THE GEOLOGY OF FANNICH FOREST

by

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ABSTRACT

Fannich Forest consists geologically of a complex of Moinian and Lewisian rocks. The area was mapped, and from the field-evidence a stratigraphy and structural interpretation were worked out. The structural interpretation was fitted into a regional interpretation of Moinian structure in Western and Central Ross. The petrology of the different rock-types was studied and used to assess the metamorphic grade of the area, while geochemical evidence strongly suggested that a Lewisian Inlier is present in Fannich.

Mapping showed that the Lewisian inlier extends south of Loch Fannich on Beinn nan Ramh and on Moine Mor. The stratigraphic succession worked out is tabulated below:

Sgurr Mor Pelite Psammites Meall an t-Sithe Pelite	Moinian
UNCONFORMITY	
Silicic Gneisses and Amphibolite	Lewisian

Complex early folding caused these units to form a repetitive succession deformed by the readily visible structures in the area. Three fold-events have occurred:

F_1 folding initiated the formation of an isoclinal anticline with a Lewisian core, and a complementary isoclinal

syncline, exposed at present with Sgurr Mor Pelite in its core.

F_2 folds refold the Lewisian of Fannich in near-isoclinal folds, and a larger F_2 fold may refold the main F_1 anticline so that it now closes east.

F_3 folds, with axial traces broadly trending north-south, are asymmetrical open folds, deforming the foliation developed in the rock during the previous fold-events. They deform an apparent succession in which the Lewisian core of the F_1 anticline forms the second-highest unit. The most important of these folds is the Fannich Synform.

Since the Sgurr Mor Pelite occurs in the core of an F_1 syncline, open to the east, the Lewisian of Fannich is separated from the Lewisian of the Central Ross-shire Inliers. It is considered to form part of the upper limb of the refolded Moine (=Morar) Nappe, and to underlie the postulated Central Ross-shire Nappe. It is admitted that sliding may have occurred in Fannich, but the available evidence in Fannich does not require such a slide in order to explain the regional structure.

Petrological studies reveal differences in mineralogy and texture between Lewisian and Moinian amphibolites; differences also occur between different amphibolite groups within the Moinian, which are considered to originate from different magmas.

In calc-silicate strips from the Sgurr Mor Pelite, a reaction in which biotite forms from hornblende was observed, often accompanied by a reaction forming zoisite at the expense of plagioclase. It was found to be directly influenced by the CaO/Al_2O_3 ratio of the rock. The different ratios at which this reaction proceeded in different places are considered to indicate differences of metamorphic grade. The reaction is retrogressive; the apparent increase of grade with increasing altitude is more probably a result of lessening influence of second, retrogressive metamorphism with increasing height, thus allowing the original (higher-grade) mineralogy to be preserved more fully.

Breakdown of kyanite in pelitic schist, and the accretion of calcic rims around almandines, were also interpreted as signs of retrogression. Electron probe microanalysis of almandines from pelite suggested that much of western Fannich may have been subjected to sillimanite-grade metamorphic conditions, and that the subsequent milder metamorphic episode induced retrogression.

By analogy with Morar, places where the hornblende-biotite reaction in calc-silicates occurs at a CaO/Al_2O_3 ratio of 0.4, are approximately on the kyanite isograd. The metamorphic grade now preserved in Fannich is of almandine grade in the north and east, and mainly kyanite grade in the south-west and centre.

The earlier metamorphic episode reached maximum intensity about the time of F_2 folding, while the milder late event probably accompanied F_3 deformation. In this respect, as in others, the structural and metamorphic history of Fannich is comparable to that of other Moinian areas.

Geochemical evidence reveals differences between Moinian and Lewisian rocks that are not eliminated by metamorphism. Silicic gneisses and amphibolites from the Lewisian rocks contain FeO/TiO_2, K/Rb ratios and zirconium contents different from those of the Moinian, but often resembling those of rocks from the Lewisian Foreland, west of the Moine Thrust. Alteration of these ratios and increase in zirconium content during sedimentation accounts adequately for the overall persistent differences in composition between Moinian and Lewisian rocks. The very high FeO/TiO_2 ratio of the Lewisian rocks suggests that they may be Scourian, rather than Laxfordian gneisses.

Increase in K_2O content and decrease in the FeO/TiO_2 ratio observed in the Lewisian near the junction with the Moinian is tentatively attributed to the effects of weathering of the Lewisian before the deposition of the Moinian.

Some K_2O enrichment of the Lewisian may also have occurred during metamorphism, resulting in the secondary growth of biotite in the amphibolites, but little other evidence of metasomatism was seen. Therefore the present chemical composition

of the Moinian rock-units is considered to be broadly that of the original sediments. Chemical evidence was used to confirm petrological evidence that Lewisian rocks occur in Fannich, both where previously mapped, and south of Loch Fannich, and the interpretations of the structure are based on this conclusion.

TABLE OF CONTENTS

Chapter		Page
1	INTRODUCTION	1
2	PREVIOUS RESEARCH IN FANNICH	
	1. The Geological Survey	6
	2. Post-Survey Studies	7
3	MOINE STRATIGRAPHY AND GENERAL PETROGRAPHY	
	1. Introduction	10
	2. Inverbroom Psammite	12
	3. Sgurr Mor Pelite	15
	4. Carn na Criche Psammite	18
	5. Meall a' Chrasgaidh Psammite	21
	6. Meall an t-Sithe Pelite	23
	7. Sgurr nan Each Psammite	28
	8. Conglomerate	30
4	THE LEWISIAN INLIER OF FANNICH	
	1. Distribution	32
	2. Silicic Gneisses	35
	3. Amphibolites	36
	4. Lewisian Calc-Silicate Rocks	38
	5. Garnet-Quartz-Biotite Gneisses	39
	6. Conclusions	40
5	STRUCTURE	
	1. Previous Research, and General Introduction	42
	2. General Morphology of Observable Folds: Major Folds	45
	3. Minor Structures	49
	4. The Evidence for Earlier Isoclinal Folding	51
	5. The Regional Significance of the Fannich Structure	60

Chapter		Page
6	PETROGRAPHY	
	1. Introduction	72
	2. Pelites and Semipelites	72
	3. Psammites and Silicic Gneisses	79
	4. Amphibolites	84
	5. Calcareous Rocks	94
	6. Heavy Mineral Seams	97
7	CALC-SILICATES	
	1. Distribution	100
	2. Previous Research	102
	3. Calcite in Calc-Silicates	105
	4. Ferromagnesian minerals and Zoisite	109
	5. Garnets in Calc-Silicates	114
	6. Calc-Silicates: The Chemical Evidence	116
8	METAMORPHISM IN FANNICH	
	1. Metamorphism and Isograds	122
	2. Previous Research in Fannich	128
	3. Pelites and Amphibolites	130
	4. Calc-Silicates and Metamorphic Grade	131
	5. Garnet Analyses	138
	6. Timing of Metamorphism	149
	7. Conditions of Metamorphism in Fannich	152
9	CHEMICAL DISTINCTIONS IN FANNICH	
	1. Reasons for attempting to discover chemical differences	157
	2. Distinctions between Lewisian and Moinian, and amphibolites	158
	3. Chemical changes caused by sedimentation	167
	4. Chemical changes caused by weathering	170
	5. Is the Fannich Lewisian Scourian or Laxfordian?	172
	6. The significance of geochemical differences between Moinian amphibolites	173

APPENDIX

METHODS OF ANALYSIS

1. Whole-rock Analysis 176
2. Garnet Analysis 181

REFERENCES 183

LIST OF FIGURES.

Figure.		Following Page:
1.	The Location of Fannich Forest.	1.
2.	The district around Fannich Forest.	13.
3.	Location map of Fannich Forest.	13.
4.	The distribution of Inverbroom Psammite.	13.
5.	The distribution of Sgurr Mor Pelite.	15.
6.	The distribution of Carn na Criche Psammite.	18.
7.	The distribution of Meall a' Chrasgaidh Psammite.	21.
8.	The distribution of Meall an t-Sithe Pelite.	23.
9.	The distribution of Sgurr nan Each Psammite.	28.
10.	The distribution of Lewisian Rocks in Fannich.	32.
11.	The axial traces of major F_3 Folds.	45.
12.	Detailed map of the Sgurr a' Chadha Dheirg area.	58.
13.	Cross-sections through the Sgurr a' Chadha Dheirg area.	58.
14.	Lithological map of the area between Fannich and Morar.	62.
15.	The area between Fannich and Morar, showing the postulated position of the Sgurr Beag Slide.	62.
16.)		66.
17.)	Three alternative explanations of the regional structure.	67.
18.)		67.
19.	Distribution of Moinian amphibolites.	85.
20.	Recorded occurrences of calc-silicates in Moinian Pelites.	100.
21.	Recorded occurrences of calc-silicates in the Fannich district.	101.
22.	CaO - MgO contents of Moinian and Lewisian calc-silicates.	117.
23.	CaO - Na_2O - K_2O contents of Moinian and Lewisian calc-silicates	117.
24.	CaO/Al_2O_3 ratio 'isograds' in the Carn na Criche area.	120.
25.	CaO/Al_2O_3 ratio isograds in the same area shown intersecting a plane surface at 500 metres above sea-level.	121.
26.	Isograds derived from calc-silicate assemblages in the Fannich district.	135.
27.	Final metamorphic grade in Fannich.	137.
28.	Former extent of sillimanite grade conditions suggested by the compositions of garnet cores.	140.

Figure.		Following Page:
29.	Localities from which analysed almandines were collected.	141.
30.	Compositions of garnets from Meall an T-Sithe Pelite.	141.
31.	Compositions of garnets from calc-silicates.	141.
32.	Compositions of garnets from amphibolites.	141.
33.	Compositions of the pelite garnets: CaO + MnO plotted against FeO + MgO.	142.
34.	Compositions of the calc-silicate garnets: CaO + MnO plotted against FeO + MgO.	147.
35.	Compositions of the amphibolite garnets: k.CaO plotted against FeO + MgO.	148.
36.	Pressure - Temperature Diagram to show the conditions of metamorphism in Fannich.	153.
37.	FeO - TiO_2 contents of Moinian and Foreland Lewisian rocks.	161.
38.	FeO - TiO_2 contents of rocks from the Fannich Inlier.	162.
39.	K_2O and Rb. contents of Moinian and Foreland Lewisian rocks.	164.
40.	K_2O and Rb contents of rocks from the Fannich Inlier.	165.
41.	MnO and FeO contents of Moinian amphibolites.	166.
42.	MnO and Ni contents of Moinian amphibolites.	166.
43.	MgO and Ni contents of Moinian amphibolites.	166.

LIST OF PLATES.

Plate.		Following Page:
1.	Coire Mor from Loch Fannich.	frontispiece.
2.	Sharp junction between Meall a' Chrasgaidh Psammite, and Meall an t-Sithe Pelite.	11
3.	Conglomerate.	12
4.	Current-bedding in Inverbroom Psammite.	13
5.	Deformed current-bedding in Inverbroom Psammite.	13.
6.	Garnet amphibolite in Sgurr Mor Pelite.	17.
7.	Meall an t-Sithe Pelite.	26.
8.	Garnet amphibolite dyke in Meall an t-Sithe Pelite.	27.
9.	Garnet amphibolite partially absorbed in pelite.	27.
10.	Biotitite at broken footbridge on the River Cabuie.	33.
11.	Inlier of silicic gneiss in the Allt Leac a' Bhealaich.	34.
12.	Lineations in Lewisian silicic gneiss.	50.
13.	Isoclinal fold in silicic gneiss.	53.
14.	Refolded isocline in Sgurr Mor Pelite.	53.
15.	Kyanite in Meall an t-Sithe Pelite.	74.
16.	Needles of zoisite and muscovite grains.	74.
17.	Replacement of garnet in silicic gneiss.	81.
18.	Sgurr Mor amphibolite.	84.
19.	Relict garnet in Lewisian amphibolite.	89.
20.	Euhedral hornblende crystals in Lewisian amphibolite.	89.
21.	Pyroxene in garnet being partially replaced by hornblende.	90.
22.	Calc-silicate concretion in Inverbroom Psammite.	94.
23.	Calc-silicate band containing calcite.	105.
24.	Calc-silicate band with calcite replacing amphibole.	105.
25.	Calc-silicate band consisting mainly of quartz and calcite.	108.
26.	Biotite pseudomorphous after hornblende.	110.
27.	Calc-silicate band containing zoisite and hornblende, but no plagioclase.	113.
28.	Zoisite, possibly pseudomorphous after twinned plagioclase.	113.
29.	Calc-silicate containing plagioclase and hornblende.	113.

Plate.		Following Page:
30.	Zoisite porphyroblasts in Sgurr Mor Pelite.	113.
31.	Zoisite porphyroblast with quartz inclusions.	114.
32.	Zoned garnet from a hornblende - zoisite calc-silicate.	114.
33.	Garnet rimming a core consisting mainly of quartz.	115.

LIST OF TABLES.

Table.		Following Page:
1.	Nomenclature of Stratigraphic Units in Fannich.	5.
2.	Proposed stratigraphic correlations in the Moinian.	63.
3.	Average compositions of Moinian and Dalradian schists.	72.
4.	Mineral assemblages in the Fannich pelitic units.	73.
5.	Analyses of Meall an t-Sithe Pelites.	78.
6.	Mineral assemblages in Psammites and Silicic Gneiss.	80.
7.	Analyses of Moinian Psammites.	80.
8.	Analyses of Lewisian Silicic Gneisses.	80.
9.	Analyses of Sgurr Mor Amphibolites.	85.
10.	Mineral assemblage in amphibolites.	86.
11.	Analyses of Meall an t-Sithe amphibolites.	86.
12.	Analyses of Lewisian Amphibolites.	87.
13.	Analyses of Lewisian calc-silicates.	96.
14.	Analyses of Sgurr Mor Calc-silicates: Hb - Zo, no plag.	119.
15.	Analyses of Sgurr Mor Calc-silicates: Bi - Zo, no plag.	119.
16.	Analyses of Sgurr Mor Calc-silicates: Hb - Plag - Zo.	119.
17.	Analyses of Sgurr Mor Calc-silicates: Bi - Plag - Zo.	119.
18.	Analyses of Sgurr Mor Calc-silicates: Bi - Hb rocks.	119.
19.	Element ratios in various crustal rock groups.	160.
20.	Analyses of amphibolites from the Ben Hope Sill.	160.



Plate 1. Coire Mor seen from Loch Fannich.

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1

I N T R O D U C T I O N

Fannich Forest is a mountainous area of northern Ross-shire, lying twenty-five kilometres west of Garve, and ranging in altitude from 200 to 1100 metres. It is bounded to the south by Loch Fannich, and to the north by the Dirrie More, a broad valley crossing the watershed, followed by the main road from Garve to Ullapool.

The Fannich mountains consist of a main ridge twelve kilometres long extending from A'Chailleach in the west to An Coileachan in the east end and usually varying between 800 to 1000 metres in height. Several subsidiary ridges branch off the main crest, separating a number of corries which drain to north and south. Further east a major branch of the ridge runs north-east to Beinn Mhor Liath Fannich, enclosing to the south Coir a'Ghuibhsachain, which drains to the east.

The area studied for this thesis covers the central and western portions of the range, and extends south to include Beinn nan Ramh, sundered from the main mountain block by the western reach of Loch Fannich, and the deep valley of the river Cabuie. Srath Chrombuill, south of Beinn nan Ramh, and Loch Fannich, further east, form the

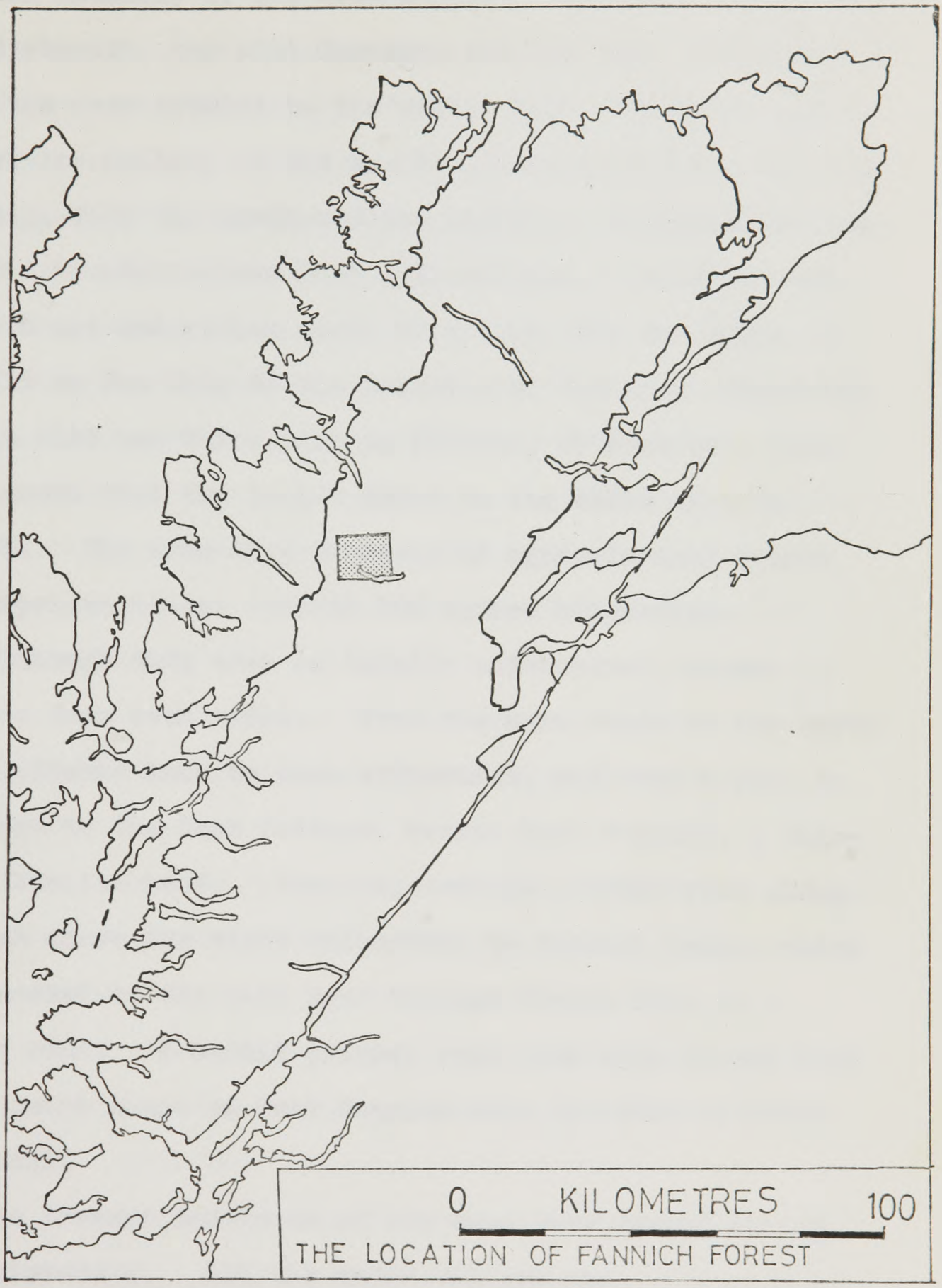


Figure 1.

southern boundary of the area mapped. The Allt Coire nam Fear Riabhaich, the Allt Ghranda, and the Allt a'Chleibh bound the area studied to the west; Loch a'Bhraoin, and the Abhuirn Cuileig as far as its junction with the Allt an Eas Bhig, form the north-western limits. To the north and east the boundaries are less well-defined. Accurate mapping was not undertaken north of a line from the mouth of the Allt an Eas Bhig to the junction of the Allt a'Mhadaidh and the Allt nam Coire Barr an Fhiodha, or east of a line drawn south from the latter point to the shore of Loch Fannich. The area thus enclosed is approximately square and comprises almost exactly 100 square kilometres.

Although this area is totally uninhabited, access is possible from both sides. From the main roads to the north good footpaths lead to Loch a'Mhadaidh, and over a pass in the range to the West Cottage, beside Loch Fannich, a kilometre from its head. From the cottage a track runs along the loch shore for eight kilometres to Fannich Lodge, which is connected to the main road through Strath Bran by a private road. A second private road runs from Strath Bran to the south shore of Loch Fannich near the head of Srath Chrombuill.

The present landforms of the area were formed during the Pleistocene. All the major valleys are

characteristically U-shaped, while Loch Fannich and Loch a'Bhraoin occupy rock-basins in these valleys. A series of corries, some containing small rock-basin lochans, occur on each side of the main Fannich ridge, while large areas of terraced rock debris, which occur on the ridge above 800 metres, were considered by Peach and Horne to result from frost action.

Moraines and boulder clay are restricted to the lower ground or the corries. Loch an Fhuar Thuill Mhoir is an excellent example of a moraine-dammed lochan, while three lochans in Coire Mor apparently fill kettle-holes in the moraine. While the main Fannich Range contains little morainic material, much of Beinn nan Ramh is covered by boulder clay, while in the area to the south and north-west of the range the rock is largely obscured by peat and boulder-clay.

Throughout this thesis, certain ill-defined terms have been constantly used in a specific sense, and these are explained below:

"Gneiss" refers here only to granular, highly metamorphosed rocks, often showing a segregation of minerals into bands. Only the Lewisian rocks of Fannich are referred to as gneisses in this work.

"Granulite" is a term used frequently by Peach and Gunn

to describe a rock with a granular texture, and is usually applied by them to Moinian Psammites. In view of its more specific meaning, used with reference to rocks subjected to "Granulite Facies metamorphism", it is only referred to in this thesis when mentioning such rocks from the Scourian complex on the Lewisian Foreland.

"Psammite" is used to describe metamorphosed sandstones of the Moinian.

"Pelite" is used in preference to the term 'schist' when referring to the schistose argillaceous metasediments in the Moinian. On occasion, certain subfacies within the pelitic units cease to be obviously schistose; when used as part of the name of a unit, the term pelite is used to cover the whole range of variation.

"Schist" is a general term describing rocks with a pronounced foliation. In this thesis it is used mainly with respect to mica-schists, and hornblende-schists, the latter being foliated amphibolites.

The term "amphibolite" is used as a general term to describe rocks consisting largely of amphibole. This term is used in preference to "epidiorite", which, used in the broader sense, as by Wiseman (1934) is virtually synonymous.

References to thin-sections and hand-specimens quote the specimen number, rather than the number of the field

locality where they were collected. All were collected by the author.

Local nomenclature of the rock-units has been used, and a few additional names have been proposed. These are tabulated in Table I.

TABLE 1

Nomenclature of Stratigraphic Units in Fannich

Peach et al. 1913	Sutton & Watson 1954	Winchester 1970
Meall an t-Sithe Rock	No. 9. (Youngest)	Meall an t-Sithe Pelite
Acid Gneiss, resembling Lewisian Gneiss	Fannich Gneiss	Lewisian Silicic Gneiss
Meall an t-Sithe Rock	Meall an t-Sithe Pelitic Group	Meall an t-Sithe Pelite
Meall a' Chrasgaidh Rock	Meall a Chrasgaidh Siliceous Group	Meall a' Chrasgaidh Psammite
Sgurr Mor Biotite-Schist with a quartzose granulitic schist band	Sgurr Mor Pelitic Group	Sgurr Mor Pelite, with Carn na Criche Psammite
Group 4, Flaggy granulitic quartzose mica-schist	Inverbroom Group	Inverbroom Group

2

PREVIOUS RESEARCH IN FANNICH

2.1 The Geological Survey

Fannich Forest was first mapped by Peach, Horne and Gunn in the years 1897, 1898 and 1899. Their findings were set out in the Summaries of Progress for these years, and in the Geological Survey Memoir for Sheet 92 (Peach et al 1913). In these publications, six distinct major lithological units were described and mapped around a south-east trending, apparently synclinal structure exposed in the west of the Fannich Range. Gunn noted the apparent order of succession of the units folded by this syncline, but pointed out that the second highest unit of the succession consisted of "coarse acid-gneisses of Lewisian type". Horne noted that the Moinian pelites underlying this "acid gneiss of Lewisian type" were identical to those overlying it, and regarded both units as repetitions of the same unit, folded around a core of Lewisian gneiss. Peach, Horne and Gunn assumed that these rocks were Lewisian, on lithological grounds, and their interpretation of the structure of Fannich rested on this assumption. Their field-mapping suggested that Fannich contained a major syncline, but the Survey geologists could find no suggestion of a root-zone,

either in Fannich or in the surrounding areas, to explain the high position of the Lewisian in the apparent succession. They therefore suggested that the root-zone for the Lewisian lay directly below the "syncline", which was therefore a complex fan-shaped anticlinorium. Because the root-zone lay below the fold it could not be seen at the surface. The units at present exposed below the Lewisian were therefore inverted, and the zone of inversion extended for several kilometres to the east and west of the axial trace of the Fannich fold. This interpretation, although not considered entirely satisfactory by the Survey geologists, as positive proof was lacking, remained the only one extant for nearly forty years.

2.2 Post-Survey studies

Rutledge and McIntyre visited Fannich Forest in 1950, and made several hundred measurements of the trend and plunge of minor fold axes and lineations. Accepting Gunn's field-evidence showing that the structure of the north-west part of Fannich was synclinal they showed that the syncline deepened towards Loch Fannich. Since this was difficult to reconcile with the apparent lack of continuity in the geology south of Loch Fannich, and the apparent absence of external root-zones for the Lewisian

slice, Rutledge and McIntyre concluded that the Lewisian Gneiss of Fannich was a very large tectonic inclusion surrounded by Moinian schists.

In the years 1949-52 Sutton and Watson re-examined the apparent succession of the Moinian units, using evidence from sedimentary structures where they were preserved in the psammites, and suggested that the gneisses assigned by the Survey geologists to the Lewisian were an integral part of the Moinian. This unit they renamed the "Fannich Gneiss" (see Table I). The psammite forming the eastern part of the Fannich Range, and containing well-preserved current-bedding in some localities they termed the Inverbroom Psammite. The current-bedding shows that the Inverbroom Psammite in eastern Fannich is uninverted; therefore Sutton and Watson concluded that the whole Moinian succession in Fannich was uninverted, finding no evidence to suggest that overturning occurs.

Their measurements of lineations and minor fold areas showed that they were related to the observed folding, which they described in some detail. The main folds they named the Droma Anticline, the Braemore Syncline and the Fannich Syncline, and they interpreted the latter as bringing down an upper Moinian succession, which included the "Fannich Gneiss".

More recently Johnstone (pers. comm.) has visited Fannich, and he equated the Meall an t-Sithe pelite with the pelites near Glenfinnan on lithological grounds.

3

MOINE STRATIGRAPHY AND GENERAL PETROGRAPHY

3.1 Introduction

Field-mapping of the Fannich Range revealed a succession of well-defined Moinian rock-units. Superficially, the structure of the area appears to be a simple syncline plunging towards the south-east, and around it a regular series of lithological units is readily mappable. How far the present succession can be related to the original sedimentary succession will be discussed in a later chapter, but these units will meanwhile be described in their present ascending order of succession, as tabulated in Table 1.

All the major units have received local names (tabulated in Table 1) whose origins are discussed below. The Inverbroom group of psammites forms the basal unit within the Fannich Fold. It is overlain by the Sgurr Mor Pelite, bisected on the east limb by the Carn na Criche Psammite. The pelite is overlain in turn by the Meall a' Chrasgaidh Psammite, and the Meall an t-Sithe Pelite. Psammitic bands within these pelites are collectively named Sgurr nan Each Psammites, and the whole group is overlain by a varied series of silicic gneisses and amphibolites, reminiscent of the Foreland Lewisian. Overlying these, and forming the highest unit preserved in the succession is a further group of Meall an t-Sithe Pelites,

identical with the group below the silicic gneisses.

With certain notable exceptions, the margins between all these units are gradational. The Sgurr Mor Pelite grades with an increasing proportion of psammitic bands into either the Meall a' Chrasgaidh psammites, the Carn na Criche psammites, or the Inverbroom Group. But the contact between the Meall a' Chrasgaidh Psammite and the Meall an t-Sithe Pelites was always sharp, wherever seen. (Plate 2). Over a thickness of less than five centimetres, a complete conversion from a typical Meall a' Chrasgaidh lithology, to a typical Meall an t-Sithe Pelite is effected, the junction often being marked by a quartz pegmatite. No positive evidence was seen implying that this junction is tectonic, no mylonitization or textural evidence hints at the presence of a thrust or slide. But Tanner et al (1969) draw the outcrop of a slide through Fannich, and if such a slide-plane is present, this junction is the only possible one along which it could occur.

The Sgurr nan Each Psammite, as a lithological variant of the Meall an t-Sithe Pelite, shows a gradation from psammite through semipelite to typical pelite.

Junctions between the Meall an t-Sithe Pelite and the silicic gneisses, observed in widely scattered parts of Fannich, were always sharp. Although silicic gneisses were observed in actual contact with the pelite, usually the junction is masked by a thin quartz-pegmatite, or a thin

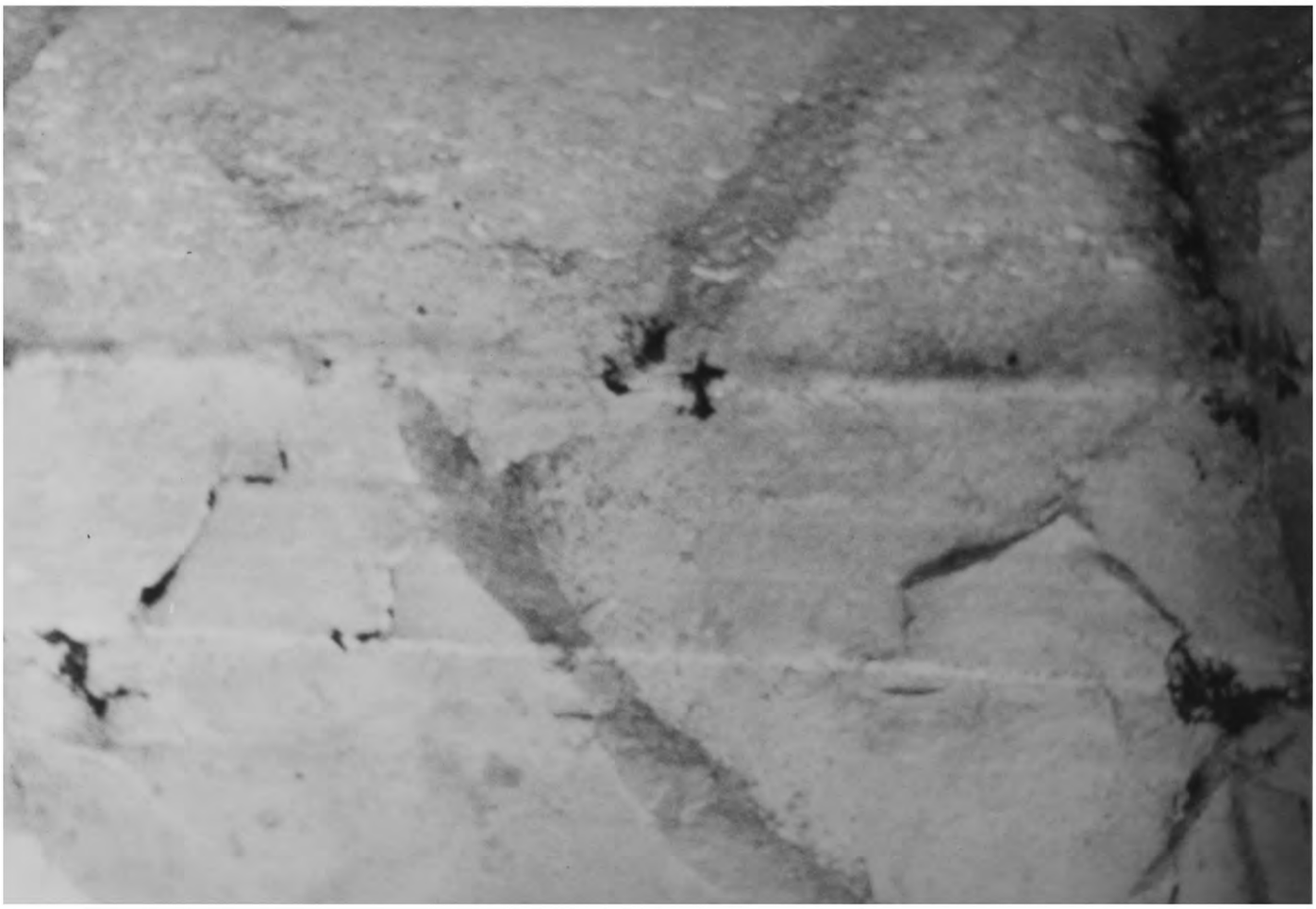


Plate 2. The sharp junction between the Meall a' Chrasgaidh Psammite (below) and the Meall an t-Sithe Pelite (above).

biotitite; the presence of the biotitite at the junction is reminiscent of the junction between Lewisian and Moinian at the Shin-Cassley Inlier (Winchester & Lambert 1970). No indication of thrusting was seen, but at one locality, the presence of a sheared conglomerate in the pelite at the junction suggests an unconformable contact. The conglomerate (Plate 3) is described more fully below.

The distribution and brief petrological description of the units are described below. Many of the place-names mentioned are shown on Figure 3; the positions of others not marked are described in connection with those that are. Table 1 sets out the nomenclature of the lithological units seen in Fannich, referred to by Peach and Gunn (1913), Sutton and Watson (1954), and in this thesis.

3.2 Inverbroom Psammites

The eastern portion of the Fannich Range is mainly composed of a series of psammites and semipsammites termed Group IV by Peach and Gunn (1913). Sutton and Watson (1954) refer to it as the Inverbroom Group, and this name is used here to describe both these psammites, and those on the western limb of the Fannich synform, lying west of an indistinct band of pelites, occurring in Coire nam Fear Riabhaich.

The Inverbroom Group forms a portion of the Fannich Range, east of the Allt Coire Beag, and the Allt Coire Barr an Fhiodha,

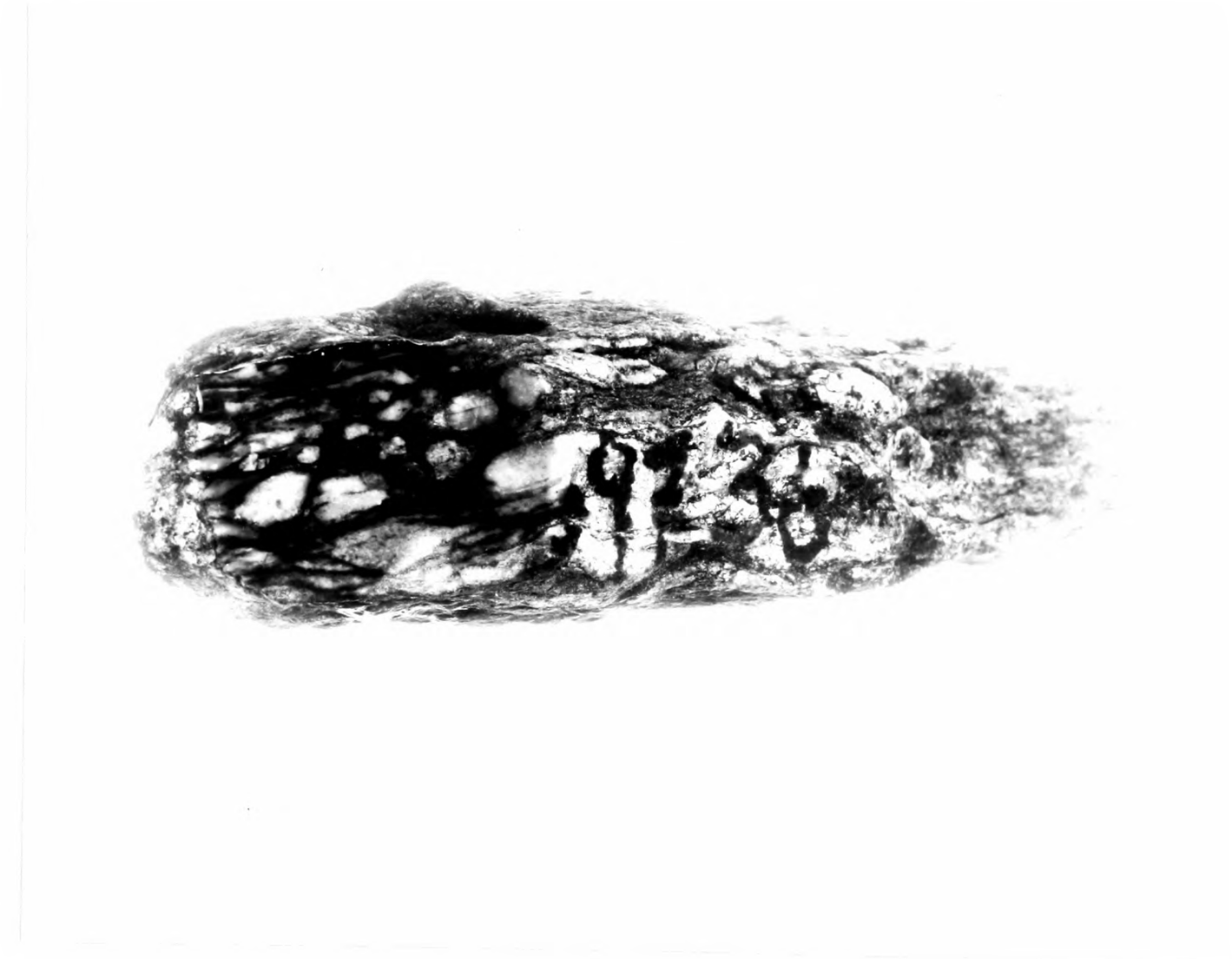


Plate 3. Conglomerate from the basal Moinian near Sgurr a' Chadha Dheirg.

west of Beinn Mhor Liath Fannich, on the east limb of the Fannich Synform. North of the area surveyed it forms the low ground in the Dirrie More (see Fig.2), the plateau north of Creag Raineach, and then swings south parallel to the Moine Thrust. To the west of Fannich Forest, it forms the hills of Groban, and much of Meallan Chuaich, west of Coire nam Fear Riabhaich, the low ground at the head of Loch a' Bhraoin and the headwaters of the River Cabuie.

Although the Inverbroom Group is mainly psammitic and semipsammitic in character, semipelites and occasional thin pelites do occur, resembling in texture and mineralogy the adjoining Sgurr Mor Pelite. The psammites and sempsammites are medium-grained granular quartzose rocks, also containing oligoclase, biotite and smaller amounts of epidote and sphene. Microscopic garnets were seen in two specimens collected from the Abhuinn Droma (see Fig.2). Microcline is frequently present, but muscovite is restricted to the more semipsammitic bands.

Concentrations of biotite may indicate the presence of original sedimentary structures. Sutton and Watson (1954) observed recognizable current-bedding in the Abhuinn Droma (Plate 4) and the River Grudie. This was confirmed in this study, but often the laminae showing the current-bedding were seen to be tectonically deformed (Plate 5) so that elsewhere, often close to seemingly undisturbed units, the



Plate 4. Current bedding in Inverbroom Psammites.



Plate 5. Deformed Inverbroom Psammites with current bedding.

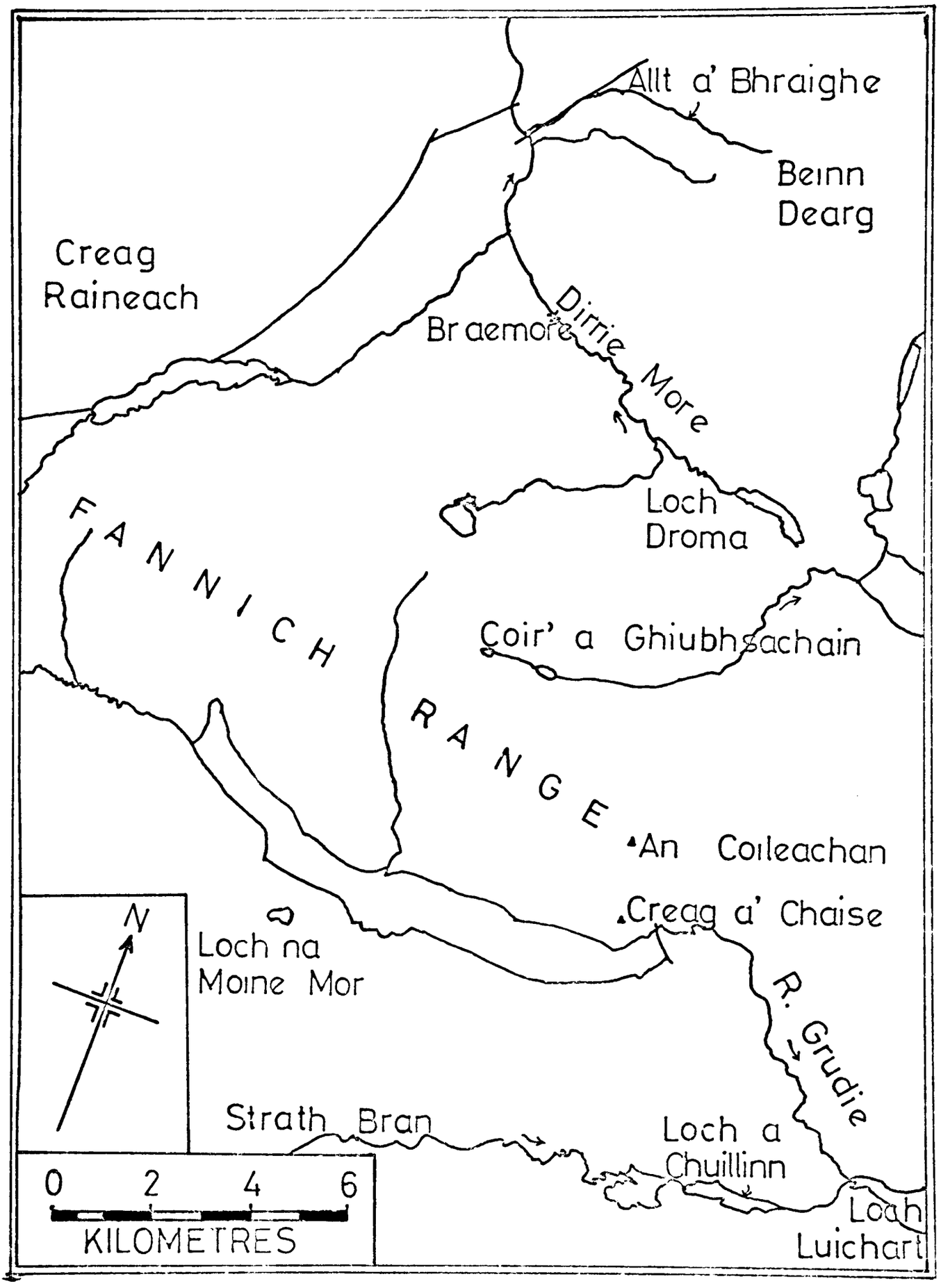


Figure 2. THE DISTRICT AROUND FANNICH FOREST.

