS1 age, and possibly has been recrystallised and reinforced during later events such as MS2. The S1 fabric is also preserved as an inclusion fabric in the porphyroblasts of feldspar, biotite and garnet (see later sections).

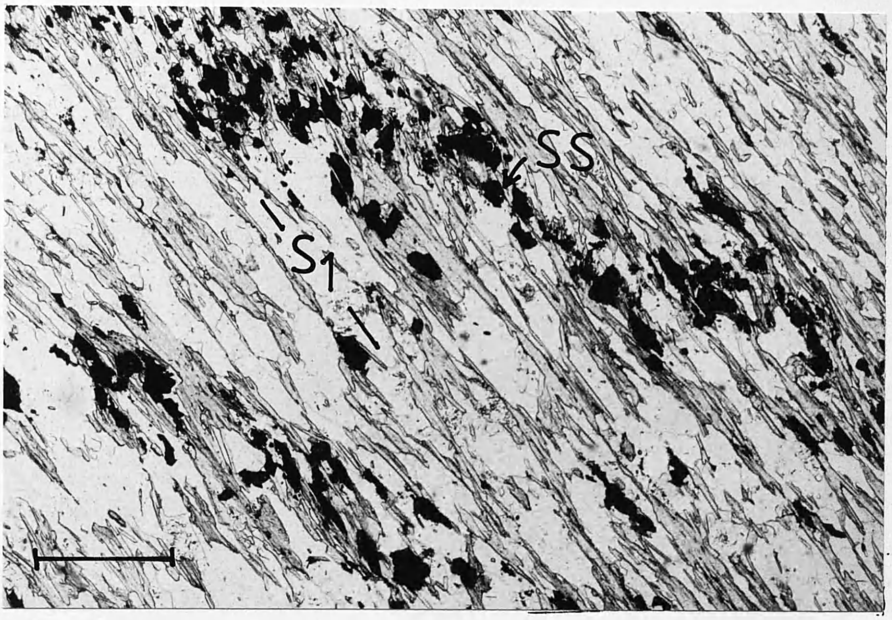



Plate 6-1: Bedding (SS) defined by the opaque mineral (dark) cut by S1 mica fabric in the semipelite Moine rocks, on the upper limb of the Beinn Chuirn Fold. Locality B53(NN21253052). The bar scale is 0.5mm long.

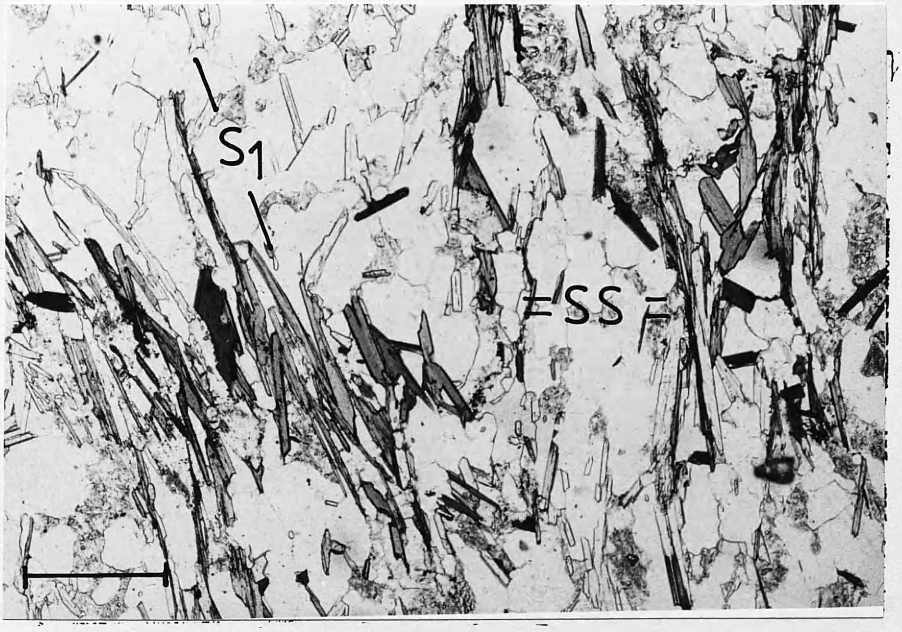



Plate 6-2: S1 mica fabric is at right angles to the bedding (S1) in the pelitic Dalradian rocks, near the hinge zone of the Beinn Udlaidh Fold. Locality A2(NN24423256). The bar scale is 0.5mm long.

## 6.3. S2 fabric

In thin-section, the S2 fabric is always marked by the zonal crenulation of the S1 fabric (plate 6-3) and in some places is expressed as spaced cleavage where the relict S1 fabric can be seen in the two microlithons (Plate 5-16). The spacing of the microlithons varies from 0.2-0.9mm. However, where D2 minor folds lack an axial plane cleavage in pelitic rocks a 'herring-bone' pattern is found ( Plate 6-4 ) in which the mica flakes overlap one another without bending or fracturing.

The S2 fabric is defined by the alignment of mainly muscovite with some biotite and chlorite. The S2 mica fabric may be composed of micas of MS1 age which have recrystallised during MS2.

## 6.4. Growth of Muscovite

### 6.4.1. MS1 muscovite

The muscovites which have developed within this period often form part of the S1 mica fabric and are in close association with MS1 biotites. These muscovites are identical in shape and grain size to the MS1 biotite.

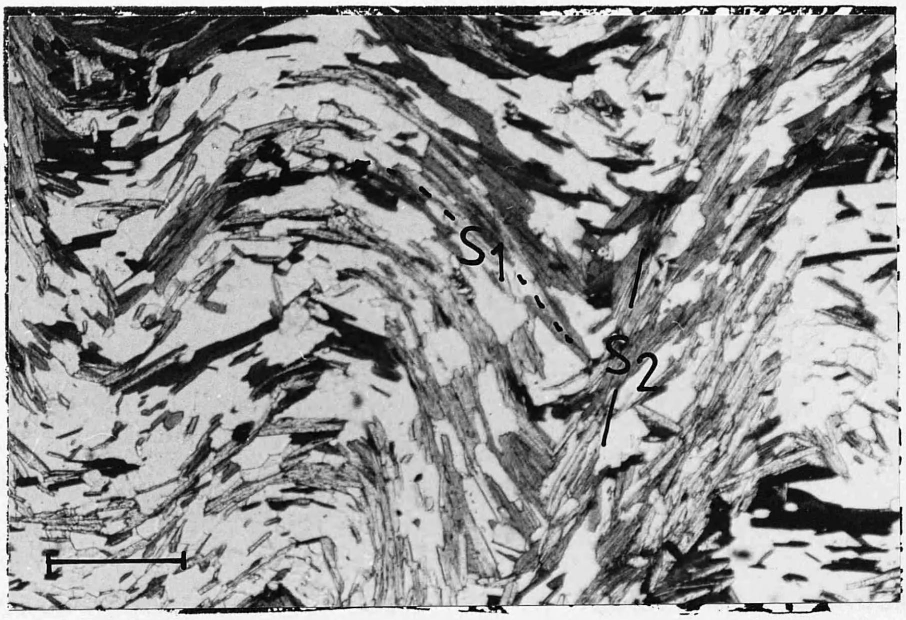



Plate 6-3: Zonal crenulation cleavage (D2) in the pelitic Dalradian rocks.
The bar scale is 0.5mm long.

Plate 6-4: ´Herring bone´ pattern:D2 fabric.
The bar scale is 0.5mm long.

### 6.4.2. MS2 muscovite

Muscovite which grew during this time is recognised as a differentiation layering (S2) along the limb of an F2 microfold ( Plate 5-19 ).

### 6.4.3. Post-D2 muscovite

These muscovites are often seen as randomly orientated crystals overprinting the MS2 fabric. These muscovite reach 0.5cm long.

## 6.5. Growth of Biotite

### 6.5.1. MS1 biotite

Biotite which grow within MS1 period are important constituents of the S1 mica fabric.

### 6.5.2. MP1 biotite

There are 3 different types of biotite which have developed within these period and can be recognised throughout the area.

(a) MP1a biotite occurs as cleaved flakes up to 2.5mm long (Plate 6-5). These biotites are seen to have a completely random orientation. These flakes also have an irregular edge and overgrow the quartz grains, indicating that they grew during static phase of MP1 or during MP2 age.

(b) MP1b biotite is a biotite which always lies at an angle to the MS1 fabric (Plate 6-6).These biotites occur as subhedral to euhedral shapes, varying from 0.5 to 2.0mm long.