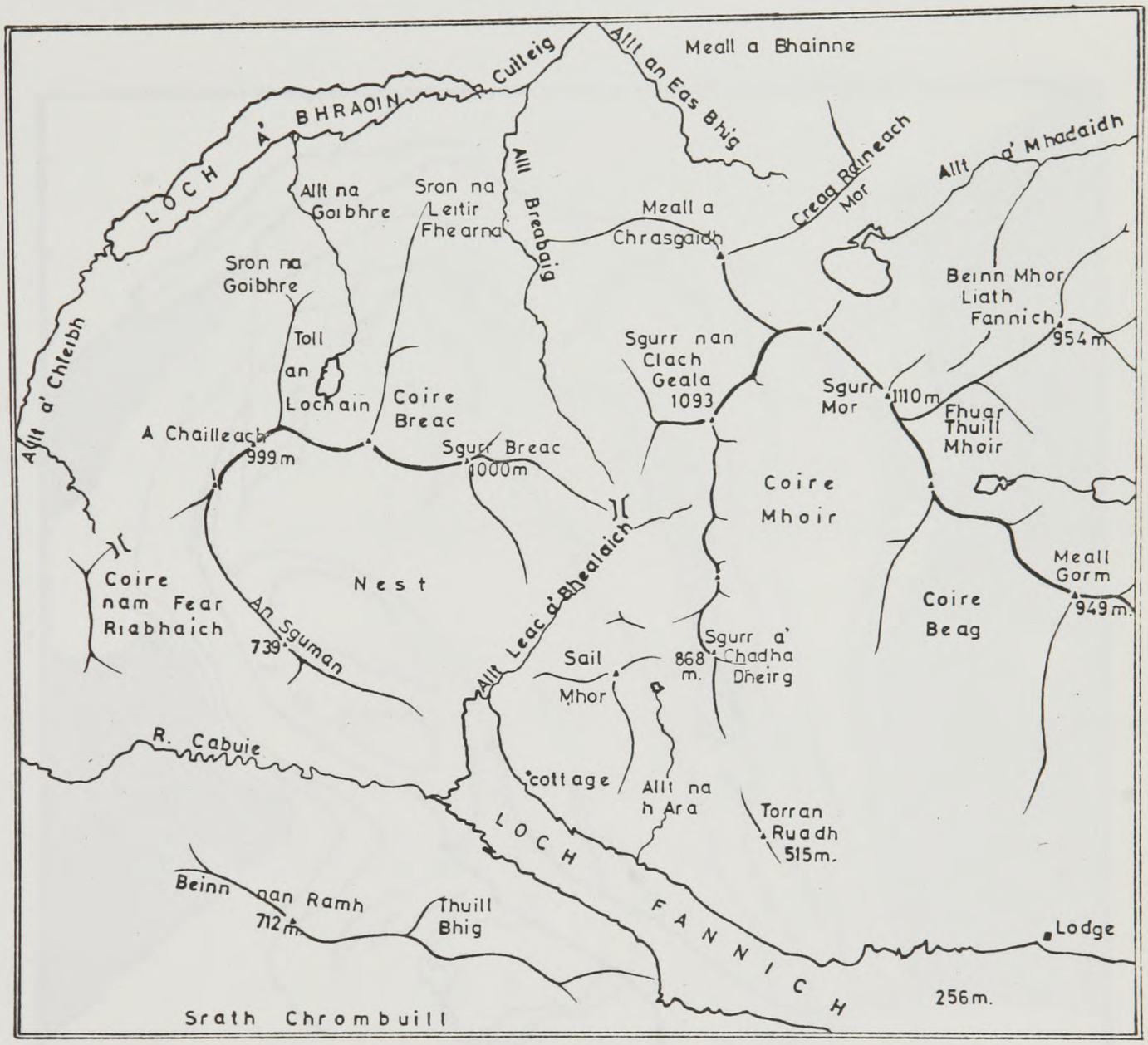
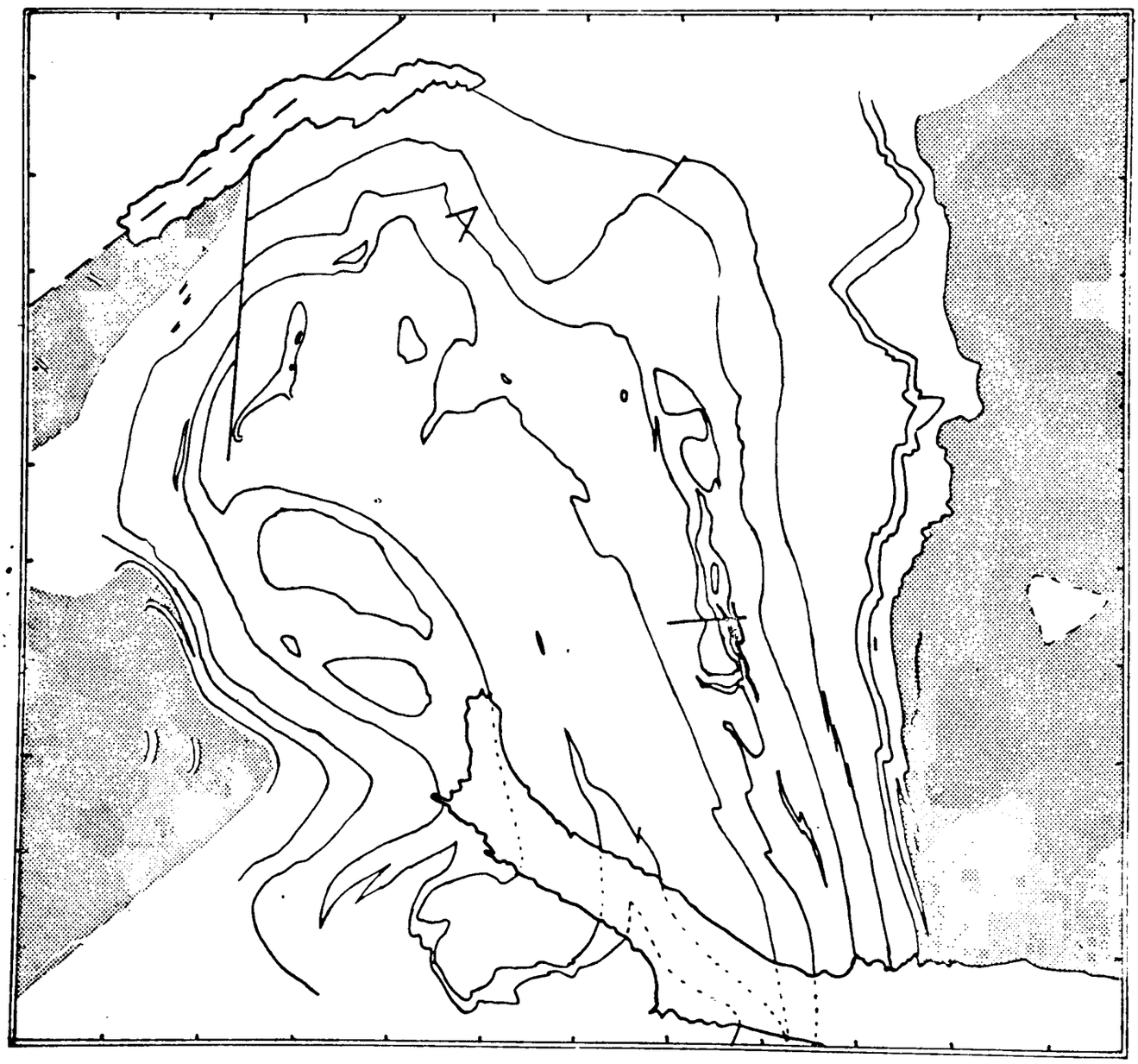


Figure 3.

A map of Fannich Forest, showing the locations of some of the places referred to. Elevations are in metres.



ig re 1.

A MAP OF FANNICH FOREST SHOWING SHADED

THE DISTRIBUTION OF THE INVERBROOM PSAMMITE

laminae are distorted into isoclinal folds. In a few rare instances the presence of isoclines is also confirmed by the juxtaposition of current-bedded units indicating younging in opposite directions. The direction of younging seen is usually to the west, indicating that the Sgurr Mor Pelite is younger than the Inverbroom Group, but because of the abundant evidence of deformation, the value of current-bedding as a reliable aid to structural interpretation may be limited

Calcareous psammites, and a heavy mineral seam were also observed in the Inverbroom Group, and as they differ markedly from the normal psammites, their distribution is discussed below, while their petrography is also described separately in Chapter 6.

The calcareous psammites were seen near the gradation into the Sgurr Mor Pelite on the crags forming the south-east side of Coire Barr an Fhiodha, where they occur as lenses or spherical bodies in a semipsammite.

The heavy mineral seam was seen north of Fannich, occurring in the upper part of Coire Ghranda on Beinn Dearg, within the psammites forming a continuation of the Inverbroom Group. No heavy mineral seams were seen in Fannich itself.

Only one amphibolite was seen in these psammites. On the west limb of the Fannich Fold in the gorge below Eas an Uillt Ghranda, on the Allt Ghranda, a tributary of the Allt a' Chleibh, an amphibolite dyke occurs, which is texturally

different from any others in Fannich. It is described in detail in Chapter 6 .

Variations in the thickness of the Inverbroom Group are hard to assess, since it forms the lowest unit in the apparent succession. If isoclinal folding occurs within the Fannich synform, it may also affect the Inverbroom Group and give it an apparent thickness much greater than its true thickness.

3.3 Sgurr Mor Pelite

Adjoining the Inverbroom Group is a series of pelites and semipelites, termed by Gunn (1913) the Sgurr Mor Biotite Schist. In this thesis it is referred to as the Sgurr Mor Pelite, and it forms the next well-defined unit in the apparent upward succession of the Fannich synform. Its outcrop is narrow at the mouth of the Allt a' Choire Mhoir, but thickens steadily northwards, forming the ridge of Druim Reidh, dividing Coire Mor from Coire Beag. It forms Sgurr Mor and reaches its greatest development around Loch a' Mhadaidh and Carn na Criche, one kilometre north-west of Sgurr Mor, where it swings west around the Fannich fold north of Meall a' Chrasgaidh to reach Loch a' Bhraoin near its outlet. North of the area mapped in this thesis, the Survey Sheet 92 shows that the outcrop of Sgurr Mor Pelite is displaced to the north-east by the Fasagh Fault (see Fig.2), and swings west around the northern end of

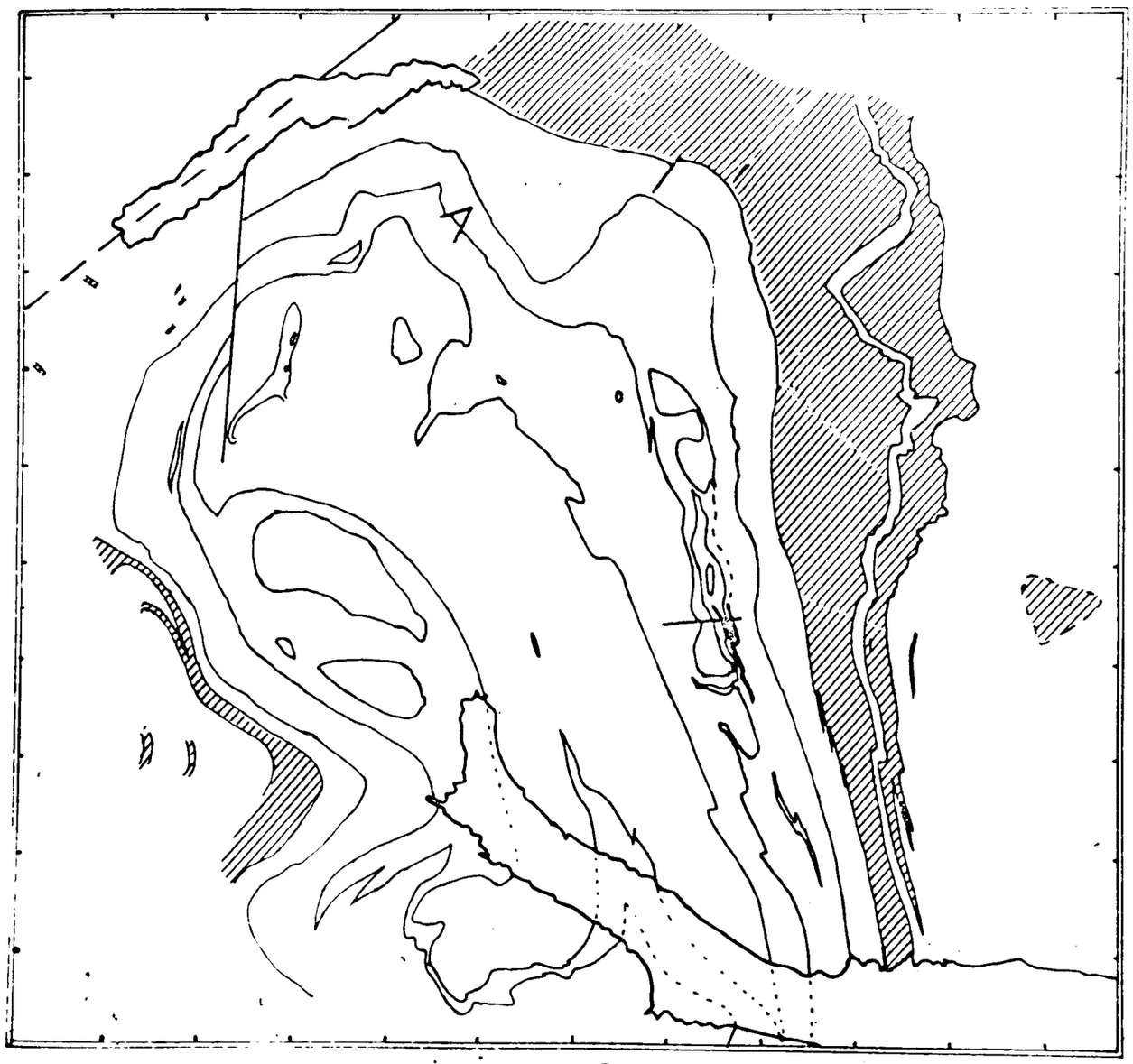


FIG. 5

A MAP OF FANNICH FOREST SHOWING SHADED

THE DISTRIBUTION OF THE SGURR MOR PELITE.

the Creag Raineach synform, thinning abruptly. West of the Fannich Range thin pelitic strips occur within the psammites underlying the Meall an t-Sithe Pelite. These strips, some of which contain poorly-developed calc-silicates, may mark the attenuated western continuation of the Sgurr Mor Pelite.

Lithologically similar pelites were also seen near Loch-luichart and Achanalt, in the River Grudie two kilometres below the dam at Loch Fannich, and in the Allt a' Choin Idhir. On the eastern summits of the Fannich Range, and on Creag a' Chaise outliers of pelite were correlated with the Sgurr Mor Pelite by Gunn (1913). Except on Creag Raineach on Beinn nan Ramh, similar pelites were not seen south of the Cabuie valley or the western and central parts of Loch Fannich.

Along its whole outcrop on the eastern limb of the Fannich synform, the Sgurr Mor Pelite is bisected by a prominent quartzose psammite, termed here the Carn na Criche psammite. Thinner and more discontinuous psammites also occur elsewhere within the pelite.

The Sgurr Mor Pelite closely resembles the No.5 Pelite of Morar (Ramsay & Spring 1963) and the Ladhar Bheinn Pelite of Glenelg and Knoydart, partly because it also contains distinctive calc-silicate bands and lenticles. In Morar, Richey and Kennedy (1939) were able to subdivide the group into three smaller units, but this was not possible in Fannich because, although rock-types typifying Richey and Kennedy's units were

seen, they were so intimately associated with each other that they could not be mapped separately. But in the parts of the Sgurr Mor Pelite adjacent to the Inverbroom Group, calc-silicate strips are notably less abundant.

Apart from the calc-silicate strips, three main metasedimentary lithologies were seen in the Sgurr Mor Pelite, and also a group of garnet-amphibolites of probable intrusive origin. The metasediments are:

1. A distinctively speckled quartz-biotite schist, which forms the bulk of the pelite, and which occurs occasionally with thin bands of flaky muscovite-biotite schist.
2. Muscovite-biotite schists, spotted with small black, or dark purple garnets.
3. Semipsammitic or psammitic bands.

Calc-silicate lenticles occur in all these units but are less common in the semipsammites, where they resemble the calc-silicates of the Inverbroom Group. In their mineralogy and textures they vary a great deal, and, as a special study was made of them, they are described in Chapter 7 in detail.

Besides the calc-silicate strips, the Sgurr Mor Pelite also contains small bodies of garnet-amphibolite. (Plate 6) They are rare, and were only observed at four localities. Three of these were in the lower course of the Allt a' Choire Mhoir; the fourth was on the eastern slope of Meall a' Chras-



Plate 6. Garnet-amphibolite band in Sgurr Mor Pelite. Allt a' Choire Mhoir.

gaidh. Always concordant with the foliation, these amphibolite strips may be derived from small pre-orogenic dykes, in which any original discordance with the country rock has been destroyed by deformation.

Structural controls may be responsible for the enormous variation in the thickness of the Sgurr Mor Pelite: these will be discussed later in Chapter 5, devoted to the structure of Fannich Forest.

3.4 Carn na Criche Psammite

The prominent psammite band bisecting the outcrop of the Sgurr Mor Pelite from Loch Fannich to a point north of Loch a' Bhraoin is referred to in this thesis as the Carn na Criche Psammite. Gunn (1913) refers to it simply as a prominent band of "Quartz-schist", but it is considered here to be sufficiently continuous to be given a local name.

Within the area studied, it is traceable from the poorly-exposed ground north of Meall a' Bhainne by a sinuous course to Loch a'Mhadaidh. On the large crag below Carn na Criche it is well exposed, folded so that it skirts the northern and eastern slopes of Sgurr Mor. In a series of sharp folds it zigzags up the south wall of Coire Barr an Fhialaidh, east of Sgurr Mor, then, running round the west lip of Fuar Thuill Mhoir, it passes west of the summit of Meall nan Fethirean, south-east of Sgurr Mor.

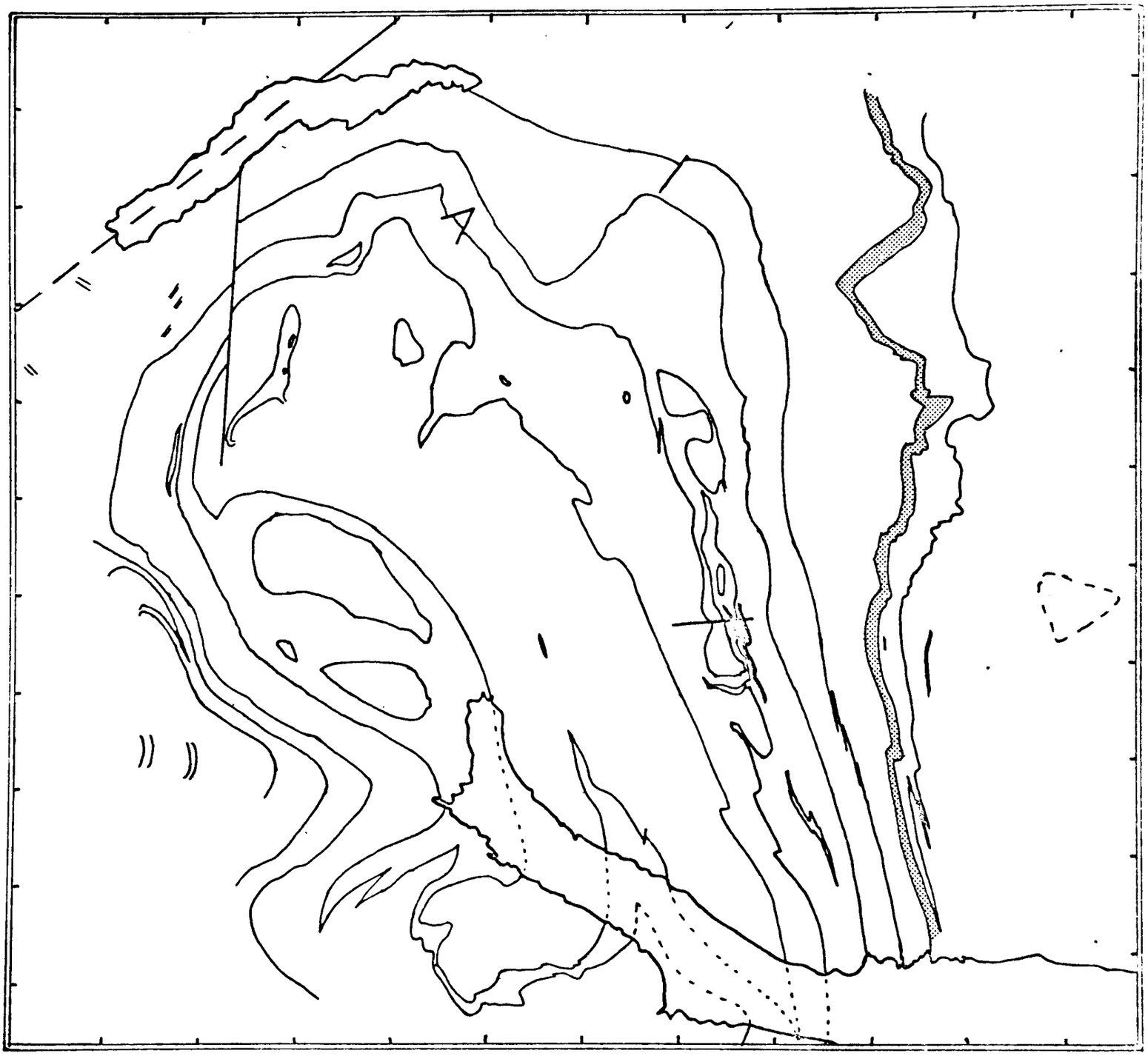


Figure 6.

A MAP OF FANNICH FOREST SHOWING SHADED

THE DISTRIBUTION OF THE CARN NA CRICHE PSAMMITE

Finally, it runs south along the crest of Druim Reidh, and is finally exposed in the lower course of the Allt a' Choire Bhig. At this point the eastern part of the Sgurr Mor Pelite is so attenuated that the Carn na Criche psammite is almost merged with the Inverbroom Group, which it frequently resembles. From the field evidence these psammites seem likely to unite, and a further merger with the Meall a' Chrasgaidh Psammite beneath Loch Fannich may account for the absence of the Sgurr Mor Pelite south of the loch. The appearance of another group of psammites within the eastern part of the Sgurr Mor Pelite, observed in the bed of the Allt a' Choire Bhig, and on the southernmost crags of Druim Reidh, suggest that the disappearance of the Sgurr Mor Pelite southwards may result from early isoclinal folding.

The junction between the Carn na Criche psammite and the Sgurr Mor Pelite is a rapid gradation, the transition from pelite to psammite occurring within two metres, and this was also true of the other similar psammites seen south of Druim Reidh.

As with the Inverbroom Group, current-bedding was seen in the Carn na Criche Psammite in a few places. Usually the direction of younging is to the west, but considerable distortion of the bedding laminae suggests that intense deformation has occurred, possibly explaining why current-bedding is only preserved in a few isolated localities. By

itself, therefore, the direction of younging may not be a reliable clue to the regional structure.

The Carn na Criche Psammite shows similar lithological variations to the Inverbroom Group. It consists largely of pale quartzose psammites, but also includes greyer semipsammites and calcareous lenses.

The quartzose psammites also contain oligoclase and flakes of black biotite. Muscovite and epidote may also be present, but garnets are rare; many samples collected contained no garnet. Typically they are redder than those in the Inverbroom Group.

The semipsammites are greyer, and contain more muscovite and biotite, concentrated in thin laminae. Apatite, observed in the Inverbroom Group, was not seen in the Carn na Criche psammites.

The calcareous bodies closely resemble those of the Inverbroom Group in being very quartzose, in containing zoïsite as a substitute for plagioclase, and in having coarse-grained aggregates of black biotite.

Although all the Moine psammites may be lithologically similar to each other, the very close resemblance of the Carn na Criche Psammite to the Inverbroom Group is striking.

3.5 Meall a' Chrasgaidh Psammite

This unit, overlying the Sgurr Mor Pelite in the apparent stratigraphic succession, was called the Meall a' Chrasgaidh Rock by Gunn (1913). Horne (1913) while mapping the southern part of the range, also referred to it as the Meall a' Chrasgaidh Siliceous Schists. It can be traced from the north shore of Loch Fannich west of the mouth of the Allt a' Choire Mhoir, up Coire Mor to Sgurr nan Clach Geala, where it forms the prominent north-east buttress. After forming the bulk of Meall a' Chrasgaidh, it swings west across the Allt Breabaig to Loch a' Bhraoin, where it forms the southern shore. On the west limb of the Fannich Synform, it is hard to distinguish it from the Inverbroom Psammites, as the Sgurr Mor Pelite is virtually absent. It appears to skirt the western slope of A' Chailleach to the Bealaich nan Tri Tigheairnan, north of Coire nam Fear Riabhaich, whence it skirts the south-western slopes of An Sguman to the River Cabuie. Crossing Beinn nan Ramh west of its summit it continues south to Srath Chrombuill.

No current-bedding was seen in the Meall a' Chrasgaidh psammite. Certain faint laminae that superficially resembled current-bedding were found to be small isoclines, about five centimetres across, which had one limb sheared out; complete isoclines usually being visible nearby. When viewed from further away, the biotite-rich bands bounding these sets of



A MAP OF FANNICH FOREST SHOWING SHADED
THE DISTRIBUTION OF THE MEALL A' CHRASGAIDH PSAMMITE

isoclines imparted a striped appearance to the psammite. In a psammite visibly acting as a competent unit compared to its flanking pelites during the formation of the Fannich syncline, the existence of such deformation strongly suggests that an earlier fold episode occurred. If so, the absence of sedimentary structures is explained, and their preservation in the other psammites may indicate that those psammites were not so strongly deformed in this earlier episode. The striping, and the commoner small-scale isoclinal folding of the Meall a' Chrasgaidh psammite suggest that it has undergone considerable lateral compression and longitudinal stretching. In this light, its present textural differences from the other psammites in Fannich do not necessarily preclude it from being derived from the same original sedimentary unit.

It is usually a massive quartzose psammite with small flakes of biotite and muscovite. Two micas are present in all but calcareous rocks. Whereas biotite is scattered as small flakes throughout the rock, muscovite occurs mainly as larger sheets forming the micaceous foliae that impart a flaggy nature to the rock. Seven non-calcareous samples contained red garnets and in one of these the garnet was extensively chloritized. Sphene and apatite occur as accessories in almost all the specimens, while epidote and microcline also occur in some.

The calcareous rocks are rare, but samples were collected

of two different types, neither of which resembled those from other Moinian sediments. Two specimens collected from Am Burach, the broad saddle connecting Meall a' Chrasgaidh to the main ridge, were found to contain abundant epidote, with tremolite and calcite, while a sample containing pale green tremolite, diopside and microcline was collected from the Allt a' Choire Mhoir. The petrology of these rocks will be discussed in more detail in chapter 6.

3.6 Meall an t-Sithe Pelite

Referred to by Gunn (1913) as the "Meall an t-Sithe Rock", this very distinctive pelite is readily recognisable over the whole area. It was termed the "Meall an t-Sithe Pelitic Group" by Sutton and Watson (1954) but they confined this title to the lower pelitic unit only, referring to the upper one only as "Number 9" in their sequence. Here the whole unit will be referred to as the Meall an t-Sithe Pelite. Gunn noted that the pelite seen overlying the Meall a' Chrasgaidh Psammite, and underlying the series of silicic gneisses and amphibolites which he interpreted as Lewisian was identical to the pelite seen resting on top of the same silicic gneisses. He concluded that the two pelites were identical, and nothing revealed in the fieldwork for this thesis has suggested that they are different. They will therefore be described as the same rock unit in this discussion. The "Lower" Meall an t-Sithe Pelite



A MAP OF FANNICH FOREST SHOWING SHADED THE

DISTRIBUTION OF THE MEALL AN 'T-SITHE PELITE

describes the schists below the silicic gneisses, and the "Upper" Meall an t-Sithe Pelite refers to those overlying the silicic gneisses and forming the highest rock unit preserved in the present Fannich synform.

The outcrop of the Lower Meall an t-Sithe Pelite runs north from the shore of Loch Fannich, south-east of Torran Ruadh, passing east of the main summits of the ridge bounding Coire Mor on the west. Outliers of Meall an t-Sithe Pelite, resulting from both topography and later folding, form the summits of both Sgurr a' Chadha Dheirg and Sgurr nan Each to the north. Further north the main outcrop of pelite forms the summit of Sgurr nan Clach Geala and the western slopes of Meall a' Chrasgaidh. Crossing the Allt Breabaig it forms the prominent crags of Sron na Leitir Fhearna, and then, turning south-west it crosses the Allt na Goibhre and skirts the northern and western slopes of Sron na Goibhre. Turning south-east, it passes west of A' Chailleach and An Sguman, reaching the River Cabuie where it enters Loch Fannich. An inlier of Lower Meall an t-Sithe Pelite is also exposed on the lowest ground in the Nest of Fannich. On Beinn nan Ramh the outcrop of the lower pelite follows a sinuous course, forming the highest part of the ridge and much of the southern slopes. It forms the head of Srath Chrombuill and forms the southern shore of Loch Fannich for about a kilometre at the eastern end of Beinn nan Ramh. It also occurs around the bay on the south shore

opposite the mouth of the Allt a' Choire Mhoir. This occurrence of Meall an t-Sithe pelite was mistakenly interpreted by Sutton and Watson (1954) as a continuation of the Sgurr Mor Pelite, Although it is clear from his description that Peach (1913) regarded it as Meall an t-Sithe pelite. During the fieldwork for this thesis (1969) this pelite was correlated on lithological and stratigraphic grounds with the Lower Meall an t-Sithe pelite. South of Loch Fannich around Loch na Moine Mor, exposure is extremely poor; the two bands of Lower Meall an t-Sithe Pelite may unite further south as the intervening band of silicic gneisses in the core of the syncline is wedged out. The small inlier of Lewisian rocks in the Allt Coire nan Laoigh, 1½ kilometres north-east of Achnasheen could possibly form the southern end of the Fannich Inlier, the exposure between it and Loch Fannich being so poor that the intervening structure is open to interpretation. Whether or not it is a part of the Fannich Inlier, and the question of its relationship with Fannich will be discussed in chapter 5.

The Upper Meall an t-Sithe Pelite occupies the core of the Fannich synform. On Beinn nan Ramh it occurs in Tuill Bhig, and for a kilometre to the east on the slope above Loch Fannich. Except for a short distance near the Allt na h'ara, the Upper Meall an t-Sithe Pelite forms the north shore of Loch Fannich from the head of the loch to a point below Torran Ruadh. From

the loch shore it runs north-north-west, forming Sail Mhor and the three main summits of the Fannich Range west of the main pass between the Allt Breabaig and the Allt Leac a' Bhealaich (later referred to as the "main pass"in this thesis). North of the watershed this pelite forms the whole of Toll an Lochain and Sron na Goibhre. Outliers of Upper Meall an t-Sithe Pelite also occur on the summit of An Sguman, and on Creag an Tairbh, at the eastern end of the An Sguman ridge.

Small inliers of Meall an t-Sithe Pelite also occur at three points within the silicic gneisses: north-west of Sgurr nan Clach Geala, in the ravine of the Allt na h'Eilig, draining the southern part of Coire Breac, and in the course of the Allt na Goibhre.

As a typical schist, the Meall an t-Sithe Pelite retains no trace of sedimentary structures; its texture is wholly metamorphic. It bears little textural resemblance to the Sgurr Mor Pelite, as it is characteristically coarse-grained and contains a typical wavy foliation-pattern. Abundant quartz lenticles, concordant with the foliation occur in all the pelitic sub-lithologies, providing a distinctive "streaked" appearance (Plate 7). Garnets are usually abundant, often clear, and virtually free of inclusions. Their distinctive pink or deep mauve colour was not seen in garnets from other Moinian units in Fannich. Garnets of a similar colour were seen in the No.1 Pelite from Morar by the author, while Clifford (1957)



Plate 7. Meall an t-Sithe Pelite with abundant crumpled quartz lenticles.

also noted their distinctive colour in Kintail in the "Garnetiferous Mica-schist Series" and the "Garnetiferous Mica Schists of Creag na h'Iolaire."

Variations in the texture of the Meall an t-Sithe Pelite stem from the proportion of micas to quartz; a greater quantity of micas induces a greater flakiness in the rock while with increasing quartz content the rock becomes increasingly semipsammitic and flaggy. Thus although the Meall an t-Sithe Group is referred to in this thesis as a pelite, it must be understood that the group as a whole includes subfacies that are semipelitic or locally semipsammitic. The most psammitic bands are locally well developed and were mapped as distinct from the main pelite by Peach and Gunn (1913). In this thesis they are mapped separately, and are discussed under the heading: "Sgurr nan Each Psammites".

No calcareous rocks were seen in the Meall an t-Sithe Pelite, but small bodies of amphibolite occur scattered widely throughout it. They occur as small lensoid bodies or as thin dykes, one of which, in the Allt Leac a' Bhealaich, cut across the foliation of the surrounding pelite at a gentle angle (Plate 8). Most amphibolites examined had sharp junctions with the pelite, but one, exposed on the north shore of Loch Fannich, showed a complete gradation of rock-type from amphibolite to pelite (Plate 9), with the red garnets of the amphibolite invading the pelite. Brown colouring around the dyke resulted

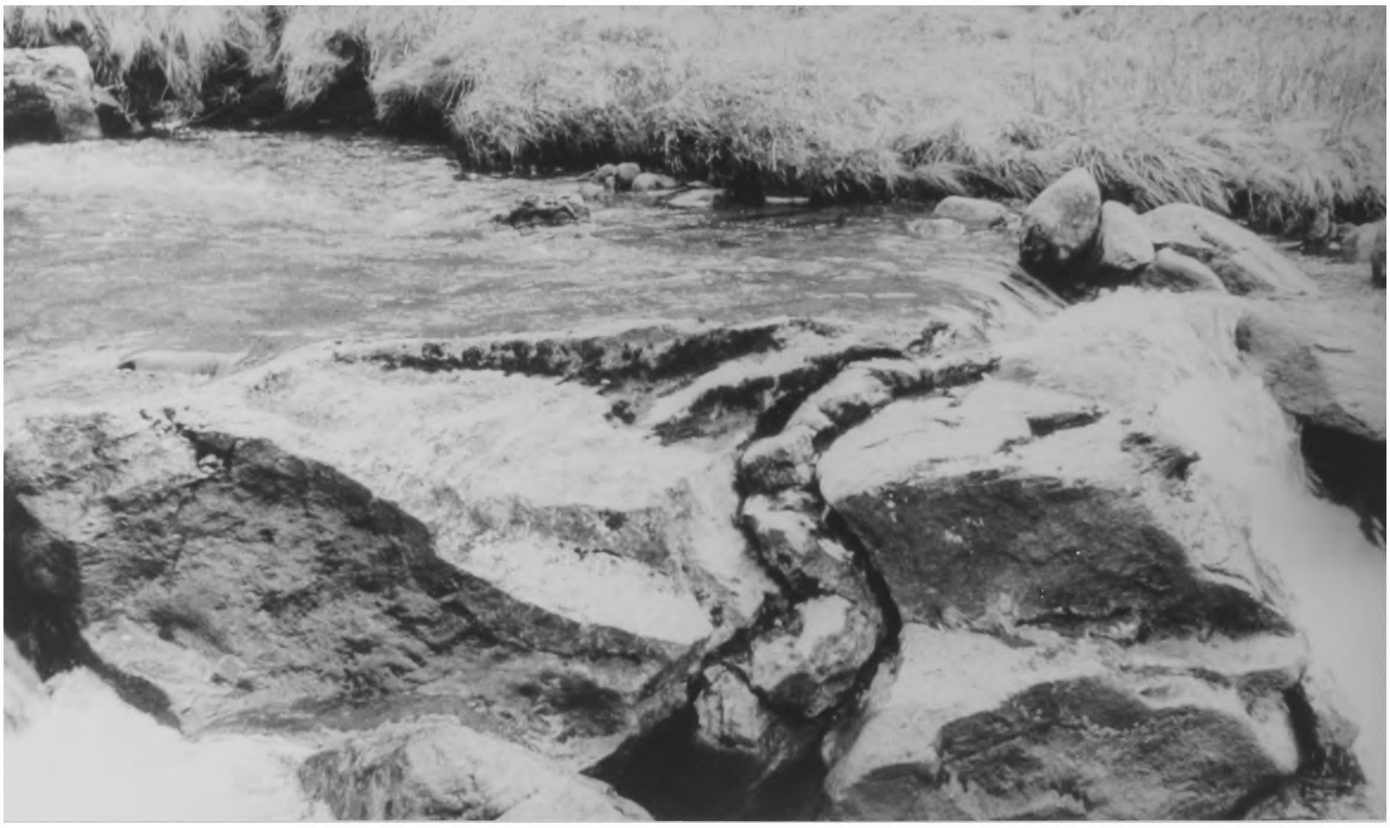


Plate 8. Garnet-amphibolite dyke in Meall an t-Sithe Pelite.



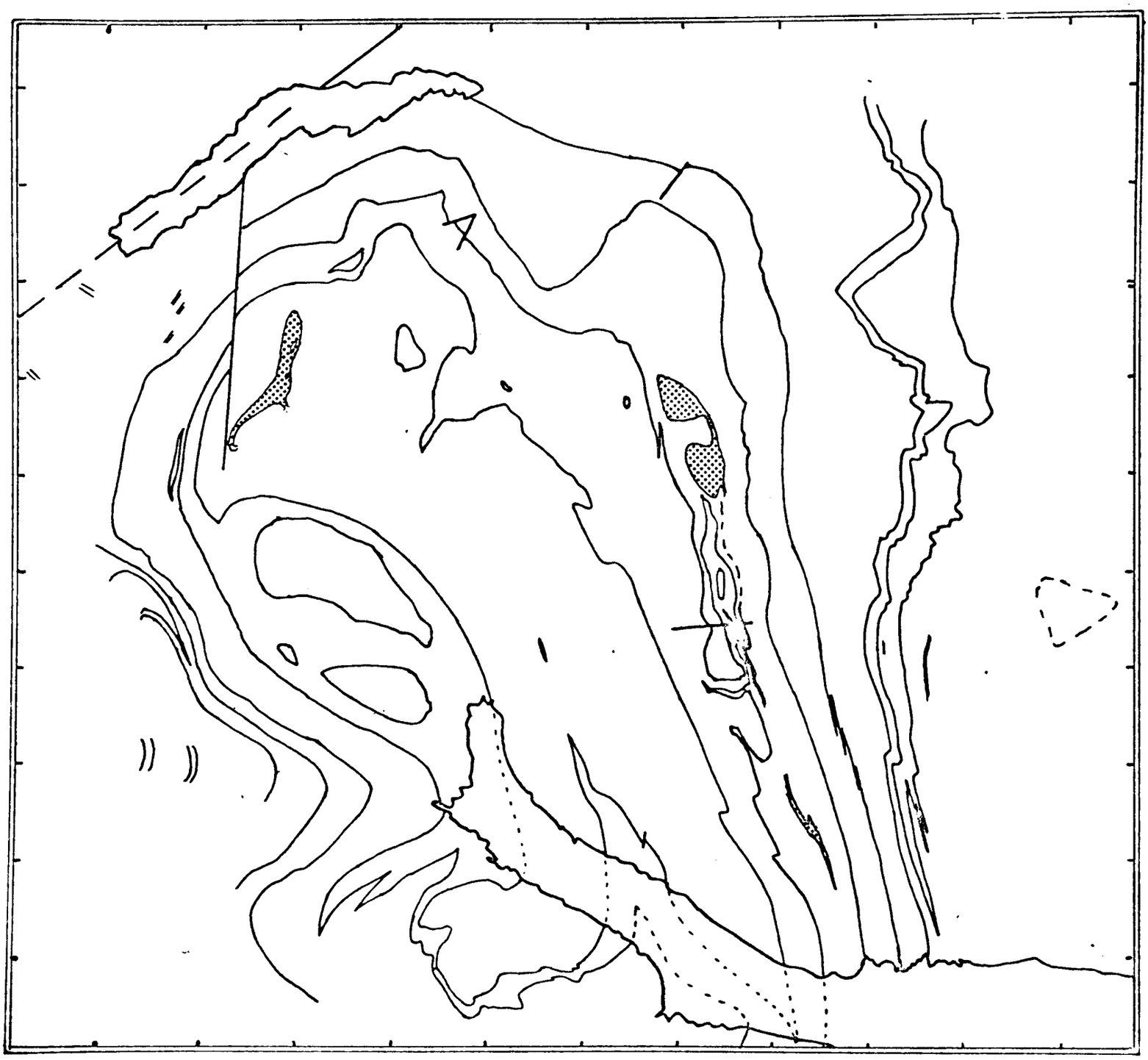
Plate 9. Garnet-amphibolite partially absorbed into Meall an t-Sithe Pelite.

from the replacement of hornblende by biotite. In this instance the amphibolite may have partially melted the pelite, probably hot already, at the time of intrusion (see Plate 9).