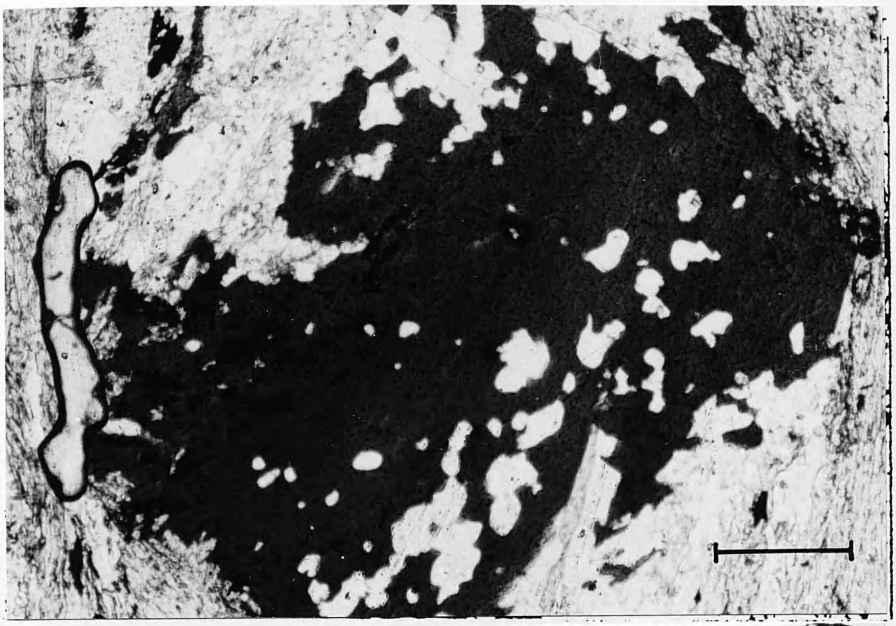
In the hinge zones of F1 microfolds, these biotites lie at an angle to the axial planar mica schistosity.

(c) MP1c biotite has an inclusion fabric (Si) of quartz and feldspar which is seen as straight trails (Si) which are generally continuous across the biotite from margin to margin. This inclusion fabric (Si) is continuous with that of the external fabric (Se) of MS1 matrix schistosity ( Plate 6-7 )

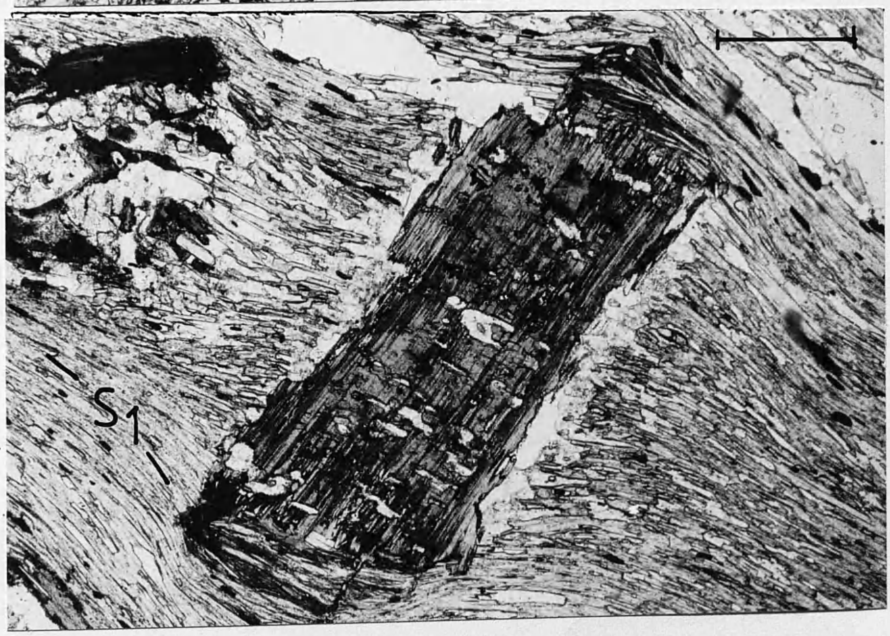
Plate 6-5: MP1a biotite.
The bar scale is 0.5mm long.

Plate 6-6: MP1b biotite porphyroblasts (B) lie at an angle to the S1 axial planar fabric.
The bar scale is 0.5mm long.

Plate 6-7: MP1c biotite with Si parallel to Se.
Where Se is the MS1 fabric.
The bar scale is 0.5mm long.




SS
$S_1$
B


$S_1$

### 6.5.3. MP2 biotite

Two different types of biotite which developed within the MP2 period can be recognised in the area.

(a) MP2a biotite always lies at an angle to the crenulated MS1 fabric and forms cyrstals up to 2.0mm long. This biotite contains a helicitic inclusion fabric (Si) which shows a similar pattern to, and is concordant with, the external fabric of the matrix schistosity (Se), Plate (6-8).

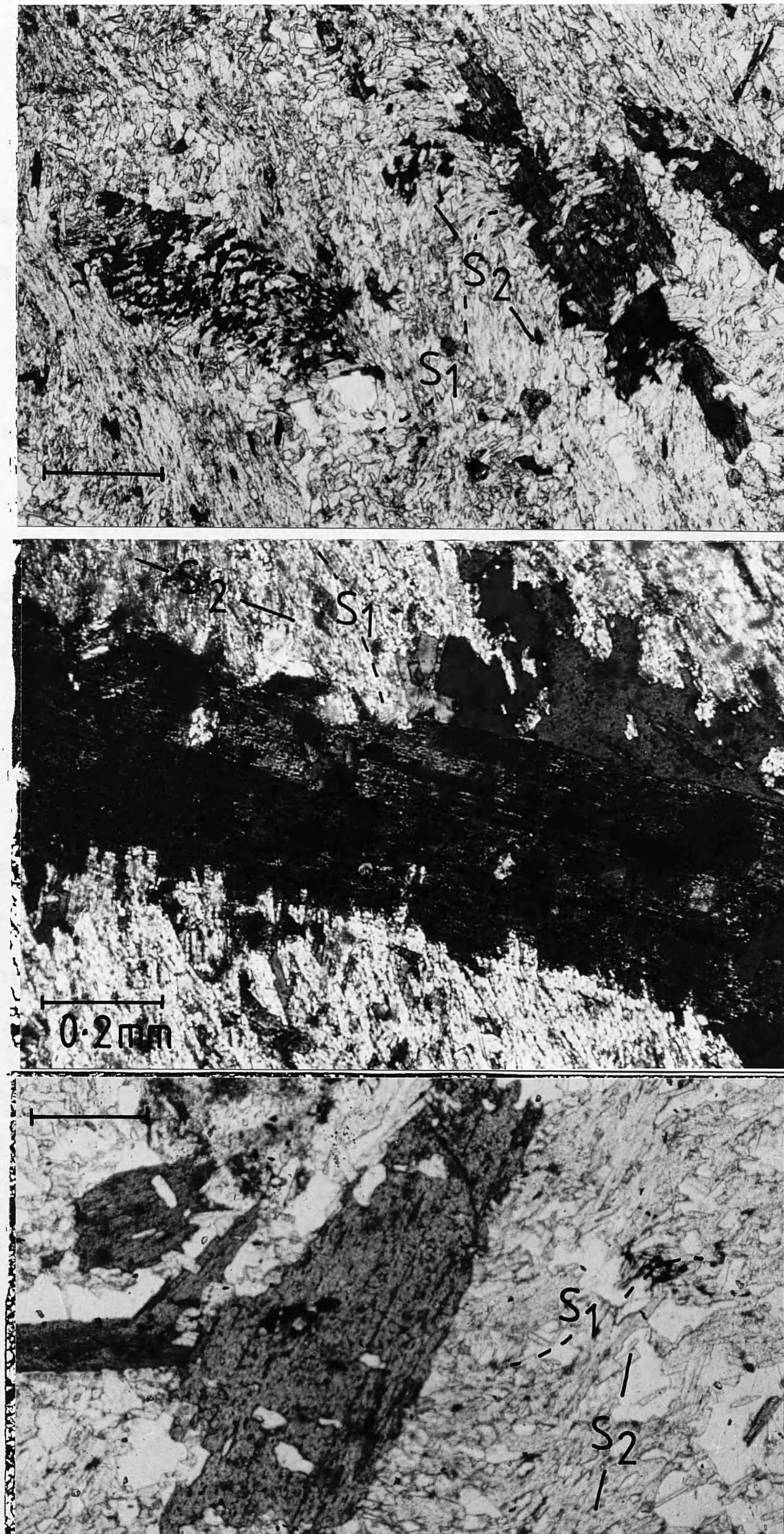
These biotites also overgrow the MP1 plagioclase with continuous boundaries, indicating that they grew during the MP2 static phase or MP3 time (Plate 6-9). These biotites have partially broken down into the an Fe-ore mineral, in which the trend of the crenulated MSI fabric is still preserved (Plate 6-8).

(b) MP2b biotite occurs as large subhedral crystals, up to 3.0mm long. These biotites are seen to overprint the crenulated MSI fabric with no inclusion fabric (Si) seen in the biotite (Plate 6-10).

Plate 6-8: MP2a biotite with preservation F2 microfold fabric.
The bar scale is 0.5mm long.

Plate 6-9: MP2a biotite which has overgrown the MP1 plagioclase.
The bar scale is 0.2mm long.

Plate 6-10: MP2b biotite grown across the crenulated MS1 fabric.
The bar scale is 0.5mm long.


$S_2$
$S_1$
$S_2$
$S_1$
0·2mm
$S_1$
$S_2$

## 6.6. Growth of Garnet

Garnet is uncommon in the Moine rocks in the area, but is commonly found in the Dalradian pelite and has generally been retrogressed to green chlorite.

It is usually subhedral to euhedral and commonly contains mineral inclusions of quartz, feldspar, mica and Fe-ore minerals. The porphyroblasts vary from 2.0 to 0.5mm in diameter, with the MS1 and MS2 matrix schistosity truncated by the garnet; continuous through the garnet; or wrapped around the garnet.

The orientation of the internal fabric in the garnet indicates an earlier phase of deformation than that recorded in the schistosity ( Harris and Rast, 1960 ; Sturt, 1960 ). The mineral inclusions particularly those of quartz, are smaller than the matrix schistosity quartz grains and this relationship is generally interpreted as suggesting that the matrix overgrown by the garnet porphyroblast was finer than the external fabric, Se ( Harte and Johnson, 1969 ). However, the smaller grain size could also be due to removal of material during incorporation in the porphyroblast ( Campbell *et al.* 1979 ).

A distinct zonation within the garnet is also found, indicating some combination of syntectonic and static growth. Rast and Sturt (1957) have described garnets which show an S- pattern, Si fabric in the inner zone indicates syntectonic growth ( MS1 or MS2 ), and the outer zone which has a non-rotational Si fabric or idioblastic massive rim ( without Si fabric ) indicative post-tectonic growth ( MP1 or MP2).

### 6.6.1. MS1 garnet

The evidence for garnet porphyroblasts which developed during the MS1 period is limited to :

(1) Porphyroblasts which contain an internal fabric (Si) which has an S-shaped or spiral arrangement, due to rotation during growth ( Plates 6-11 and 6-12 ).

(2) Porphyroblasts which show a zonation ( Plate 6-13 ).The garnet in the inner-zone contains an internal fabric ( Si ) with a rotaional arrangement which developed during MS1, whereas the garnet of the outer zone with a non-rotational arrangement or lack of internal fabric (Si) developed after MS1.

(3) Porphyroblasts showing 'snowball structure', possibly with 360 degrees rotation (Plate 6-14).

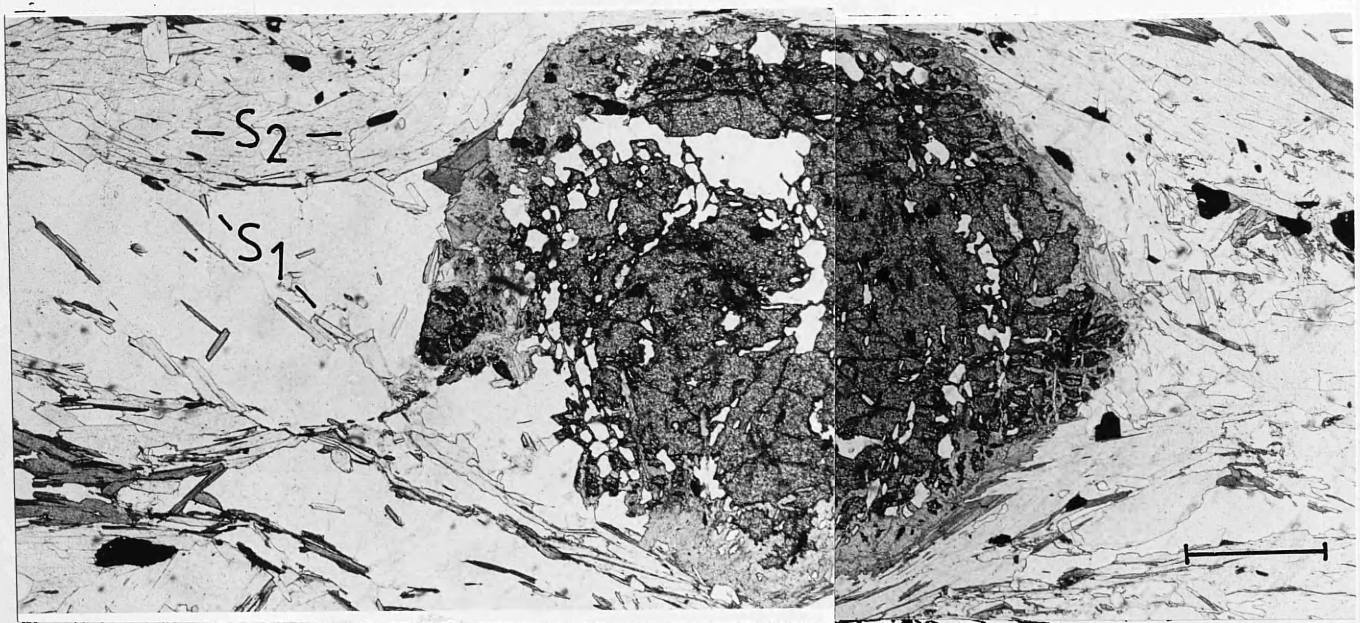
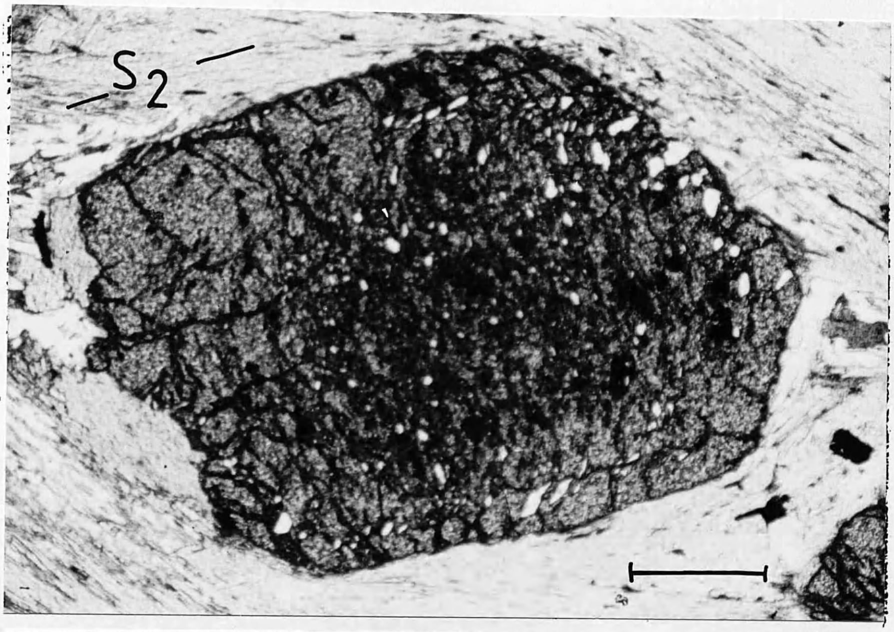



Plate 6-11: MS1 garnet with a spiral arrangement of inclusion fabrics and MS2 mica fabric wrapped around it.
The MS1 mica fabric lies at a moderate angle to the MS2 fabric.
The bar scale is 0.5mm diameter.

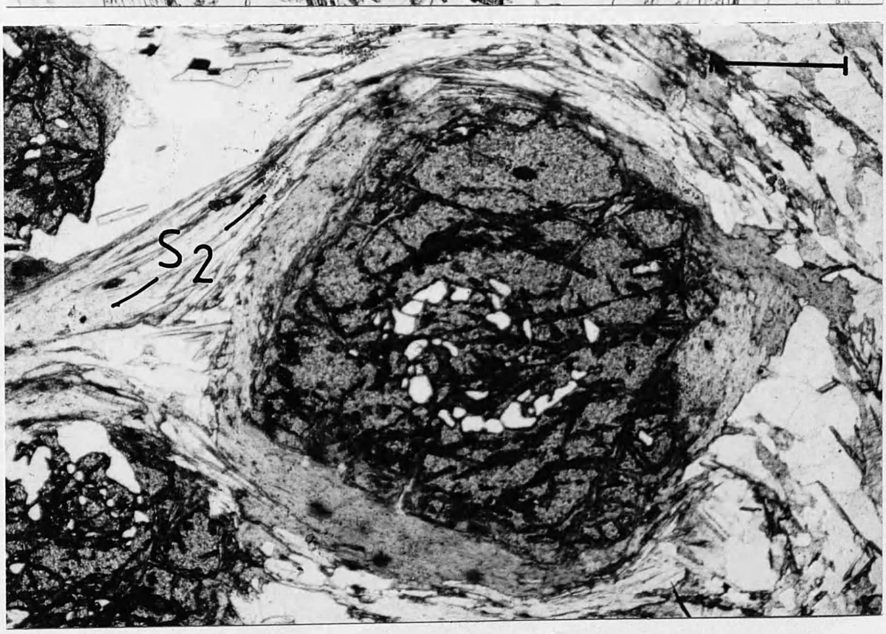
Plate 6-12: MS1 garnet with a curved inclusion fabric.
The bar scale is 0.5mm long.

Plate 6-13: Zoned garnet with MS1 garnet in the inner-zone and MP1 garnet in the outer-zone.
The bar scale is 0.5mm long.

Plate 6-14: MS1 garnet, possibly with 360 degrees rotation.
The bar scale is 0.5mm long.


S2


S2


S2

(4) A mica fabric of probable MS2 age around some garnets, giving pressure shadows and indicating that these garnets developed before D2 (Plate 5-26).