North of Loch Fannich these amphibolites were only seen in the Upper Meall an t-Sithe Pelite, but south of the loch they also occur in the lower pelite. Nonetheless, of thirty-three amphibolitic bodies observed in Fannich, all but five occurred in the upper pelite. The implications of this distribution are not clear, but if the two pelites are derived from the same sedimentary unit, folded around an isoclinal Lewisian core, the pelite overlying the Lewisian may have originated from a point many kilometres away from the pelite underlying the Lewisian. If so, the unequal distribution of amphibolite bodies may simply be the result of a localised intrusive episode.

3.7 Sgurr nan Each Psammite

As mentioned above (p. 27), psammitic bands are locally well-developed in the Meall an t-Sithe Pelite. They are described separately here, although they are probably lithological lateral variations of the pelite. They are named Sgurr nan Each psammites in this thesis as they are developed on the eastern crags of that mountain, and intermittently for over three kilometres to the south. Horne (1913) mapped it separately east of Torran Ruadh, but surmised that it might



A MAP OF FANNICH FOREST SHOWING SHADED
THE DISTRIBUTION OF THE SGURR NAN EACH PSAMMITE

Figure 8.

be an infold of the Meall a' Chrasgaidh psammite.

As a lithological variant of the Meall an t-Sithe Pelite, the Sgurr nan Each psammite cannot be traced as a complete strip around the Fannich fold. It is well exposed in the Allt nam Breac Beag, east of Torran Ruadh, where it is rather semipelitic, and can be traced again running north immediately below the crags of Sgurr a' Chadha Dheirg and Sgurr nan Each. Frost-shatter fragments high on the western slopes of Sgurr nan Clach Geala indicate that it spreads out to cover a considerable area, and becomes rather psammitic. A further outcrop of Sgurr nan Each psammite occurs on the ridge of Sron na Goibhre, where it is both overlain and underlain by normal Meall an t-Sithe pelites. This band can be traced for a kilometre south to Bealaich na Caime, between A' Chailleach and Garbh Ceann a' Chailleach. Other minor psammitic variants of the Meall an t-Sithe pelites were seen near the Allt Breabaig and in the Allt Leac a' Bhealaich, but these are too small to be significant.

Texturally the Sgurr nan Each psammites vary between flaggy quartzose psammites or semipelites. The semipelites in their turn can grade into true pelites with the appearance of more abundant micas and garnets, and the introduction of the pegmatitic lenticles typical of the Meall an t-Sithe Pelite.

The garnets seen in several Sgurr nan Each psammites are usually red, although pinkish garnets occur in the more semi-

pelitic types. Muscovite is also a common constituent, but epidote is rare. Sphene is always present; it is usually absent in the Meall an t-Sithe pelite; otherwise the mineralogy differs in little except proportions from that of the pelite.

If the Meall an t-Sithe Pelite is, as suggested by Peach and Gunn, the basal pelite of the Moine Series, the Sgurr nan Fach psammite may represent the basal psammite as seen at Morar. Unlike in Morar, it is very poorly developed in Fannich, and does not form the base of the Moine Series.

3.8 Conglomerate

Basal conglomerates have been recorded from several Lewisian inliers in the Moine Series. In Glenelg Peach (1910) first recorded their existence; this has been more recently confirmed by Ramsay (1958) who considered that "although there are signs of considerable tectonic deformation...it does seem very likely that "certain structures" represent a conglomerate. Peach (1913) also reported the occurrence near Attadale by Loch Carron of "conglomeratic rock composed of irregularly foliated micaceous and sometimes actinolitic schist, containing fusiform fragments of granulitic gneiss like the more 'acid' portion of the adjoining Lewisian rocks." In the same memoir he also records the occurrence of conglomeratic rock adjoining the Glen Strathfarrar Lewisian Inlier. Conglomeratic rocks

have been noted at other horizons in the Moine Series (Peach et al. 1912), but their concentration along the junction with the Lewisian does suggest an unconformable relationship. If these rocks represent shear-breccias along thrust-planes underlying Lewisian wedges, they would not be confined to the localised distribution observed.

A conglomerate occurs in Fannich south-east of Sgurr a' Chadha Dheirg (Plate 3), at the junction between the Meall an t-Sithe Pelite and the Lewisian silicic gneisses. It contains spindle-shaped pods of quartzo-feldspathic material that may be highly deformed pebbles. Although the same junction is exposed at several other localities in Fannich, no other conglomerates were seen. This implies that the junction is unconformable, with pockets of conglomerate, and is perhaps locally sheared as a result of the differing competences of the pelite and the silicic gneisses, rather than a tectonic contact. Therefore the discussion of the structure of Fannich in chapter 5 is based on the assumption that the Lewisian forms the core of a nappe, rather than a thrust slice.

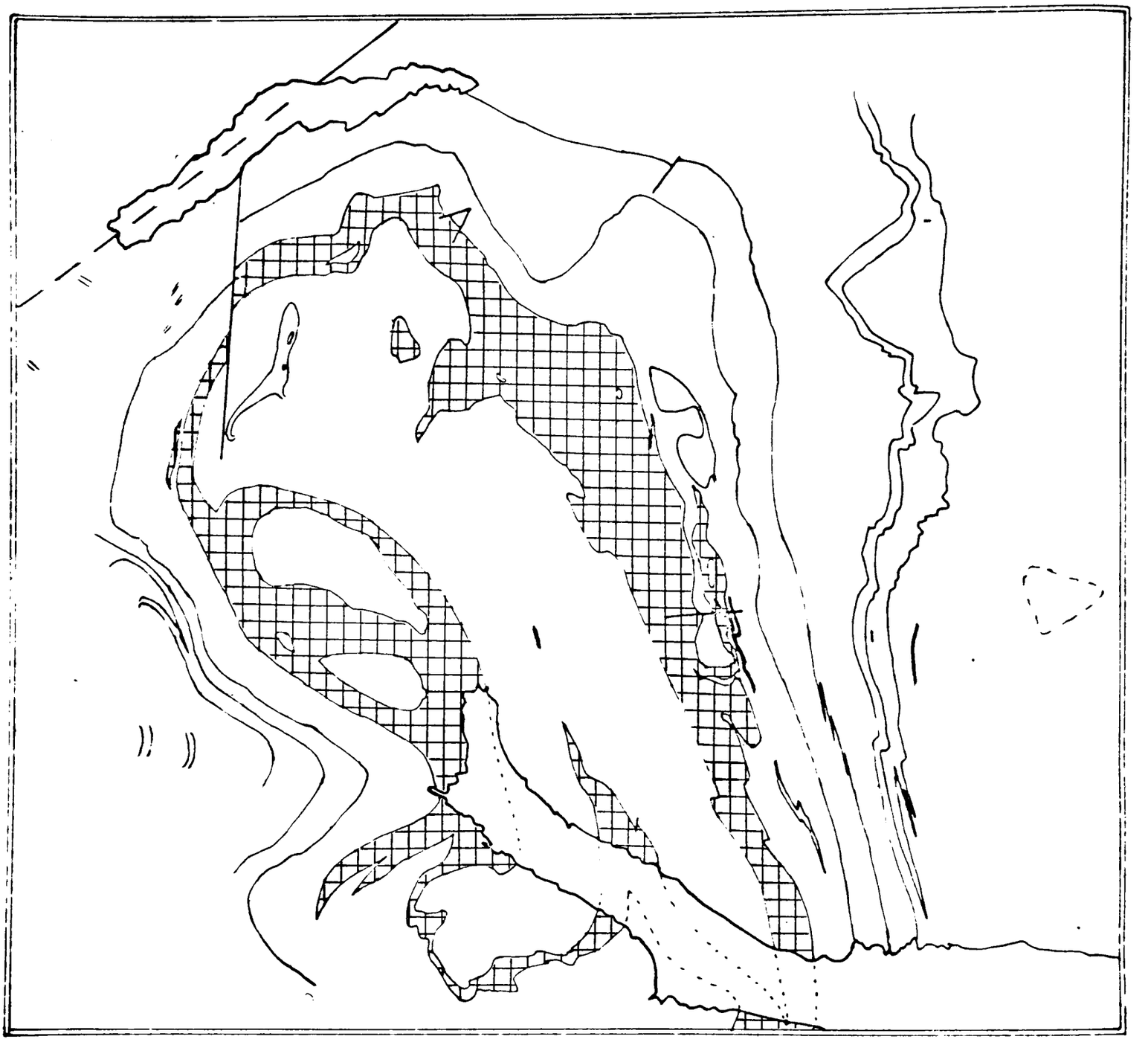
4

THE LEWISIAN INLIER OF FANNICH

4.1 Distribution

The suite of banded silicic gneisses and amphibolites lying between the two horizons of Meall an t-Sithe Pelite, is the most controversial unit in Fannich. Peach and Gunn (1913) correlated it with the Lewisian seen west of the Moine Thrust on lithological grounds; Sutton and Watson (1954) decided that it was part of the Moinian succession and called it the Fannich Gneiss basing their conclusion on the evidence supplied by current-bedding in the district and on the absence of structural evidence suggesting that it forms the core of an early fold. Chemical evidence, discussed in chapter 9, revealed in the work for this thesis, and further field evidence, both suggest that this unit is Lewisian, and therefore it is described as such in this chapter.

Peach and Gunn (1913) mapped it as outcropping in a horseshoe-shaped pattern, with an extensive lobe in the south-west resulting from topography, rather than structural complication. Double outcrops were mapped in three places: in the course of the Allt na Goibhre, east of Sgurr a' Chadha Dheirg, and west of Garbh Ceann a' Chailleach. No Lewisian rocks belonging to the Fannich Inlier were marked south of Loch



A MAP OF FANNICH FOREST SHOWING THE DISTRIBUTION OF LEWISIAN ROCKS

Figure 10

Fannich or the River Cabuie, although Pocock (1913) noted the occurrence of similar gneiss on Beinn nan Ramh.

Rutledge (1952) and Sutton and Watson (1954) did not set out to remap the area, but rather to reinterpret the structure in the light of more recent ideas. The fieldwork for this thesis was therefore the first systematic remapping of the area since the work of Peach and Horne. Most of their observations were confirmed, but extensions to the Lewisian outcrop were also revealed. Structure contours used on the planar west limb of the Fannich synform, in the absence of direct exposure, indicated that the lobe ringing the Sguman ridge could rejoin the main Lewisian outcrop east of Creag an Tairbh. South of Creag an Tairbh, at the broken footbridge at the mouth of the River Cabuie, an exposure of highly contorted biotitite may mark the edge of the Lewisian (Plate 10). Meall an t-Sithe Pelites were seen thirty metres upstream, and the relationship may be similar to the junction at Cassley (Winchester & Lambert 1970 in [illegible]) where biotitite also marks the junction.

A band of Lewisian silicic gneisses were mapped on Beinn nan Ramh to the south-west, but could not be traced over the ridge. A second band of similar gneisses runs parallel to it, from Loch Fannich to Tuill Bhig. This band crosses the ridge south of the corrie, and after running diagonally down towards Srath Chrombuill for two hundred metres, turns east, and,



Plate 10. Contorted biotitite at the broken footbridge on the River Cabuie.

recrossing the ridge, descends to Loch Fannich.

Across Loch Fannich, at the mouth of the Allt na h'Ara, Pocock mapped Lewisian rocks extending along the loch shore to join the gneisses of the western limb of the fold. While the presence of such gneisses in the Allt na h'Ara was confirmed by recent fieldwork, small isolated exposures of Meall an t-Sithe Pelite around the Nest Cottage strongly suggest that Lewisian rocks do not occur along the loch shore as shown by the Survey. Instead the gneisses are traceable for over a kilometre away from the loch, in a narrowing band, until they disappear in the poorly exposed ground below Sail Mhor. But a very small inlier of similar gneisses, not mapped by the Survey, occurs along the same line in the bed of the Allt Leac a' Bhealaich (Plate 11).

South of Loch Fannich, a second outcrop of silicic gneisses occurs. It was interpreted by Peach (1913) as Meall a' Chrasgaidh psammite, but recent fieldwork and chemical analyses suggest that it is Lewisian. Although locally well exposed along the loch shore, it is concealed to the south by the extensive peat bog surrounding Loch na Moine Mor, and all interpretation of its continuation to the south must be speculative.

Repetition of the silicic gneisses by isoclinal folding is frequently indicated, notably in the three places where double outcrops were mapped by Peach and Gunn. The exposures

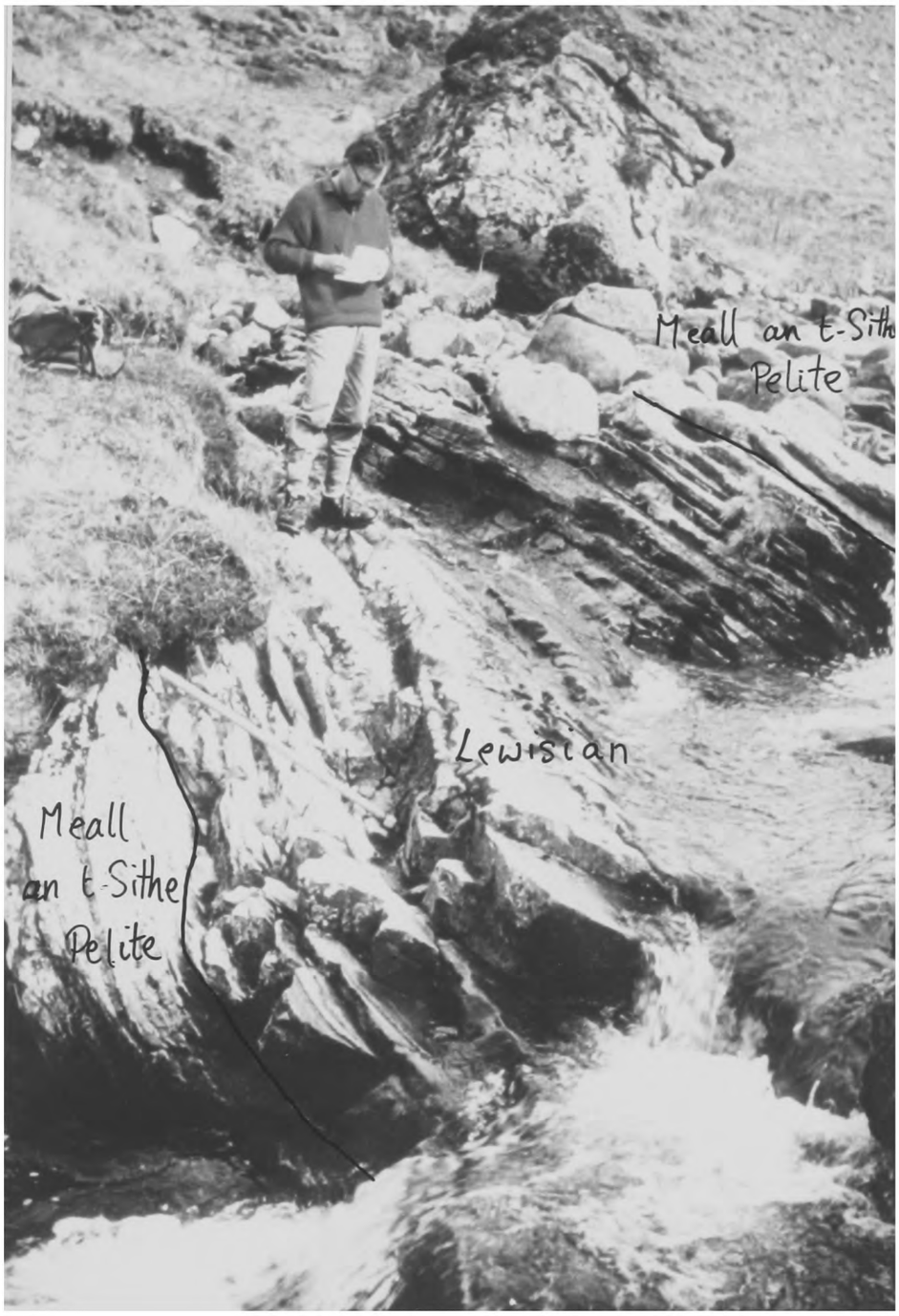


Plate 11. Small inlier of Lewisian silicic gneisses. Allt Leac a' Bhealaich.

east of Sgurr a' Chadha Dheirg show this most clearly. The Lewisian is seen to be deformed into large isoclinal folds that have themselves been gently warped. An isoclinal fold is also visible along the junction of the Lewisian and Meall an t-Sithe Pelite above Creag an Fhuarain on the west side of Sgurr nan Clach Geala, where a thin sliver of pelite is folded into the silicic gneisses.

Repeated reference has already been made silicic gneisses and amphibolites when describing this unit. Four constituent rock-groupings were identified in the Fannich Lewisian: silicic gneisses, amphibolites, calc-silicates, and garnet-quartz-biotite gneisses. These will now be described in turn.

4.2 Silicic Gneisses

The Silicic Gneisses form most of the Fannich Lewisian Inlier. Large amphibolitic bodies occur in the north, but in the south the inlier consists almost exclusively of silicic gneisses.

They are more resistant to weathering and less fissile than Moine psammites; in Coire Breac the topography locally resembles that of the Lewisian Foreland in containing numerous bare rock knobs, rather than the smoother contours of corries eroded in Moine psammites. These silicic gneisses are usually banded, and grey or pink in colour. The darker bands contain more biotite, but muscovite hardly occurs in the rock, other

than as sheets along the planes of preferential fracture, usually parallel to the banding.

Quartz, oligoclase and biotite are present in all but two of the rocks examined; in the two exceptions muscovite was the only mica. Epidote is common, and in some massive gneisses from the Allt na Goibhre it is a major constituent. It never occurs in the same rocks as muscovite or microcline; possibly this division indicates a distinction between the potassic and calcic rocks. Red garnets occur in these gneisses with a higher iron content; sphene and apatite are common as accessories.

In more mafic gneisses, biotite becomes more abundant, and small quantities of hornblende appear. A gradation occurs, with the progressive depletion of leucocratic minerals into amphibolites, which are discussed below.

4.3 Amphibolites

Amphibolites within the Lewisian Inlier of Fannich are much more extensive than those in Moine pelites. Small amphibolites occur south of Loch Fannich, and more massive bands occur on Creag na h'Ara, in Fliuch Choire, on Ceann Garbh a' Chailleach and Craig an Fhuarain. But the largest amphibolitic body extends from the head of the Allt Leac a' Bhealaich to Sron na Leitir Fhearna, a distance of over four kilometres.

These amphibolites display considerable variation in texture.

Massive, compact, granular amphibolites may grade into a somewhat foliated hornblende schist. Striped amphibolites similar but not identical to those of Durcha Type (Read et al. 1926, Francis 1958, Winchester & Lambert 1970) were seen both on Torran Ruadh and Creag an Tairbh. Flaky biotite-rich amphibolites occur in Coire Breac, while a complete compositional gradation into silicic gneiss accounts for the presence of varied quartz-hornblende-plagioclase gneisses. This gradation in which hornblendic and quartzo-feldspathic gneisses are interbanded may be the result of early deformation the structural traces of which have since been destroyed by recrystallization of the rock during a later metamorphic event. Very mafic pyroxene-bearing amphibolites were collected from Creag an Fhuarain, while massive quartz-bearing garnet-amphibolites occur particularly on Sron na Leitir Fhearna, and in the Allt na Goibhre. In some of these anhedral aggregates of orange-red garnet form up to 60% of the rock.

Although these amphibolites display greater variety than those in the Moinian, lithology by itself is not considered adequate proof of their Lewisian origin. These amphibolites were therefore analysed and are compared with Moinian examples in chapter 9.

4.4 Lewisian Calc-Silicate Rocks

Calc-silicate rocks are rare in the Fannich Lewisian Inlier, compared with their relative abundances at Glenelg or in the Central Ross-shire inliers.

Broadly, they fall into two categories: epidosites, and tremolite-diopside gneisses. Of these, the epidosites seem to be more calcic variants of the amphibolites, and were seen associated as pods with the amphibolites in the ravine of the Allt na H'Eilig below Coire Breac. One epidosite was also seen in association with the tremolitic calc-silicates seen at the base of the waterfall descending from the high corrie on the north-east face of Sgurr Breac.

Although these epidosites, and a few calcite-bearing amphibolites were seen, the tremolite-diopside rocks were the calc-silicates most typical of the Fannich Lewisian. They were only seen below the north-east face of Sgurr Breac, in three scattered localities.

When their field-relations were visible, they proved to be either associated with, or very close to an amphibolite band, even though they were sometimes entirely enclosed by silicic gneiss.

Their textures vary considerably. At the most northerly of the outcrops noted, one sample contained pegmatitic plagioclase, with which quartz, pyrite, epidote, and green pyroxene were associated, while another was an even-grained granular

quartzose rock, containing stumpy diopside crystals, and a few scattered grains of pyrite and epidote, possibly representing the normal, non-pegmatitic texture of this calc-silicate band. Both these rock-types closely resembled calc-silicate rocks collected from Arscaig, in the Loch Shin Lewisian Inlier (Winchester & Lambert 1970).

Tremolite-bearing calc-silicate rocks were seen close to the waterfall already mentioned below Sgurr Breac. Thin bands of pale fibrous tremolite occur in a biotite-banded silicic gneiss, perhaps suggesting that the rock is magnesium rich as well; a feature it has in common with the calc-silicates from Shin, and which sets it apart from the chemistry of the Moinian calc-silicates from Morar and the Sgurr Mor Pelite. In one of these tremolitic calc-silicates pyroxene was also present.

The mineralogy of these calc-silicates therefore supports on lithological grounds the claim that this group of rocks in Fannich is Lewisian.

4.5 Garnet-Quartz-Biotite Gneisses

A fourth, and very distinctive rock-type noted in the Lewisian of Fannich is a garnet-quartz-biotite gneiss. It is unique in the Lewisian in several respects. It contains abundant large pink anhedral garnets, whereas all other garnets seen in the Lewisian of Fannich are red or orange. Pink garnets

are seen elsewhere only in the Meall an t-Sithe Pelites of the Moine Series.

These garnet-quartz-biotite gneisses occur as dyke-like bands associated with the amphibolites. Although silicic themselves, they are not associated in the field with other Lewisian silicic gneisses. They were not seen to cut the amphibolites, but garnets in the amphibolites immediately adjacent take on a similar pinkish tinge. In view of their brecciated appearance in the field, they have been tentatively interpreted as metamorphosed shear zones. In these, solutions have percolated through the amphibolites converting hornblende to biotite, and accounting for the growth of garnet similar in composition to those in the Moinian. Where such shears cut the silicic gneisses, lack of ferromagnesian minerals has inhibited the growth of biotite and garnet, so this distinctive garnet-quartz-biotite-gneiss does not occur.

4.6 Conclusions

Chemical evidence, discussed in chapter 9, suggests that the Fannich silicic gneiss group is Lewisian. The Moinian was deposited on the Lewisian after a considerable time-lapse. This is indicated by Strontium isotope data, which suggests that, given an initial $^{87}Sr/^{86}Sr$ ratio of 0.710, the maximum age of the Moinian sediments is 1,300 million years, or, given an initial ratio of 0.700, which is unlikely, the absolute

maximum age is 1,500 million years (Lambert, pers. comm, Lambert1968). Recent work (Lambert and Holland, in press) has indicated that the minimum age of the Laxfordian event in the Lewisian can be placed at 1,800 million years. The Moinian was therefore laid down on Lewisian rocks that were already metamorphosed.

Although the amphibolites may be the equivalent of the dykes seen in the Lewisian of the Foreland, generally the Lewisian gneisses cannot be identified as metasediments or meta-igneous rocks.

In the Foreland Lewisian the characteristic mineral assemblages typify higher metamorphic regimes (Muecke 1969) than those induced by metamorphism after the deposition of the Moinian in Fannich. Therefore, the Lewisian rocks of Fannich, after subjections to a later, less intense metamorphic episode, can be expected to show textures characteristic of retrogression. Such textures do occur, providing additional evidence that these rocks are Lewisian.

5

STRUCTURE

5.1 Previous research, and general introduction

In Fannich, as elsewhere in the Northern Highlands, the rocks have clearly been intensely deformed. Small and large-scale folds are ubiquitous, frequently accompanied by well-developed lineations. Careful mapping of these structures may help clarify the nature of this folding, complicated as it is by repeated deformation.

The orientations of lineations and minor fold axes were plotted in Fannich Forest by Sutton and Watson (1954). Since then, others have undertaken the structural analysis of Moinian areas elsewhere. Ramsay (1958a) undertook a structural analysis of the Monar district, and of Glenelg (1958b); similar work was carried out by T. Clifford in Kintail (1957), by P. Clifford in Lochluichart (1960), by Fleuty in Glen Orrin (1961), and Johnson in Lochcarron (1960). Their studies indicate that all parts of the Moine cover and infolded Lewisian basement were in a plastic and mobile condition at certain phases of orogenic history, and that multiple folding is commonplace, if not universal, if the Lewisian inliers are assumed to be Lewisian. If they are not, then structural analysis of the visible lineaments does not show that they are

the cores of isoclinal folds, and therefore they can only be explained on the basis of structural analysis as integral parts of the Moine Series, if somewhat unusual. Sutton and Watson concluded that the Fannich Inlier was part of an upper Moinian succession, because the results of their structural analysis of Fannich did not indicate any further structural complications. They were correct in not assuming that the Fannich inlier was Lewisian on the basis of weak lithological ties, and in attempting to interpret the regional structure by pure structural methods. But they had to assume that the visible lineations were all the lineations that ever had been present, and to ignore the possibility that earlier lineations had been obliterated by recrystallization in a later intensification of metamorphism.

Clues about the probable identity of the disputed inliers can be sought elsewhere. Clough (Peach et al. 1910) first recognized in Glenelg that narrow belts of Lewisian basement and Moine cover, with a clearly visible unconformable relationship in the west, could be the products of early isoclinal folding. Further east in Glenelg, the more intense shear deformation that produced these folds led to the progressive obliteration of any angular discordance between Lewisian and Moine, and of early structures in the Lewisian (Ramsay 1963).

Strong deformation in the first event may obliterate any previous signs of sedimentary discontinuity, but will leave

distinctive lineaments by which the structure can be analysed. But if a second strong deformational episode occurs, all the lineaments induced in the first event may be obliterated in the recrystallization of the constituent minerals of the rock and their reorientation to accommodate the new stresses. Chemical evidence suggests that the disputed inlier at Fannich is Lewisian, and since structural evidence to prove its origin is lacking, it must have been destroyed in a later metamorphic recrystallization. The lineations seen in Fannich by Sutton and Watson appear to be, as they said, related to the folding of the Fannich Synform. Therefore the recrystallization which followed the F_2 deformation, but preceded the late F_3 formation of the synform, has apparently accounted for the obliteration of most earlier signs of deformation. A further structural analysis of Fannich Forest would therefore serve only to duplicate their work and throw more light on the geometry of the synform and the type of deformation that produced it.

The discussion that follows, therefore, does not set out to perform a structural analysis of the lineations and foliation dips at present visible, but attempts to interpret the regional structure from the configuration of lithological units. One of these is assumed to be the "basement" of the series, and on this assumption, supported by chemical evidence, an interpretation of the Moinian succession is founded.

5.2 General Morphology of Observable Folds: Major Folds.

Gunn quickly recognized the obvious synclinal fold that occupies the centre of the area mapped (referred to in this thesis as the Fannich Synform). Sutton and Watson (1954) studied the structure of the whole district in detail and identified several other major folds, whose existence recent mapping has broadly confirmed (see Fig.11). These are consistent in their morphology with the F_3 folds defined by Ramsay as characterised by the alternation of steeply inclined and gently dipping fold limbs (1963 in British Caledonides, Johnson & Stewart). In this they resemble the F_3 folds in Morar, the Morar and Loch Hourn antiforms.

To the north, the Fannich synform becomes ill-defined, and in the Dirrie More, rocks with shallow foliation dips occur until a point three kilometres east of Braemore is reached, where they are inverted and acquire a steep easterly dip. This fold, termed by Sutton and Watson the 'Braemore Syncline" is essentially similar to the Fannich Synform. Steeply dipping rocks occur for four kilometres to the east, where, by Loch Droma, they roll back again to regain a gently inclined attitude similar to that seen around Braemore. Sutton and Watson termed this fold the "Droma Anticline" and traced it south-west to a point above Loch an Fhuar Thuill Mhoir, whence it ran south to the shore of Loch Fannich near Fannich Lodge. In the near-horizontal rocks east of this fold, outliers of

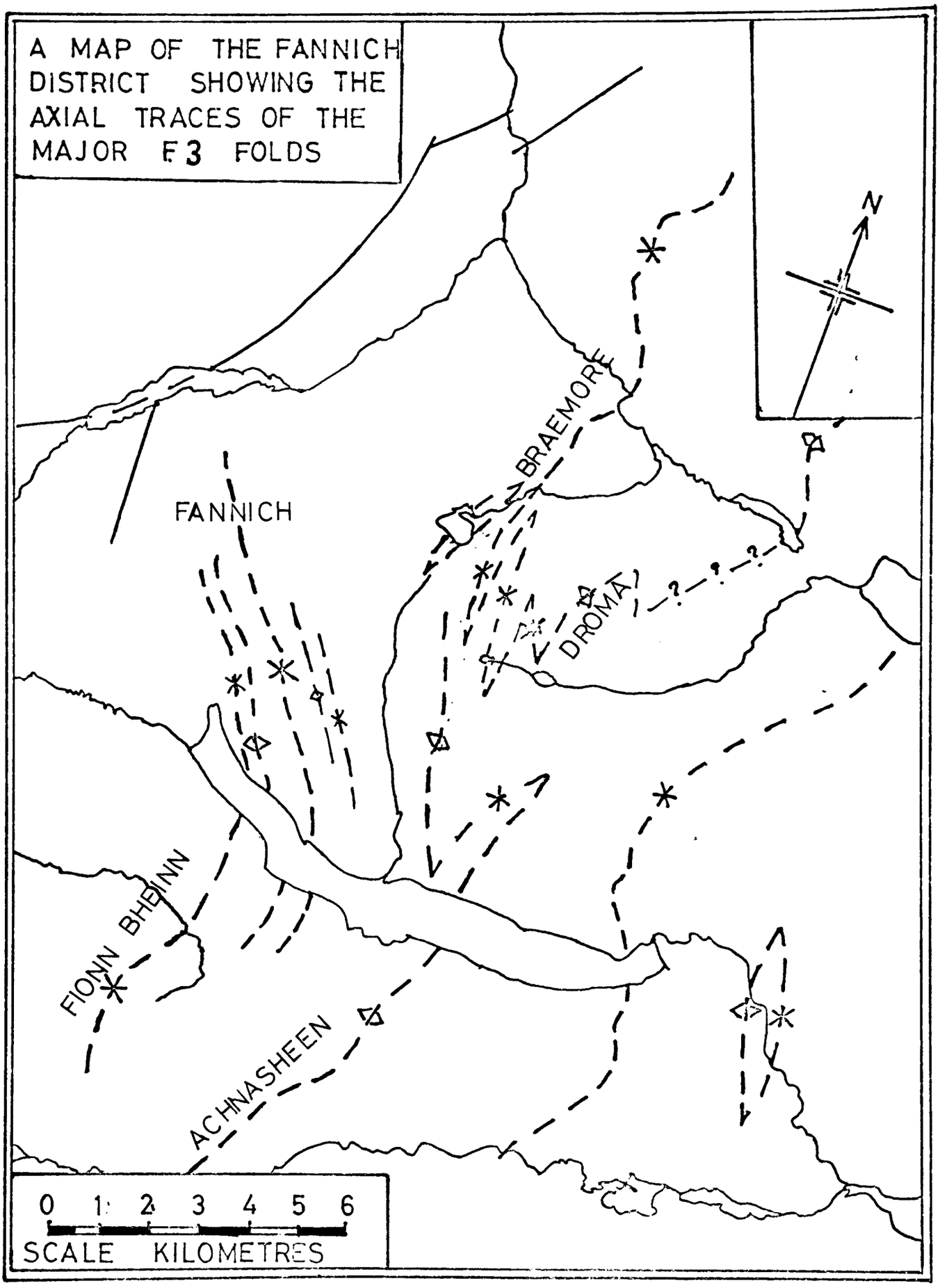


Figure 11. Anticline: ⩚

Syncline: ✳

Sgurr Mor Pelite are preserved on the eastern summits of the Fannich Range overlying the Inverbroom Psammites.

South of Loch Fannich, Sutton and Watson showed the Fannich Synform to swing south-west to Fionn Bheinn, while to the east, steeply dipping rocks occur until an anticline analogous to the Droma Anticline, which they term the Achnasheen Anticline, folds the rocks back to gently-inclined attitudes analogous to those in the west.

Recent mapping for this thesis broadly confirms this plan, but differs in detail. South of the Dirrie More, the broad outline of the structure of the 'Droma Anticline' was confirmed, but in detail it was found that the anticline was not a single fold, but consisted of a series of en echelon monoclines in which steep-dipping limbs become dominant northwards, while near horizontal limbs become prevalent southwards. The axial traces of these folds were virtually parallel to the lineations seen in the rocks of the area. Thus although the shallow dips seen on Creachan Rairigidh and the near-vertical dips on Beinn Mhor Liath Fannich suggest a major fold trending north-east across the local lineations, this does not happen.

On Meall nam Pethirean, Sutton and Watson show their 'Droma Anticline' to turn south, its axial trace parallel to the regional foliation trend. This fold remains complex, as in detail it consists of a series of asymmetrical anticlines with steep, or overturned western limbs, and gently-dipping

easterly limbs. They are more continuous than those further north, and are well-exposed at the back of Coire Beag. The syncline and anticline shown by Sutton and Watson near Fannich Lodge lie east of the area mapped for this thesis and were not studied.

Monoclinal folds, similar to the folds just described, occur in the north of Fannich Forest; the most westerly occurring on Creag a' Mhadaidh. Sutton and Watson show it as continuous with their Braemore Syncline, but around Loch a Mhadaidh a series of en echelon folds like those further east are the only structural equivalent of the syncline which becomes more definite further north. To the south the western limit of steeply-dipping rocks becomes the Fannich synform, as seen west of Coire Mor. This important fold, which brings down the whole controversial Fannich succession, was found to run exactly as mapped by Sutton and Watson. It is an asymmetrical synform, with an axial trace trending south-south-east, and a gently-dipping plunge to the south. While the inclination of the western limb remains gentle, the east limb steepens as it is followed south, until, three kilometres from Loch Fannich, it becomes inverted. Both the lineations, and the foliation strikes measured run parallel to the axial trace of the fold. Further south, the fold becomes more complex. Within Coire Breac, foliation dips are variable, but in the south-west corner, a small sharp anticline, with an overturned

western limb, is exposed. Further south-east a small inlier of silicic gneisses seen in the Allt Leac a' Bhealaich, and the much larger wedge of similar gneisses seen below Creag na h'Ara extending to Loch Fannich, indicate that this anticline becomes more pronounced southwards. West of these silicic gneisses, repetition of the upper Meall an t-Sithe Pelite indicates that a second syncline occurs, also with a recumbent east limb. Its axial trace parallels that of the main Fannich Synform, and runs from Bealaich a' Choire Bhric in the north, reaching Loch Fannich east of the Nest Cottage. This syncline can be traced across the east ridge of Beinn nan Ramh, by the configuration of the outcrop of silicic gneisses, rather than the foliation dips which do not parallel the unit boundaries there. No mapping was done on the south side of Srath Chrombuill but this syncline appears to be continuous with the Fionn Bheinn Syncline described by Sutton and Watson. This syncline extending to Coire Breac is therefore the northern extension of the Fionn Bheinn Syncline. (Figure 11)

The anticline seen below Creag na h'Ara, dividing the Fionn Bheinn syncline from the Fannich Syncline, reaches the south shore of Loch Fannich east of the mouth of the Allt na Moine. In the Allt na Moine, and along the lochshore north of its mouth, steep westerly dips occur in the lower Meall an t-Sithe pelite, while to the east in the pelites and silicic gneisses, dips are to the east. The silicic gneisses

occupy the core of the Fannich syncline, here almost isoclinal. Lack of exposure in the featureless bog around Loch na Moine Mor prevented effective mapping further south, but the Fannich Syncline appears to die out southwards, its function being taken over by the Fionn Bheinn Syncline to the west.

Based on their structural analysis of Fannich, Sutton and Watson concluded that the visible succession in Fannich is in its proper order, and that all the folds they observed belong to the same set of movements. During the mapping for this thesis it became clear that all the major folds described by Sutton and Watson result from the same deformational episode; they are generally open asymmetrical folds, possibly contemporaneous with the Morar and Loch Hourn antiforms. The succession these folds deform is not the true stratigraphic sequence, but is a succession of Moinian units (repeated by earlier isoclinal folding) in the midst of which is a core of Lewisian rocks. Evidence for these earlier folds can be seen both in visible isoclines and in the curious outcrop of the different lithological units. Further evidence is also apparent in a study of minor fold structures.

5.3 Minor Structures

Minor folds occur abundantly in both the pelites and the silicic gneisses. In the pelites they are evidently related to the major folds, and, near the cores of the major folds,

they increase in size and number. Usually they are asymmetrical drag-folds, but towards the major fold cores they become symmetrical, and their axes are subparallel to those of the major folds. In the pelites these folds always deform the foliation planes of the schist.

In the silicic gneisses, the minor folds are usually isoclinal, recumbent folds, their axial planes tending to lie parallel to the boundary of the silicic gneiss. By comparison with the drag folds in the pelite, these folds have a very tight form; they are totally unlike any folds seen in Moinian metasediments, and locally give rise to rodding structures in the silicic gneisses. Such folds are well displayed south of the Allt na h'Eilig (Plate 12) where lineations oriented in two directions alternately betray the existence of such folds.

Lineations are ubiquitous in both Moinian and Lewisian. Their trends in Fannich are to the north-north-west, and in this sense they conform to the regional pattern developed over the North-West Highlands (Phillips 1937). In the Moinian they run subparallel to the axis of the Fannich Synform, but in the Lewisian they are deflected by minor isoclinal folds (Plate 12). In the psammites lineations were only seen on the micaceous foliation planes, although they occur throughout the pelites. It seems that the lineations in the Moines originated in the same deformational episode that produced the major folds, but



Plate 12. Lineations with different orientations in Lewisian silicic gneiss. Coire Breac.

that they only developed in the less competent rock-units. In the psammites, lineations are only developed in micaceous partings. In the silicic gneisses lineations are abundant, but they apparently predate the minor isoclinal folds, and since the Lewisian is a competent rock unit, not likely to have developed lineation if it was not developed in the psammites, it seems probable that the Lewisian lineations are an earlier set than those in the Moinian, preserved only because the Lewisian was not recrystallized as extensively as the Moinian.

Crenulations on a small scale also occur in Moinian pelites, but were not seen as well in Fannich as in the pelite near Loch Droma. True cleavage, as reported by Sutton and Watson from localities further east, was not seen in Fannich itself.

Visible minor structures, therefore, do not provide reliable evidence for earlier folding, except that it is always the pre-existing foliation which has been folded by the major open folds. That foliation was presumably induced by an earlier deformational episode, and the evidence for earlier folding is discussed below.

5.4 The Evidence for Earlier Isoclinal Folding

Chemical evidence, together with lithological and petrological evidence, suggests that the series of silicic gneiss and amphibolite are Lewisian in origin. If so, the apparent succession seen in Fannich cannot be the true one, for the

observable major folds are clearly not the cause of any change in the order of the units; they simply affected a "succession" that was already there. Also, if these folds are so dominant in the region, they may have been accompanied by a metamorphic event which, by crystallization, eliminated minor structural features derived from previous episodes, rendering structural analysis of earlier folding impossible. In the following discussion, therefore, other lines of evidence will be examined.