6.6.2. MP1 garnet

Garnets which have developed under static growth (MP1) can be recognised in a number of ways :

(1) MP1 garnets contain an inclusion fabric (Si) of MS1 age which is not always continuous with the external fabric (Se).
This indicates that the Se and Si fabrics are of two different generations and may be that the garnets have been rotated by movement post-dating their growth. This is a common way for recognising post-growth rotations of garnets whose Si fabric is arranged as trails of inclusions representing relict of earlier fabrics. Due to the rotation, these relict fabrics are now oblique or make an angle to the matrix schistosity (Plate 6-15). When the garnets are rotated, the surrounding micas of the matrix are deflected or wrapped round the porphyroblasts.

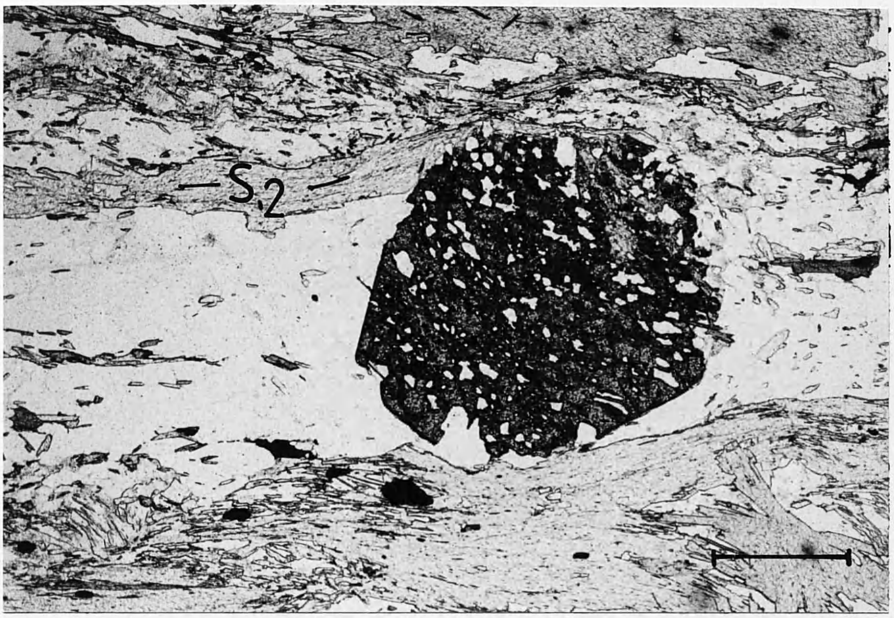



Plate 6-15: MP1 garnet with Si oblique to Se.
Where Se is the MS2 fabric.
The bar scale is 0.5mm long.

(2) In other cases the MPl garnets are recognised from the zonation of garnet (Plate 6-13) where the garnets show a combination of syntectonic (MSI) and post-tectonic (MPI) growth. Inner zone, syntectonic growth (MSI); outer zone, post-tectonic growth (MPI).

Recognition of garnet porphyroblasts of MSI age might enable the interpretation to be made that garnet growth was continous from MSI to MPI. No garnet has been identified of possible MS2 or MP2 age.

## 6.7. Growth of Quartz

In this study there is seen to be a marked contrast between the shape and size of quartz grains preserved as an inclusion fabric in biotite, garnet and feldspar porphyroblast and the shape and size of matrix quartz grains (Se). In the matrix of mica-schists the quartz grains often show a fair variation in size ranging from less than 0.1mm to porphyroblasts ( in quartzose foliation ) about 3.0mm in maximum dimensions.

Approach to a low energy equilibrium fabric amongst these matrix quartz grains is shown by a marked tendency towards polygonal equidimensional grains with triple junctions approaching 120 degrees in some quartz aggregates ( Spry, 1969 ). Nevertheless some grains do have curved undulose extinction and subgrain structure is common, particularly in the larger grains. These features are a result of later deformation.

The quartz grains forming the inclusion fabric in biotite, feldspar and garnet porphyroblasts differ from the matrix quartz in showing a distinct tendency towards elongate shape and in being appreciably smaller. The elongate shape of the included quartz grains could have resulted from plastic deformation or pressure solution processes during the D1 deformation, though some annealing recrystallisation and grain growth could have occurred immediately after D1 or D2. The elongate habit of the grains could have been maintained because the interfacial energy of quartz against phyllosilicates has limited growth in directions other than parallel to the schistosity (Voll, 1960). Also, the matrix fabric (especially quartz) could have increased in size during or following the D3 deformation.

## 6.8. Growth of Feldspar

The development of feldspar (K-feldspar and plagioclase, An 15-25) grains within the matrix of pelite and semipelites in the area appears to be synchronous to that of quartz. However, porphyroblasts containing trails of fine-grained inclusions that appear to pre-date the micas of the MS2 fabric and post-date the MS1 fabric.

The inclusion fabric in the feldspar is usually of quartz, mica, and Fe-ore mineral.

This inclusion fabric lies at an angle to the MS2 matrix schistosity ( Plates 6-16 ) and is continuous in trend with MS1 matrix schistosity ( Plate 6-17 ). This evidence indicates that the feldspar ( K-feldspar and plagioclase ) grew during MP1.

## 6.9. Growth of Chlorite

The growth of chlorite in the area can be identified by using the evidence such as below :

(1) Chlorite often seen as envelopes to MS1 and MP1 garnet due to retrogressive alteration of the porphyroblasts (Plate 6-13).

(2) Chlorite is intergrown with the muscovite of S2 fabric, therefore the chlorite has grown during D2 time or post- D2 time by retrogression of MS1 or MS2 biotite.

(3) Some of the chlorite is randomly oriented within or overprints the S2 fabric.

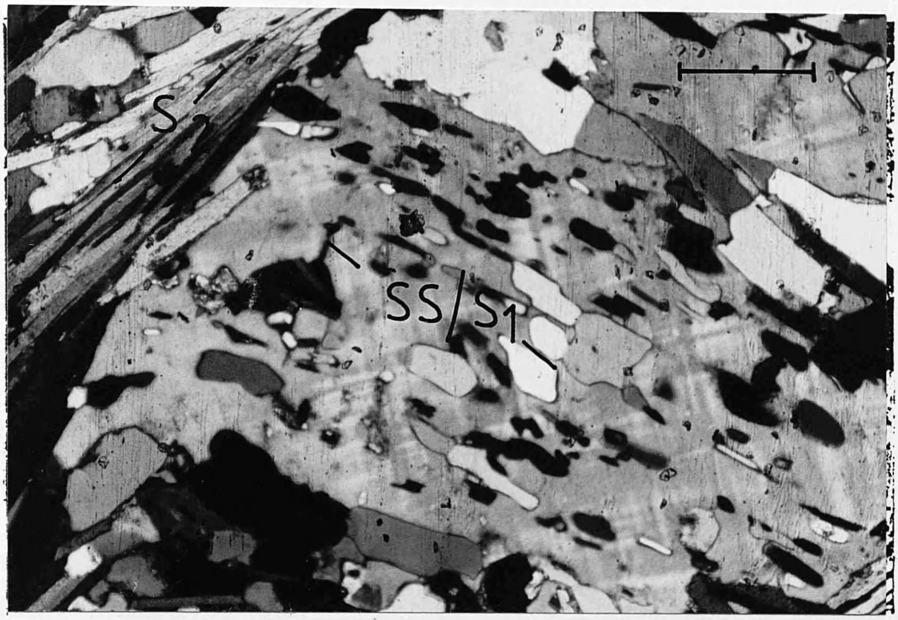



Plate 6-16: MP1 K-feldspar with Si fabric oblique to the MS2 fabric.
K-feldspar shows the Baveno twinning.
The bar scale is 0.5mm long.

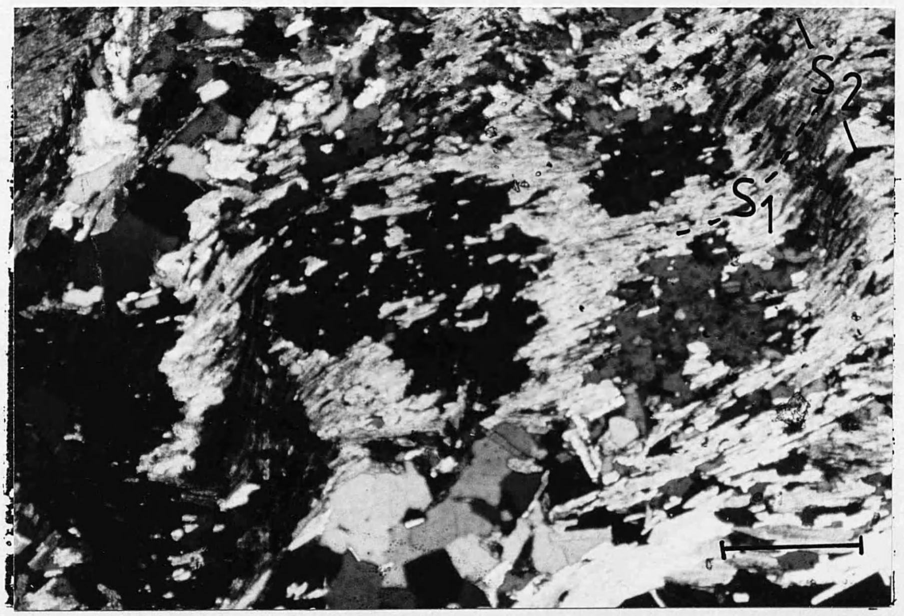



Plate 6-17: MP1 plagioclase with Si parallel to the MS1 fabric.
MS1 fabric has been crenulated by F2 microfolds.
The bar scale is 0.5mm long.