Sutton and Watson's contention that the Fannich succession is uninverted is largely based on the evidence of current-bedding. During the fieldwork for this thesis, the occurrence of current-bedding was confirmed; it was seen in the Abhuinn Droma, on the slope draining to the Allt a' Mhadaidh north of Beinn Mhor Liath Fannich, in the quarry east of Creag a' Chaise, and below Creag a' Mhadaidh. All but the last-named locality are in Inverbroom Psammites: the Creag a' Mhadaidh exposure is in Carn na Criche Psammites. As reported by Sutton and Watson, these sedimentary structures indicate that the direction of younging is to the west, and therefore that the Sgurr Mor Pelite is younger than the Inverbroom Psammite.

But small-scale structures not easily explained by the obvious fold pattern do occur. Both in the Creag a' Chaise quarry, and near Loch Sgeireach, isoclinal folds were seen within the units showing current-bedding. In some of these

folds one limb becomes sheared out to produce a tectonic structure closely resembling current-bedding in appearance. For the relatively competent psammitic units to be deformed in this manner demands a more intense stress than is apparently responsible for the later, open folds. Also, stretching of these units in other places may account for the absence of sedimentary structures elsewhere in the psammites. Sutton and Watson do not record any sedimentary structures in the Meall a' Chrasgaidh psammite, nor was any current-bedding seen in it during the fieldwork for this thesis. Instead, the psammite frequently presents a striped appearance, and at one stream-washed rock-platform in the Allt Coire Mor, the paler quartzose rock between the biotite-rich bands was seen to consist entirely of isoclinally-folded units. This implies that the whole rock has been very intensely deformed. Measurement of the attitudes of these folds was not possible; the rock is typically flaggy, and breaks parallel to the biotite-rich bands. At this point these bands are straight, and apart from its steeply-dipping attitude and isoclinal folding, the rock seems undeformed.

Sutton and Watson also observed current-bedding "in siliceous rocks on the col a mile and a half south-west of Sgurr Mor". The col was identified as Cadha Dearg Mor: the silicic rocks are Lewisian silicic gneisses. Only isoclinal folds (Plate 13) were seen in these rocks, their upper limbs occasionally sheared out to give a deceptive appearance of

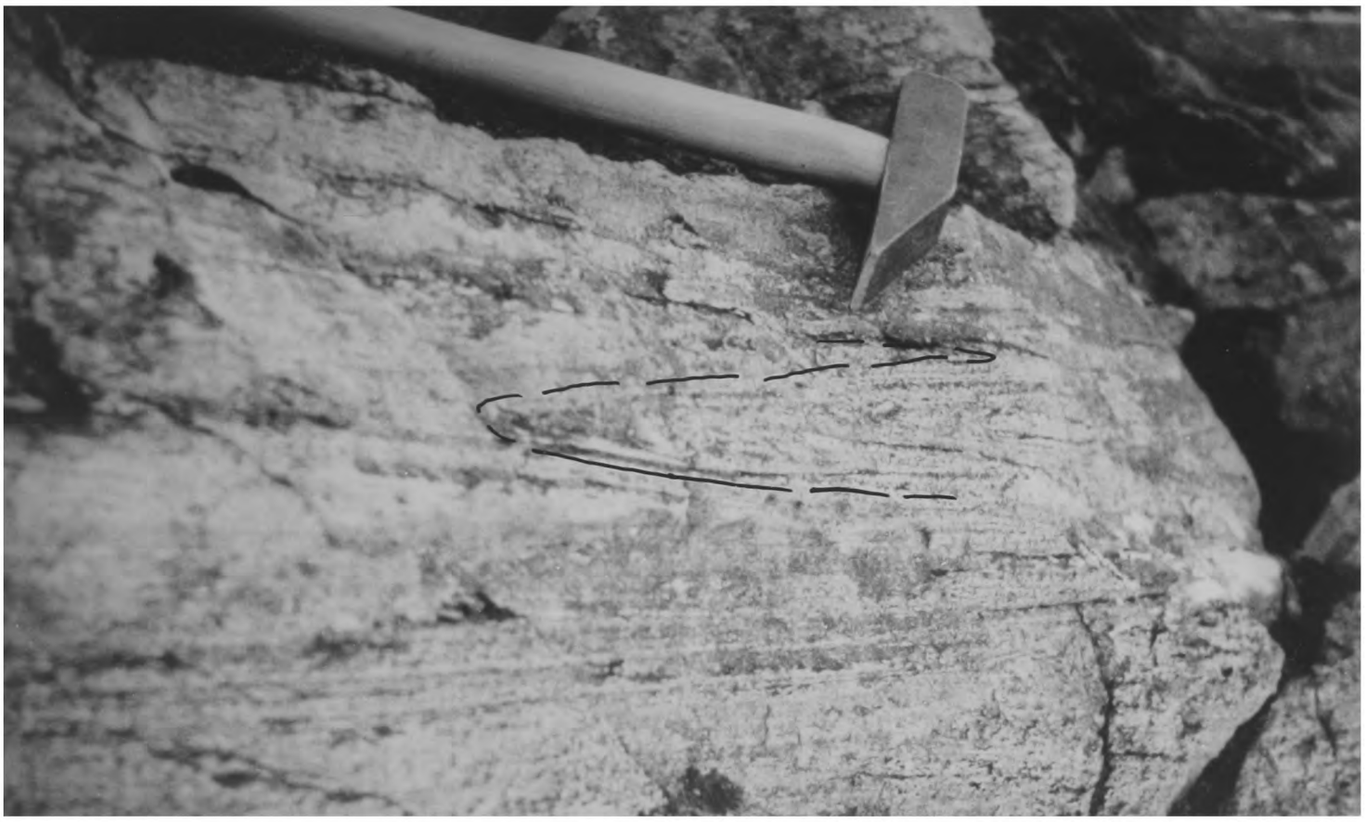


Plate 13. Isoclinal fold in silicic gneiss. Cadha Dearg.

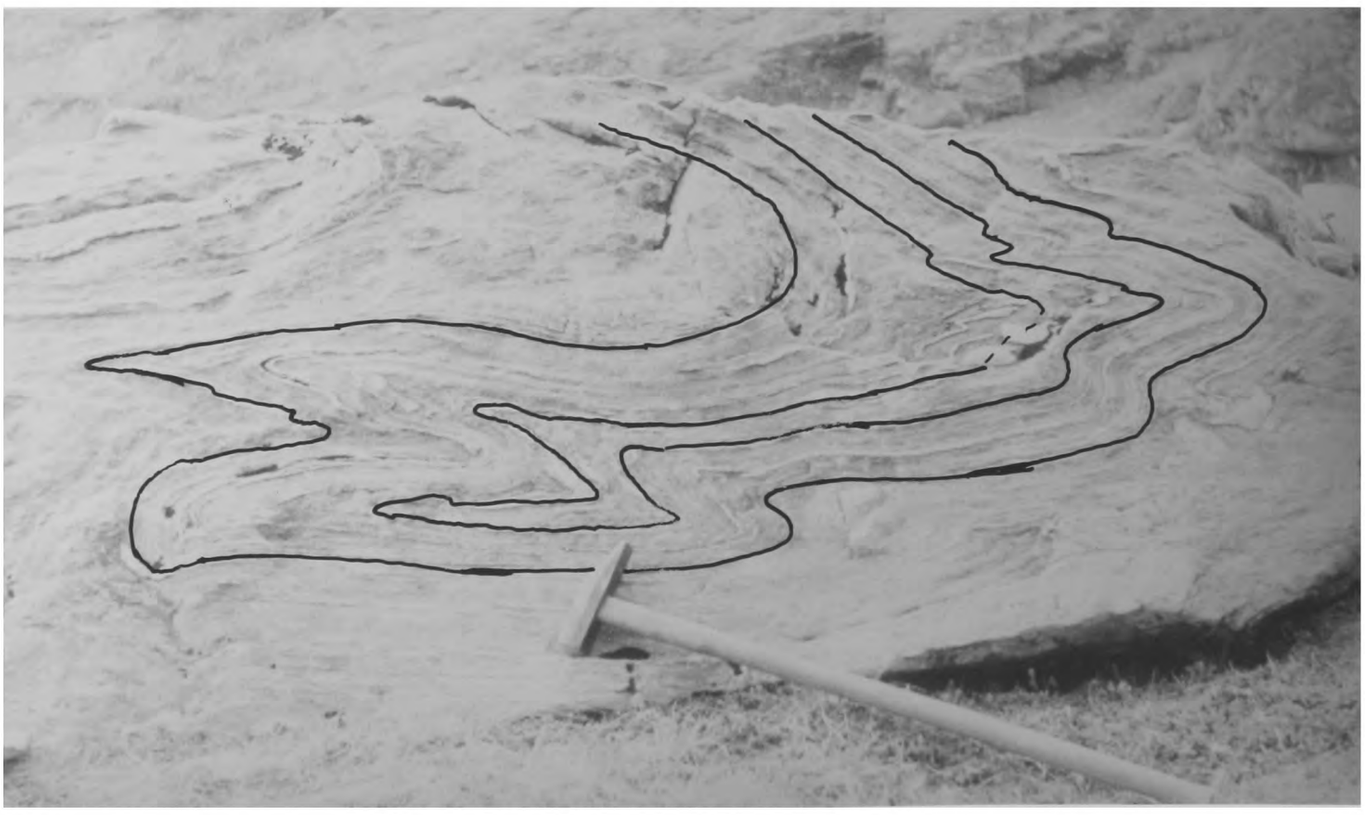


Plate 14. Refolded isocline in Sgurr Mor Pelite. Coire Mor.

current-bedding. Such small isoclines are abundant in the Lewisian of Fannich; often they are visibly refolded by later flexures similar to the drag-folds described by Sutton and Watson. They are well-exposed in both silicic gneisses and amphibolites and are revealed by the gneissose banding of the rock, rather than by any feature that could be interpreted as bedding.

Refolded isoclines were also observed in the Sgurr Mor pelite, but in view of the highly deformed nature of the rock, and its lesser competence compared to its bordering psammites, such evidence is not considered decisive. However, all the measurements of dip record the inclination of the foliation, rather than the original bedding, which is usually obscured. Where isoclinal folding has occurred, cleavage or foliation becomes subparallel to the bedding and therefore the occurrence of current-bedding in certain areas need not contradict the concept of isoclinal folding in the district as a whole. Also, the refolded isoclines seen in the Sgurr Mor Pelite (plate 14) deform the foliation of the rock, which had presumably been induced during a deformational episode accompanying metamorphism which predated the visible isocline. Although, as already suggested, the foliation and original bedding may be subparallel, the outcrop pattern of the silicic gneisses on the east ridge of Beinn nan Ramh does not follow the foliation seen in the surrounding Meall an t-Sithe Pelites. The frequent minor folds

disrupting the silicic gneisses may be partly responsible for their true dip to the north.

So far, reference has only been made to the evidence supplied by minor folding, while even more telling evidence can be gained by considering large-scale structures. At least three major deformational episodes occur in Fannich, and these can perhaps be tied in with those seen elsewhere in Scotland as listed by Ramsay (1963). They can be summarized as follows:

F_1: Formation of an early isocline containing a core of Lewisian rocks, around which Moinian stratigraphic units are symmetrically disposed.

F_2: Tight, near-isoclinal folds seen in 'kinking' of the Lewisian F_1 fold-core in Fannich. Probably also the deformational event giving rise to the near-isoclinal small-scale folds seen in the silicic gneisses, and the isoclines in the Meall a' Chrasgaidh Psammite.

F_3: More open folds, folding pre-existing foliation with alternating steeply inclined and gently dipping limbs. The Fannich and Fionn Bheinn synclines belong to this group.

The evidence for the two earlier fold-episodes will now be discussed in turn.

The presence of a parallel-sided inlier of Lewisian rocks is the most powerful evidence for the F_1 folds. No direct

evidence within the Lewisian outcrop suggests that it is a fold core, but the symmetrical disposition of Meall an t-Sithe pelite above and below it hints that it is the core of a fold, rather than a thrust slice. Conditions of structural deformation in which even rocks as competent as the silicic gneisses are folded into isoclines suggests that plastic deformation rather than brittle fracture is more likely to account for the emplacement of the Lewisian. Tanner (1969) envisages a slide, the "Sgurr Beag Slide" at Kinloch Hourn to explain the position of the Lewisian there and (Johnstone et al. 1969) envisages its extension north to Fannich, the slide-plane occurring below the Meall an t-Sithe Pelite. While the existence of a slide might be useful in explaining the very sharp junction below the Meall an t-Sithe Pelite in Fannich, there is nonetheless no positive evidence for the existence of a slide, and the stratigraphic sequence in the Moinian of Fannich does not require a tectonic break to account for the position of the Lewisian in the succession. Early isoclinal F_1 folding is considered here to explain the positioning of the Lewisian inlier in Fannich.

In several places, Peach and Gunn show the outcrop of the Lewisian in Fannich to be repeated. Sutton and Watson (1954) considered the silicic gneisses and pelites to belong to the same series because they show "interbanding on every scale from that of the map to that of a hand-specimen." The

junctions are actually sharp; interfelting was only seen in exposures south of Loch Fannich, and repetition of the Lewisian is considered here to be a result of near-isoclinal folds refolding the Lewisian core of the F_1 isocline. Since they are apparently later, these folds are ascribed to an F_2 deformational event. That the different bands mapped are all silicic gneiss is confirmed by chemical evidence, since bands of the Sgurr nan Each Psammite occurring within the Meall an t-Sithe Pelite often closely resemble the Lewisian in appearance. This resemblance undoubtedly confused the Survey geologists, who mapped all silicic rocks immediately south of Loch Fannich as Moinian psammites. Likewise, Sutton and Watson state they could detect no difference between the three bands, two Lewisian and one Sgurr nan Each Psammite, on the western flank of A' Chailleach. This locality is one where the Lewisian is repeated; the lower band was never seen to unite with the upper one. In the Allt na Goibhre, the outcrop of Lewisian is divided by an inlier of pelite restricted to the recess eroded by the stream in the general north-facing slope. On Druim Reidh, to the west of Coire Breac, a higher outlier of Lewisian is preserved, separated from the main outcrop by a sliver of pelite that extends well to the east across the corrie floor, suggesting that the style of folding is isoclinal, or near-isoclinal. On Beinn nan Ramh, although exposure is poor, and the evidence is therefore less conclusive, the apparent course of the Lewisian suggests that the western

tongue of silicic gneisses seen on the northern slopeis likewise an isoclinal fold, refolding the Lewisian F_1 fold core. These folds may also be contemporaneous with the formation of the small-scale isoclines seen within the silicic gneisses. The best exposure of the Lewisian refolded by later isoclinal folds occurs on the south-east face of Sgurr a' Chadha Dhearg. Although this area lies on the steep-dipping east limb of the main F_3 Fannich Synform, a subsidiary F_3 syncline has refolded these Lewisian isoclines so that they dip at relatively shallow angles. North of the eastern spur of Sgurr a' Chadha Dheirg, this subsidiary F_3 syncline becomes more complicated, and a whole series of sharp anticlines and synclines refold the earlier isoclines in the corrie to the north. Exposure is excellent, and the considerable relief of that part of Fannich gives a valuable three-dimension view of the complex structure. The F_3 anticline which must lie between this subsidiary syncline, referred to in this thesis as the Sgurr a' Chadha Dheirg Syncline, is not seen near Sgurr a' Chadha Dheirg. But immediately west of the main pass, an open anticline is well exposed at the junction of the Lewisian with the Upper Meall an t-Sithe Pelite. Since this lies along the axial trend of the F_3 folds, it may be the same anticline. The isoclines refolding the Lewisian and in turn refolded by the F_3 Sgurr a' Chadha Dheirg Syncline include two Moinian anticlinal cores closing west, and at least three Lewisian-

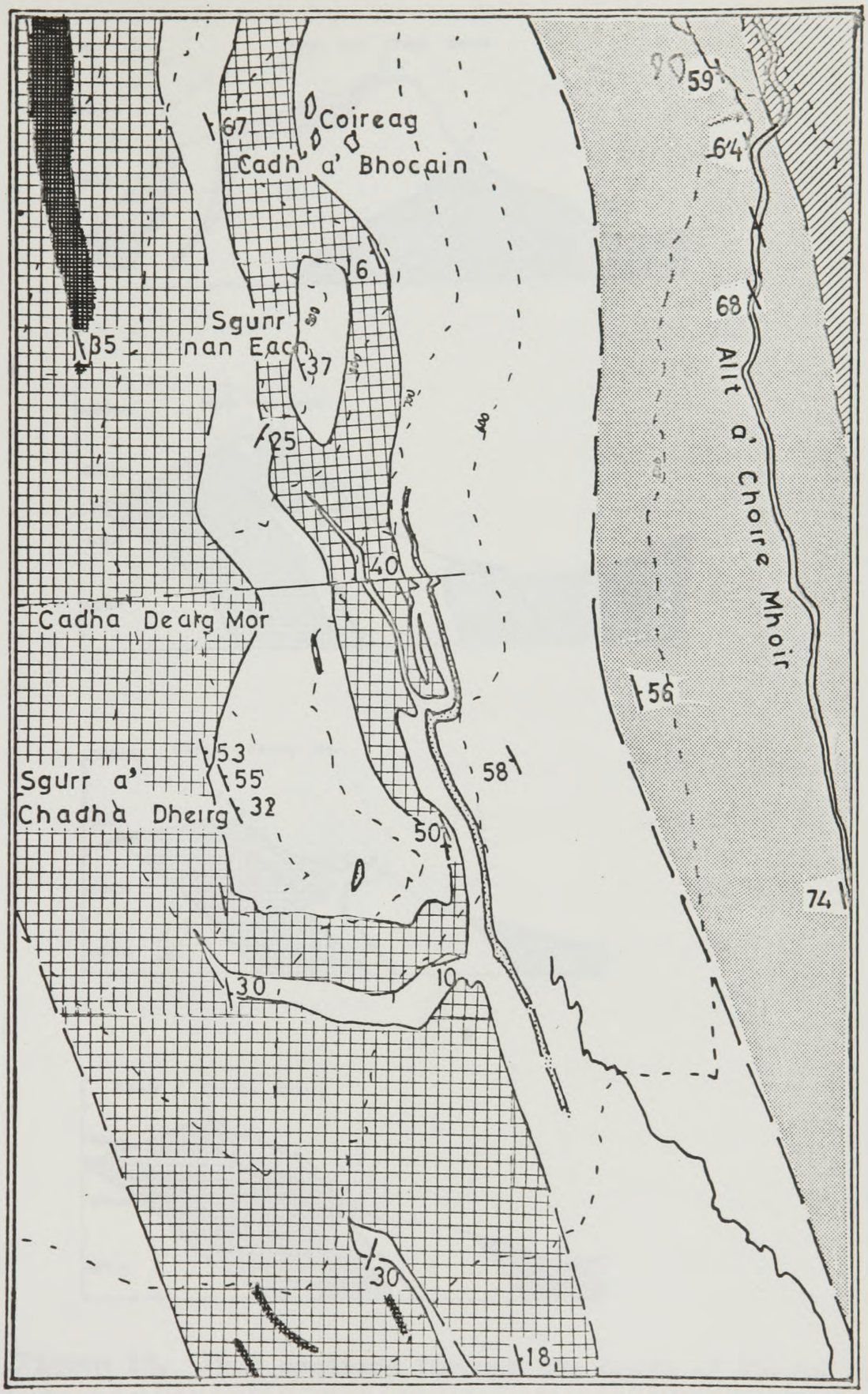


Figure 12. A detailed map at a scale of 1:250,000 of the area around Sgurr a' Chadha Dheirg. Lewisian: checked ornament; Meall an t'Sithe Pelite: blank; Psammites: stippled; Sgurr Mor Pelite: diagonal stripes.

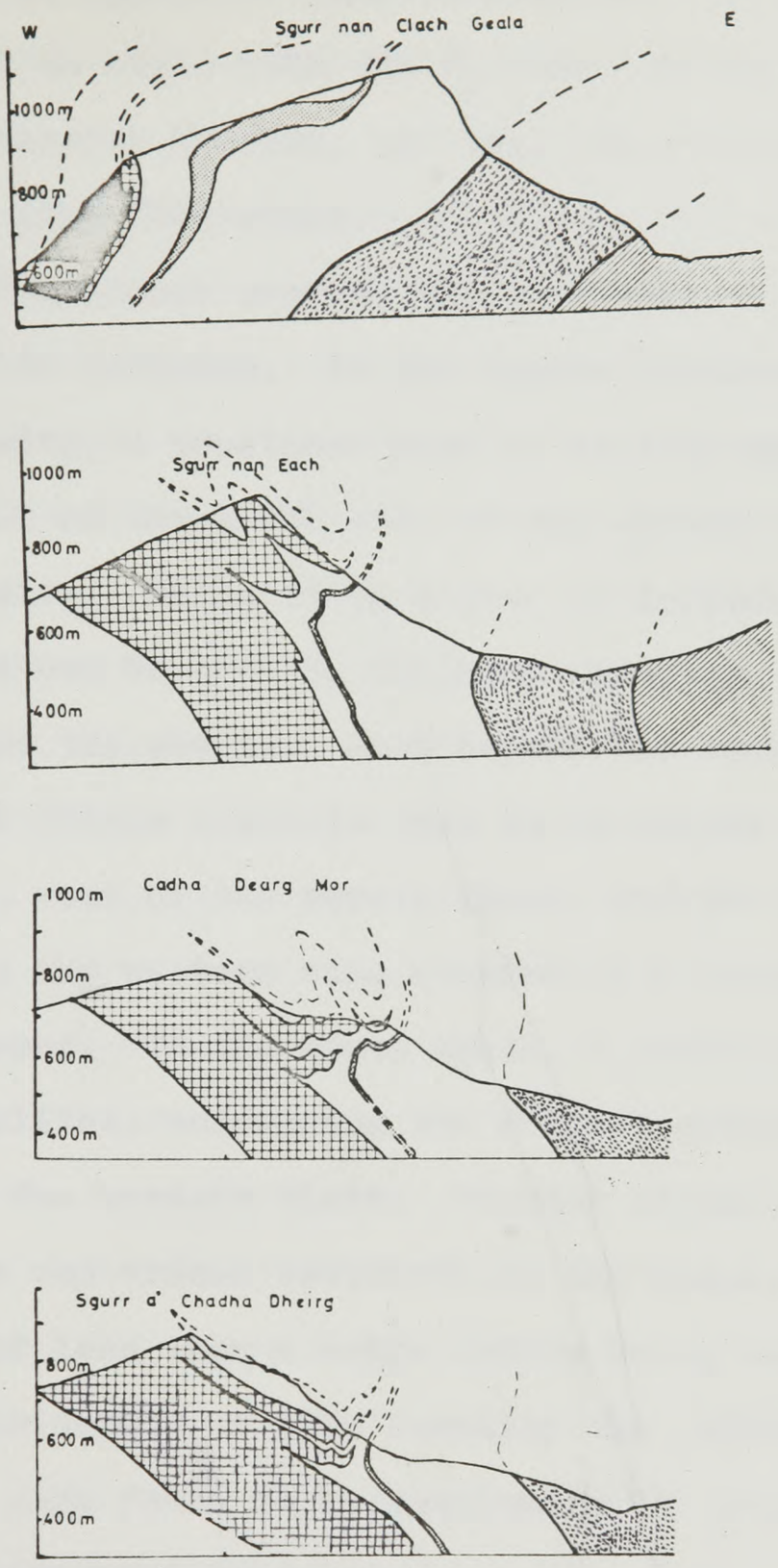


Figure 13. Four sections through the Sgurr a' Chadha Dheirg area, showing the observed F_2 Folds.

cored isoclinal synclines close eastwards. In this they are identical in style with the F_2 folds on the west limb of the main Fannich Synform, and they are presumably all products of the same fold event.

The field-evidence proving the existence of the F_2 isoclines is quite definite. In the corrie south-east of Sgurr a' Chadha Dheirg, a prominent band of silicic gneisses forms the lower part of the south side of the eastern spur of Sgurr a' Chadha Dheirg. Below it is a band of typical Meall an t-Sithe Pelites which can be traced, thinning steadily, into the north-west corner of the corrie. Just beyond the back of the corrie, frost-shatter debris indicate that it is wedged out altogether. To the south, most of the corrie floor, and the prominent rock-slabs on the western side consist of a second band of silicic gneisses. To the south again, a second sliver of Meall an t-Sithe pelites, underlying the silicic gneisses could be traced below the western slabs. Dipping at the same angle as the slope, it was traced westwards up the slope, thinning to a thickness of less than a metre before being covered again by silicic gneisses. At this locality the pelites adjoining the Lewisian were found to be conglomeratic, containing deformed pebbles of quartz and feldspar.

F_2 folds were not seen on the junctions of other units in Fannich, although refolded isoclines do occur within the pelites. This absence of definite F_2 folds may be significant in discuss-

ion about the regional significance of the structures seen in Fannich, and will be discussed under that heading.

5.5 The Regional Significance of the Fannich Structure

If isoclines on the scale seen at Sgurr a' Chadha Dheirg exist, it is but a short step to suggesting that the whole Lewisian Inlier may be the core of a large recumbent isocline. No evidence for this hypothesis is supplied by the distribution of rock-types within the Lewisian, but the Moinian is symmetrically disposed about it. Also, the discovery of a conglomerate in the Moinian bounding the lower surface of the Lewisian suggests that it does not lie on a tectonic thrust- or slide-plane. If a nappe exists in Fannich, no root-zone which could be related to it can be seen to east or west at the same latitude; this was a contributary reason for Rutledge (1952) to suggest that the Fannich Lewisian is a tectonic inclusion. On the other hand, by analogy with the structure postulated by Poole for his Sgurr Mor - Sgurr Breac synform (unpubl. D.Phil. Oxon 1962), the root-zone would occur some kilometres to the west, which in Fannich could be beyond the Moine Thrust. Such a structure, with a corresponding early syncline, could account for both an inverted Moinian succession immediately below the Lewisian, and the uninverted Moinian succession shown to exist in the Inverbroom Group from the evidence of sedimentary structures.

If Poole's interpretation can be applied to Fannich, a root-zone belonging to the postulated Fannich nappe should occur to the west. No Lewisian occurs between Fannich and the Moine Thrust. But, to the south, a broad inlier of Lewisian occurs east of Loch Carron which is cut off diagonally by the Moine Thrust to the north, and this may adequately explain why no inlier occurs west of Fannich. Mapping by both the Survey geologists and later workers appears to preclude the possibility of the Central Ross-shire inliers being root-zones to Fannich (Peach et al. 1913, Sutton & Watson 1962).

A glance at the map will also show that whatever interpretation is supplied for Fannich should also apply to the long strip of pelite extending continuously for forty-three kilometres south from Fannich to Beinn Dronaig. Extending for three kilometres from the western shoulder of Beinn Dronaig to Loch Calavie there is a discontinuous Lewisian Inlier, presumably occupying the core of a fold like that of Fannich. Crampton (Peach et al. 1913) does not at first specify the type of fold in which this Lewisian sliver occurs, but later describes it as "forming the very core of the anticline", presumably on the grounds that it has the oldest rocks exposed at its hinge. He interpreted it as a major "upfold" bringing the basement complex to the surface.

McIntyre studied the same area, and suggested (1952), as Rutledge had for the Fannich Inlier, that the Lewisian of

Beinn Dronaig occurred as a tectonic inclusion, and was not rooted 'in situ'. Certainly, in view of the continuous structure connecting Beinn Dronaig to Fannich, the same interpretation must apply to both areas. The Survey geologists suggested that both were anticlines, that of Fannich fan-shaped. Rutledge and McIntyre interpreted both as tectonic inclusions, while, following the recent fieldwork in Fannich, and tentatively drawing a correlation with Poole's structure analysis of North-East Morar, it is suggested here that both inliers form the nose of an F_1 isocline, isoclinally refolded by an F_2 anticline closing westwards, and brought down by an F_3 syncline so that they are preserved at the present erosional level. At Beinn Dronaig the Lewisian is preserved in the nose only; at Fannich it has been refolded into a syncline and the nose itself is not exposed. In between these two points the level at which the Lewisian in the upper limb of the major refolded isocline was tectonically emplaced is above the present erosion level, so no inliers occur within the pelite outcrop. Johnstone (pers. comm.) reports that inliers of Lewisian rocks occur at the outer edge of the pelite outcrop south of Achnasheen, and uses this to support Tanner's (1969) hypothesis that an extensive slide, the Sgurr Beag Slide, occurs within the Moinian. This hypothesis, if correct, has fundamental implications for Moinian structure, and therefore the evidence for and against the existence of a slide must be considered.

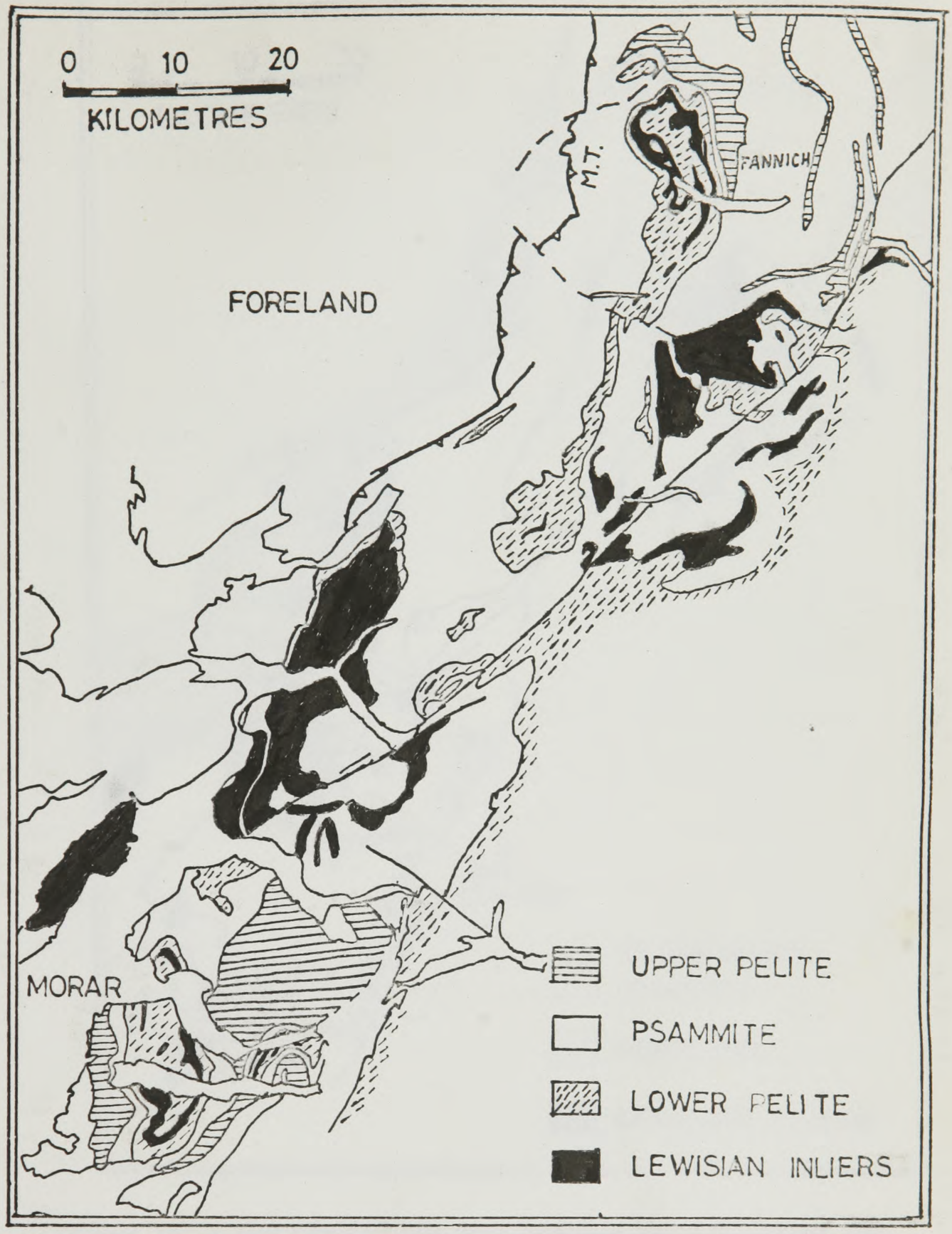


Figure 14. Map showing the area between Fannich Forest and Morar, distinguishing the upper and lower pelites, as correlated in Table 2.

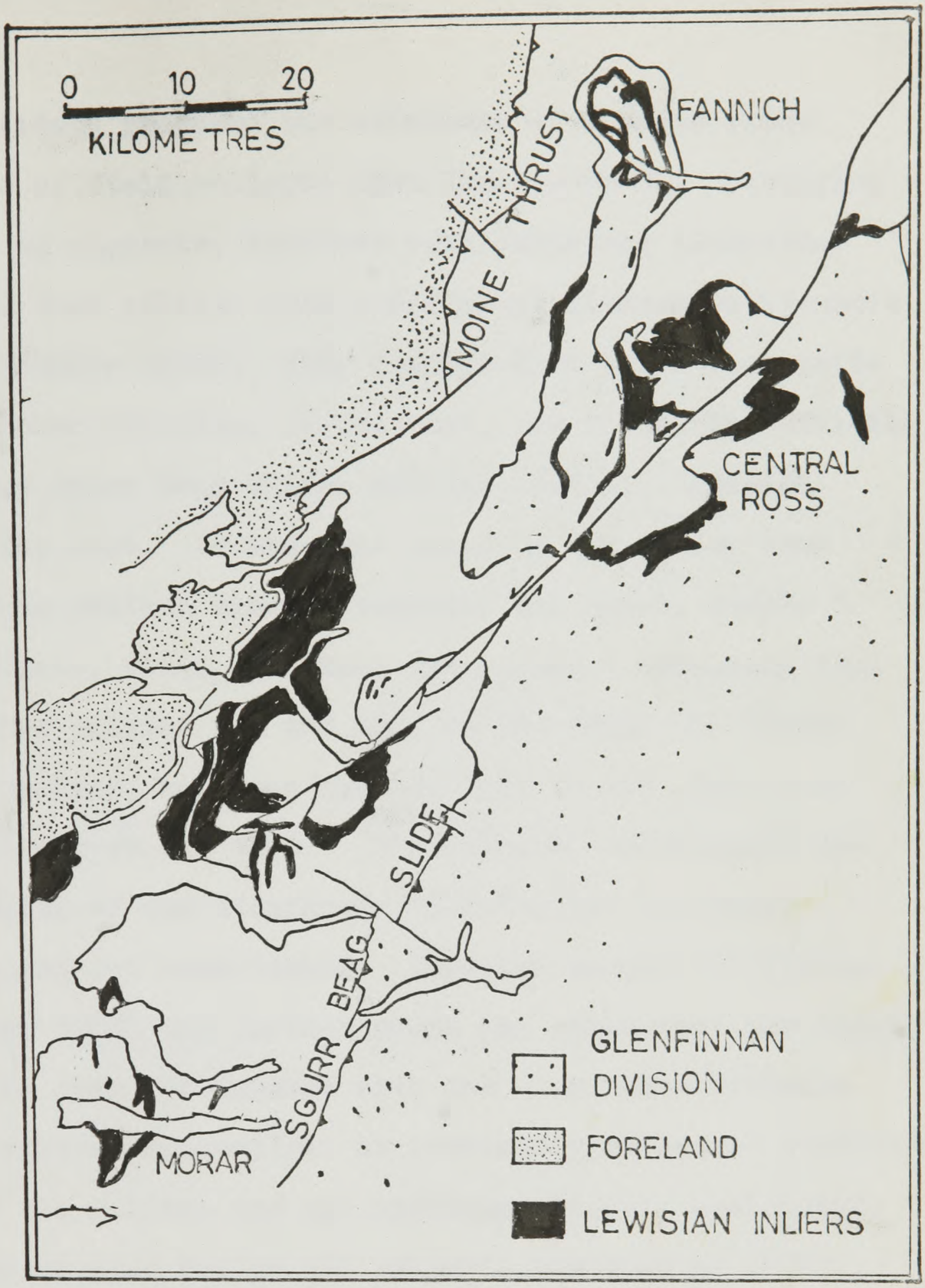


Figure 15. A map showing the area between Fannich Forest and Morar, showing the postulated position of the Sgurr Beag Slide, after Tanner et al. 1969. The Glenfinnan Division overlies the Slide Surface.

Tanner (1969) proposed the existence of a major slide on the basis of field evidence from Kinloch Hourn. Overlying this slide, he suggests, together with Johnstone (Johnstone et al. 1969) that pelites from a different litho-stratigraphic unit in the Moines occur. They propose that three such units occur: the Morar Division, in the west, the Glenfinnan Division, overlying the Sgurr Beag Slide, and the Loch Eil Division, further to the east. It has been noted by the author that the Glenfinnan pelites closely resemble the basal, Number 1 pelites of Morar, while Johnstone (pers.comm.) maintains that the Glenfinnan pelites are the same as the Meall an t-Sithe Pelites in Fannich, and maps them as part of his Glenfinnan Division (Tanner et al. 1970). A meaningful correlation between the units of the Glenfinnan Division and the Morar Division is not yet established. Detailed mapping at Kinloch Hourn (Tanner 1969) and further south has shown that the Ladhar Bheinn Pelite does not connect with the Glenfinnan Division pelites of central Ross-shire, as previously suggested (Clifford 1958). The two pelites are not stratigraphically equivalent, and this invalidates Sutton and Watson's correlation (1962), and agrees with the findings in Fannich Forest, where the Sgurr Mor Pelite is considered an equivalent of the Ladhar Bheinn Pelite. (See Table 2)

At Lochailort, Powell (1964) mapped his Lochailort Pelitic Group as overlying the Ardnish Psammitic Group which he

TABLE 2

Proposed Correlations in the Moinian

Fannich	Kintail	Glenelg-Kneydart	Morar
-	-	Aonach Sgoilte Psammite	No 6 Psammite
Sgurr Mor Pelite with calc-silicates	-	Ladhar Bheinn Pelite with calc-silicates	No 5 Pelite with calc-silicates
Meall a' Chrasgaidh Psammite	Psammite	Barrisdale Psammite	No 2-4 Psammite
Carn na Criche Psammite		Rubha Ruadh Semipelite	
Inverbroom Group		Arnisdale Psammite	
Meall an t-Sithe Pelite	Garnetiferous Mica-Schist Series	Basal Semipelite	No 1 Pelites and Psammites
Local conglomerate	Psammite	Local conglomerate	
unconformity	?unconformity	unconformity	?unconformity
Lewisian	Lewisian	Lewisian	Lewisian

interpreted as straphically equivalent to the No. 6 Psammite of Morar, and therefore the highest unit present in the Morar succession. He used sedimentary structures within the psammite to support his sequence. But Johnstone maps the Lochailort Pelitic Group as part of his Glenfinnan Division, on the grounds of lithological similarity. It is also along this junction that they draw the Sgurr Beag Slide. If the junction in question is tectonic, then the pelites of the Glenfinnan Division may still be stratigraphic equivalents of the Number 1 Morar Pelite, transported into their present position by a slide.

In Fannich the structure is somewhat different. A succession analogous to that of Morar occurs, and the Meall an t-Sithe Pelite occurs in the stratigraphic position expected, adjacent to the Lewisian, and bounded on the other side by a psammite lithologically similar to the No. 2 and 4 psammite of Morar. Since the stratigraphy presents no problems like those of Kinloch Hourn, no slide is required to explain any anomalies. If the Lewisian Inliers only occurred within the outcrop of the Meall an t-Sithe Pelite, no slide would be required to explain the structure of the Fannich-Beinn Dronaig pelitic strip. But a Lewisian Inlier has recently been mapped (Johnstone pers.comm.) fringing this pelite on the west, south of Loch Sgamhain. Unless a rapid lithological facies change occurs, this juxtaposition of Lewisian with presumed No.2

Psammite implies that a tectonic boundary occurs here. The same junction in Fannich, between the Meall an t-Sithe Pelite and the Meall a' Chrasgaidh Psammite shows no inliers of Lewisian anywhere, but it shows a remarkably sharp facies change from pelite to psammite. The sharpness of this junction is the strongest positive evidence for the presence of a slide in Fannich; as elsewhere along the course of the postulated slide, any cataclastic textures resulting from movement have been destroyed by recrystallization in a later metamorphic event.

The slide postulated by Tanner et al. to underlie the Central Ross-shire Inliers, which they show as continuous with the Sgurr Beag Slide is tacitly assumed to be the same as the one they draw around the Fannich-Beinn Dronaig pelitic belt. But no attempt is made to connect the Fannich Lewisian Inlier with those of Central Ross-shire, and the question of whether they form part of the same slice remains open. It is merely stated (Tanner et al.) that the Fannich Lewisian "is either part of the Scardroy sheet interfolded with the Glenfinnan Division, or a separate slice of Lewisian resting on a higher slide plane." The petrology of the Fannich Lewisian does not resemble that of the Scardroy inlier as closely as it resembles that of Morar. The Scardroy inlier contains abundant variety of rock-types lacking in Fannich, and it seems preferable to consider them as belonging to different "infolds' of Lewisian,

of the Eastern and Western facies of Glenelg respectively.

The movement of the postulated Sgurr Beag Slide is taken to be from east to west, but this is not specifically stated. But any sliding that may have occurred in the Fannich-Beinn Dronaig area more probably involved movement of the upper slice from west to east. It has been already stated that no discontinuity in Fannich can be seen in the beds underlying the postulated slide, and the apparent wedging out of the Sgurr Mor Pelite to the west beneath the F_3 Fannich Synform still suggests that it forms the core of a major F_1 recumbent syncline closing westwards. To explain the upper part of the present Fannich succession as an "outlier" of a slide in which the upper sheet moved from east to west would involve a cut-off of the Sgurr Mor Pelite (see Fig.16) below the slide-plane which the available evidence does not support. Any slide-movement in Fannich therefore, should involve the movement of the upper sheet from west to east, possibly as a localised shear associated with the formation of the F_2 isocline. If this movement is incompatible with that suggested for the main slide postulated to underlie the Central Ross-shire Inliers, it is quite possible that more than one slide is present. In such a concept the slide suggested by Tanner et al. in Fannich would be a localised structure augmenting the F_2 refolding of the F_1 isocline, overlain by the main postulated "Sgurr Beag Slide" taken by Tanner et al. to mark the base

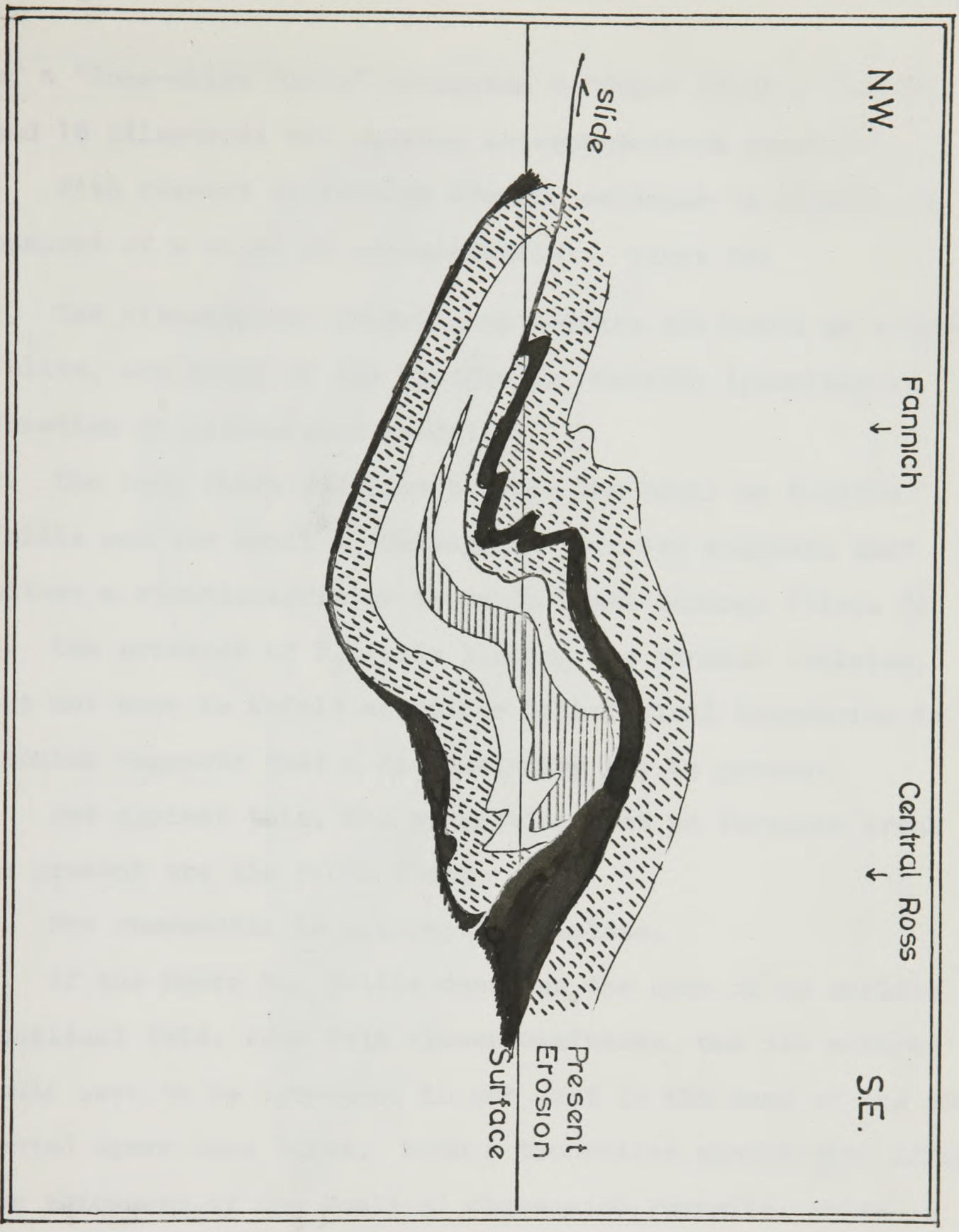


Figure 16. Cross-section through Fannich Forest and Central Ross-shire showing the postulated structure if the Meall an t-Sithe Pelite and Lewisian overlie the Sgurr Beag Slide, as suggested by Tanner et al. 1939. Lewisian: black. Meall an t-Sithe Pelite: dashed ornament. Sgurr Mor Pelite: ruled.

of a "Ross-shire Nappe" overlying a "Morar Nappe", Figs 17 and 18 illustrate the various interpretations possible.

With respect to Fannich itself, evidence to support the concept of a slide is circumstantial. There is:

1. The lithological resemblance between the Meall an t-Sithe Pelite, and those of the Glenfinnan Division (possibly a function of metamorphic grade).
2. The very sharp junction between the Meall an t-Sithe Pelite and the Meall a' Chrasgaidh Psammite suggests that either a stratigraphic or tectonic break occurs. (Plate 2)
3. The presence of F_2 folds linking the Fannich Lewisian, but not seen to refold any other lithological boundaries in Fannich suggests that a discontinuity may be present.

Set against this, and suggesting that no tectonic break is present are the facts that:

1. The succession is apparently complete.
2. If the Sgurr Mor Pelite occupies the core of an earlier isoclinal fold, this fold closes westwards, and its outcrop would have to be truncated in the east by the base of the projected Sgurr Beag Slide. Such a truncation should also affect the thickness of the Meall a' Chrasgaidh Psammite, which in Fannich shows little variation in thickness.
3. No structural evidence of discontinuity, and no mylonitization was seen in Fannich at this junction.
4. Conglomerate at the base of the Moinian on the lower edge

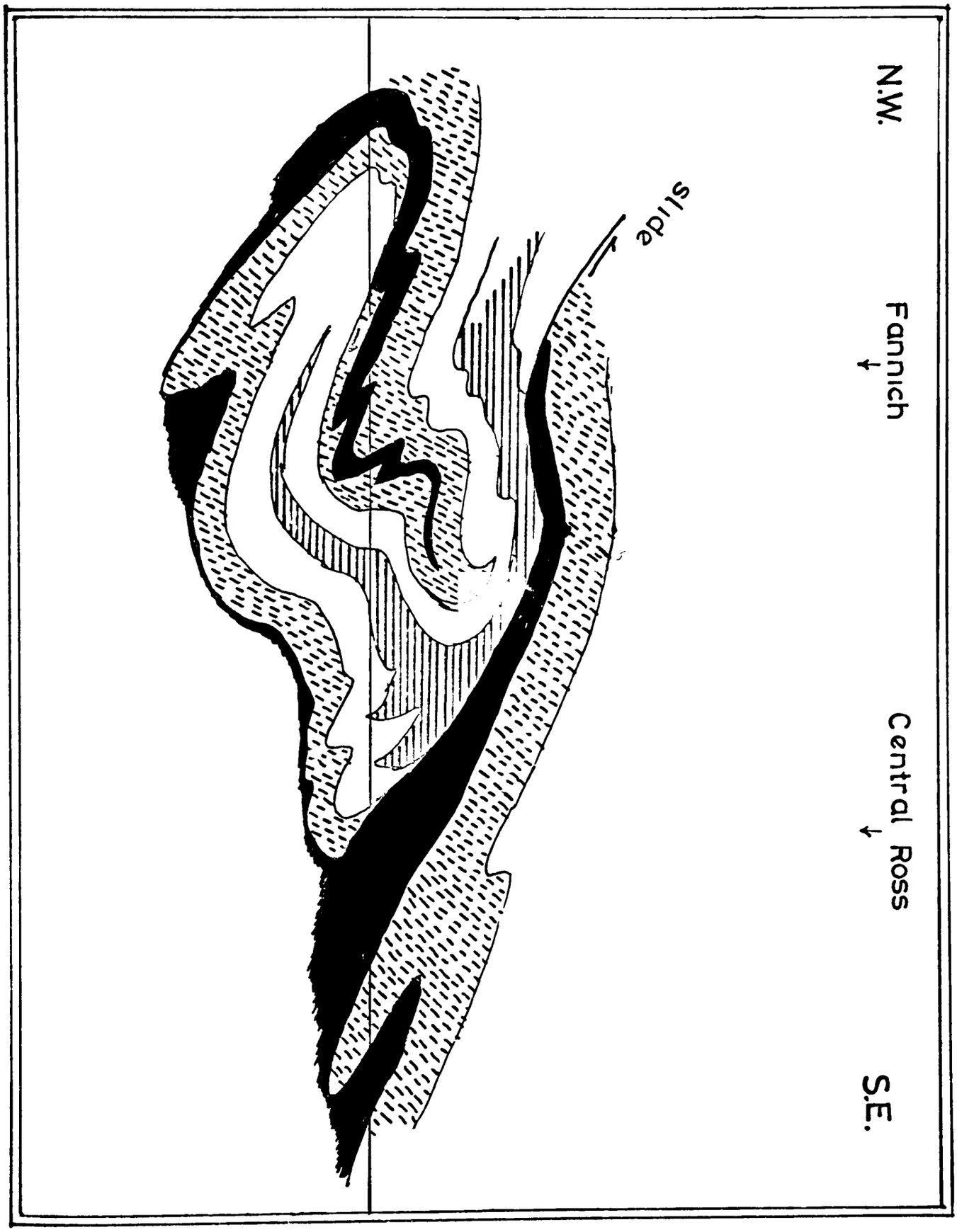


Figure 17. Cross-section through Fannich Forest and Central Ross-shire showing the postulated structure if the Sgurr Beag Slide underlies the Central Ross inliers, but does not occur in Fannich. Ornament as in Figure 16.

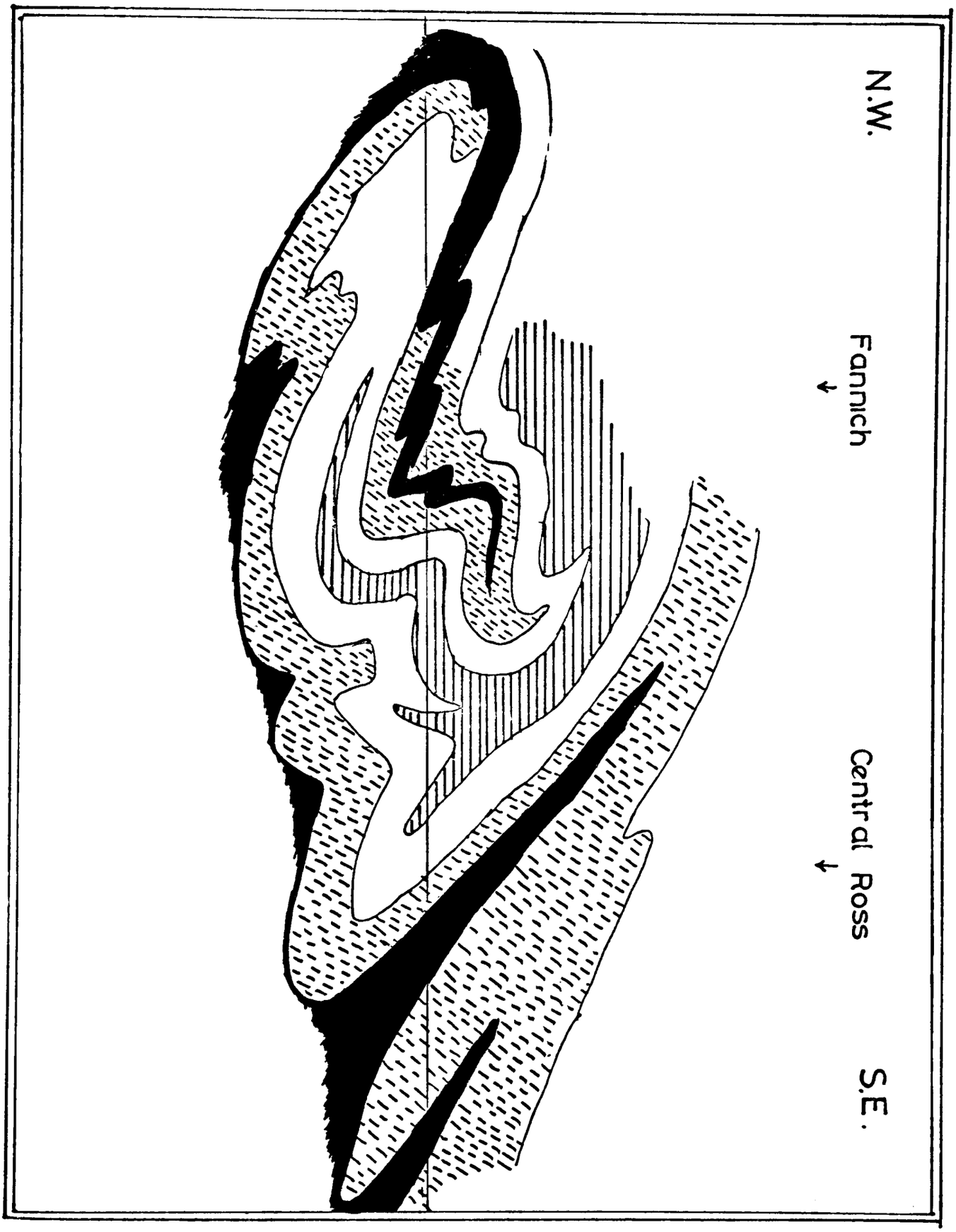


Figure 18. An interpretation of the structure of Fannich Forest and Central Ross-shire, if no slide occurs beneath the Central Ross inliers. Ornament as in Figure 16.

of the Lewisian inlier suggests that the Lewisian-Moine junction is unconformable.

Accepting that a complete succession, and the lack of visible structural evidence to suggest a tectonic break do not preclude the possibility that a slide was initiated before or during the final peak of metamorphism, the main obstacle to the concept of a major slide with movement of the upper slice from east to west, is the presence of the Sgurr Mor Pelite, apparently in an early syncline closing to the west. The only slide compatible with this structure would be one in which the movement of the upper slice was from west to east. But the reasons for believing that the Sgurr Mor Pelite occurs in such a structure have not been discussed.

If the Lewisian forms the core of an isocline, the Moinian units underlying it must be inverted. Fannich appears to display a continuous succession down to the Inverbroom Group of psammites, which Sutton and Watson showed to be uninverted. Unless a second early isoclinal fold, with a synclinal core, complementary to the Lewisian-cored isocline occurs, these two pieces of evidence are contradictory. The Meall an t-Sithe pelite is adjacent to the Lewisian throughout, and is always succeeded by the Meall a' Chrasgaidh Psammite. In neither of these units is there evidence of a large-scale isocline. But the distribution of the Sgurr Mor Pelite is significant, as it does not form a continuous rim round the Fannich Synform.

Evidence from current-bedding (Sutton & Watson 1954) shows that it is younger than the Inverbroom Group, while the Meall a' Chrasgaidh psammite does not resemble the overlying quartzose psammites of the No.6 Group seen in Morar. Mapping showed that the Sgurr Mor Pelite is thick and forms a broad outcrop in the north-east, but thins rapidly both to the south and west. If it forms the core of an early pre-F_3 syncline, that syncline appears to close towards the west. No tectonic break occurs; all the margins of the Sgurr Mor Pelite were gradational wherever seen. Without invoking a slide, this synform would be of F_1 age, but refolded into its present position closing west by the same F_2 fold that induces the Lewisian to close eastwards, as suggested in Morar. If this synform is cut off above the present erosion surface by a slide extending into Fannich from Central Ross-shire, it is difficult to fit it into the required structural deformational sequence. But a west-closing syncline fits more easily into the concept of a refolded isocline already described, in which some localized tectonic movement occurred between the Meall an t-Sithe Pelite and Meall a' Chrasgaidh Psammite. Johnstone (pers. comm.) mentioned that Lewisian inliers occur along this junction further south; this may support the slide hypothesis, but it does not prove that this slide is the same as the Sgurr Beag Slide further east.

It is concluded here therefore that

1. The Morar Succession can be applied to the Fannich area.

2. That the F_1 Lewisian anticline in Fannich overlies a recumbent F_1 syncline, closing westwards, which contains Sgurr Mor Pelite in its core. (Figure 18)

3. Sliding may have occurred along the Meall an t-Sithe Pelite - Meall a' Chrasgaidh Psammite junction, but in Fannich itself there is no direct evidence of this. If it has occurred, the movement of the upper slice would be from west to east, possibly attenuating the F_1 Sgurr Mor Syncline in an F_2 fold episode.

4. The Central Ross-shire Inliers are lithologically much more varied than that of Fannich, and probably belong to a different nappe. This nappe, whether with or without a slide at its base, overrode the Fannich area, with its upper part moving from east to west, or opposed to the direction suggested in Fannich.

5. The relative west-to-east movement in Fannich may result from its position above an F_2 anticline closing west; the relative east-to-west movement in Central Ross-shire can be explained by its positioning below a similar F_2 anticlinal core. Any sliding which may have occurred would be initiated during this episode.

6. Late F_3 folds, generally trending approximately north to south, refolded the foliation and preserved the upper limb of the Morar Nappe preserved in Fannich slight kinking in the

axial trend of these folds, and variations in axial plunge may result from a late mild fold event. Faulting also post-dates these F_3 folds, as none of the faults seen were folded.

6

PETROGRAPHY

6.1 Introduction

Although a brief summary of the mineral assemblage typifying each unit was included in the discussion of stratigraphy in Fannich, in Chapters 3 and 4, little reference was made to the textural and mineralogical relationships seen in the rock-types. In this chapter the pelites, psammites, silicic gneisses and amphibolites will be described in turn. The conglomerate at the base of the Meall an t-Sithe Pelite is examined with the pelites, while the calc-silicate rocks seen in the Lewisian and the Moines (other than those in the Sgurr Mor Pelite) and a heavy mineral seam are also discussed. The calc-silicates of the Sgurr Mor Pelite were the subject of a special study, and are described more fully in Chapter 7.

6.2 Pelites and Semipelites.

The term pelite is applied in this thesis to the schistose garnet-mica-quartz rocks of Fannich. Although these rocks are true schists in texture, their chemical composition and mineralogy is more comparable with semipelites from the Dalradian. A comparison between average Dalradian pelitic gneisses from Glen Clova (Chinner 1960), average Moine pelites from various

TABLE 3

Average compositions of Moinian and Dalradian Schists.

(All major element analyses in weight %)

	Mts	Mts + kyanite	Moinian	Dalradian	Leven Schists
	Fannich	Fannich	Butler '65	Chinner '60	Holland & Lambert. pers. comm.
SiO_2	61.85	58.46	58.19	49.82	62.49
Al_2O_3	18.87	21.00	19.87	26.07	19.79
FeO	7.03	8.47	7.49	10.14	5.72
MgO	2.37	2.66	2.39	2.37	2.83
CaO	2.37	1.08	1.97	0.93	1.12
Na_2O	3.26	2.41	2.59	1.57	1.84
K_2O	3.06	4.04	3.89	4.08	4.39
TiO_2	1.07	1.28	1.05	1.37	0.79
MnO	0.11	0.11	0.13	0.19	0.09

Abbreviations: Mts = Meall an t-Sithe Pelite.

localities (Butler 1965) and the pelites from Fannich is shown in Table 3. From these figures, Moinian pelites are shown to be richer in silica, calcium and sodium and depleted in alumina and potash compared to Dalradian pelites.

A brief description of the two different pelitic units in Fannich has already been given in Chapter 3, in which textural differences between them were mentioned. But there are several mineral assemblages that are common to both pelites, and the main assemblages are listed in Table 4.

In the kyanite-bearing rocks, plagioclase is scarce, and this is probably a result of the calcium depletion in these rocks. Their average composition is listed in Table 3, which shows that they are compositionally more similar to Dalradian pelites than are most of the Moinian.

The kyanite, not previously recorded from Fannich, is brownish (possibly from microscopic iron exsolution) and occurs as small aggregates of blocky crystals showing two cleavages. It occurs in the least calcic schists as the depletion in calcium inhibited the growth of plagioclase which would also have absorbed the available alumina. The Moinian pelites apparently do not readily develop aluminosilicate minerals on account of their greater calcium content than the Dalradian pelites, and plagioclase develops instead: (Plate 15)

$$(CaO) + \underset{qz}{SiO_2} + \underset{ky}{Al_2SiO_5} \longrightarrow \underset{an}{CaAl_2Si_2O_8} \qquad ---1$$

TABLE 4

Mineral Assemblages in Fannich Pelites

		Mts (No. of samples.)	Smp (No. of samples.)
1.	Kyanite - Muscovite	3	-
2.	Muscovite - (Sphene)	24	20
3.	Muscovite - Epidote - Sphene	1	4
4.	Muscovite - Microcline - (Sphene)	6	2
5.	Microcline - Sphene	3	1
6.	Microline - Epidote - Sphene	2	1
7.	Epidote - Sphene	2	-
8.	Sphene	-	3

Garnet, Quartz, Plagioclase (An_{23-40}), Biotite
Apatite and Magnetite are always present.

Clifford (1958) mentions that kyanite had only been recorded in rocks of unquestionable Moinian age in six areas, two of them in Kintail (Clifford 1957). The kyanite from Fannich occurs in the pelite believed by the author to be identical with the garnetiferous mica schists of Kintail, and likewise occurs in calcium-depleted rocks.

In the samples from Fannich, the kyanite is clearly unstable, occurring as small aggregates in muscovite (see Plate 15). Garnet does not occur near the kyanite, although present in the same rock. Clifford (1958) observed garnet developing directly from the kyanite, and postulated that it was formed by the reaction:

$$4Al_2SiO_5 + K_2Fe_6Al_2Si_6O_{20}(OH)_4 + 2SiO_2 \longrightarrow$$

Kyanite — Iron-rich Biotite — Quartz

$$\longrightarrow 2Fe_3Al_2Si_3O_{12} + K_2Al_6Si_6O_{20}(OH)_4$$

Almandine (gt) — Muscovite

But in Fannich, garnet was never seen forming from the kyanite; indeed the kyanite only occurs in garnet-free parts of the rock. It might be argued that the garnet-bearing parts of the rock are those where the kyanite has been completely replaced, but the garnets are too well-developed, and it seems that they are not involved in the reaction.

In Fannich, the Moine pelites frequently contain magnetite

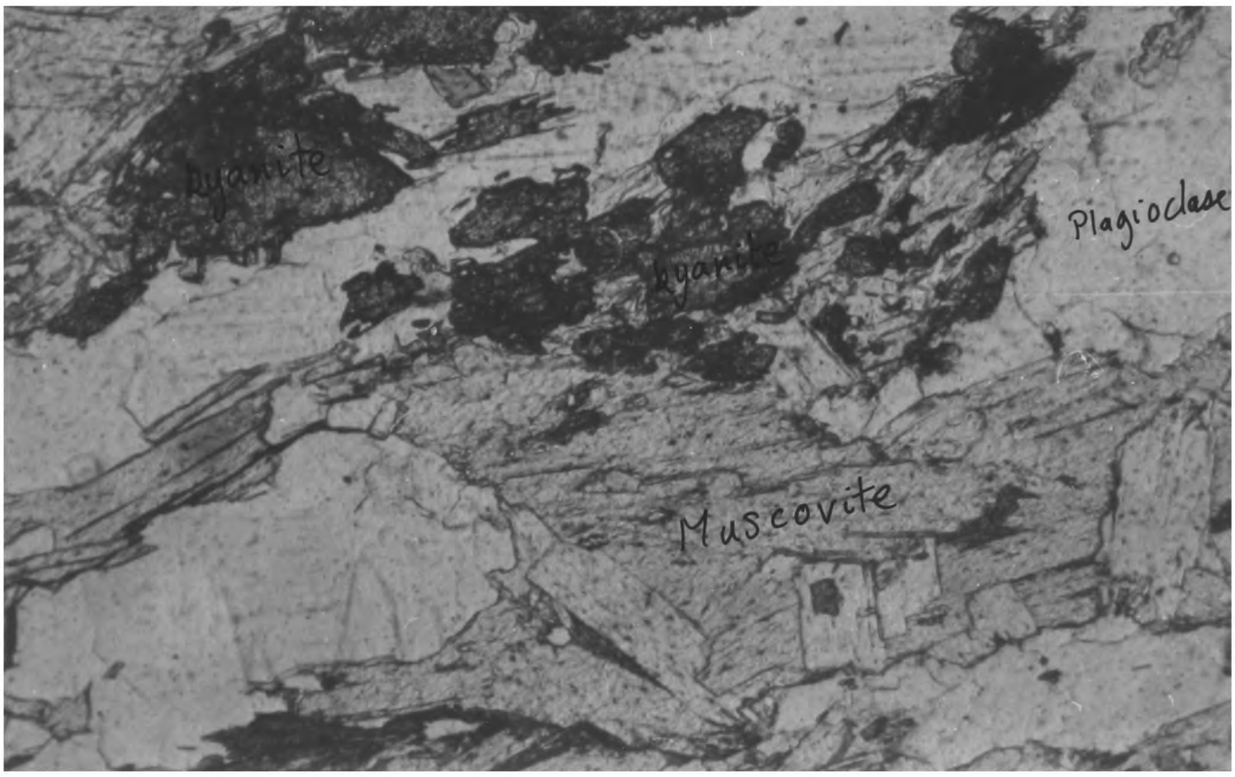


Plate 15. Kyanite in Meall an t-Sithe Pelite.

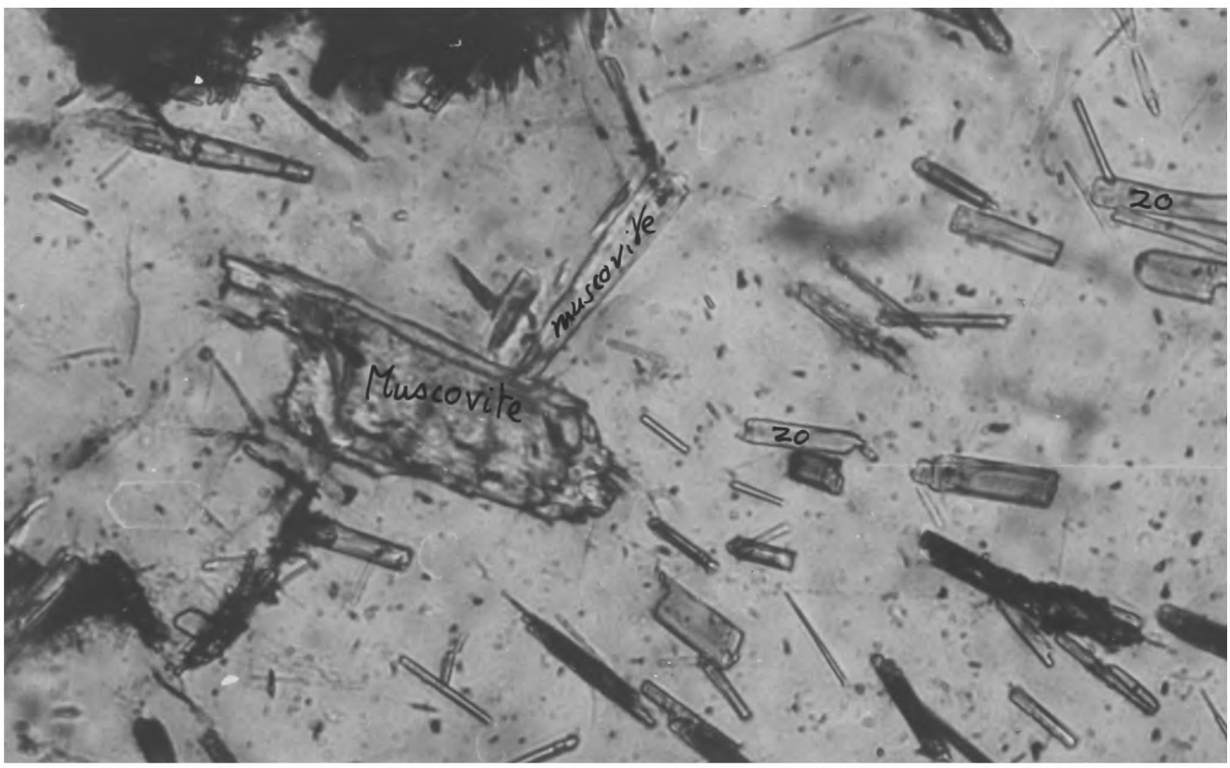


Plate 16. Needles of zoisite and muscovite grains in Meall an t-Sithe Pelite.

or haematite and small grains of magnetite are forming with the muscovite where the kyanite is being replaced. The decay of kyanite in Fannich, therefore, appears to be the result of an oxidation reaction which does not affect garnet:

$$2Al_2SiO_5 + K_2Fe_6Al_2Si_6O_{20}(OH)_4 + O_2 \longrightarrow$$

Kyanite Iron-rich Biotite

$$\longrightarrow K_2Al_6Si_6O_{20}(OH)_4 + 2Fe_3O_4 + 2SiO_2 \qquad \text{---------3}$$

Muscovite Magnetite Quartz

Garnet is always present in the pelites, and when analysed was found to be almandine. It is often compositionally zoned. The zonation was studied and is discussed in Chapter 8. Garnet colour, already mentioned in Chapter 3, was found to be a valuable method of distinguishing the pelites, as different units in Fannich contain garnets of different colours. In the Meall an t-Sithe Pelite, the garnets vary in colour from pale pink to deep mauve, and are usually clear. By contrast the garnets from the Sgurr Mor Pelite are always cloudy and almost opaque. Their colour is more variable but is consistent in each of the sublithologies that occur in the Sgurr Mor Pelite. In the speckled schist that comprises most of the unit, the garnets are euhedral and dull brown in colour. In the flakier muscovite-biotite schist that occurs as thin bands in the speckled schist garnets are rare, but when present, tend to be black and subhedral. In the finer-grained flaky schists

that occur in force on Creag Raineach Mor abundant small black garnets occur, while in the sempsammitic bands the garnets are dull red-brown. Finally, garnets associated with the calc-silicate bands are brown or orange. No pink garnets occur anywhere in the Sgurr Mor Pelite.

In thin-section, many of the clear garnets from the Meall on t-Sithe Pelite can be seen to be free of fractures or inclusions, but other garnets, often in the same rock contain inclusions of several minerals, notably quartz, biotite, muscovite, apatite and magnetite. Yet even these garnets often contain cores free of inclusions. The textural difference between core and rim suggests that there have been at least two periods of garnet growth. Garnets from the Sgurr Mor Pelite tend to be euhedral, showing distinct crystal faces in thin-section, unlike those from the Meall an t-Sithe Pelite. In these garnets a clear core is surrounded by a sharply defined zone crowded with quartz inclusions which merge into the well-shaped, inclusion-free outer rim. (see Plate 32).

Garnets in the Meall an t-Sithe Pelite show no sign of rotation beyond 20°, the original orientation being betrayed by a linear arrangement of inclusions. In the Sgurr Mor Pelite, abundant quartz inclusions were often evenly distributed and gave no indication of the direction of rotation.

In nearly all the samples examined, garnet is metastable,

and no sign of breakdown is visible. But one pegmatitic plagioclase-garnet rock collected near the head of Loch Fannich contains garnets chloritized along fracture planes.

Another sample, collected from Creag Dubh, east of the Allt Leac a ' Bhealaich, contains aggregates of epidote, sometimes rimming a grain of orthite, apparently replacing garnet which is sometimes partially preserved. Chloritized garnet was also seen in a sample of Meall an t-Sithe pelite from near Garve. The breakdown of garnet to form chlorite in these reactions appears to proceed according to the reaction:

$$K_2(Mg_2Fe)_4\ Al_2Si_6O_{20}(OH)_4 + 4Fe_3Al_2Si_3O_{12} + 8H_2O + 2O_2 \longrightarrow$$

Biotite — Almandine

$$\longrightarrow\ 2(MgFe)_4Al_2Si_3O_{10}(OH)_8 + K_2Al_6Si_6O_{20}(OH)_4 + 4Fe_2O_5 + 6SiO_2$$

Ripidolitic chlorite — Muscovite — Hm — Qtz

in which hydration and oxidation of the rock occur.

Two micas are usually present in both the pelitic units (see Table 4). Out of forty-one Meall an t-Sithe Pelites examined muscovite was seen in thirty-four, while out of thirty-one Sgurr Mor Pelites, it was detected in twenty-six. Muscovite usually occurs in fresh colourless sheaves, but in some grains, particularly in the Sgurr Mor Pelite, incipient exsolution of iron oxides along the cleavage planes was seen.

Biotite is always strongly pleochroic, its colour varying

from pale yellow to a dark, rich, chestnut brown. The colour of biotite is generally related to its composition (Deer, Howie, Zussman, Vol.III, p.71, 1962), and the rich brown of the biotite from the Moinian pelites indicates that it is titanium-rich. Whole-rock analyses of the Meall an t-Sithe Pelite (Table 5) show that they are without exception titanium-rich, and the titanium is probably concentrated in the biotite. Like muscovite, the biotite, which is present in all the pelites, forms as laths parallel to, and defining, the foliation. It also occurs as inclusions in the garnets. In the Sgurr Mor Pelite small zircon grains commonly occur in the biotite, and are revealed by strongly pleochroic haloes. Although zircon also occurs in the Meall an t-Sithe Pelite, it is not as prominent.

Quartz and plagioclase occur in all the pelites, usually occurring as interlocking granules forming the leucocratic matrix of the rock. The grain-size is variable, but larger quartz grains occur adjacent to garnet porphyroblasts. The plagioclase composition varies between An_{23} and An_{40}, while reversed zoning was seen in several specimens. Albite or pericline twinning were seen, but often the grains were untwinned. The symmetrical extinction angle method was used to determine plagioclase composition. In the plagioclase grains from one of the kyanite-bearing samples small needles are preserved

TABLE 5 (a)

Analyses of Meall an t-Sithe Pelites

	6841	6844	6851	6854	68514	68518	68531	68543	68550	68563	68610	68729	68730	68824
SiO_2	58.19	61.00	65.44	65.51	62.28	64.38	63.13	60.33	69.47	59.76	65.04	60.54	60.18	61.00
Al_2O_3	21.33	18.67	17.61	16.96	16.93	17.49	16.89	18.59	14.40	18.70	16.67	19.25	19.65	10.14
FeO(tot.)	8.79	7.69	4.51	5.25	7.05	5.46	6.28	5.80	5.04	6.24	6.41	7.62	7.87	7.85
MgO	2.62	2.53	1.83	1.65	2.15	2.14	2.34	2.69	1.49	2.44	2.26	2.32	2.33	2.32
CaO	1.20	2.05	3.39	2.60	3.64	2.94	2.98	4.36	2.25	4.44	2.26	2.31	1.99	1.50
Na_2O	2.10	2.73	4.43	4.23	4.05	4.25	4.28	4.87	3.72	5.11	2.79	2.87	2.36	3.42
K_2O	4.01	3.61	1.78	2.33	1.85	1.93	2.65	1.40	2.24	1.41	3.28	3.55	4.06	3.10
TiO_2	1.23	1.16	0.76	0.90	0.88	1.03	1.07	0.96	1.00	0.98	1.04	1.08	1.10	1.19
MnO	0.15	0.22	0.10	0.08	0.17	0.08	0.09	0.09	0.07	0.09	0.10	0.11	0.11	0.09
S	0.01	0.12	0.01	0.23	0.73	0.05	0.04	0.76	0.11	0.54	0.02	0.03	0.29	0.21
P_2O_5	0.36	0.20	0.14	0.25	0.28	0.25	0.26	0.15	0.21	0.29	0.14	0.30	0.28	0.18

TABLE 5 (b)

Analyses of Meall an t-Sithe Pelites

	68825	68827	68828	68829	68830	68832	68725	68517	6868	68826	68833	68732	Average Values Upper Pelite	Average Values Lower Pelite
SiO_2	57.06	59.63	63.48	64.01	64.31	59.60	60.72	59.04	61.10	57.31	60.56	65.14	61.29	62.43
Al_2O_3	22.37	19.65	18.02	17.59	17.04	19.75	19.07	20.10	17.69	21.48	18.84	13.92	18.69	18.32
FeO(tot.)	8.16	8.87	6.36	6.43	6.66	8.56	4.96	7.22	7.25	9.39	8.44	6.53	7.21	6.85
MgO	2.88	2.39	2.14	2.38	2.22	2.95	3.08	2.39	3.03	2.77	2.89	2.99	2.46	2.28
CaO	0.88	1.76	2.13	2.00	2.25	1.33	2.65	2.93	3.26	0.87	1.65	1.75	2.40	2.34
Na_2O	2.01	2.45	3.86	2.89	3.33	1.68	2.53	4.11	2.60	1.80	2.17	3.73	3.36	3.15
K_2O	4.67	3.60	2.64	3.38	2.90	4.60	5.78	2.77	2.92	4.36	3.95	4.82	3.30	3.12
TiO	1.36	1.19	1.02	1.06	0.99	1.14	1.11	1.23	1.05	1.28	1.12	0.98	1.10	1.03
MnO	0.08	0.11	0.10	0.09	0.10	0.11	0.13	0.09	0.14	0.16	0.11	0.13	0.11	0.10
S	0.35	0.02	0.05	0.01	0.003	0.01	-	0.003	0.15	0.36	0.01	-	0.20	0.13
P_2O_5	0.17	0.34	0.22	0.17	0.19	0.26	-	0.12	0.29	0.23	0.27	-	0.22	0.25
Sr p.p.m.	-	-	-	-	-	-	-	377	279	126	202	743	261	472
Rb "	-	-	-	-	-	-	-	123	119	163	169	163	135	166
Zr "	-	-	-	-	-	-	-	359	284	268	265	484	304	374
Nb "	-	-	-	-	-	-	-	16	12	15	13	n.d	14	7
Ni "	-	-	-	-	-	-	-	26	36	29	25	27	30	26

(Plate 15), which may be of zoisite . Iron-poor epidote, with low birefringence is present in sixteen of the samples studied, and occurs in both the pelitic units.

Microcline was seen in some samples, but fully-developed microcline twinning was only seen in grains within the pebbles of the basal conglomerate.

In a few samples of Meall an t-Sithe Pelite blades of black tourmaline were also seen. In one slice the tourmaline has been replaced by magnetite and biotite.

Although several different mineral assemblages occur, a study of twenty-five Meall an t-Sithe Pelite analyses (Table 5) did not relate the different groupings to the whole-rock composition. In fact, the quantity present of the minerals used to define these assemblages is usually so small that their presence or absence has a negligible effect on the composition of the rock, which is typical of Moine pelites seen elsewhere (Butler 1965).

6.3 Psammites and Silicic Gneisses

Psammites and Lewisian Silicic Gneisses are discussed together so that their petrography can be compared and contrasted. Since they are broadly similar in composition, petrological differences may result from differing metamorphic history.

Eleven major assemblages were found, but numerous other

combinations occur, usually in single specimens, and several of these may simply reflect the positioning of the slice selected for thin-sectioning. In a banded rock, there are obvious difficulties in obtaining a representative sample. Only the commonest assemblages are listed in Table 6.

These show that the mineralogies of psammites and silicic gneisses are essentially similar; both can be garnetiferous, both can contain either muscovite or epidote, and both usually contain sphene.

Eighteen psammites and thirty silicic gneisses were analysed. They are listed in Tables 7 and 8. According to these, whether a mineral is present or absent can be related either to the composition of the rock, or to other factors, which can be collectively described as the metamorphic environment. As with the pelites, the minerals in the psammites and silicic gneisses are discussed in turn.

In both the silicic gneisses and psammites the garnets are orange or red, unlike those in the pelites. In thin-section their textures can be seen to vary greatly. The garnets in the Inverbroom Group are skeletal, poikilitically surrounding clear quartz grains. In the Meall a' Chrasgaidh psammite the garnets are also skeletal, having been partially replaced by biotite, epidote, quartz, and sometimes sphene. But the remaining garnet in most of these samples shows no signs of instability except

TABLE 6

Mineral Assemblages in Psammites and Silicic Gneisses

	Psammites (No. of samples)	Silicic Gneiss (No. of samples)
1. Garnet-Biotite-Muscovite-Sphene-(Microcline)	6	5
2. Garnet-Biotite-Muscovite-Epidote-Sphene-(Microcline)	4	4
3. Garnet-Biotite-Epidote-Sphene-(Microcline)	-	3
4. Garnet-Biotite-Epidote-Sphene	1	3
5. Biotite-Epidote-Sphene	3	12
6. Biotite-Epidote-Sphene-(Microcline)	3	5
7. Biotite-Muscovite-Epidote-Sphene-Microcline	4	3
8. Biotite-Muscovite-Sphene-Microcline	4	3
9. Biotite-Muscovite-Epidote-Sphene	1	3
10. Biotite-Muscovite-Sphene	3	4
11. Muscovite-Microcline-Sphene	-	4

Quartz and Plagioclase are present in all these assemblages.