(4) Some chlorite grows in parallel orientation along the extensional crenulation cleavage (Plate 5-29 ).

## 6.10. Conclusions

The sequence of mineral growths indicates a metamorphic peak during MS1 and a later decline during D2 and D3 ( Table 6-1 ). The peak of metamorphism is indicated by the development of garnet porphyroblasts. No higher grade metamorphic minerals are found in the rocks of the area.

It can be assumed that biotite grade conditions were reached by at least, early MS1, and the garnet grade conditions were reached by late MS1. The increase in metamorphic grade continued until MP1 with regards to the formation of the MP1 garnet. No garnet of MS2 age has been recognised.

It is not known exactly whether the extensive chloritisation of muscovite, biotite and garnet occurred, but it was after MP1 time.

Roberts and Treagus (1975) considered that the peak of metamorphism in the Glen Orchy was closely connected with the D2 deformation, culminating in the

Table 6-1: Sequence of mineral growth.

| | F1 | | F2 | | F3 | | F4 | |
|---|---|---|---|---|---|---|---|---|
| | MS1 | MP1 | MS2 | MP2 | MS3 | MP3 | MS4 | MP4 |
| Muscovite | — | | — | — | — | — ? — | — | |
| Biotite | — | — | — | — | — ? — | — | | |
| Garnet | — | — | | | | | | |
| Quartz | — | — | — | — | — ? | — | | |
| K-feldspar | ? — | — | — ? | — | | | | |
| Plagioclase | ? — | — | | | | | | |
| Chlorite | ? — | — | — ? | — | — | — ? — | — | |

growth of garnet. However, Cummins and Shackleton (1955) postulated that the peak of the regional metamorphism had a close connection with the primary deformation.

# CHAPTER 7

# DISCUSSION AND REGIONAL CORRELATIONS

## 7.1. Discussion

### 7.1.1. D1 Folds

#### Beinn Udlaidh Syncline

This fold is a major D1 fold facing to the south-east. Evidence from the stratigraphy, sedimentary structures, geometry of the minor F1 folds and fabrics confirm that this fold is a D1 syncline.

In the Glen Orchy area the fold is upward facing but in the Glen Lochy ( Fig. 3-C; Thomas and Treagus, 1968 section ) it is downward facing. This change in facing direction is due to the effect of the D3 Glen Orchy Antiform ( Thomas and Treagus, 1968 ; Roberts and Treagus, 1977 ).

#### Beinn Chuirn Anticline

Repetition of stratigraphical units and evidence from minor structures (minor D1 folds and D1 fabrics ) confirms the existence of the Beinn Chuirn Fold in the area. As mentioned in the previous chapter the closure of this fold lies within the Moine rocks. The Moine rocks which lie in the core of this fold, even though they always display a planar flagginess, show the best preservation of cross-lamination, especially near the hinge zone ( NN22982971 ) and on the upper limb of this fold ( NN21303040 ).

The fold axis of the Beinn Chuirn Fold in the Glen Lochy area has a similar trend as the fold axis of the adjacent Beinn Udlaidh Fold and both folds plunge at a low to moderate angles to the south-west.

In the Glen Lochy area the Beinn Chuirn Fold forms as a synformal anticline whereas in the Glen Orchy area it forms as an ( antiformal ) anticline.

The geometry of the minor D1 folds, S1 cleavage-bedding relationships and sedimentary structures show that the Beinn Chuirn Fold is a D1 anticline and forms a fold pair with Beinn Udlaidh syncline. In the Glen Orchy area, this major fold faces upward to the SE.

The evidence for the D1 age of the Beinn Chuirn anticline is particularly clear on its upper limb and near the hinge zone.

A large number of minor F1 folds of bedding, approximately 40 folds, have been observed in the rocks on the upper limb of the Beinn Chuirn anticline and about 10 in the rocks on the lower limb. These minor folds, which are well developed in psammite, quartzite, pelite and calcareous beds on the upper limb of the Beinn Chuirn anticline, consistently verge to the south or south-east, indicate that the major fold closes to the east or south-east.

Most of these minor D1 folds are seen to have a strongly developed axial planar cleavage (S1) when examined under the microscope. There are also minor folds which do not show a good axial planar cleavage. These folds were considered to be of D1 age as they have a same vergence and orientation as the previous group.

The S1 cleavages have been seen oblique to bedding on the upper limb of the Beinn Chuirn anticline ( NN21303040 ). Conversely, Roberts and Treagus ( 1975; p.68 ) pointed out that the cleavages axial planar to the minor folds in this area do not show clear evidence of being of D1 age and they stated that they did not see S1 cleavages oblique to bedding on this limb of the Beinn Chuirn Fold. Roberts and Treagus ( 1975; p.69 ) also suggested that all the minor structures on the upper limb of the Beinn Chuirn Fold are of D2 age.

The present study provided both field and microscopic evidence that these minor structures are of D1 age and are related to a major D1 anticline, not a D2 synform as currently accepted.

7.1.2. D2 Fold

Roberts and Treagus (1975) considered that the Beinn Chuirn Fold is a major D2 synform. According to them, the critical evidence comes from the exposures that occur at the margin of the quartzite with the pelitic transition to the Moine psammite in the River Orchy ( NN24193176 ). They pointed out that the isoclinal D1 folds at this locality verge west ( Z-vergence ) and are overprinted by the D2 spaced cleavage related to D2 minor folds verging east ( S-vergence ). About 7-10 metres downstream from this locality ( NN24193176 ), the first exposures of psammitic Moine rock show strong ( S2-SS/S1 ) relationships which support a D2 synform to the south-west.

The present study agrees with this observation. However, they then suggest that the Beinn Chuirn Fold is of D2 age and must close to the west/north-west ( Fig.7-1a). The flaw in this interpretation is that these same relationships ( S2-SS/S1 ) can also be seen in the Moine rocks exposed close to the hinge zone ( NN21333133 ) and on the upper limb ( NN20553170 ) of the Beinn Chuirn Fold.

Here, the S2 fabric is defined by a spaced crenulation cleavage which affects the composite fabric ( SS/S1 ). This evidence suggests that any D2 synform lies to the south-west/west ( i.e. outside the mapped area ) and that the D2 fabric is superimposed upon a pre-existing major structure.

Also, if the Beinn Chuirn Fold is of D2 age, then the D2 minor folds which occur in the rocks on the upper limb of these fold should show a Z-vergence ( verging west/south-west ). But this is not seen in the area. The minor folds which developed in the rocks on the upper limb of the Beinn Chuirn Fold have a consistent sense of south easterly vergence and are of D1 age. No D2 minor folds have been recognised in the rocks on the upper limb of the Beinn Chuirn Fold.

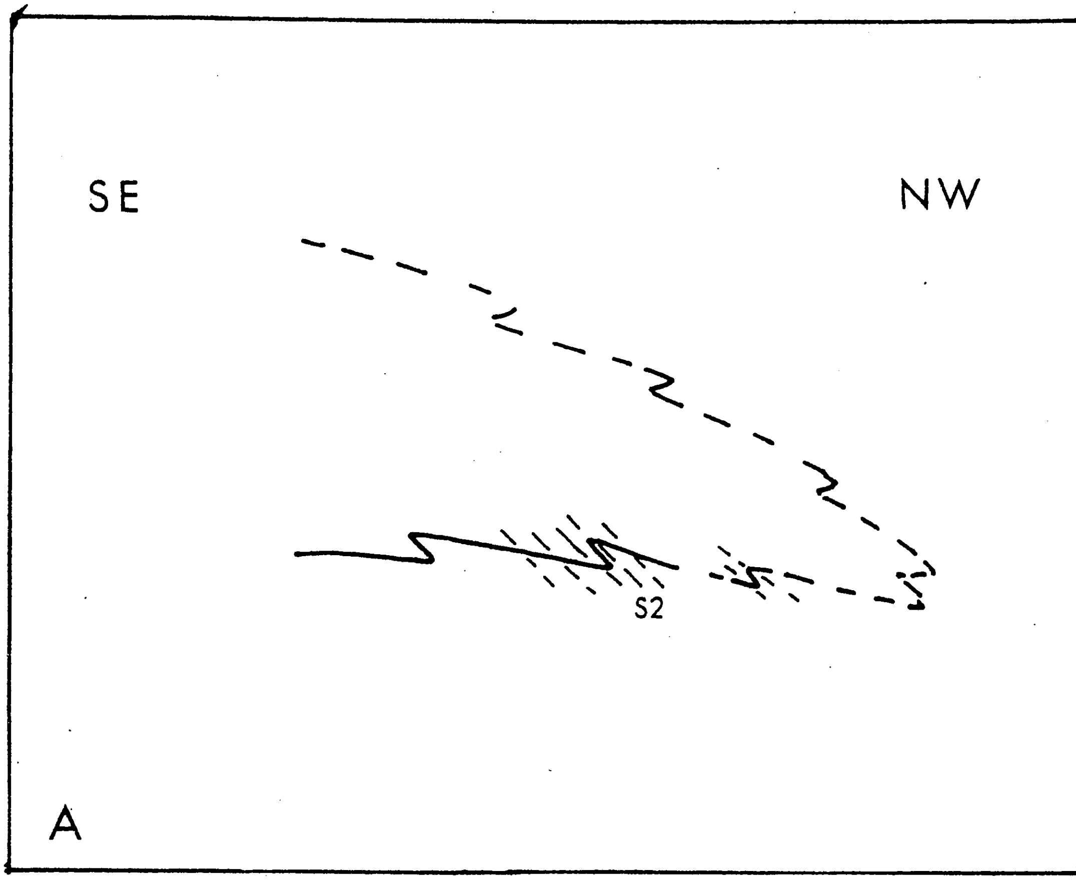
All of the fabrics ( SS,S1 and S2 ) locally become parallel one another in the ( ? higher strain ) rocks close to the slide ( Fig. 7-1b ).