TABLE 7 (a)

Analyses of Moinian Psammites

Sgurr nan Each Psammite

	68553	68566	68569	68731	69482	69483	69434	69754
SiO_2	84.00	75.86	70.91	72.76	75.90	88.01	73.05	73.31
Al_2O_3	8.82	11.63	15.47	12.76	13.03	6.50	11.00	13.64
FeO(Tot.)	1.63	3.62	3.75	2.14	3.19	2.12	4.28	3.20
MgO	0.23	1.43	1.33	1.25	0.82	0.34	2.20	1.19
CaO	0.04	1.17	1.08	5.76	1.38	0.29	3.30	1.91
Na_2O	1.17	2.11	3.22	2.74	1.67	0.64	3.37	2.25
K_2O	3.85	3.37	2.98	1.58	3.21	1.68	1.90	3.68
TiO_2	0.21	0.59	0.77	0.70	0.71	0.37	0.78	0.74
Mno	0.01	0.07	0.06	0.17	0.09	0.05	0.11	0.08
S	trace	trace	0.29	0.03				
P_2O_5	0.04	0.15	0.13	0.11				
Sr p.p.m.					301		180	195
Rb "					106		77	140
Zr "					281		509	304
Nb "					3.5		7	6.5
Ni "					7		21	8

TABLE 7 (b)

Analyses of Moinian Psammites

	Inverbroom Group				Carn na Criche		Meall a' Chrasgaidh Psammite			
	69418	69513	69514	69515	68624	68723	68567	68575	6947	69477
SiO_2	81.52	70.41	77.62	77.34	74.12	78.23	78.12	80.45	79.21	80.09
Al_2O_3	9.55	13.81	11.09	11.18	11.75	9.27	9.35	9.08	9.01	8.90
FeO(tot.)	2.11	4.02	2.23	2.24	3.17	5.06	4.18	4.59	3.98	4.02
MgO	0.30	1.59	0.57	0.37	1.21	0.12	1.02	0.27	0.55	0.45
CaO	1.01	2.27	2.04	1.36	3.28	1.36	1.64	1.07	1.60	1.25
Na_2O	1.95	3.68	2.53	3.39	2.76	1.75	1.39	1.39	2.53	1.69
K_2O	3.13	3.44	3.44	3.69	2.63	3.98	3.62	2.65	2.57	3.06
TiO_2	0.37	0.69	0.42	0.31	1.00	0.42	0.62	0.47	0.50	0.50
MnO	0.06	0.10	0.07	0.06	0.11	0.05	0.08	0.06	0.07	0.06
Sr p.p.m.		381		240	346		122			
Rb		113		62	79		115			
Zr		195		120	600		477			
Nb		tr.		n.d	9		10			
Ni		18		5	14		6			

TABLE 8 (a)

Analyses of Lewisian Silicic-Gneisses

,	68413	68548	68565	68640	69410	69412	69480	69535	69536	69730	69759	69760	69762	69763
SiO_2	74.46	74.90	70.04	84.72	71.09	81.37	70.51	82.48	82.17	79.23	77.18	82.46	85.20	79.97
Al_2O_3	13.48	10.54	15.83	8.78	14.96	8.84	13.35	8.49	8.65	8.30	9.43	6.93	5.63	7.92
Fe(tot.)	1.51	5.35	2.17	0.37	2.71	2.83	2.43	3.06	2.56	4.51	5.17	4.76	4.68	4.35
MgO	0.62	2.05	1.02	0.08	0.80	0.44	0.23	0.05	0.09	0.43	0.23	0.30	0.19	0.40
CaO	1.52	2.64	2.40	0.03	2.30	0.99	1.79	0.41	0.41	1.59	1.66	1.08	a.30	1.24
Na_2O	3.48	3.09	5.04	1.09	6.55	1.88	5.13	0.81	0.77	2.00	2.63	1.19	2.11	1.87
K_2O	4.65	0.69	3.04	4.85	1.21	3.19	4.26	4.40	5.19	3.43	3.46	3.02	0.64	3.96
TiO_2	0.16	0.28	0.24	0.02	0.34	0.40	0.25	0.26	0.24	0.44	0.39	0.41	0.39	0.43
MnO	0.03	0.19	0.04	0.01	0.04	0.05	0.04	0.04	0.04	0.06	0.05	0.05	0.07	0.06
S	0.01	0.21	0.02	0.001										
P_2O_5	0.07	0.06	0.15	0.04										

TABLE 8 (b)

Analyses of Lewisian Silicic- Gneisses

	68611	69419	69438	69471	6951	6953	69521	69528	69529	69530	69533	69534	69538	69761	69413	69724
SiO_2	71.18	85.56	81.54	80.78	78.62	81.83	83.59	82.64	81.77	81.09	84.87	81.18	84.62	85.45	68.69	80.19
Al_2O_3	14.88	6.59	7.93	9.01	10.01	7.98	7.63	7.58	8.38	8.95	7.40	8.58	7.12	5.48	16.98	9.08
Fe(tot.)	2.23	2.43	2.63	2.80	2.88	2.70	2.54	2.64	2.62	2.68	2.50	2.74	2.46	4.62	2.92	2.76
MgO	0.56	0.19	0.52	0.71	0.65	0.58	0.45	0.42	0.39	0.39	0.35	0.61	0.32	0.21	2.38	0.68
CaO	2.12	0.54	0.88	0.91	1.06	1.07	0.85	0.74	0.79	0.91	1.11	1.10	0.75	1.11	1.47	1.06
Na_2O	4.42	1.15	2.00	1.55	2.12	1.54	2.16	1.52	1.41	1.70	1.30	2.56	1.36	1.07	4.29	2.14
K_2O	4.14	3.23	4.06	3.73	4.11	3.82	2.34	3.98	4.17	3.79	2.08	2.73	3.09	1.61	2.79	3.47
TiO_2	0.28	0.27	0.39	0.44	0.47	0.42	0.38	0.42	0.40	0.42	0.33	0.43	0.31	0.40	0.42	0.54
MnO	0.04	0.04	0.06	0.06	0.07	0.07	0.06	0.06	0.06	0.07	0.06	0.08	0.05	0.05	0.07	0.07
S	0.01															
P_2O_5	0.13															
Sr p.p.m	143	113	139	125	143	145	298	128	121	145	127	163	116	132	404	211
Rb	113	73	101	112	117	99	48	100	107	105	50	72	76	37	81	102
Zr	147	114	164	214	161	231	232	213	186	217	163	227	176	178	214	401
Nb	tr.	n.d	1	2	2	1	n.d	4	5	3.5	n.d	5	n.d	tr.	n.d	tr.
Ni	13	4	5	8	10	8	9	6	6	7	6	7	4	tr.	37	6

Abbreviations tr = trace

in one sample collected from Coire Mor where garnet is replaced in its fractures and round the rim by chlorite and magnetite.

In the Sgurr nan Each Psammite, garnet textures are more akin to those of the Meall an t-Sithe Pelite. Although skeletal garnets do occur, others are anhedral, clear, and free from inclusions. No signs of instability were detected.

In silicic gneisses the garnets are usually small, anhedral, and contain some inclusions, usually of quartz. Mostly they are fresh, but in a sample from the Allt na Goibhre the garnet is extensively chloritized along its fracture-planes. In another sample from west of Ceann Garbh a' Chailleach, the textures indicate that the garnets have been entirely replaced mainly by epidote and biotite (Plate 17). The reaction below is suggested for the replacement of almandine garnet by epidote and other minerals:

$$2Fe_3O_4 + 4Fe_2O_3 + 4KAlSi_3O_8 + 4Fe_3Al_2Si_3O_{12} + 8CaAl_2Si_2O_8 + 22H_2O + 3O_2 \rightarrow$$

mt hm microcline almandine anorthite

$$\rightarrow 4Ca_2Al_3Si_3O_{12}(OH) + K_2Ie_6Al_2Si_6O_{20}(OH)_4 + 4Fe_5Al_2Si_3O_{10}(OH)_8 +$$

zo Biotite Ripidolite

$$K_2Al_6Si_6O_{20}(OH)_4 + 4SiO_2$$

muscovite

------- 5

Like reactions 3 and 4, this reaction involves oxidation and hydration, and it is therefore consistent to suggest that



Plate 17. Replacement of garnet in silicic gneiss.

extensive oxidation and hydration affected all the rock units in Fannich Forest at a late stage in its metamorphic history. In the silicic gneisses the garnets can attain a size of eight to ten millimetres across, a size considerably bigger than any garnets seen in Moine Psammites.

Two micas are commonly present in both the psammites and silicic gneisses (Table 6). Biotite is present in all non-calcareous psammites, and in all but four of the silicic gneisses. Out of thirty-two psammites examined twenty-four contain muscovite, while out of fifty-seven silicic gneisses, muscovite occurs in thirty. It is therefore less common in the Lewisian than in the Moinian, especially as amounts in the silicic gneisses are usually small. Biotite is usually grey-green in both psammites and silicic gneisses, although brown grains do occur. The colour may indicate a high ferric iron content (Deer, Howie, Zussman, Vol.III, p.71 1962)

Quartz and plagioclase, often with lesser amounts of microcline, from the bulk of these rocks. The grain-size is variable, but the silicic gneisses tend to be coarser-grained than the psammites. In both rock-types these minerals form a groundmass of interlocking grains. Plagioclase is usually untwinned, particularly in the Meall a' Chrasgaidh Psammite, but twinning on the albite or pericline laws was seen in some grains. The composition in both silicic gneisses and psammites ranges between

An_{25} and An_{35}. Myrmekitic intergrowths were seen occasionally in both rock groups.

Microcline was detected in thirty out of sixty silicic gneisses, and in twenty-two out of thirty-five psammites. According to these ratios, therefore, it occurs in 65% of Moine psammites, but only in 50% of the Lewisian silicic gneisses. It is significant that twenty of the thirty microcline-bearing silicic gneisses were collected within five metres of the junction with the Moinian, leaving only 30% of the silicic gneisses away from the junction containing microcline. The presence or absence of microcline appears to be directly dependent on the potassium content of the rock. In the silicic gneisses, rocks containing over 2.5% potassium contain microcline, whereas in those with less than 2.5% potassium it was absent. In the psammites microcline occurs in rocks with over 2.6% potassium, except in the Sgurr nan Each psammite, where a rock containing 2.98% potassium lacks microcline. The greater content of muscovite in these psammites accounts for the lack of microcline in quite potassic rocks.

Epidote commonly occurs in both silicic gneisses and psammites, as an accessory, so its presence or absence cannot easily be related to the composition of the rock. Unlike in the pelites, the epidote has a higher birefringence indicating a higher iron content; it is a pistacite-epidote rather than

clinozoisite, which is uncommon, and usually only seen rimming iron-rich epidote in zoned grains. Epidote also occurs in silicic gneisses rimming a core of orthite; usually where a garnet is being replaced.

Sphene, apatite and opaque iron ore occur in both psammites and silicic gneisses. The ore is usually haematite or magnetite in the psammites, but magnetite or pyrite in the silicic gneisses.

Heavy mineral seams, and calcareous psammites are described after the amphibolites.

6.4 Amphibolites

Three main groups of amphibolite were observed in Fannich Forest. Small bodies in the Meall an t-Sithe Pelite were found to be distinct from those in the Sgurr Mor Pelite, in texture, mineralogy and chemical composition. Both these Moinian amphibolite types differ from those seen in the Lewisian of Fannich. A fourth type of amphibolite was seen in the gorge below Eas an Uillt Ghranda. It resembles samples collected from the Ben Hope Sill in Sutherland rather than any from Fannich. It is a flaky garnet-free schist, containing both hornblende and biotite, but entirely lacking sphene and epidote. But in spite of the absence of sphene, this amphibolite contains almost 3.8% titanium, which probably occurs in the abundant

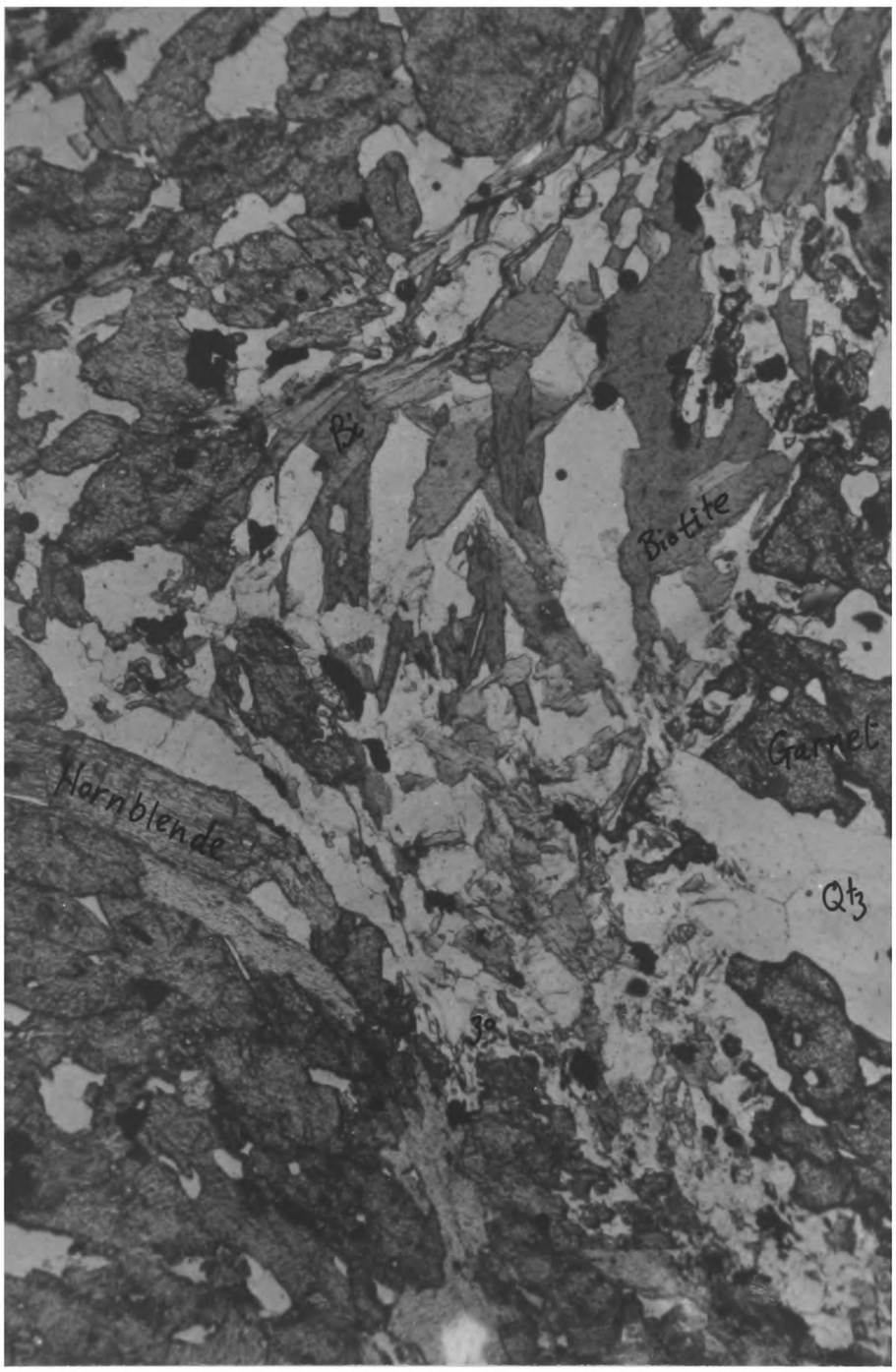


Plate 18. Sgurr Mor Amphibolite.

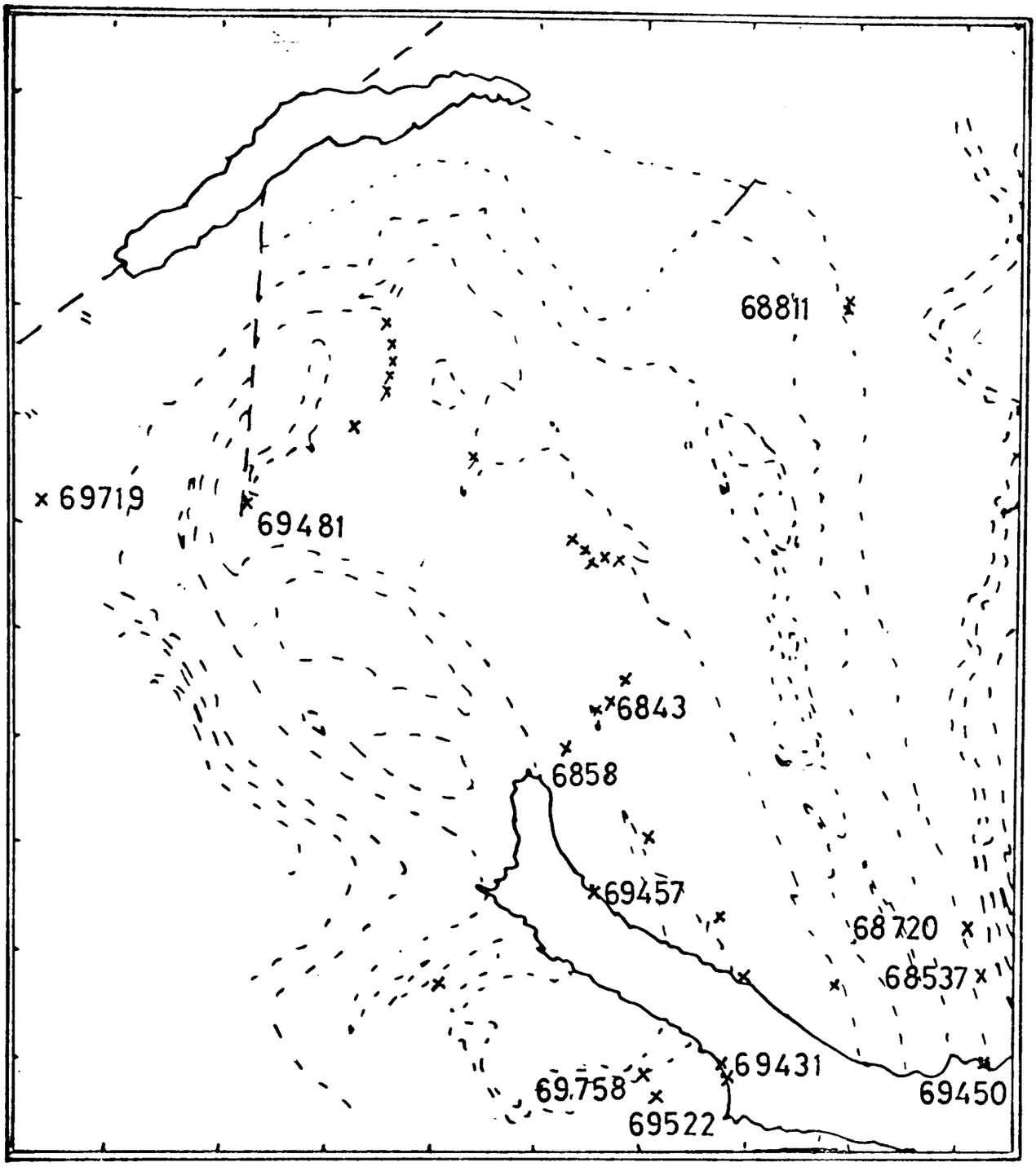
brown biotite. No other amphibolites were seen in Inverbroom psammites, and this small dyke may be the sole representative in Fannich of a Moinian amphibolite suite that is commoner elsewhere. Fig.19 shows the distribution of the Moinian amphibolites in Fannich.

The compositions of Sgurr Mor amphibolites are shown in Table 9. They contain high concentrations of potassium, titanium, zirconium, nickel and niobium compared to the other amphibolites analysed. Abundant biotite containing common inclusions of zircon probably results from the abundance of potassium, titanium, and zirconium. Both in mineralogy and texture these amphibolites are very uniform (Plate 18). All are flaky garnet-biotite-hornblende schists, often showing repeated kinking of the foliae. Large subhedral orange garnets occur as porphyroblasts, containing abundant inclusions of quartz and sphene. Around the garnets, biotite and hornblende grains have flowed in the foliation to form quartz "eyes". Little evidence was seen of garnet rotation. The hornblende in this amphibolite is characteristically pale, and only shows slight pleochroism. The biotite is strongly pleochroic from pale yellow to rich red-brown. Grains of sphene, zircon and zoisite occur with the biotite. Plagioclase is very subordinate to clear quartz in the leucocratic background. Its composition varies between An_{37} and An_{26}. Microcline and pyroxene are both absent. The

TABLE 9

Analyses of Sgurr Mor Amphibolites

	68537	68720	68811	68812	69449	69450	69451	Average
SiO_2	50.72	50.55	50.11	49.73	46.48	46.64	46.30	48.65
Al_2O_3	12.69	12.30	11.12	12.16	12.40	12.42	11.62	12.09
FeO(tot)	15.38	15.27	15.55	15.80	16.45	16.31	17.05	15.97
MgO	7.36	8.10	8.35	8.28	8.85	9.17	9.45	8.51
CaO	8.19	8.38	9.11	8.77	7.95	8.35	8.37	8.47
Na_2O	1.38	0.96	1.18	1.31	0.94	0.80	0.97	1.08
K_2O	1.11	1.15	0.93	1.01	3.49	3.16	3.03	1.98
TiO_2	2.26	2.23	2.14	2.17	3.19	2.97	3.01	2.57
MnO	0.18	0.14	0.14	0.17	0.24	0.18	0.20	0.18
S	0.09	0.30	0.01	0.01				0.10
P_2O_5	0.64	0.61	0.56	0.58				0.60
Sr ppm		114	104			124		114
Rb "		30	24			96		50
Zr "		247	225			233		235
Nb "		24	25			27		25
Ni "		153	148			161		154



A MAP OF FANNICH FOREST SHOWING THE DISTRIBUTION OF MOINE AMPHIBOLITES

Figure 10.

mineral assemblages of the amphibolites are listed in Table 10, and in it all Sgurr Mor amphibolites are shown to contain the same assemblage. This conformity suggests that they are either derived from the same suite of dykes, or alternatively they are a thin metamorphosed layer of basaltic tuffs.

Although chemically similar to the Sgurr Mor Amphibolite in containing a high titanium and zirconium content, the Meall an t-Sithe amphibolites differ in having a lower potassium content, and a nickel content averaging only 35% of that seen in the Sgurr Mor Amphibolite (see Table 11). They also differ in texture. Whereas the Sgurr Mor amphibolites are flaky and schistose, the Meall an t-Sithe amphibolites are uniformly compact granular rocks containing scattered garnet porphyroblasts. The garnets are red or orange, usually anhedral and crowded with inclusions of quartz, sphene, hornblende, biotite, apatite and magnetite. As with the Sgurr Mor amphibolites, all the amphibolites from the Meall an t-Sithe group contain the same mineral assemblage. They contain the same minerals as the Sgurr Mor amphibolites, but biotite is less abundant, and epidote is commoner. The hornblendes are a darker green, although still pale. Quartz is the dominant leucocratic mineral. It occurs as small grains between much larger hornblende crystals. Plagioclase is much less common, and, when present shows twinning on both albite and pericline laws. It is

TABLE 10

Mineral Assemblages in Amphibolites

	No in		
	Lew	Mts	Smp
(Hornblende, Quartz, always present)			
1. Garnet-Plagioclase-Biotite	9	-	-
2. Garnet-Plagioclase-Biotite-Sphene	7	-	-
3. Garnet-Plagioclase-Biotite-Sphene-Epidote	1	9	7
4. Garnet-Plagioclase-Sphene-Epidote	4	-	-
5. Pyroxene-(Plagioclase)-Sphene-Epidote	4	-	-
6. Plagioclase-(Biotite)-Sphene-Epidote	24	-	-
7. Plagioclase-(Biotite)-Sphene	9	-	-

Abbreviations Lew = Lewisian

Mts = Meall an t-Sithe Pelite

Smp = Sgurr Mor Pelite

TABLE 11

Analyses of Meall an t'Sithe Amphibolites.

	6843	6858	69431	69432	69451	69458	69481	69522	69758	Average
SiO_2	47.69	48.07	49.92	47.68	46.97	47.48	46.61	45.90	47.93	47.58
Al_2O_3	12.12	10.04	13.11	13.22	11.16	11.25	13.04	13.01	16.39	12.59
Fe (tot)	16.61	18.57	14.34	15.05	19.17	18.31	16.67	18.08	11.25	16.45
MgO	7.84	7.93	8.40	8.74	7.90	7.17	7.44	7.74	7.69	7.87
CaO	10.06	11.08	9.74	10.21	9.54	10.07	9.66	10.50	10.07	10.10
Na_2O	0.88	0.52	1.32	1.45	1.00	1.20	1.42	1.31	2.49	1.28
K_2O	1.17	0.48	0.79	0.75	0.50	1.23	1.48	0.57	1.96	0.99
TiO_2	2.53	2.32	2.13	2.63	3.51	3.03	3.41	2.56	2.03	2.68
MnO	0.24	0.23	0.24	0.26	0.27	0.26	0.28	0.34	0.20	0.26
S	0.39	0.34								0.37
P_2O_5	0.48	0.41								0.45
Sr p.p.m.			104	115	66				223	127
Rb			15	9	11				83	29
Zr			204	186	227				234	213
Nb			n.d	n.d	n.d				n.d	n.d
Ni			64	63	58				48	58

distinctly more calcic than plagioclase from the Sgurr Mor Amphibolite, varying in composition between An_{35} and An_{55}. As with the Sgurr Mor Amphibolite microcline and pyroxene are both absent.

Although a wider range of mineral assemblages occurs in the Ben Hope Sill, the restricted range (Table 10) is characteristic of the Fannich Moine amphibolites.

In contrast, the amphibolites from the Lewisian Inlier are extremely varied, and seven mineral assemblages are listed in Table 10. Out of fifty-eight Lewisian amphibolites only twenty, or one-third, contain garnet. By contrast, excepting only the dyke below the Eas an Uillt Ghranda, all Moinian amphibolites in Fannich contain garnet. Twenty-six Lewisian amphibolites do not contain biotite, whereas all Moinian ones do. Opaque minerals can be either pyrite or magnetite in the Lewisian amphibolites, but pyrite is absent from Moinian examples, perhaps reflecting the more oxidised Moinian assemblages. The amphibolites used to compile these figures come both from the part of the Fannich Inlier mapped by Peach and Gunn, from its extension south of Loch Fannich, and from the Lewisian Inlier mapped in the Allt Coire nan Laoigh near Achnasheen.

The chemical composition of Lewisian Amphibolites also differs from those of the Moinian. Twenty-five Lewisian amphibolites were analysed for nine major elements (Table 12);

TABLE 12 (a)

Analyses of Lewisian Amphibolites

	6852	68521	68524	68556	68570	6864	6865	68616	68634	6945	69420	69425	6955	6956	6957	69531
SiO_2	49.36	55.42	46.21	48.49	48.97	48.79	47.72	44.01	46.57	46.79	49.78	49.22	47.78	48.21	49.13	50.02
Al_2O_3	11.36	12.44	12.23	12.35	5.13	12.81	11.04	13.48	13.11	12.73	12.43	7.57	12.81	12.67	11.17	5.70
FeO(tot)	17.49	11.24	17.96	15.17	13.67	11.96	16.62	15.43	16.77	16.75	15.57	12.90	15.33	15.12	15.74	11.30
MgO	5.85	6.76	7.75	7.42	14.84	9.88	8.47	9.50	8.20	8.23	7.80	13.53	8.16	9.20	8.40	17.02
CaO	9.37	9.11	9.75	9.70	14.21	10.44	12.30	8.70	9.86	9.93	9.49	12.77	10.52	9.79	10.64	13.22
Na_2O	3.80	3.27	2.98	3.74	1.48	3.13	1.83	4.05	2.90	3.06	2.49	1.83	2.78	2.31	2.47	1.23
K_2O	0.78	0.72	1.10	1.85	0.48	1.36	0.70	2.32	1.24	1.07	0.69	1.03	1.32	1.36	1.20	0.63
TiO_2	1.64	0.76	1.74	1.02	0.93	1.30	0.94	2.33	1.10	1.21	1.46	0.89	1.04	1.15	0.99	0.66
MnO	0.18	0.16	0.27	0.24	0.17	0.33	0.22	0.18	0.25	0.23	0.30	0.24	0.26	0.19	0.26	0.23
S	0.01	0.03			0.02											
P_2O_5	0.16	0.10			0.10											

TABLE 12 (b)

Analyses of Lewisian Amphibolites

	68534	68633	69436	69437	6959	69518	69520	69523	69737	Average
SiO_2	51.05	44.58	49.17	48.34	54.37	55.09	49.91	49 26	53.07	49.25
Al_2O_3	13.98	13.66	13.15	12.87	10.54	11.79	11.23	15.03	13.14	11.78
FeO(tot)	12.06	16.26	13.42	13.99	19.14	13.25	15.83	11.88	10.92	14.64
MgO	7.45	8.63	7.60	7.92	4.76	5.83	7.71	8.60	8.61	8.69
CaO	8.94	9.35	8.80	9.48	7.45	8.62	9.95	9.33	9.63	10.05
Na_2O	3.24	3.18	4.20	4.07	1.29	2.64	2.50	2.22	2.73	2.78
K_2O	1.93	1.88	1.55	1.26	0.51	1.26	1.11	2.29	0.35	1.20
TiO_2	0.80	2.25	1.72	1.67	1.60	1.27	1.47	1.13	1.39	1.30
MnO	0.23	0.23	0.39	0.41	0.33	0.23	0.29	0.26	0.17	0.25
S	0.02									
P_2O_5	0.21									
Sr p.p.m.	300	136	276	321	78	158	151	299	258	220
Rb "	74	27	30	26	6	26	18	108	8	37
Zr "	48	215	246	215	106	119	91	82	91	135
Nb "	n.d.	21	6	21	45	5	1.5	n.d.	1.5	7
Ni "	110	131	58	62	58	60	85	85	152	89

of these nine were also analysed for strontium, rubidium, zirconium, niobium and nickel. These are listed in Table 12. Average analyses of the different amphibolite types are listed in Table 13, and show the chemical differences clearly. Compared with the Moine amphibolites of Fannich, the Lewisian is sodic, but not as sodic as the amphibolites analysed from the Ben Hope Sill, intruding Moinian psammites. Likewise, the strontium values for the Lewisian amphibolites of Fannich are double those of the Moinian examples, yet they are not as high as those from the Ben Hope Sill. It is the titanium and zirconium values that are distinctive. Both are low in Lewisian amphibolites; this appears to be a unique feature of the Lewisian in general, and will be discussed more fully in Chapter 12.

Lewisian amphibolites exhibit great variety of texture. Although samples with a definite foliation were collected, there was nothing as flaky as the Sgurr Mor Amphibolites. Generally the foliation-planes are indicated by a preferred orientation of the hornblende crystals, but a granular texture is imparted by quartz grains binding the hornblendes together. Certain amphibolites contain abundant quartz and plagioclase, and with the interbanding of leucocratic and hornblende-bearing bands, grade into silicic gneisses.

Garnet occurs either as small porphyroblasts not greatly disrupting the foliation planes, or as large anhedral porphyroblasts up to 38 millimetres in diameter, distorting the foliation

Pods of highly garnetiferous amphibolite occur in which garnet can form up to 60% of the rock. Where garnet is absent, grains of green hornblende form a loosely interlocking pattern, with quartz and plagioclase filling the interstitial spaces. But specimens from the Allt na Goibhre also show a distinctive texture where relict garnet has been replaced by hornblende and quartz. Small skeletal fragments of garnet remain, together with small discrete euhedral hornblende grains, poikilitically enclosed in the quartz (Plate 19). In another sample the garnet was only seen in one place, elsewhere the mineral textures suggest that it has been entirely replaced by discrete hornblende, often with sphene and magnetite, poikilitically enclosed by quartz and albite-twinned plagioclase. Apatite is also present and the whole area showing this distinctive texture is surrounded by pegmatitic brown biotite. (Plate 20).

Bands of silicic gneiss occur striped with the amphibolites in the field; these bands may be 10 millimetres thick, or sparsely scattered veins one millimetre thick, but no true equivalent was seen of the striped Durcha amphibolite characteristic of the Loch Shin inlier. (Winchester & Lambert, 1970; Francis, 1958; Read, 1934). Larger infolds of silicic gneiss were also observed in the field, and amphibolites also occur as pods in silicic gneiss. Fibrous green actinolitic amphibole occurs on Creag an Tairbh and An Sguman; the long blades appear to have

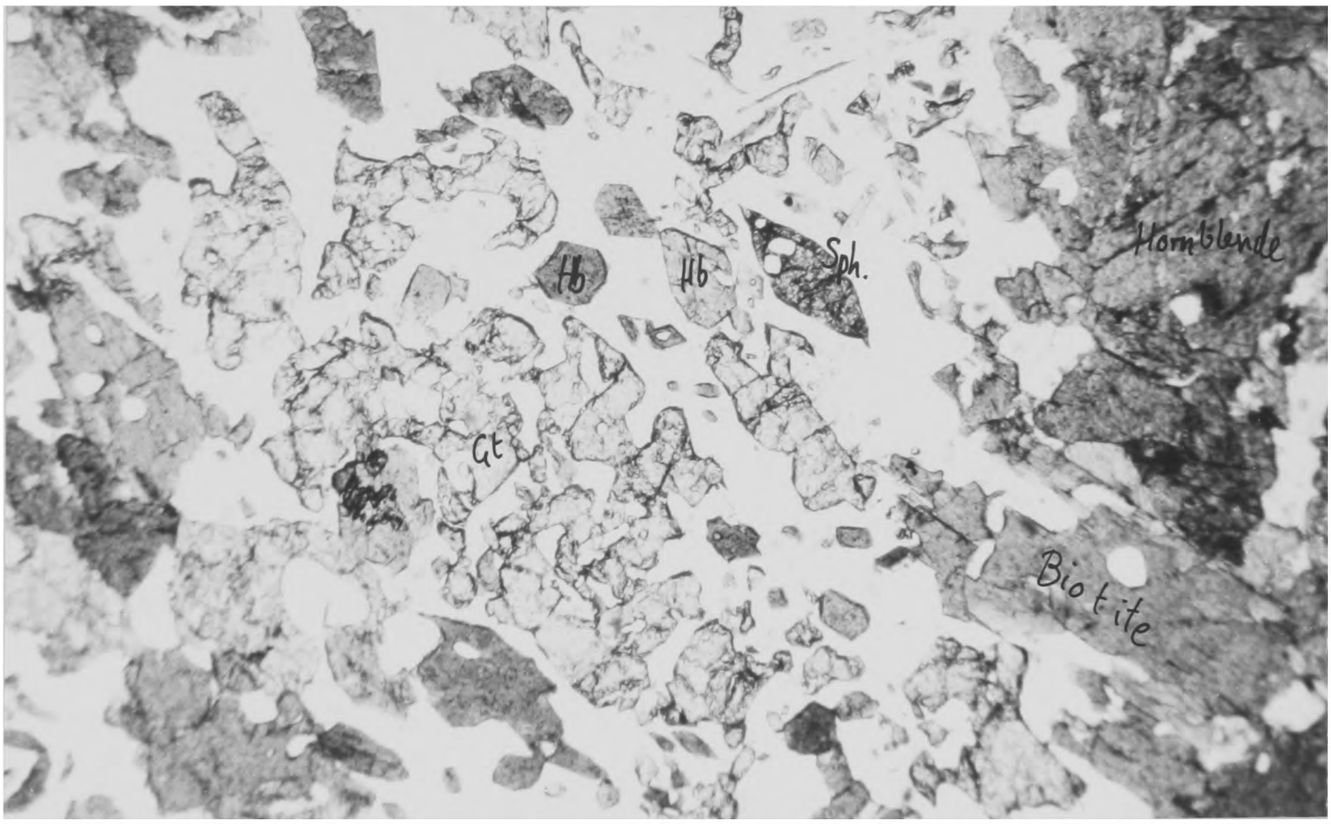


Plate 19. Growth of discrete hornblende crystals in zone surrounding relict garnet. Lewisian amphibolite, Allt na Goibhre.

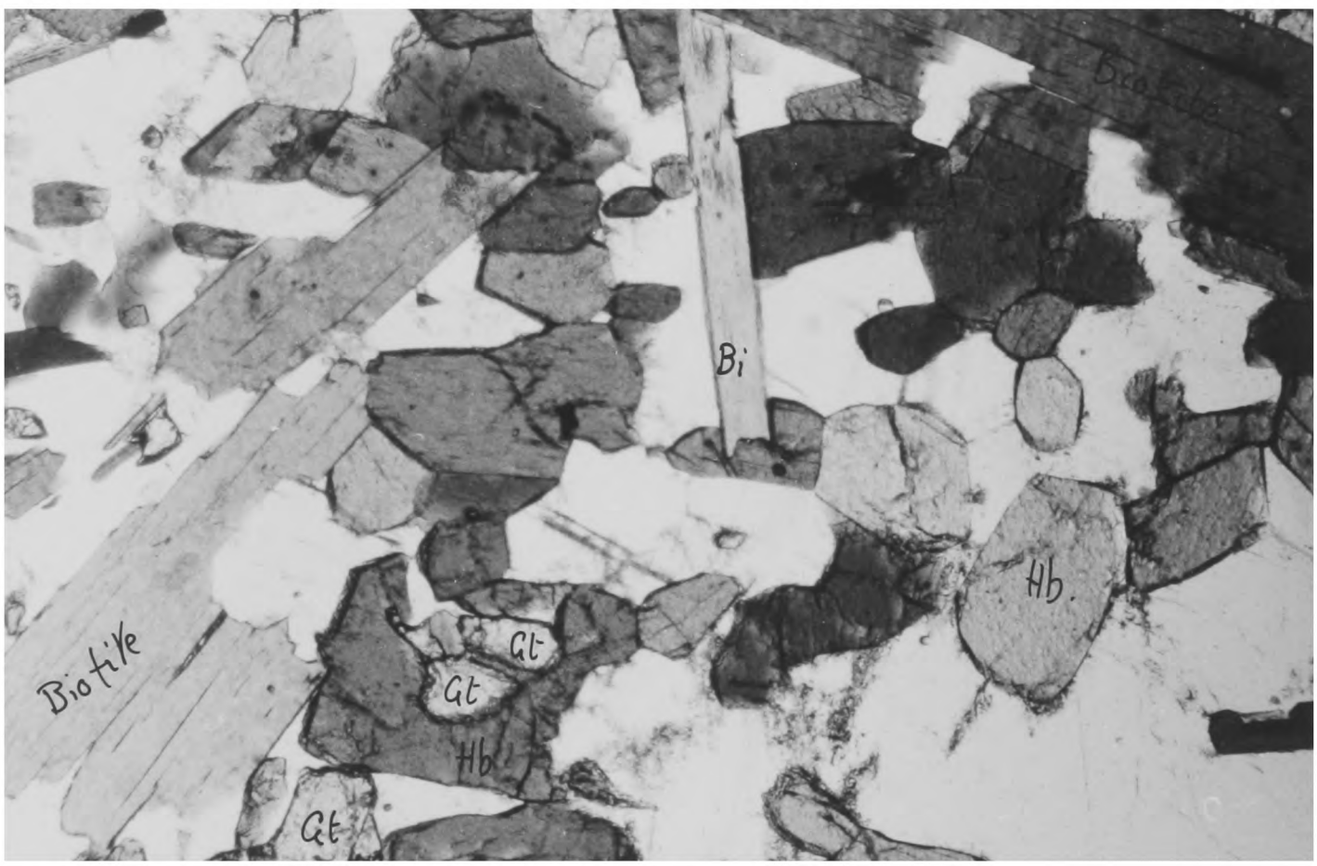


Plate 20. Discrete hornblende crystals, some surrounding garnet cores. Fresh biotite laths may be replacing the hornblende.

grown along shear planes.

Clinopyroxene was only seen in four specimens collected, three of them garnet-free. One sample from Creag an Fhuarain on Sgurr nan Clach Geala contains over 30% pyroxene. The large optic axial angles and large extinction angle indicate that it is a diopsidic augite. Although it appears to coexist in equilibrium with green hornblende in one sample, in others hornblende blades cut across the pyroxene as if replacing it. Pyroxene occurs in one other sample, where it is preserved within garnet, the only occasion it occurs with garnet. Both garnet and pyroxene appear to have been involved in the amphibolising reaction, which proceeded until one of the components was entirely replaced. Muecke (1969) proposes the following reaction for the breakdown of garnet and pyroxene from the pyroxene granulites of the Scourian. Here it has been modified to account for the almandine garnet and diopsidic pyroxene seen in Fannich: (Plate 21)

$$CaFe_4MgAl_4Si_6O_{24} + 2NaAlSi_3O_8 + 3CaMgSi_2O_6 + 2H_2O \longrightarrow$$

calcic almandine albite diopside ------ 6

$$\longrightarrow 2NaCa_2(MgFe)_4Si_6Al_3O_{22}(OH)_2 + 6SiO_2$$

Pargasitic hornblende Quartz.