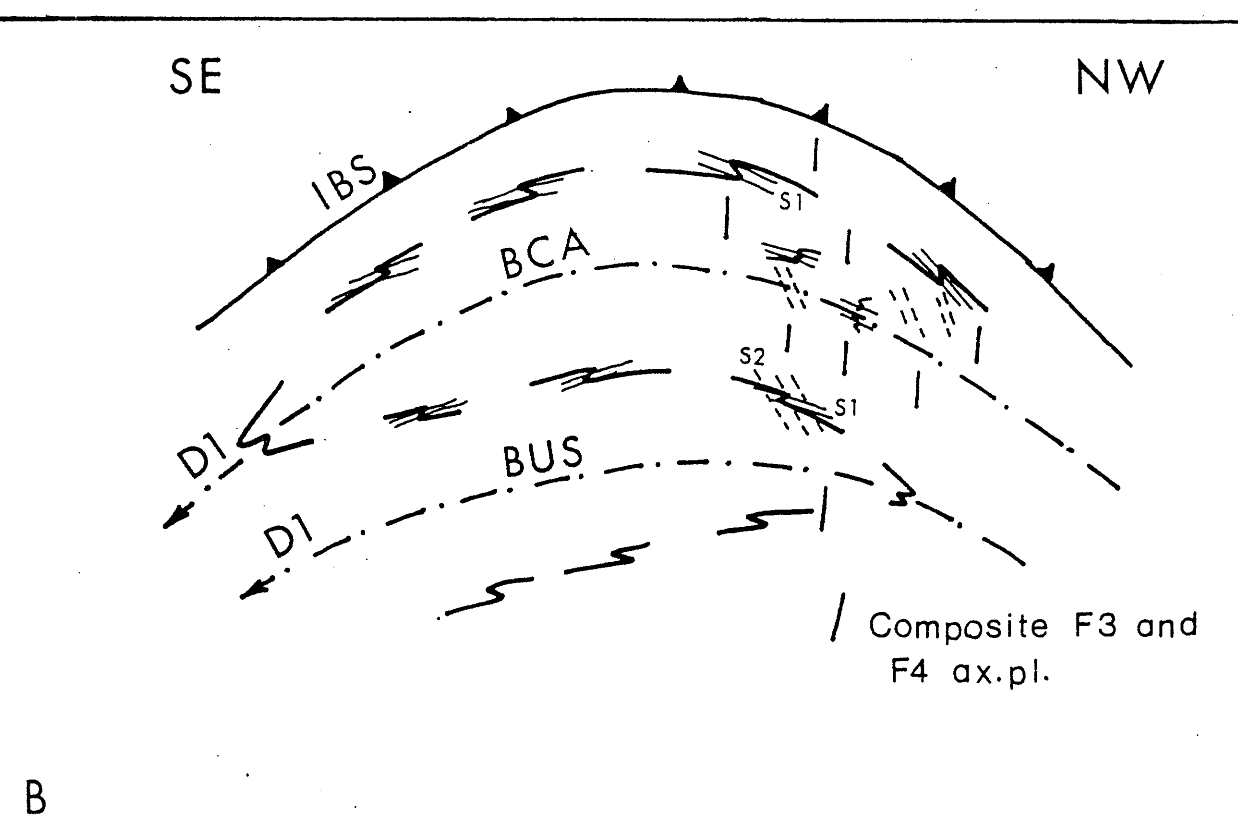
Fig. 7-1: (A) The Beinn Chuirn Fold shown as a D2 synform: The Roberts and Treagus (1975) interpretation.

(B) A down plunge sketch diagram to illustrate the relationship between D1 and D2 structures and the geometry of the Beinn Chuirn Fold.

BCA Beinn Chuirn Anticlinle
BUS Beinn Udlaidh Syncline
IBS Iltay Boundary Slide

Fig. 7-1


SE
NW
S2
A


SE
NW
IBS
S1
BCA
S2
S1
D1
BUS
D1
Composite F3 and F4 ax.pl.
B

## 7.2. Regional correlations

### 7.2.1. Stratigraphy

The stratigraphic sequence of the rocks in the area has been correlated with the Moine and Dalradian rocks elsewhere ( cf. Harris and Pitcher, 1975 ) and for lack of further evidence is accepted here.

The Moine rocks of the area are equated with the Grampian Division of the upper Moine succession. Whereas, the Dalradian rocks of the area belong to the Lochaber and Easdale subgroups of the Appin and Argyll Groups, respectively.

### 7.2.2. Structure

Roberts and Treagus ( 1975, Fig. 5 ) considered that the Beinn Chuirn Fold is a D2 synform. The evidence comes from their observations in the Dalmally area, particularly on the minor structures. According to these authors, some of the minor structures verge southeast, while others verge northwest when close to the Iltay Boundary Slide. From this they suggest that large-scale folding has affected the rocks near the Iltay Boundary Slide during the D2 deformation. The closure of this major D2 fold, is located according to them, in the River Orchy at NN196283. Roberts and Treagus (1975) interpret this fold as a downward facing synform, plunging at a low angle to the south-southeast. It affects the horizon of the pebbly quartzite outside the mapped area.

Roberts and Treagus ( 1977a, Fig. 2; 1977b, Fig.3 ) also postulated that the Beinn Chuirn synform (D2) folds both the Beinn Udlaidh syncline (D1) and the Glen Lochy anticline (D1). They also correlated the Beinn Chuirn synform with the D2 Blackwater antiform ( a component of the Kinlochleven Folds ) which lies to the north-west of the area.

Bradbury ( 1985, Fig.4 ) clearly defined the Beinn Chuirn Fold as a D2 synform and showed that this fold refolds the Atholl nappe. A synopsis of the Roberts and Treagus, and Bradbury interpretations of the regional structure is show in Fig. 7-2.

Thomas ( 1979, Fig. 4 ) considered that the Beinn Chuirn Fold is a D1 anticline, based on his observations ( with Treagus) in the Glen Lochy area in 1968. Thomas showed that this fold has the same geometry as the Atholl nappe which lie at a lower structural level to the north-east of Glen Orchy. Both of these folds face downward to the south-east and are of the same age. Also, Thomas showed the 'Meall Reamhar Synform' as the