Usually the reaction has proceeded until either pyroxene or garnet is entirely replaced, but in this sample, the garnet has

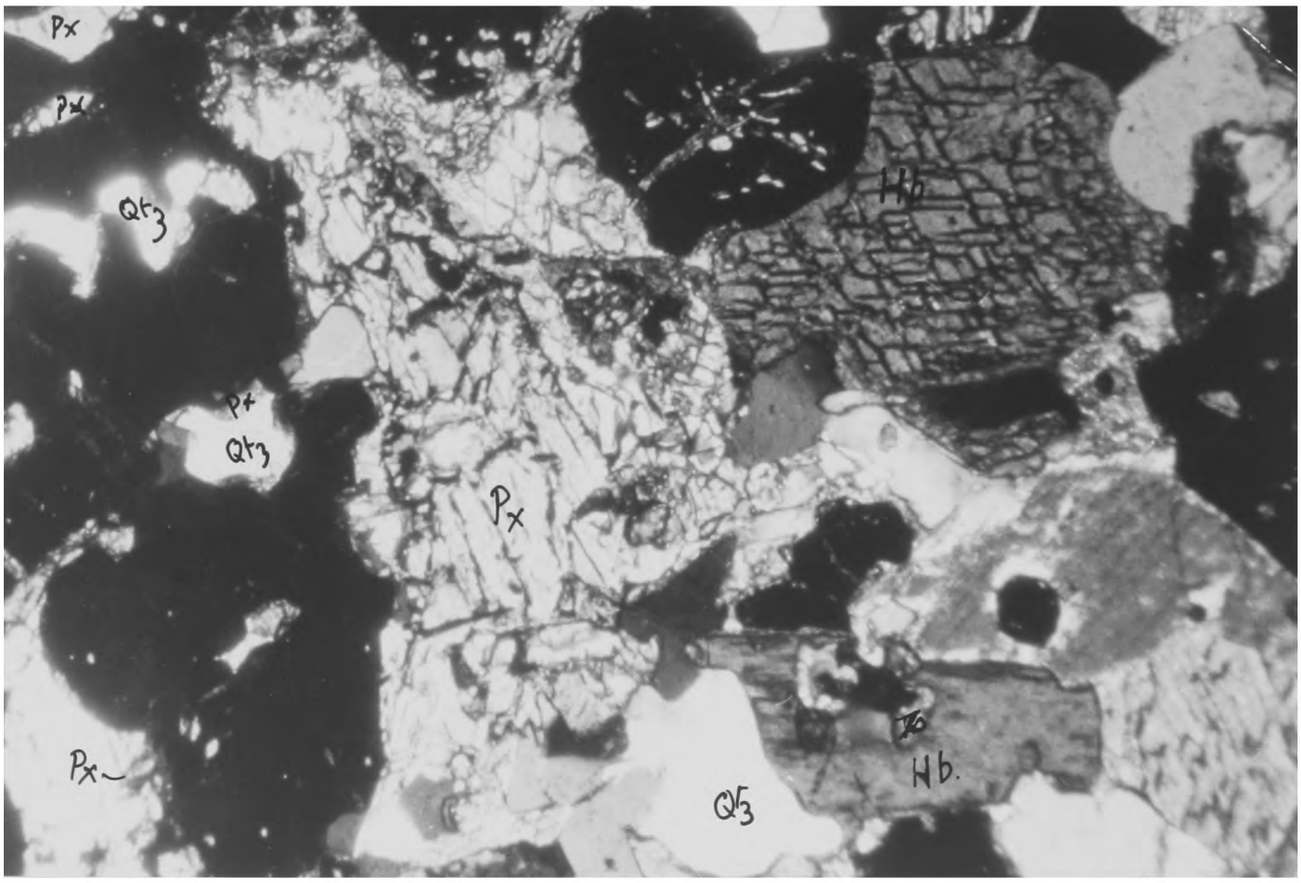


Plate 21. Pyroxene, partially enclosed by garnet (black), being replaced by hornblende.

preserved the pyroxene. Often discrete pyroxene inclusions are optically continuous, and this was interpreted as a sign that the garnet grew around the pyroxene during an earlier metamorphic environment, thus protecting the enclosed grains from amphibolization. Outside the garnet hornblende is the dominant ferromagnesian mineral. Orthopyroxene inclusions are absent, but sphene inclusions are present, implying that the original rock had not been subjected to granulite-grade metamorphism, as sphene disappears at the amphibolite-granulite transition (Turner 1968, Buddington 1963). Not all Lewisian rocks exhibit granulite-facies parageneses so the presence of the original sphene does not disprove the Lewisian origin of this rock. If sphene, clinopyroxene and quartz were preserved, the garnet must have formed at the expense of other minerals. Plagioclase and black magnetite are notably absent as inclusions, and the reaction suggested by Muecke (1969) for the formation of garnet from magnetite plagioclase and quartz seems to fit:

$$4Fe_3O_4 + 6CaAl_2Si_2O_8 + 6SiO_2 \longrightarrow 3(Ca_2Fe_4)Al_4Si_6O_{24} + 2O_2 \qquad (7)$$

Magnetite — Anorthite — Quartz — Calcic-Almandine

Formation of garnet by a reducing reaction, followed by amphibolization by a hydration-reaction, suggests that these Lewisian amphibolites have been subjected to several metamorphic processes.

Elsewhere garnet contains inclusions of magnetite, apatite, plagioclase and hornblende, as well as quartz. These rarely form grains that are optically continuous, even if minerals outside the garnet are coarse-grained. Both the mineralogy and small grain-size of the inclusions in these other garnets support the idea that the pyroxene inclusions are relics of an earlier mineral assemblage. Garnets seen in the Lewisian amphibolites are characteristically anhedral and show no sign of rotation. Chloritization of garnet is rare, but replacement, as described above, was seen more often.

Hornblende is a darker green than in Moinian amphibolites, and is strongly pleochroic. Pyrite, sphene or plagioclase can all occur as inclusions within the grains. Paler actinolitic amphibole occurs on An Sguman and Craig an Tairbh where the whole-rock composition is more magnesian. Quartz is always present, but plagioclase is often rare, and occasionally absent. Usually both minerals occur interstitially as large grains between hornblendes, but occasionally they surround the ferromagnesian minerals poikilitically. Plagioclase compositions, measured by the symmetrical extinction method in albite twins vary between An_{20} and An_{36}. Reversed zoning is common. Hornblende has apparently crystallized after the plagioclase, as blades of green hornblende cut across plagioclase grains at random angles to the twin planes.

Both iron-rich and iron-poor epidotes occur, but whereas the iron-poor epidote is frequently concentrated in bands, the iron-rich epidote occurs intimately associated with the hornblende. Sphene occurs in all rocks containing epidote, but the few amphibolites seen that lacked sphene, were also free of epidote.

Biotite occurs in thirty samples out of fifty-eight. It occurs as large red-brown laths, often associated with pyrite or zoisite. Since most Lewisian amphibolites are titanium-depleted, its colour may be attributed to its content of ferrous rather than ferric iron. Biotite laths are cut by hornblende grains, but cut the hornblende themselves more frequently; therefore biotite may be among the latest minerals to form.

Zircon and orthite both occur associated with biotite, and both show pleochroic haloes. Opaque minerals include magnetite, ilmenite, and pyrite. Microcline and calcite also occur in some pegmatite-impregnated actinolite-amphibolites collected from Craig an Tairbh. Haematite is very rare.

To summarize the overall mineralogical differences between the Lewisian and Moinian amphibolites, the following points can be made:

1. No pyroxene occurs in Moinian amphibolites
2. No pyrite occurs in Moinian amphibolites
3. All Moinian amphibolites, but one, contain garnet

4. All Moinian amphibolites contain biotite.

None of these distinctions can alone separate the Moinian from Lewisian amphibolites; therefore the petrology alone is not a reliable guide to establish the derivation of these amphibolites. It is their chemical composition that distinguishes them.

6.5 Calcareous Rocks.

The calc-silicate strips so characteristic of the Sgurr Mor Pelite are described in greater detail in Chapter 7. Calcareous psammites were seen in all the major psammitic units in Fannich. In the Inverbroom Group, calcareous psammites were seen close to the gradation into Sgurr Mor Pelites in the crags south-east of Coire Barr an Fhiodha. They occur as lenses or spherical bodies in semipsammite, and contain zoisite and aggregates of biotite. Texturally, they are quite different from the surrounding rock. When, in a laminated semipsammite, the laminae enter a calcareous body, the laminae fade on entering the outer, biotite-flecked zone, and become ultimately indistinguishable in an inner leucocratic zoisite rich zone. But in the core, a zone of coarse-grained biotite, aligned with the biotite-rich laminae outside, suggests that these laminae once continued through the calcareous body before metamorphism.



Plate 22. Calc-silicate concretion in Inverbroom Psammite.

(Plate 22). Such bodies seem explained best as metamorphosed calcareous concretions, or thin bands of metamorphosed calcareous sandstone. Calcareous bodies seen in the Carn na Criche psammite appear to be identical with those in the Inverbroom Group.

Calcareous rocks also occur in the Sgurr nan Each Psammite and the Meall a' Chrasgaidh Psammite, and are described in turn. The single calcareous rock collected from the Sgurr nan Each psammite is unique. Its analysis (see Table 7) shows it to be calcium-rich, but magnesium poor, and it contains abundant clinozoisite, all characteristics shared by the Sgurr Mor calc-silicates. Garnet is present, and also rare colourless tremolite. Biotite is the most abundant ferromagnesian mineral, but magnetite is notably more abundant than in the surrounding psammite. Plagioclase, showing albite twinning, has a composition of about An_{40}.

Calcareous rocks from the Meall a' Chrasgaidh Psammite are quite different. Tremolite occurs in all of them; diopside also occurs in one sample from the Allt a' Choire Mhoir. In it, colourless diopside and colourless tremolite are set in a groundmass of interlocking grains of quartz and microcline. Plagioclase is rare. The diopside occurs as blocky, usually ahedral grains containing large quartz inclusions, whereas tremolite blades often cut across the groundmass. Although it is rarely seen in contact with diopside, it is clearly replacing the

diopside in a similar reaction to that observed at Loch Shin (Winchester & Lambert, 1970). The pitted appearance of the rock hand-specimen hints that calcite may once have been present.

No diopside was detected in other calcareous rocks from the Meall a' Chrasgaidh psammite, but in epidote-rich rocks from Am Burach, colourless tremolite blades are seen being replaced by iron-rich epidote. In one band calcite and dolomite occur interstitially between the grains of quartz, epidote and tremolite. Sphene is present, and the dominance of iron-rich epidote suggests that these rocks are lithologically similar to calc-silicates of Arnipol type from South Morar (MacGregor 1948).

Calc-silicate rocks from the Fannich Lewisian Inlier are rare but two main types are distinguishable: epidosites and tremolite-diopside rocks. The field-relations of these rocks have already been described in Chapter 4. Of eight samples three contain diopside. The relationship between diopside and tremolite or epidote is usually hard to assess, but in one slice a skeletal crystal of diopside, largely replaced by quartz, also has blades of colourless tremolite both cutting the original diopside, and growing from it into the quartz. Biotite, although common elsewhere in the rock, is scarce where this reaction is proceeding.

TABLE 13

Analysis of Lewisian Calc-Silicates

	68535	68536	68541
SiO_2	81.69	56.23	76.04
Al_2O_3	7.70	12.88	10.55
FeO(tot)	1.28	7.16	1.44
MgO	1.44	4.38	4.16
CaO	3.74	9.56	1.64
Na_2O	3.61	5.60	2.33
K_2O	0.21	0.67	3.48
TiO_2	tr	0.12	0.19
MnO	0.04	0.11	0.04
S	0.21	3.09	0.06
P_2O_5	0.92	0.19	0.06

In the epidosites, perhaps segregations of more aluminous calcic rock, green pleochroic hornblende is the only amphibole present. Unlike in diopside-bearing calc-silicates, epidote, set in a background of equigranular interlocking quartz grains, shows no sign of instability. Similar epidote-bearing rocks have been recorded from the Airde of Shin, while the similarity of the tremolite-diopside rocks to the calc-silicates associated with Lewisian marbles, at Glen Tulucha (Peach et al. 1913), Glenelg (Peach et al. 1910) and Loch Shin (Crampton 1956, Winchester and Lambert, 1970) is notable. Analyses of the three diopside bearing rocks are shown in Table 13, and are comparable to those from Shin if the silica content is considered. That such rocks occur in Fannich is not surprising, but their scarcity is notable.

6.6 Heavy Mineral Seams

A comprehensive description of heavy mineral seams in Moinian psammites has been given by Butler (1962). They have also been described from North-East Morar (Poole 1962) and recorded from Carn Breac, north-east of Achnashellach (Peach et al. 1913b). In North-East Morar, Poole says they are confined to the Number 2 Psammite, but in Ardnamurchan (Butler), heavy mineral seams are commoner in the Upper Psammitic Group. Their

stratigraphic value may, therefore, be limited.

No heavy mineral seams were seen in Fannich itself, but one seam was found in Coire Ghranda on Beinn Dearg, within psammites of the Inverbroom Group. In mineralogy, it closely resembles the seams described by Butler; its mineral content is:

Quartz 5.4%, Plagioclase 9.1%, K-Feldspar 1.0%, Biotite 45.5%, Magnetite-Ilmenite 4.0%, Sphene 12.6%, Epidote 17.2%, Zircon 3.5%, Apatite 1.1%, Calcite 0.7%.

The abundance of dark green biotite, sphene, and epidote is obvious. The sphene occurs as aggregates of grains or single semihedral grains. The biotite, strongly pleochroic from pale yellow to an almost opaque green-black, occurs in laths aligned according to a foliation inclined at about 30° to the compositional banding. Ilmenitic magnetite occurs with the biotite, while quartz, zoned plagioclase and epidote are also common. Calcite, partially replaced by epidote, sphene and biotite also occurs; and the following reaction is proposed to illustrate its replacement:

$$K_2Fe_4Al_4Si_4O_{20}(OH)_4 + 3CaCO_3 + FeTiO_3 + 6SiO_2 + (OH) \longrightarrow$$

Aluminous-biotite · calcite · ilm · quartz · hydrated

$$\longrightarrow Ca_2FeAl_2Si_3O_{12}(OH) + CaTiSiO_5 + K_2Fe_6Al_2Si_6O_{20}(OH)_4 + 3CO_2 + \tfrac{1}{2}O_2$$

epidote · sphene · iron-rich biotite

This reaction involves hydration and the release of carbon dioxide, like most of the other reactions which explain the mineral relationships seen in the Moinian.

Since these heavy mineral seams are so rare, they cannot be used with certainty as stratigraphic markers, and therefore they can only be considered as interesting lithological variants.

7

CALC-SILICATES.

7.1 Distribution

The calc-silicate bands in the Sgurr Mor Pelite were studied in detail, because, by analogy with the distinct zonal assemblages at Morar (Kennedy 1949, Poole, D.Phil.Thesis Oxford 1962 unpubl.), they offered the means for establishing the metamorphic grade of the area.

Calcareous rocks of this type have been noted at numerous localities in the Moine Series, and nearly all the pelites forming the host rock to well-developed calc-silicate bands in other parts of the Moine Series resemble the Sgurr Mor Pelite in lithology.

At Ballindalloch, on Lower Speyside, Flett reported a "zoisite-granulite" band containing biotite aggregates in micaceous schists (Mem.Geol.Survey, Sheet 85, 1902), while Grant Wilson and Teall recorded hornblende-bearing calc-silicates (Summ.Prog. 1899) from a section in the Moine Schists of the River Spean below Spean Bridge. In northern Scotland, Flett noted zoisite-hornblende calc-silicates at Glen Calvie, and from various localities north of Ben Wyvis (Mem.Geol.Survey Sheet 93, 1912), and Read recorded hornblende-zoisite calc-silicate strips from Corriemulzie (Mem.Geol.Survey, Sheet 102,



RECORDED OCCURRENCES OF CALC-SILICATES IN MOINE PELITE

1926), Ben Klibreck and Strath Naver (Mem.Geol.Survey, Sheets 108-9, 1931). On Ben Klibreck, certain of these bands contain a pyroxene-anorthite assemblage, but their field-relations show that they belong to the same group of rocks. In South-West Mull (Mem.Geol.Survey, Shee 43, 1925) Bosworth observed calcite-hornblende-bearing bands, and noted their similarity to zoisite-bearing bands seen elsewhere. Calc-silicate bands also occur in Morar and Knoydart, and more recently have been recorded from Kinloch Hourn (Tanner 1969) (Fig.20).

In Fannich Forest itself, (Mem.Geol.Survey Sheet 92, 1913, Summs.Prog. 1897, 1898, 1899) Gunn, mapping north of the main watershed, found calc-silicate bands in the River Cuileig, the Allt an Eas Bhig, and the Allt a Bhraighe, while Peach noted similar bands on Sgurr Mor, near Loch Fannich, and to the west of Beinn nan Ramh. In the eastern part of the range Peach also records calc-silicate bands from Meall Gorm, Creag a' Chaise, and in the Allt a' Choin[illegible] Idhir. In addition to these localities, work for this thesis also revealed calc-silicate bands in the Allt na h'Ighine, on Meall a'Chrasgaidh, Carn na Criche and Creag Raineach Mor, and in the Allt a' Chleibh, north of the watershed, while south of the watershed calc-silicates were seen in the Allt a' Choire Mhoir and on Meallan Chuaich. Further east calc-silicate bands were also found on An Coileachan, north of Loch Chuilinn in Strath Bran, and near Lochluichart

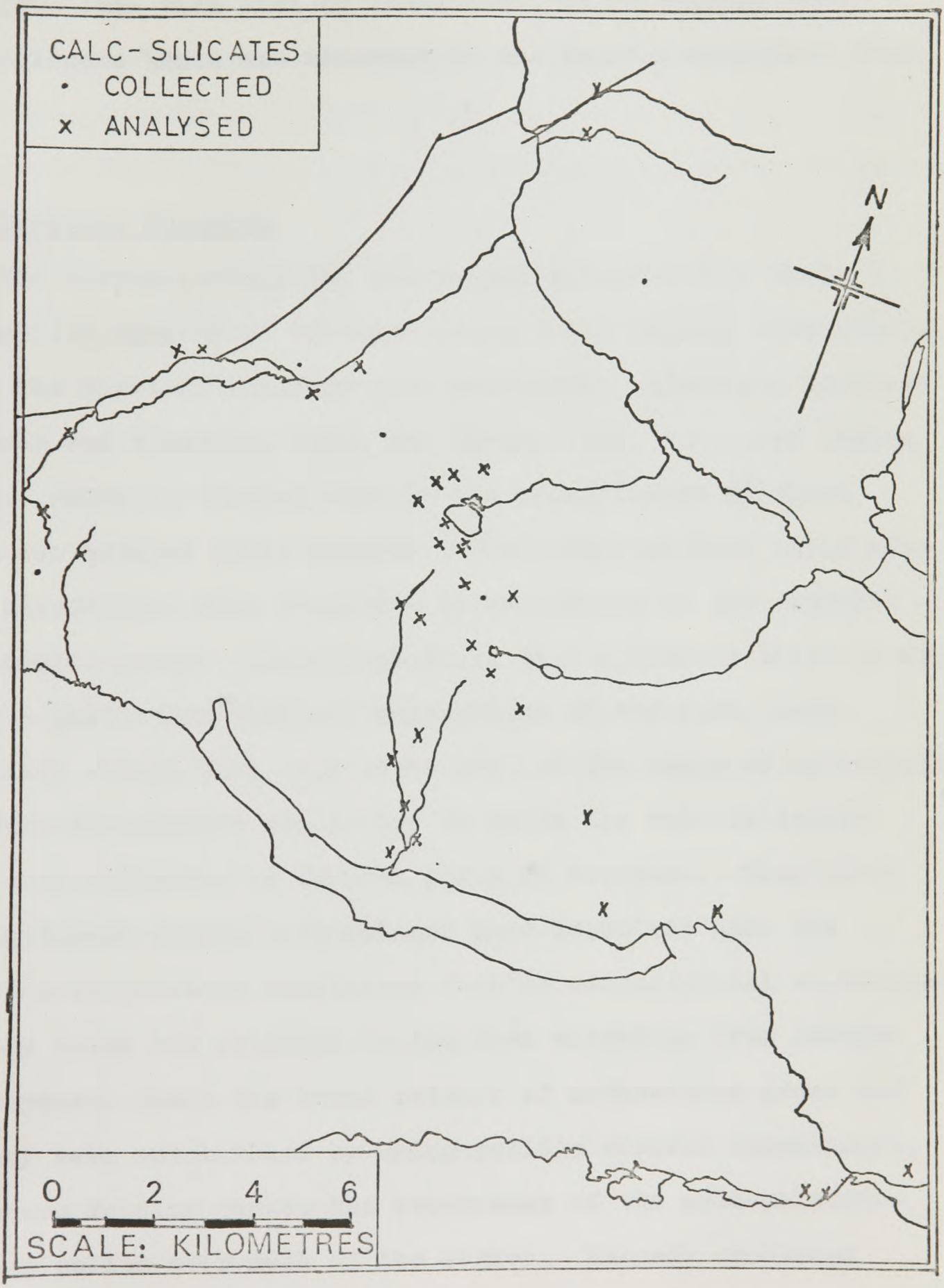


Figure 21. Several calc-silicates were collected from each collecting site.

village. From this list of localities, it is evident that calc-silicate bands are abundant in the Fannich district. (Fig. 21).

7.2 Previous Research

The Survey geologists, who mapped calc-silicate bands in the pelitic Moinian of Scotland noted their unusual mineralogy, and a few chemical analyses were published. (Chemical Analyses of Rocks and Minerals, Guppy and Thomas 1931, Guppy and Sabine 1954). However, further work on the significance of these bands was delayed until Kennedy (1949) observed that their mineral assemblages were sensitive to variations in the regional metamorphic grade. Certain minerals that appear in these bands, given a particular chemical composition of the rock, have stability fields that only cover part of the range of metamorphic pressure-temperature conditions to which the calc-silicates have been subjected in various parts of Scotland. Thus there are different mineral assemblages more dependent upon the pressure-temperature conditions than on compositional variations. Kennedy based his evidence on the area extending from Morvern to Knoydart, where the broad pattern of metamorphic grade had already been established by using pelitic mineral assemblages, and where folding causes the recurrence of the calc-silicate-bearing pelite over much of the region. Kennedy concluded

that chemical reactions in the calc-silicates were isograds, which could be plotted on the map, and correlated with the Barrovian isograds. He divided the area into four zones identified by index minerals, listed as follows in order of ascending grade:

1. Zoisite - (Calcite)-Biotite Zone
2. Zoisite Zone
3. Anorthite-Hornblende Zone
4. Anorthite-Pyroxene Zone.

Barth's (1936) study of the metamorphism of calcareous rocks in Dutchess county, New York, and Goldschmidt's (1921) work on similar rocks in the Trondheim district, lent weight to Kennedy's hypothesis and enabled him to correlate his lower two zones with the Barrovian Garnet Zone, his anorthite-hornblende zone with the Kyanite Zone, and his anorthite-pyroxene zone with the Sillimanite Zone.

In his first zone Kennedy recognized three diagnostic mineral assemblages, which he tabulated as:

1a Calcite-Zoisite

1b Calcite-Zoisite-Hornblende

1c Zoisite.

Garnet, sodic plagioclase, quartz and biotite were always present in these lower grades. However, later studies, notably those of Lambert (1955), Butler (1960), Spring (1960), and

Poole (1962), record considerable variation in the mineral assemblages of these zones. For example Poole found that zoisite was present in Zone 3 in North-East Morar, while Butler noted that biotite and hornblende coexisted in Ardnamurchan, and postulated that the biotite was preserved when the reaction:

$$\text{Biotite} + \text{Calcite(Zoisite)} \longrightarrow \text{Hornblende}$$

achieved completion in an environment of excess potash. Furthermore, in Knoydart Spring found that microcline occurs in Zone 3, where it is presumed to have formed to accommodate this excess potash.

Poole's adjustments to Kennedy's correlations with pelite grading affect only the upper zones. He extends the Zoisite Zone so that it is also equivalent to the Staurolite and lower Kyanite Zone, and also shifts Kennedy's anorthite-hornblende zone so that it is partly equivalent to the Sillimanite Zone. Kennedy's anorthite-pyroxene zone therefore becomes indicative of a metamorphic grade within the Sillimanite Zone.

In Fannich Forest, where the metamorphic grade is imperfectly known, abundant calc-silicate bands provide an opportunity for studying variations of grade, and making regional correlations. Consequently, during the field seasons of 1968 and 1969, 140 calc-silicate specimens were collected for examination, and a fuller description of their textures,

mineral assemblages, and the chemical reactions which have apparently taken place, follows.

7.3 Calcite in Calc-Silicates

The full range of mineral facies described by Kennedy was not recorded from Fannich. Neither anorthite-bearing, nor pyroxene-bearing calc-silicates have been found in the Sgurr Mor Pelite, and therefore all the mineral assemblages belong to Kennedy's first and second zones.

The Fannich calc-silicates contain almandine, biotite or hornblende, plagioclase, zoisite and quartz. Calcite, however, is a rare constituent, and was only seen in calc-silicates from near Loch Chuilinn (Plate 23), in the Allt a' Bhraighe, and in the lower part of the Allt a' Choire Mhoir. Although it is of restricted regional occurrence, the mineral assemblages with which the calcite is found cover the whole range of those seen in Fannich, and therefore, the presence of calcite is apparently governed by the partial pressure of CO_2, rather than the overall metamorphic grade. Calcite is entirely absent from large areas where calc-silicates of varying assemblages are abundant. With respect to Fannich, therefore, Kennedy's Zone 1a is equivalent to Zone 1c.

Textures in calc-silicates reveal the directions in which the visible reactions are proceeding. In some garnets calcite

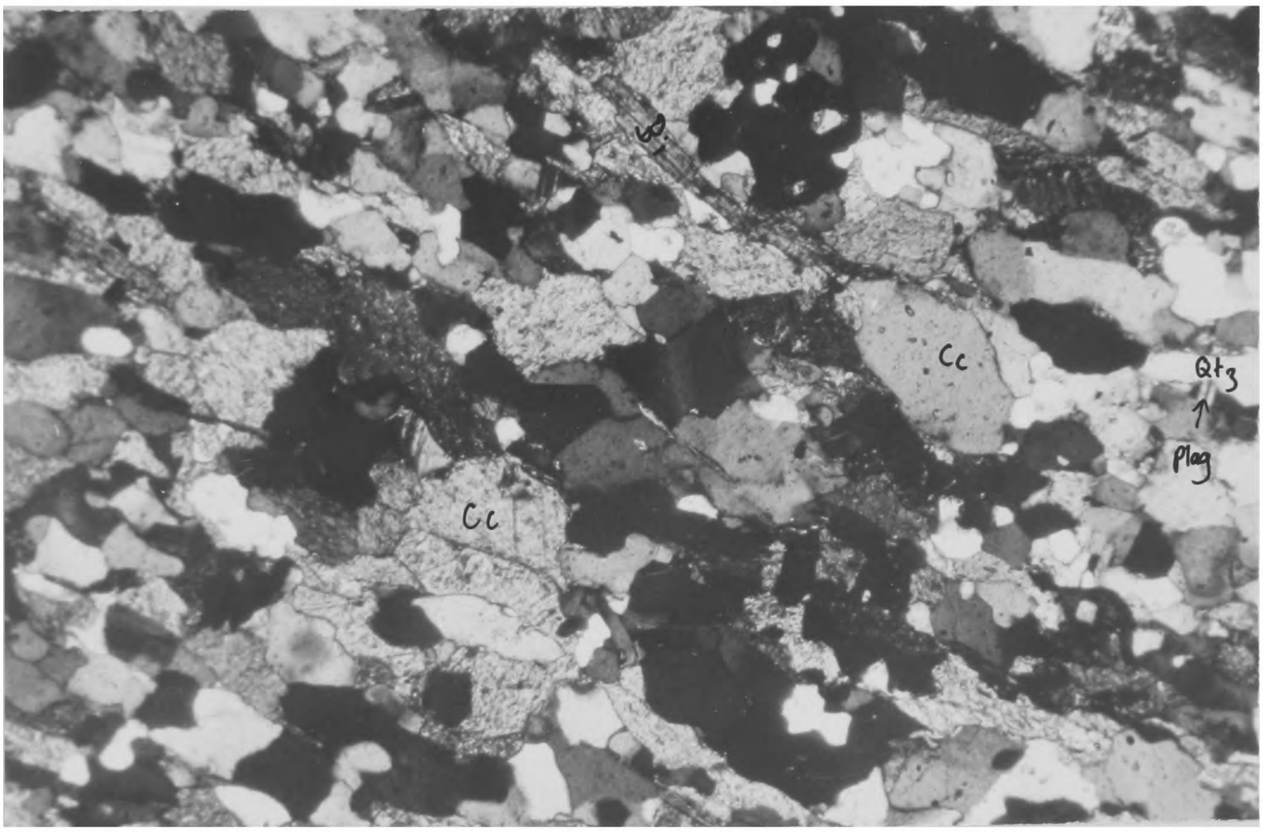


Plate 23. Calc-silicate band containing calcite.

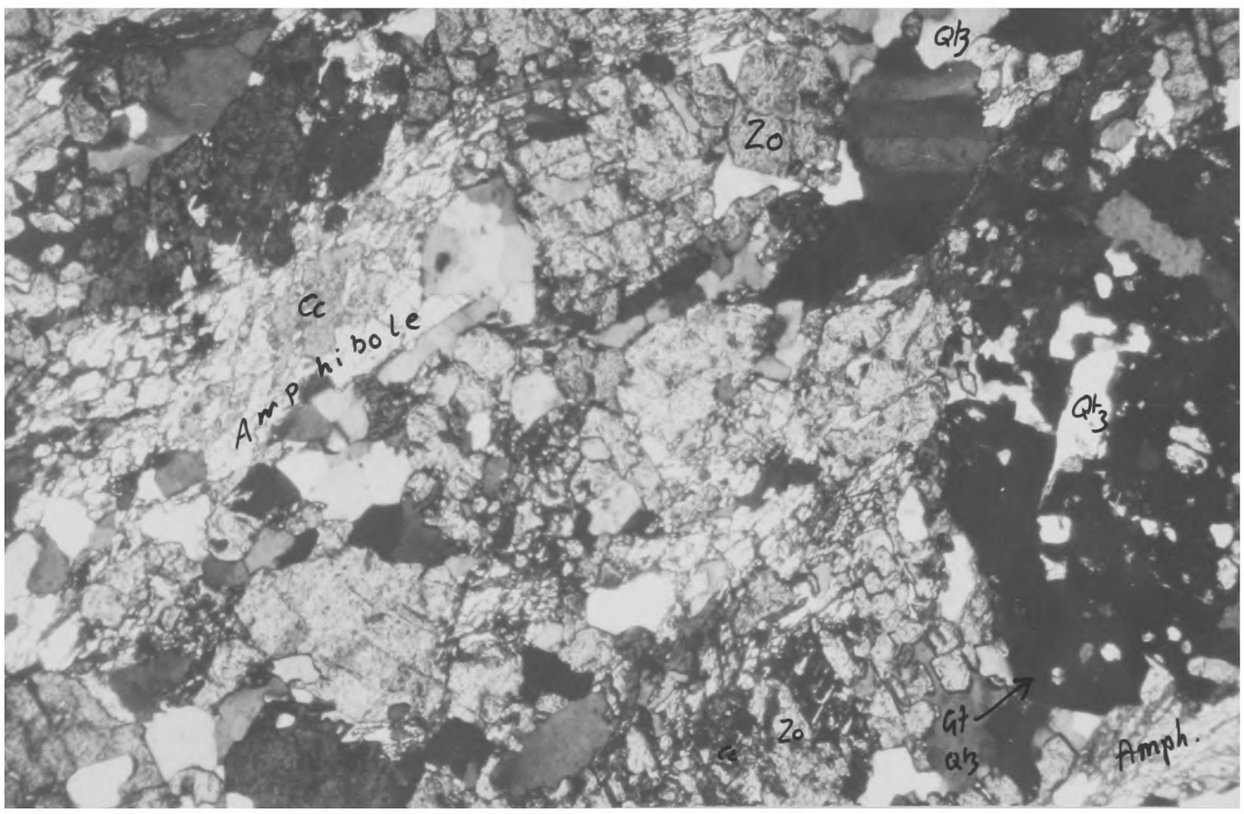


Plate 24. Calc-silicate band showing the replacement of amphibole by calcite

is found preserved as inclusions, when it is absent in the rest of the slide, suggesting that it was a constituent mineral of the rock when the garnet was forming. In most of the amphibole-bearing calc-silicates, however, calcite is absent, although a sample from the Allt a' Choire Mhoir shows calcite replacing tremolite amphibole in concert with ripidolitic chlorite (Plate 24). The zoisite in the same rock has also been replaced by calcite along its cleavage planes. Similar reactions have been seen in thin-sections taken from calc-silicates in Ardnamurchan (Butler pers. comm.), and may be written:

$$3Ca_2Mg_5Si_8O_{22}(OH)_2 + 2Ca_2Al_3Si_3O_{12}(OH) + 10CO_2 + 8H_2O \longrightarrow$$

Tremolite Zoisite

$$\longrightarrow 3Mg_5Al_2Si_3O_{10}(OH)_8 + 10CaCO_3 + 21SiO_2 \qquad 9$$

Ripidolite Calcite Quartz

Because this reaction involves the breakdown of amphibole by the addition of carbon dioxide and water, it could be considered retrogressive. However, Winkler (1967) quotes reaction 9 as a progressive reaction characteristic of his Quartz-Albite-Epidote-Biotite Subfacies, equivalent to Barrow's Biotite Zone. In the Moinian calc-silicates, the occurrence of this reaction "in reverse" is not interpreted as the result of a retrogression to the metamorphic conditions of the Biotite Zone, but more a consequence of the introduction of CO_2 and water into the

system, possibly on account of the proximity of the sample in question to a shear-zone along which the volatile components were migrating. That other samples from the Allt Coire Mor do not show the same retrogressive reaction supports this.

Samples containing grains of calcite that are apparently primary were also collected from locations outside the Fannich Range. These were interpreted as containing the mineralogy characteristic of calc-silicates within the Fannich Range at the time of formation of those garnets that contain calcite inclusions. They were seen north of Fannich in the gorges of the Allt a' Bhraighe and the Allt na h'Ighine, and south of Fannich in the road-section, half a kilometre west of the Grudie River Power Station. In these rocks the abundance of calcite is apparently inversely proportional to that of zoisite, and it seems that zoisite is formed by the breakdown of calcite, in conjunction with the production of more sodic plagioclase, according to the reaction:

$$3CaAl_2Si_2O_8 + CaCO_3 + H_2O \longrightarrow 2Ca_2Al_3Si_3O_{12}(OH) + CO_2$$

Anorthite Calcite Zoisite -------10

Again, the factors controlling if or when this reaction should proceed are partly the previous abundance of plagioclase in the rock, the P_{H_2O} and P_{CO_2}, and finally the pressure-temperature conditions. In certain rocks showing this reaction the calcite being replaced was originally preserved as inclusions within

garnet. With the dissolution of the outer rim of the garnet protecting these inclusions, carbon dioxide is released and the calcite reacts to form new epidote. This reaction is the reverse of the one seen in the Allt a' Coire Mhoir, where zoisite has been calcitized along its cleavage-planes, whether or not the amphiboles are also calcitized according to reaction 9. According to these reactions, the original abundance of calcite may influence the abundance of zoisite in calc-silicate rocks that have been subjected to more intense metamorphism. One calcite-bearing rock remains to be described: a calcareous rib from the Allt a' Bhraighe in which calcite and quartz coexist (Plate 25). Plagioclase occurs less abundantly, zoisite is rare, and all ferromagnesian minerals are absent from the main calcite bands. In nearby calc-silicate ribs, zoisite, garnet, and either biotite or hornblende are abundant. It seems that the presence of ferromagnesian minerals may hasten reaction 10, and their absence from this sample has enabled it to preserve a calcite-quartz mineralogy.

A major shear runs down the gorge of the Allt a' Bhraighe. Outgassing of CO_2 from greater depths may provide an alternative explanation of the presence of calcite in certain places and not others of apparently the same 'metamorphic grade'. But the presence or absence of calcite in the Fannich calc-silicates does not seem to be a significant indicator of their metamorphic

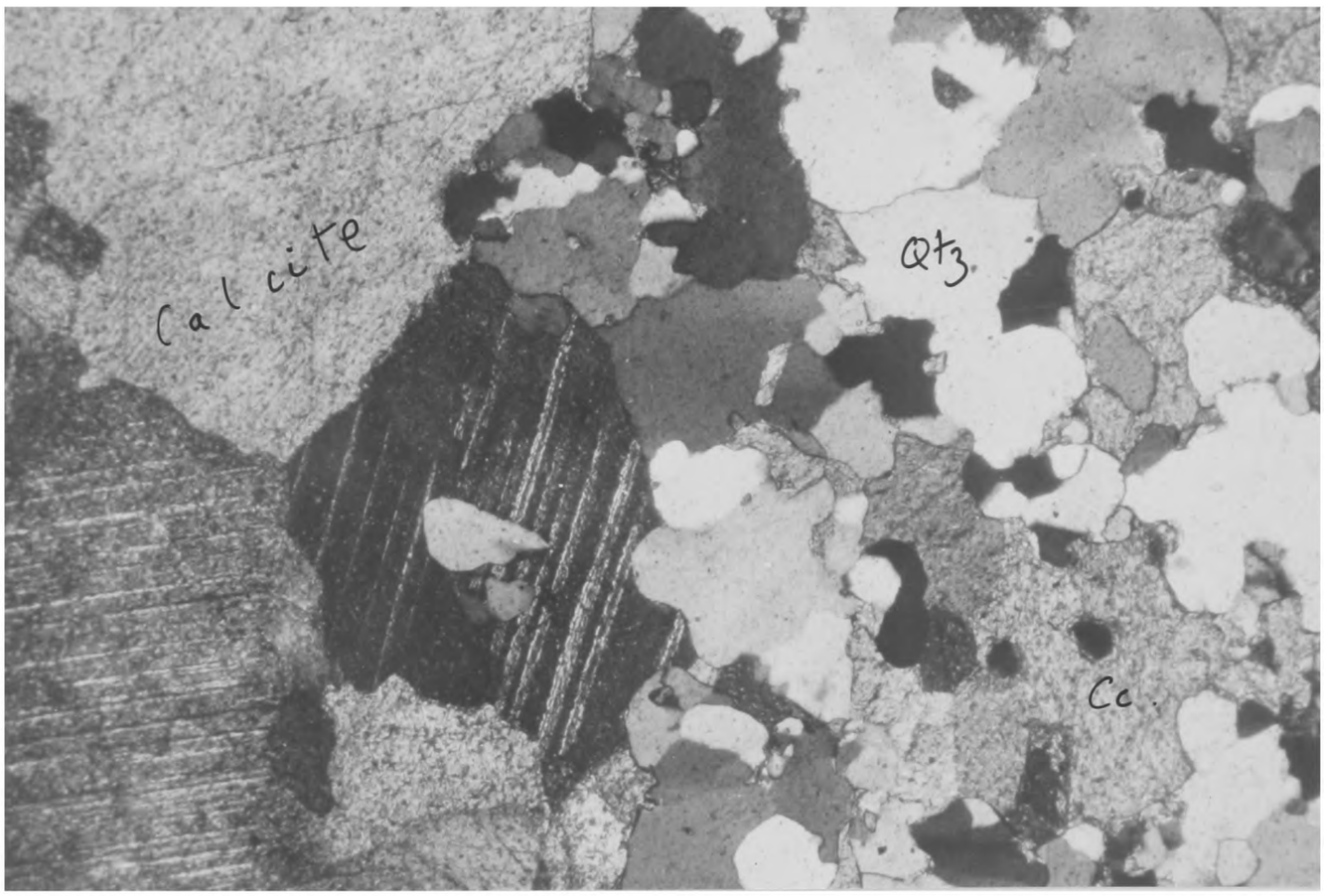


Plate 25. Calc-silicate band consisting almost entirely of quartz and calcite.

grade.