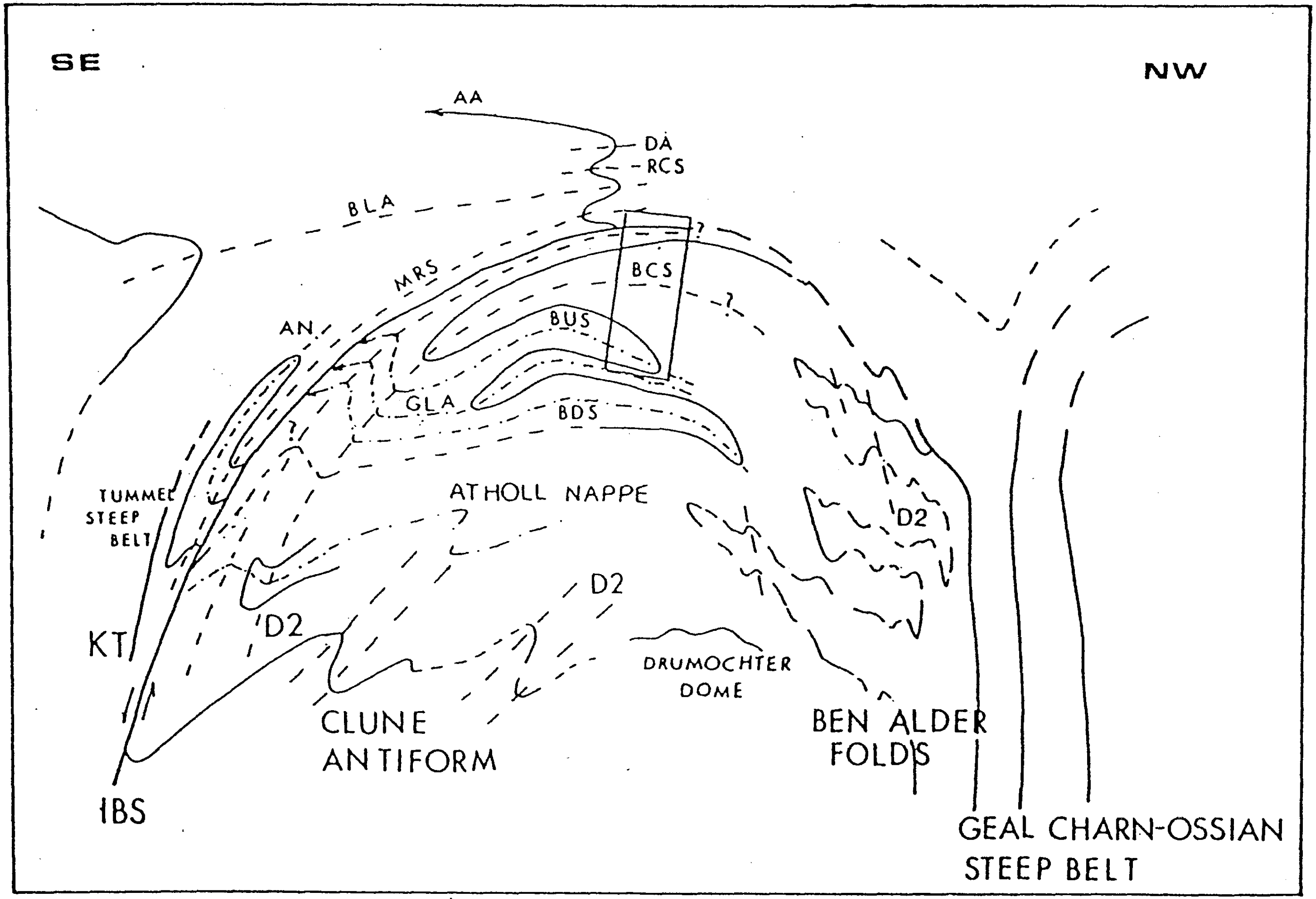
Fig. 7-2: A combined interpretation of the structural correlations in SW Highlands by the previous workers (after Roberts and Treagus, 1977; Thomas, 1979 and Bradbury, 1985).

Box inserts show approximately the study area.

Abbreviations:

AA, Ardrishaig Anticline; AN, Atholl Nappe; BCA, Beinn Chuirn Anticline; BDS, Beinn Dochard Syncline; BUS, Beinn Udlaidh Syncline; DA, Dalmally Antiform; GLA, Glen Lochy Anticline; MRS, Meall Reamhar Synform; RCS, Ra Chreag Synform; IBS, Iltay Boundary Slide and KT, Killiecrankie Thrust.

Fig. 7-2


SE
NW
AA
DA
RCS
BLA
MRS
BCS
BUS
AN
GLA
BDS
ATHOLL NAPPE
TUMMEL STEEP BELT
D2
D2
D2
D2
KT
IBS
CLUNE ANTIFORM
DRUMOCHTER DOME
BEN ALDER FOLDS
GEAL CHARN-OSSIAN STEEP BELT

F1 hinge of the Atholl nappe which has been displaced by the Iltay Boundary Slide at a lower structural level in the Tummel steep belt. The refolding of the F1 hinge (Atholl nappe) above the Iltay Boundary Slide results in a composite F1/F2 structure. He also correlated the Beinn Chuirn Anticline with F1 Kinlochlaggan closures in the Ben Alder region.

As described in Chapter 5 (Section 5.2.2.), the present study has concluded that the Beinn Chuirn Fold is a D1 anticline which faces to the south-east. The evidence comes from the D1 minor folds and D1 fabrics which are the dominant tectonic structures in the area, especially in the Moine rocks.

The relationships between the SS/S1 and S2 fabrics indicate that there is no a major D2 synform in the rocks below the Iltay Boundary Slide and the interpretation of the Beinn Chuirn Fold as a D2 structure can be rejected. If a major D2 synform exist it must lie further to the south or southwest.

The present work confirms Thomas (1968,1979) suggestion for a correlation between the Beinn Chuirn anticline and the adjacent folds, and this interpretation is shown in Fig. 7-3.

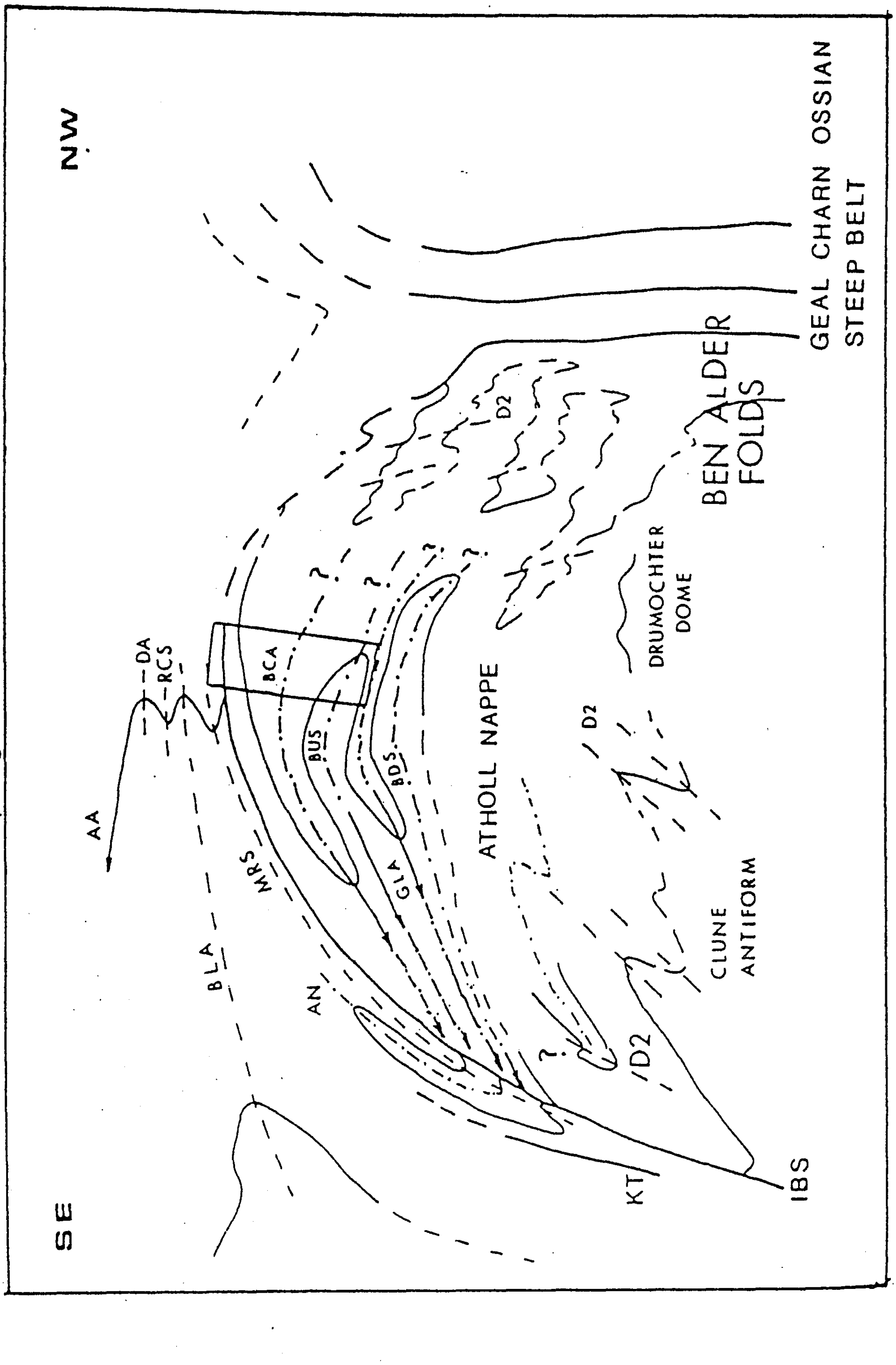
Fig. 7-3: The present interpretation of the structural correlation in the SW Highlands, based on the Thomas (1979) interpretation.

Box inserts shows approximately the study area.

Abbreviations:

AA, Ardrishaig Anticline; AN, Atholl Nappe; BCA, Beinn Chuirn Anticline; BDS, Beinn Dochard Syncline; BUS, Beinn Udlaidh Syncline; DA, Dalmally Antiform; GLA, Glen Lochy Anticline; MRS, Meall Reamhar Synform; RCS, Ra Chreag Synform; IBS, Iltay Boundary Slide and KT, Killiecrankie Thrust.

Fig. 7-3


NW
SE
GEAL CHARN OSSIAN
STEEP BELT
BEN ALDER
FOLDS
D2
DRUMOCHTER
DOME
ATHOLL NAPPE
D2
CLUNE
ANTIFORM
D2
DA
RCS
AA
BCA
BUS
BDS
GLA
MRS
BLA
AN
KT
IBS

# CHAPTER 8

# CONCLUSIONS

The main conclusions of this study of the structural and metamorphic history of the Glen Orchy area are:

(1) The rocks of the Glen Orchy area consists of Moine rocks ('Young Moine') and parts of the Appin and Argyll Groups of the Dalradian Supergroup. The Moine rocks belong to the upper part of the Grampian Division and consists of psammite, semipelite and 'passage zone' banded rocks.

The Dalradian rocks consists of quartzite, pelite ( with a few metres of limestone ) and pebbly quartzite.

(2) Four phases of deformation (D1 to D4) have been recognised in the Glen Orchy area (Table 8-1).

(3) The D1 deformation is responsible for the development of two major tight to isoclinal recumbent folds: the BEINN CHUIRN ANTICLINE and BEINN UDLAIDH SYNCLINE. Both of these folds face upward to the south-east and plunge at a low to moderate angle to the south-west or south south-west in the Glen Orchy area.

D1 minor folds and D1 cleavage are the dominant structural elements in the area, especially in the Moine outcrops. F1 minor folds show interlimb angles of about 30 - 50 degrees on average.

(4) The peak metamorphism of the area occurred before the D2 deformation, indicated by the growth of MS1 and MP1 garnet porphyroblasts. The MS1 fabric is marked by a penetrative cleavage (0.05 - 0.1mm) and defined by the alignment of brownish biotite and muscovite flakes.

(5) The D2 deformation is locally important but is not related to any major fold in the area. However,the relationship between the composite fabric (SS/S1) and S2 fabric suggests that a major D2 fold occurs outside the mapped

area to the south or south-west.

Also,the D2 deformation has strongly affected the pelite which lies below the Iltay Boundary slide. The evidence for this fabric being of S2 age is limited to the presence of garnet porphyroblasts which contain an inclusion fabric oriented at an angles to the external matrix fabric.The strong development of the F2 fabric in the pelite adjacent to the slide may be due to the movement of the slide during D2 deformation.

The MS2 fabric is defined by a zonal crenulation of the MS1 fabric.No garnet of MS2 age is recognised.

(6) The D3 deformation is associated with the development of a major late fold, the Glen Orchy antiform. This fold plunges at low angles (10-30 degrees) to the south-west.It is associated with the development of the minor folds and no S3 fabric is related to this fold.

(7) D4 minor structures are only developed locally and no major fold related to this deformation occurs in the area.

(8) The Iltay Boundary Slide zone is not exposed in the area but it probably occurs at the junction between the pelite and overlying pebbly quartzite in the south of the area. Evidence which indicates that a slide or zone of ductile thrusting has affected the rocks in the area is seen when the rocks are examined under the microscope. The evidence from the microtextures seen in rocks close to the slide indicates that the slide movement probably took place during the D1 deformation and the slide was reactivated locally during the D2 deformation.

(9) The regional correlation of the Beinn Chuirn Anticline with major folds in adjacent areas is discussed.

Table 8-1: The structural and metamorphic history of the area.

| Event | | Minor structures | Major fold |
|---|---|---|---|
| D1 | F1 | Tight to isoclinal minor folds which fold bedding (SS) Interlimb angles of minor folds average of 30-50 degrees | BEINN CHUIRN ANTICLINE and BEINN UDLAIDH SYNCLINE |
| | S1 | Penetrative, often spaced cleavage (0.05 - 0.1 mm), defined by alignment of biotite and muscovite flakes | |
| | L1 | Mineral, rodding, stretching and (SS-S1) intersection lineations | |
| | | Associated with MSI and MP1 garnet porphyroblasts, MP1 biotite and MP1 feldspar | |
| D2 | F2 | Asymmetrical minor folds (S-Shaped) which fold the composite foliation (SS/S1) Fold hinges trend SE-NW to SSE-NNW, axial planes SW-dipping | NO MAJOR FOLDS |
| | S2 | Spaced cleavage (0.5-1.0 mm) or zonal crenulation | |
| | L2 | Intersection (S2-SS/S1) and crenulation lineations | |
| | | Associated with MP2 biotite; no MS2 garnet is recognised | |

| Event | | Minor structures | Major folds |
|---|---|---|---|
| D3 | F3 | Open asymmetrical minor folds (S-shaped and Z-shaped), Fold hinges trend generally to S-N or SSW-NNE, axial planes WSW-dipping (S-shaped) and ESE-dipping (Z-shaped) | GLEN ORCHY ANTIFORM |
| | S3 | No S3 fabric is developed in association with minor F3 folds | |
| | L3 | Crenulations and F3 hinges | |
| | Associated with the ? MS3 chlorite | | |
| D4 | F4 | Open upright folds, warps and kinks Fold hinges trend roughly W to SW. Axial planes vertical or steeply-dipping | NO MAJOR FOLD |
| | S4 | Crenulations or kink bands | |
| | L4 | Crenulations, kinks and F4 hinges | |
| | Associated with the retrogression of biotite and garnet to chlorite | | |

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# Appendix 1

Fig. 1-2 : Sample locations

| Location | Sample | Grid ref. (NN) |
|---|---|---|
| A1 | SO1 | 2472 3308 |
| A2 | SO2 | 2442 3256 |
| A3 | SO3,SO4, SO5,SO6, SO7 | 2446 3243 |
| A4 | SO8,SO9,SO10 | 2414 3228 |
| A5 | SO11 | 2423 3206 |
| A6 | SO12 | 2422 3206 |
| A7 | —— | 2423 3196 |
| B1 | SO13 | 2394 3316 |
| B2 | SO14,SO15 | 2399 3293 |
| B3 | SO16 | 2407 3295 |
| B4 | SO17,SO18 | 2119 3171 |
| B5 | SO19,SO20 | 2416 3170 |
| B6 | SO21,SO22 | 2406 3142 |
| B7 | SO23 | 2404 3141 |
| B8 | SO24 | 2460 3117 |
| B9 | SO25 | 2403 3143 |

| | | |
|---|---|---|
| B10 | SO26 | 2407 3125 |
| B11 | SO27 | 2400 3116 |
| B12 | SO28 | 2373 3087 |
| B13 | SO29 | 2361 3079 |
| B14 | SO30 | 2355 3077 |
| B15 | SO31 | 2428 3033 |
| B16 | SO32 | 2360 3000 |
| B17 | SO33 | |
| B18 | SO34,SO35,SO36 | 2334 2982 |
| B19 | — | 2334 2980 |
| B20 | SO37,SO38 | 2298 2971 |
| B21 | SO39 | 2296 2972 |
| B22 | SO40 | 2292 2972 |
| B23 | SO41 | 2287 2973 |
| B24 | SO42,SO43 | 2233 3012 |
| B25 | SO44 | 2235 3015 |
| B26 | SO45,SO46,SO47 | 2238 3058 |
| B27 | SO48 | 2240 3061 |
| B28 | SO49 | 2212 3080 |
| B29 | SO50 | |
| B30 | SO51 | 2248 3036 |
| B31 | SO52 | 2266 3095 |
| B32 | SO53,SO54 | 2214 3139 |
| B33 | SO55 | 2217 3141 |
| B34 | — | 2231 3165 |
| B35 | SO56 | 2269 3163 |

| | | |
|---|---|---|
| B36 | SO57 | 2300 3140 |
| B37 | SO58 | 2125 3052 |
| B38 | SO59 | 2193 3235 |
| B39 | SO60 | 2186 3216 |
| B40 | — | 2086 3194 |
| B41 | SO61,SO62,SO63 | 2049 3191 |
| B42 | — | 2037 3195 |
| B43 | SO64,SO65 | 2055 3170 |
| B44 | — | 2114 3154 |
| B45 | SO66 | 2133 3133 |
| B46 | — | 2129 3137 |
| B47 | SO67 | 2133 3133 |
| B48 | SO68 | 2139 3060 |
| B49 | SO69,SO70 | 2139 3051 |
| B50 | SO71 | 2146 3050 |
| B51 | SO72,SO73 | 2140 3046 |
| B52 | — | 2124 3053 |
| B53 | SO74 | 2125 3052 |
| B54 | — | 2112 3032 |
| C1 | — | 2012 3069 |
| C2 | — | 2018 3022 |
| C3 | — | 2024 3008 |
| C4 | — | 2050 3016 |
| C5 | — | 2048 2980 |
| C6 | SO75 | 2060 2982 |

| | | | |
|---|---|---|---|
| C7 | SO76 | 2060 | 2961 |
| C8 | SO77 | 2024 | 2960 |
| C9 | — | 2020 | 2930 |
| C10 | — | 2022 | 2928 |
| C11 | — | 2026 | 2901 |
| C12 | — | 2026 | 2898 |
| C13 | — | 2028 | 2893 |
| C14 | SO78 | 2155 | 2930 |
| C15 | — | 2157 | 2927 |
| C17 | SO79 | 2145 | 2920 |
| C19 | SO81 | 2146 | 2919 |
| C20 | SO81 | 2146 | 2902 |
| C21 | SO82 | 2174 | 2901 |
| C22 | SO83 | 2195 | 2925 |
| C23 | SO84 | 2399 | 3293 |
| C24 | SO85 | 2201 | 2929 |
| C25 | SO86 | 2122 | 2918 |
| C26 | SO87 | 2215 | 2921 |
| C27 | — | 2296 | 2914 |
| C28 | — | 2352 | 2867 |
| C29 | SO88 | 2405 | 2875 |
| C30 | SO89,SO90 | 2311 | 2801 |
| C31 | — | 2400 | 2749 |
| C32 | — | 2414 | 2746 |