7.4 Ferromagnesian minerals and Zoisite

Kennedy's Zone 1b shows biotite and hornblende coexisting. This was also observed in Fannich, although the coexistence of the two minerals is rare, and always accompanied by a texture revealing the breakdown of the amphibole. It seems, therefore, that rocks containing both ferromagnesian minerals preserve a texture initiated while a reaction involving hornblende and biotite was in progress, and the relative scarcity of these rocks indicates that this reaction proceeded rapidly. Out of 140 rocks, only 25 showed the two minerals together. For this mineral transition Kennedy invokes the reaction:

Biotite + Calcite (Zoisite) ——→ Hornblende

--------11

But in Fannich two observed facts refute the suggestion. Firstly, in all the rocks examined, it is the amphibole that is being destroyed. Often only a small core of colourless amphibole remains, its entire rim replaced by biotite. Therefore, according to Kennedy's order, the reaction in Fannich is retrograde. Good illustrations of the growth of biotite in place of amphibole were seen in several calc-silicates. Few grains showed the reaction in progress, but biotite clearly pseudomorphous after hornblende occurs (Plate 26). Since this

reaction seems to be dependent on both the whole-rock composition, and the metamorphic grade, it is considered a useful indicator of metamorphic grade. Biotite was never seen breaking down to form hornblende, and since the reaction that proceeds involves oxidation and introduction of potash from the country-rock it may be considered retrogressive:

$$2Ca_2(MgFe)_3Al_4Si_6O_{22}(OH)_2 + 2KAlSi_3O_8 \longrightarrow$$

Hornblende Microcline

$$\longrightarrow K_2(MgFe)_6Al_2Si_6O_{20}(OH)_4 + 4CaAl_2Si_2O_8 + 4SiO_2$$

Biotite Anorthite Quartz. ------12

Analysis of garnets from the calc-silicates has shown that they are all calcic almandines; therefore the participation of grossular can only be considered in the understanding that it forms part of the calcic almandine molecule. According to Kennedy's zonation of calc-silicates (1949) biotite is characteristic of lower grade zones than hornblende; this also tends to suggest that the reaction is retrograde

Compositional zoning has been briefly mentioned. It occurs in most calc-silicates, even if only close to the junctions with the surrounding pelite. In Plate 26 a band normally containing amphibole is shown, in which biotite grains have replaced the amphibole near the margin. In the pseudomorph, the biotite shows cleavage inclined at a varying and anomalous angle to its outline. On Creag a' Chaise, above the outlet

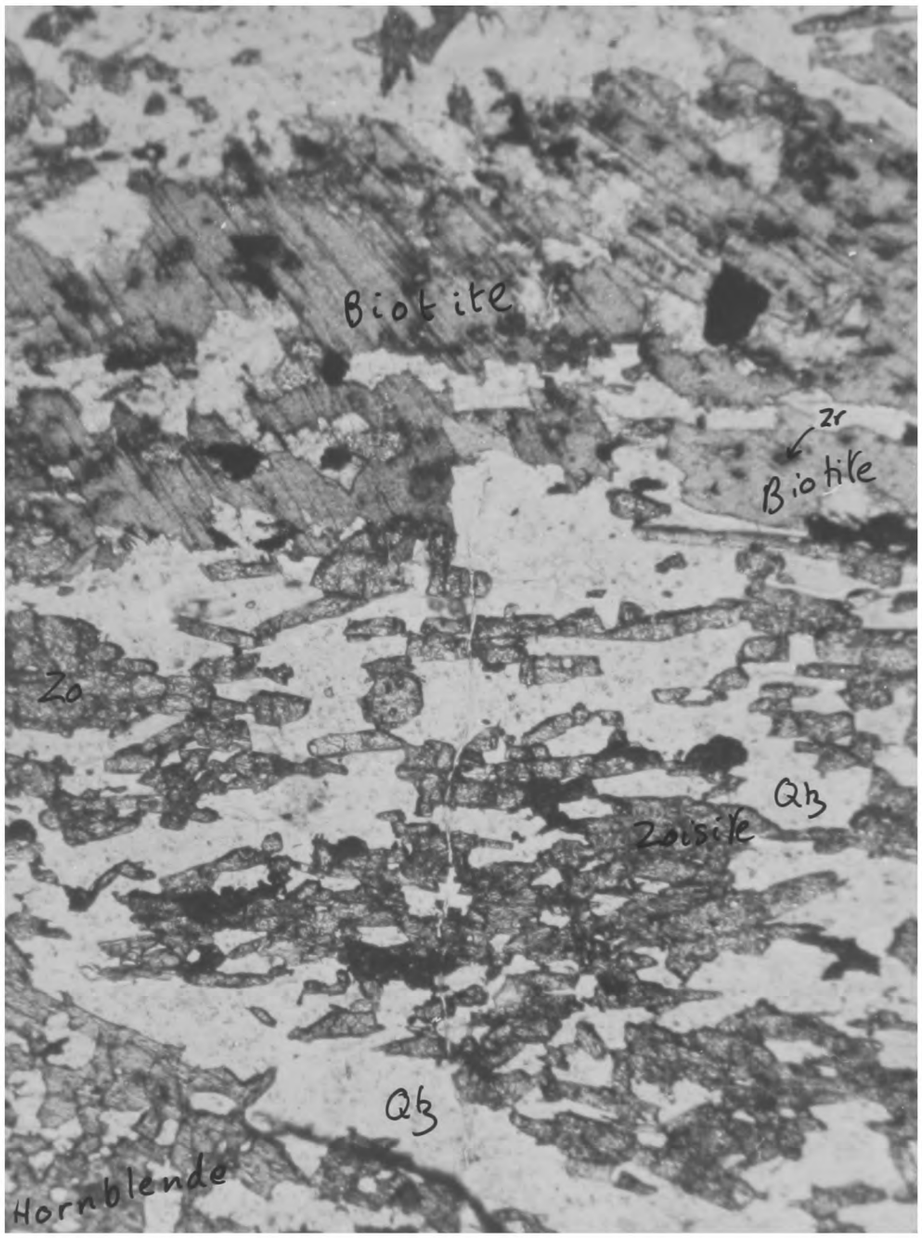


Plate 26. Calc-silicate with biotite pseudomorphous after hornblende.

of Loch Fannich, several well-defined zones within the calc-silicates occur. In these bands, up to 80 mm. broad, there is a central zone, rich in zoisite, containing a few anhedral grains of hornblende. A thin zone with less common zoisite separates it from a zone consisting mainly of quartz, with some garnet. Continuing outwards, a band rich in large hornblende grains is followed finally by a zone containing zoisite, quartz and garnet, which grades by the gradual substitution of plagioclase for zoisite, and the introduction of biotite grains, into normal pelite. Yet in this rock containing grains of both biotite and hornblende in different bands, no zone occurs in which biotite is actively replacing amphibole; this shows how rapidly the reaction proceeds, given the required change in composition or metamorphic grade.

So far, the hornblende-biotite reaction has been described in isolation. But the calc-silicates in Fannich show both in their textures and their mineral assemblages that this reaction is almost invariably accompanied by a reaction between plagioclase to zoisite. The occurrence together of these reactions suggests that they may be linked. Perhaps the change in mineral assemblages consequent from one reaction renders the calc-aluminous minerals of the original mineralogy unstable, and so triggers off the other reaction.

The calc-silicates in Fannich can therefore be grouped

into four extreme mineral assemblages, according to how far either, or both of these reactions has taken place: The characteristic minerals found in these assemblages are listed below:

1. Biotite-Sodic Plagioclase-Zoisite
2. Biotite-Zoisite (no feldspar)
3. Hornblende-Sodic Plagioclase-Zoisite
4. Hornblende-Zoisite. (no feldspar)

The number of rocks collected in which plagioclase is entirely absent is large compared to Forar. All Kennedy's zonal assemblages include plagioclase, but Poole lists two specimens in which plagioclase is absent. In Fannich 30% of the calc-silicates contain no plagioclase, and many more show only a few decomposed traces of it. Where zoisite and plagioclase occur together, the zoisite is always fresh, and some rocks collected showed textures indicating that the zoisite was progressively replacing the plagioclase. Kennedy does not list this reaction, and only shows one reaction involving both minerals, namely:

$$2\ \text{Zoisite} \longrightarrow 3\ \text{Anorthite} + Ca(OH)_2$$

But he invokes this reaction to account for the transition to his third zone in which calcic plagioclase is the diagnostic mineral. This zone is not recorded in Fannich, where all reactions involve sodic plagioclase. Also, in Fannich, the

the zoisite is replacing plagioclase, and as this reaction involves the production of a more hydrated rock, it can be considered retrograde and can be written as shown below:

$$5CaAl_2Si_2O_8 + Ca_3Al_2Si_3O_{12} + 2H_2O \longrightarrow 4Ca_2Al_3Si_3O_{12}(OH) + SiO_2$$

Anorthite Grossular Zoisite Quartz

----------14

The more sodic plagioclase produced by the participation of the anorthite molecule in the reaction is probably absorbed into the country rock, while the participation of the grossular molecule in calcic almandine may account for the pitted appearance of some garnets. Unlike Reaction 12, this reaction absorbs garnet;

$$2Ca_2(MgFe)_3Al_4Si_6O_{22}(OH)_2 + CaAl_2Si_2O_8 + 2KAlSi_3O_8 + Ca_3Al_2Si_3O_{12} + 2H_2O \longrightarrow$$

Hornblende Anorthite Microcline Grossular

$$\longrightarrow K_2(MgFe)_6Al_2Si_6O_{20}(OH)_4 + 4Ca_2Al_3Si_3O_{12}(OH) + 5SiO_2$$

Biotite Zoisite Quartz.

----------15

In this reaction, calcic almandine becomes more iron-rich, with the removal of the grossular molecule. Where rims of calcic almandine occur, they are probably formed according to reaction 7. Perhaps an increase in the partial pressures of oxygen and wanter initiate this reaction, reflecting a decrease in the

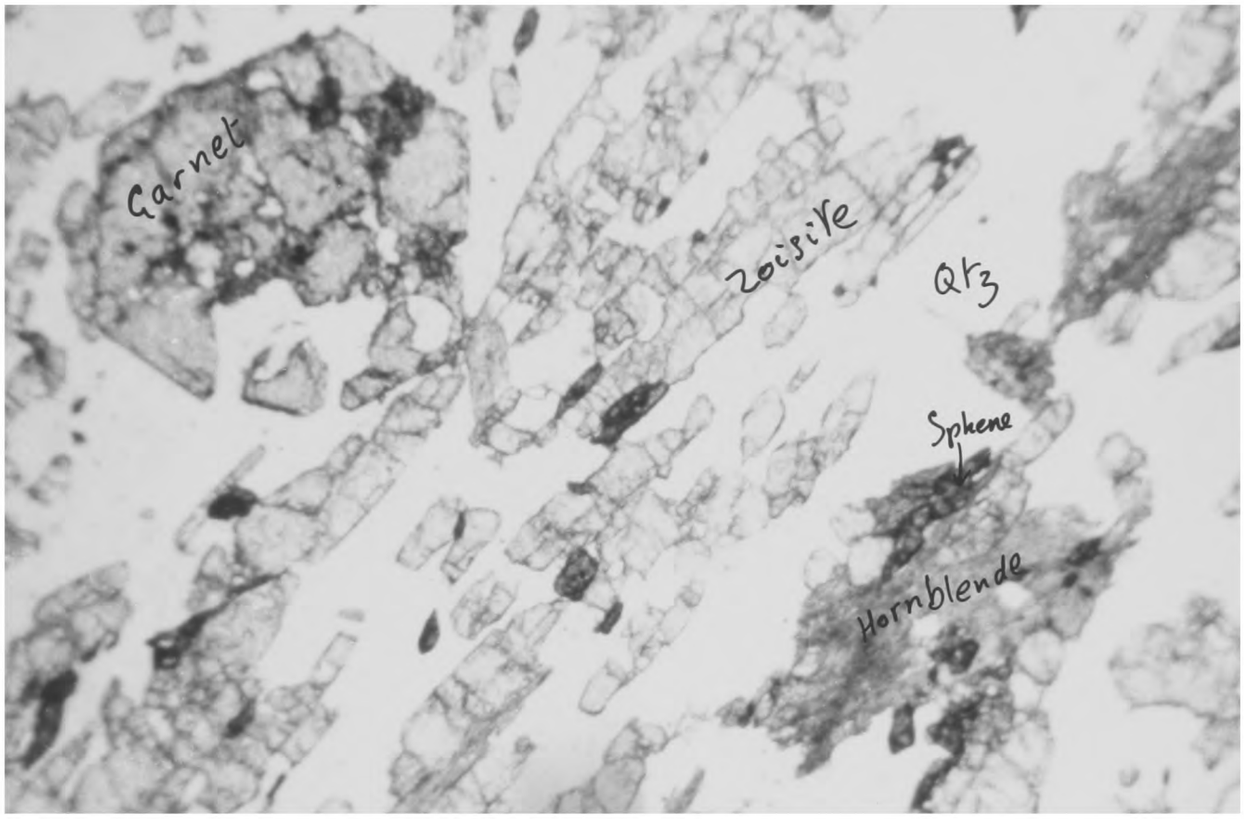


Plate 27. Calc-silicate containing Garnet, Zoisite and Hornblende, but no plagioclase.

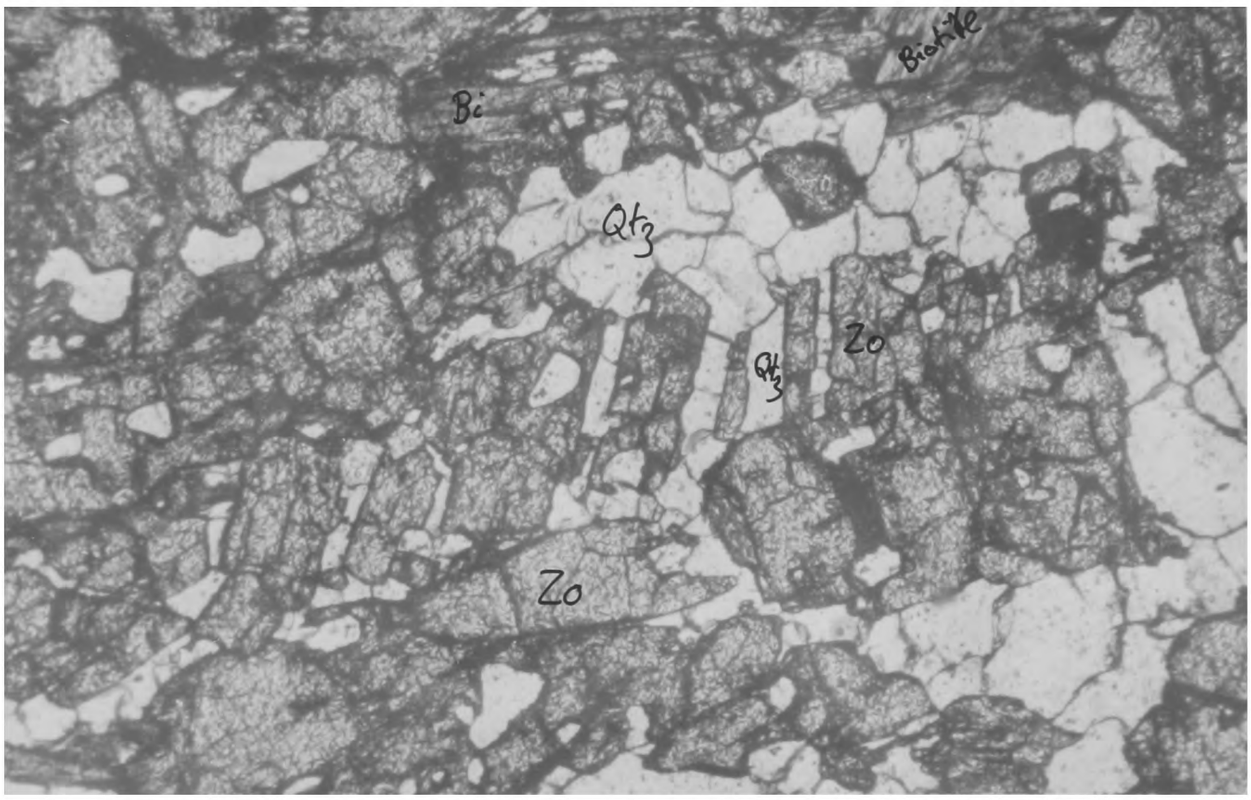


Plate 28. Zoisite, possibly pseudomorphous after twinned plagioclase.

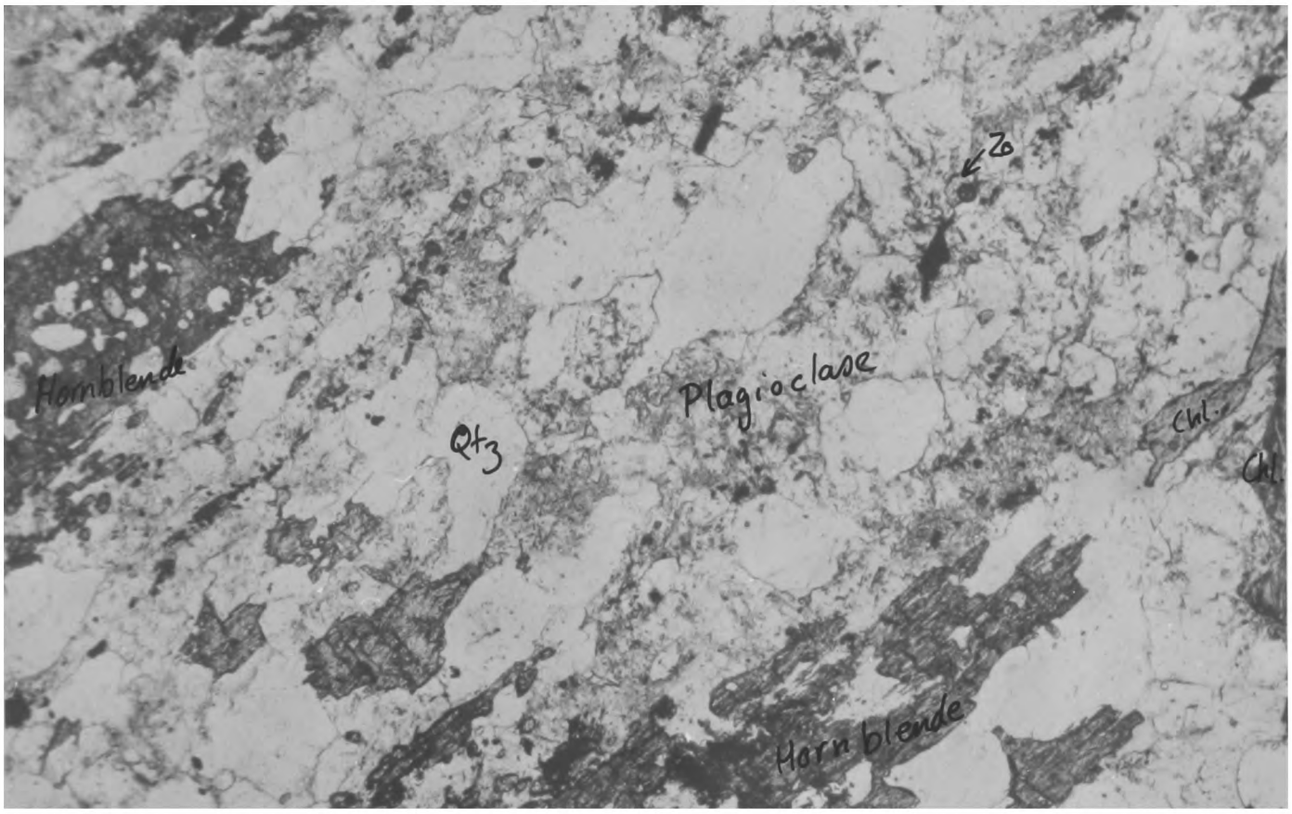


Plate 29. Calc-silicate containing Garnet, Plagioclase and Hornblende.

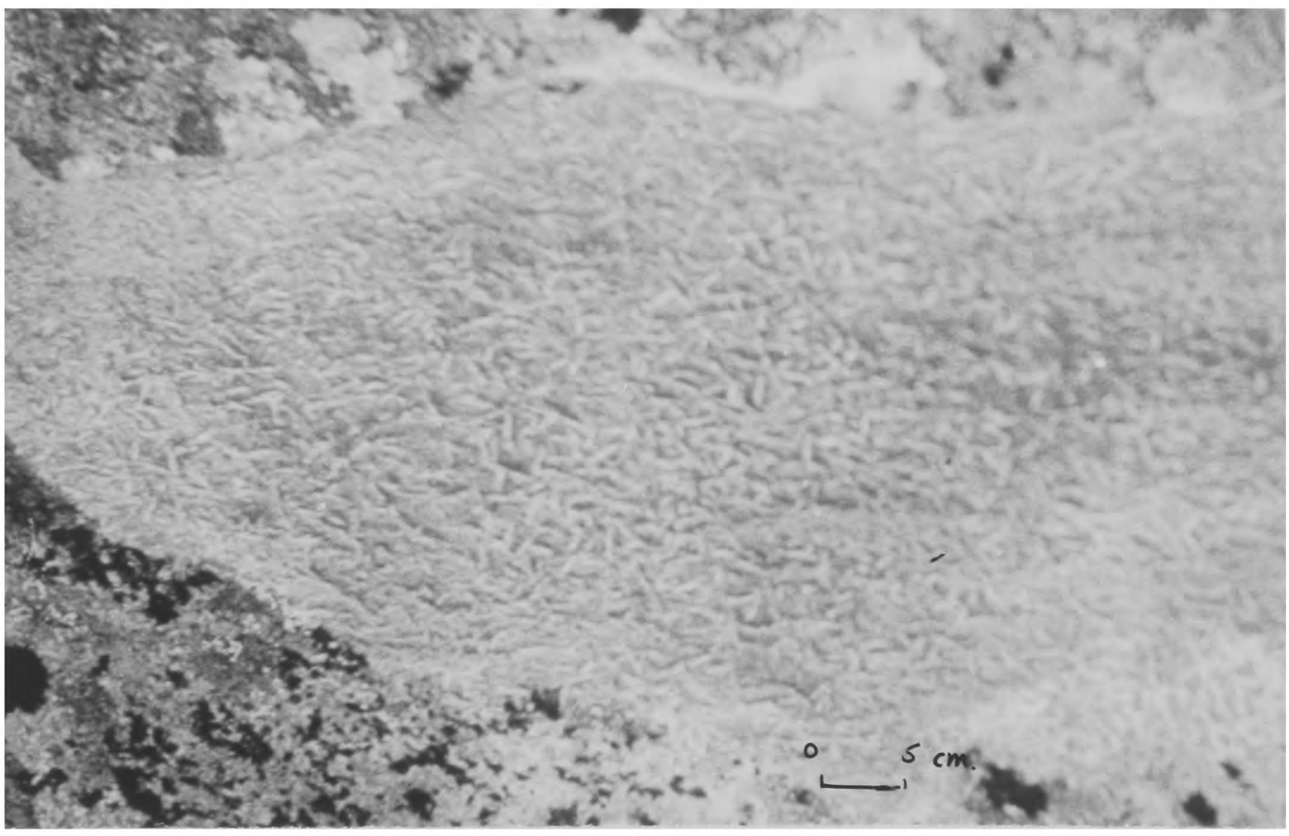


Plate 30. Zoisite porphyroblasts on a foliation surface in Sgurr Mor Pelite.

metamorphic grade of the area. Abundant quartz does occur in plagioclase-free rocks, (Plate 27) and sometimes zoisite textures hint that alternations of quartz and zoisite may be pseudomorphous after twinned plagioclase (Plate 28).

Zoisite is present in all the Fannich calc-silicates; it also occurs in smaller quantities in rocks containing hornblende and plagioclase (Plate 29). The zoisite already present before Reaction 15 proceeds may be remanent from the progressive metamorphism of the rocks, in which it formed according to the Reaction 10 at the expense of calcite. It shows a variety of textures, from occurring as a mass of small granules, to its occurrence as large elongate porphyroblasts (Plate 30), up to 50 millimetres long and perforated with numerous quartz inclusions (Plate 31). Except in calcitized rocks, already described, the zoisite is always fresh. Some blades of zoisite appear to have grown into crystals of amphibole, but usually the two minerals coexist side by side. Most of the zoisite present, therefore, seems to have replaced either calcite or plagioclase. Apatite, and sphene also occur, but do not appear to take part in these reactions.

7.5 Garnets in Calc-Silicates

Garnets are present in almost all the calc-silicates examined. As they have also been used to assess metamorphic

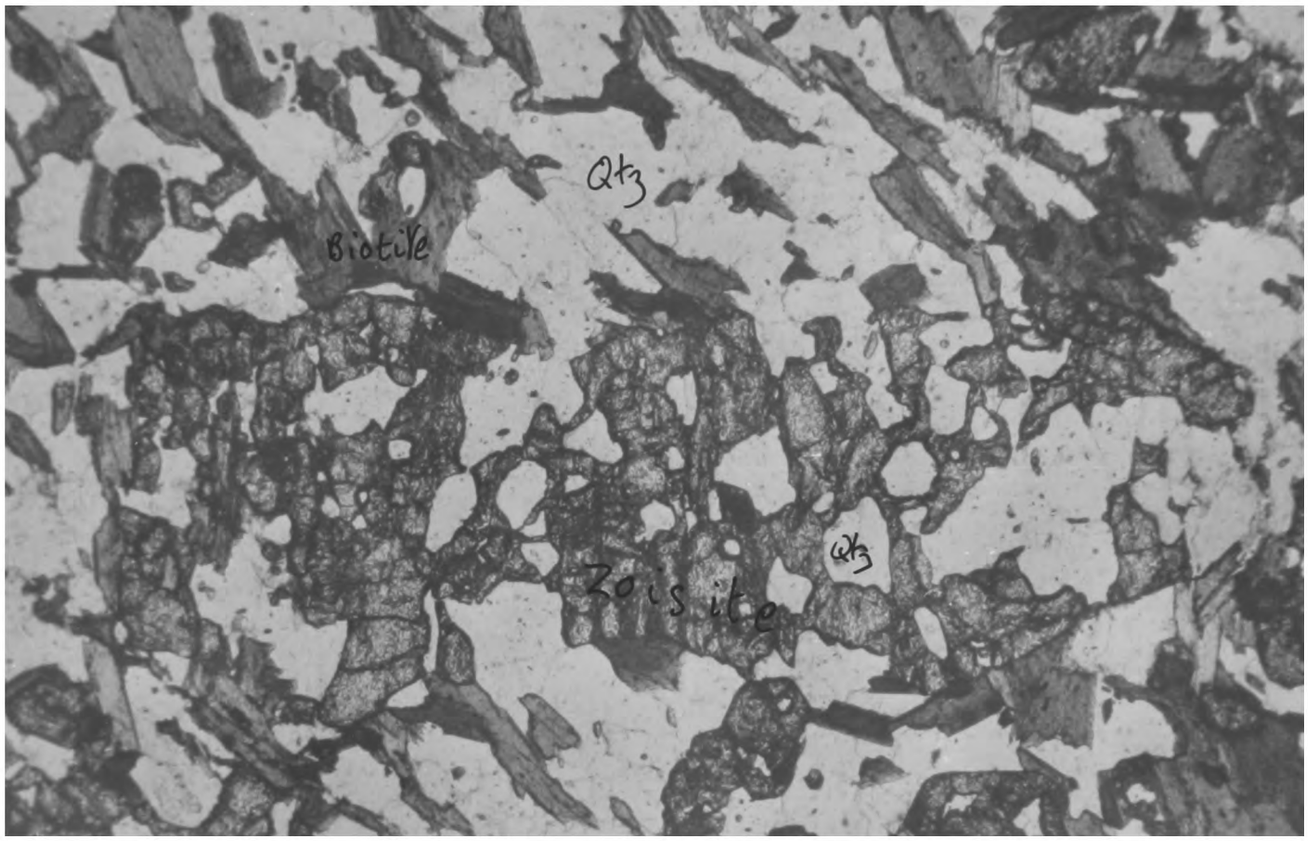


Plate 31. Zoisite porphyroblast with quartz inclusions.

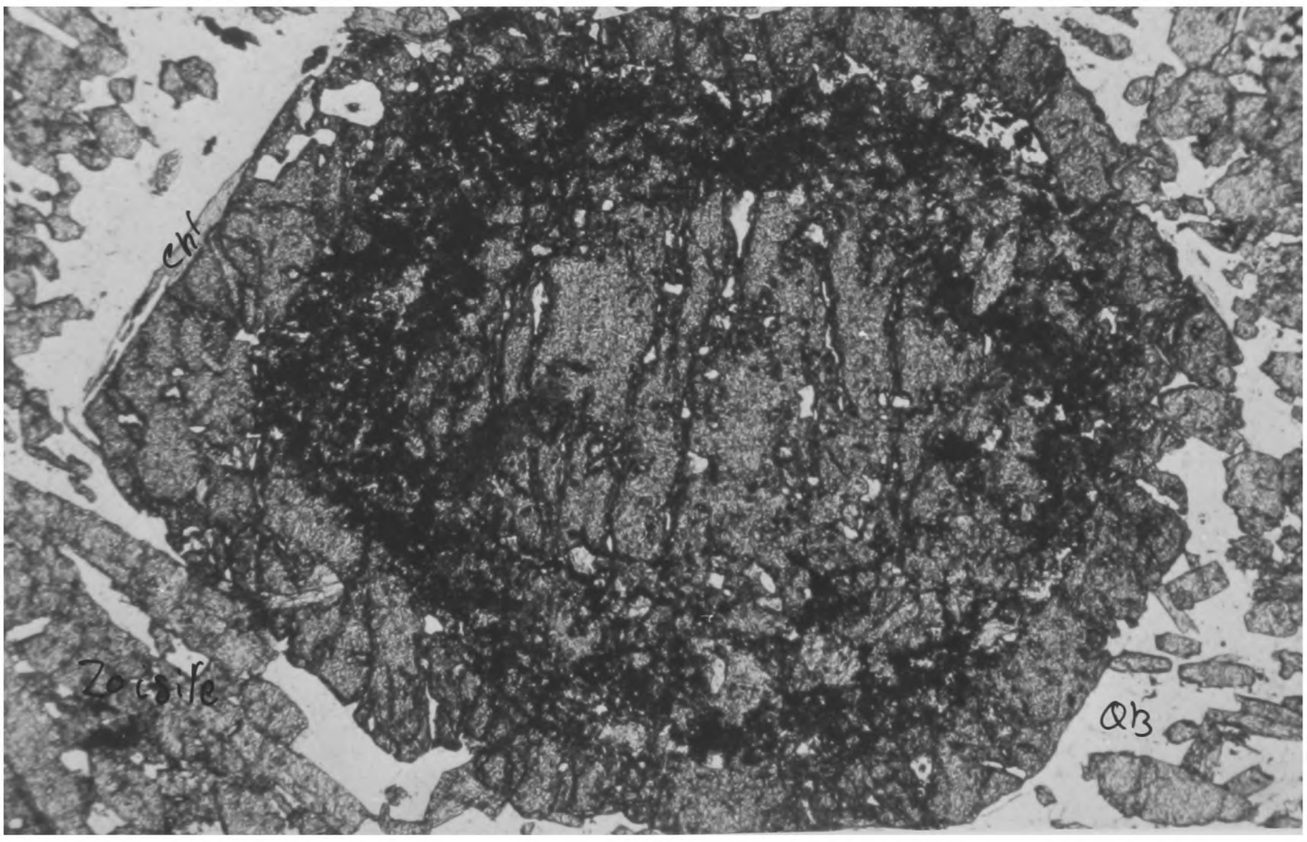


Plate 32. Zoned garnet from a hornblende - zoisite calc-silicate.

grade in the Meall an t-Sithe Pelite, five were also selected for probe analysis from the calc-silicates. All proved to be somewhat calcic almandines, and all, with one notable exception showed some reversed zoning with a higher calcium content in their rims. The exception came from a rock in which virtually no zoisite, and no biotite had formed at the expense of plagioclase and amphibole. This compositional variation in the garnets was interpreted as confirming that Reactions 12, 14 and 15 are retrogressive.

The garnets also show considerable textural variation. Whereas, in some calc-silicates the garnets are euhedral and contain a small proportion of numerous quartz inclusions, in others only skeletal fragments indicate the former size of the crystal, while, in yet others the garnets are rounded, and sometimes chloritized. Strong zoning often occurs; some garnets contain a core surrounded by an envelope so crowded with inclusions that pure garnet is almost absent, and this is in turn rimmed by garnet almost free of inclusions, and often showing perfect crystal faces (Plate 32). One garnet analysed from a plagioclase-free, hornblende bearing rock contained a more calcic rim than core. While reaction 14 proceeded the garnet was etched around the core; but later calcic almandine formed at the expense of the remaining plagioclase according to the reaction:

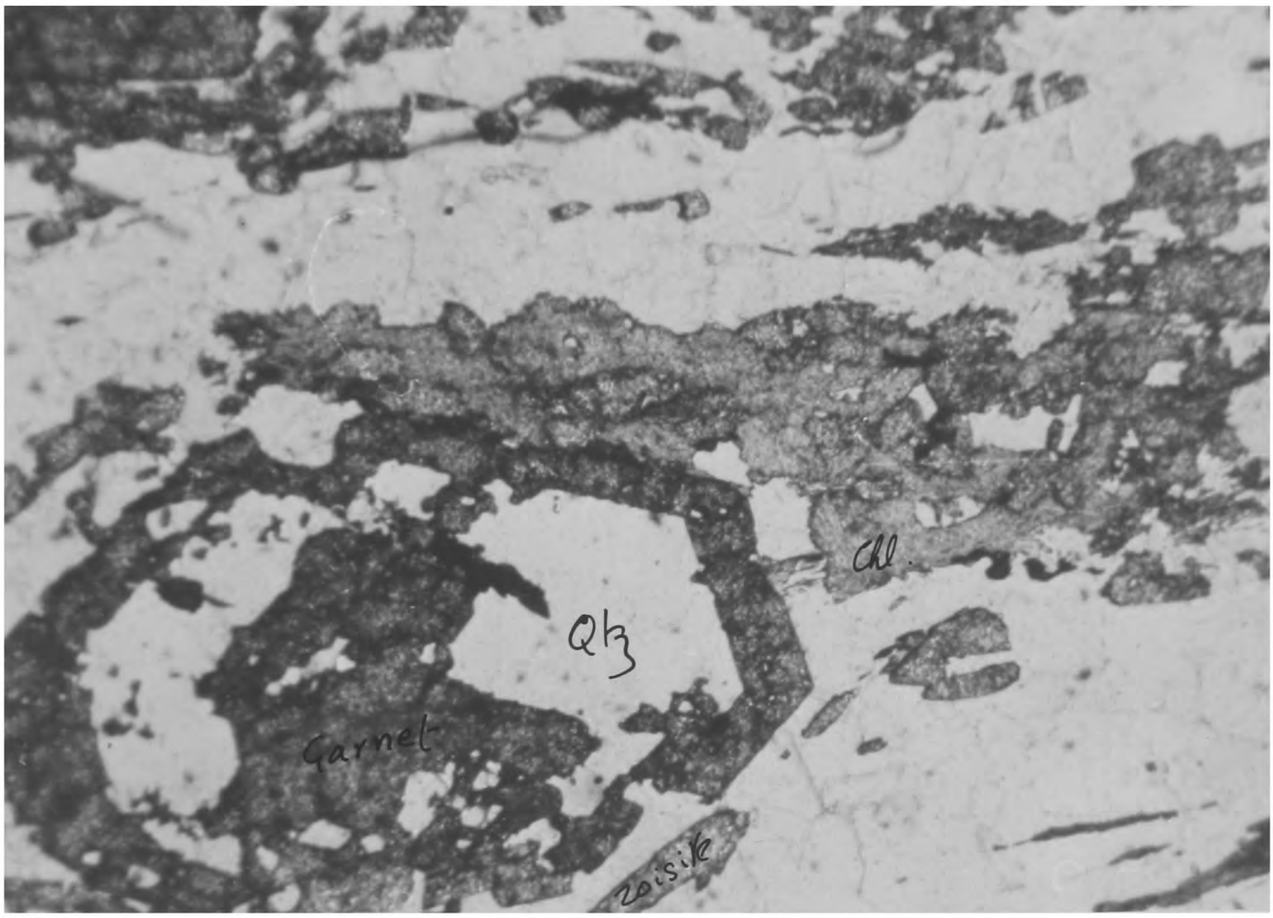


Plate 33. Euhedral rim of garnet, surrounding a core area consisting mainly of quartz.

$$6SiO_2 + 6CaAl_2Si_3O_8 + 4Fe_3O_4 \longrightarrow 6CaFe_2Al_2Si_3O_{12} + 2O_2$$

Quartz Anorthite Magnetite Calcic-Almandine

-------- 7

Whereas the first reaction involves hydration, this is a reducing reaction, possibly balancing in part the oxidising reactions that also occur. These two reactions explain the decay around the rim of the original garnet, and the accretion of somewhat more calcic, and more aluminous almandine garnet rim. The late garnet usually nucleates around pre-existing garnets but rims of garnet were also seen around apatite, and surrounding a garnet core almost entirely replaced by quartz (Plate 33). A few small fresh garnets were also seen, probably resulting from this second growth of garnet.

Quartz, zoisite and muscovite all occur as inclusions within the garnet. Calcite is also present in some, possibly preserved from an earlier mineralogy, but almost all the inclusions are of quartz.

Garnets are significant in assessing metamorphic grade in the calc-silicates, as well as the pelites, but before metamorphic grade is considered, their chemical compositions must be considered.

7.6. Calc-Silicates: The Chemical Evidence

Out of 140 calc-silicates, 107 were analysed by X.R.F. in

a series of whole-rock determinations for 9 major elements. Analuses of calc-silicates from other parts of the Moines made by the Survey and by Poole (pers. comm.) show that certain characteristics are common to all of them. All are relatively calcium-rich, by definition, but notably magnesium-poor, and in this they differ markedly from the Lewisian calc-silicates seen in the Cassley-Shin Inlier (Winchester & Lambert 1970). A comparison of the compositions of the two types of calc-silicate can be seen in Figure 22. All Sgurr Mor calc-silicates were deficient in potash. Out of 107 samples analysed, only 8 contain more than 1.5% potash, while 50 contain less than 0.5%, although they form only thin ribs in a pelite which often contains 4-5% of potash. Microcline is absent, and muscovite is more rare on account of this potash deficiency; biotite seems to be the only potash-bearing mineral that is common. The amphibole present is usually green hornblende, rather than tremolite, but pale tremolitic amphibole does occur, especially where amphibole is being replaced by biotite.

These are chemical characteristics of all the Sgurr Mor calc-silicates. But the reason that they were analysed was to assess the effect of their differing chemical compositions on the timing of the mineral reactions that Kennedy (1949) considered to be indices of metamorphic grade. To attempt to draw an isograd based on mineral assemblages, without reference to chemical composition is difficult if the reaction defining the isograd is delayed or speeded by chemical variation. In Fannich,

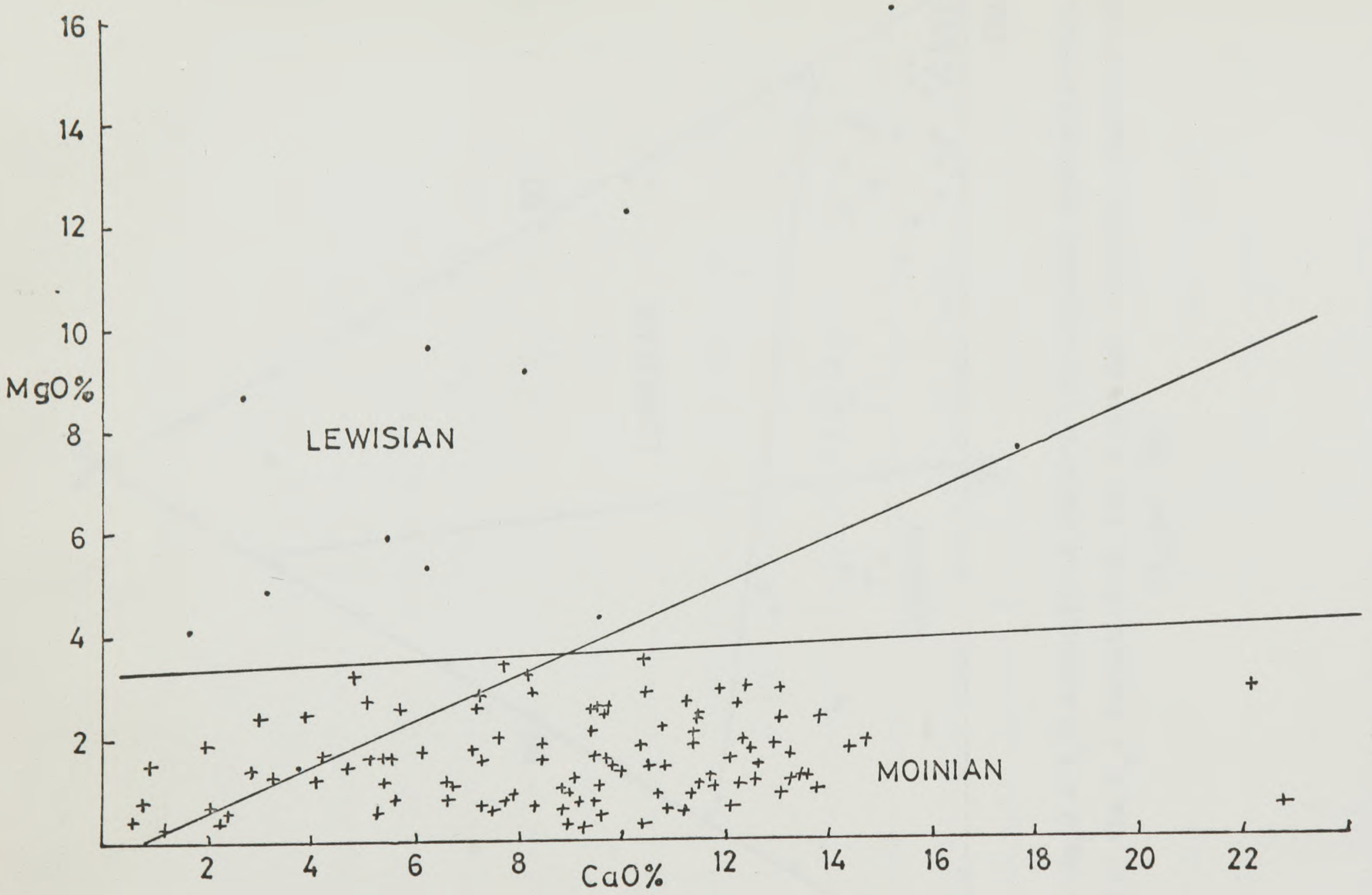
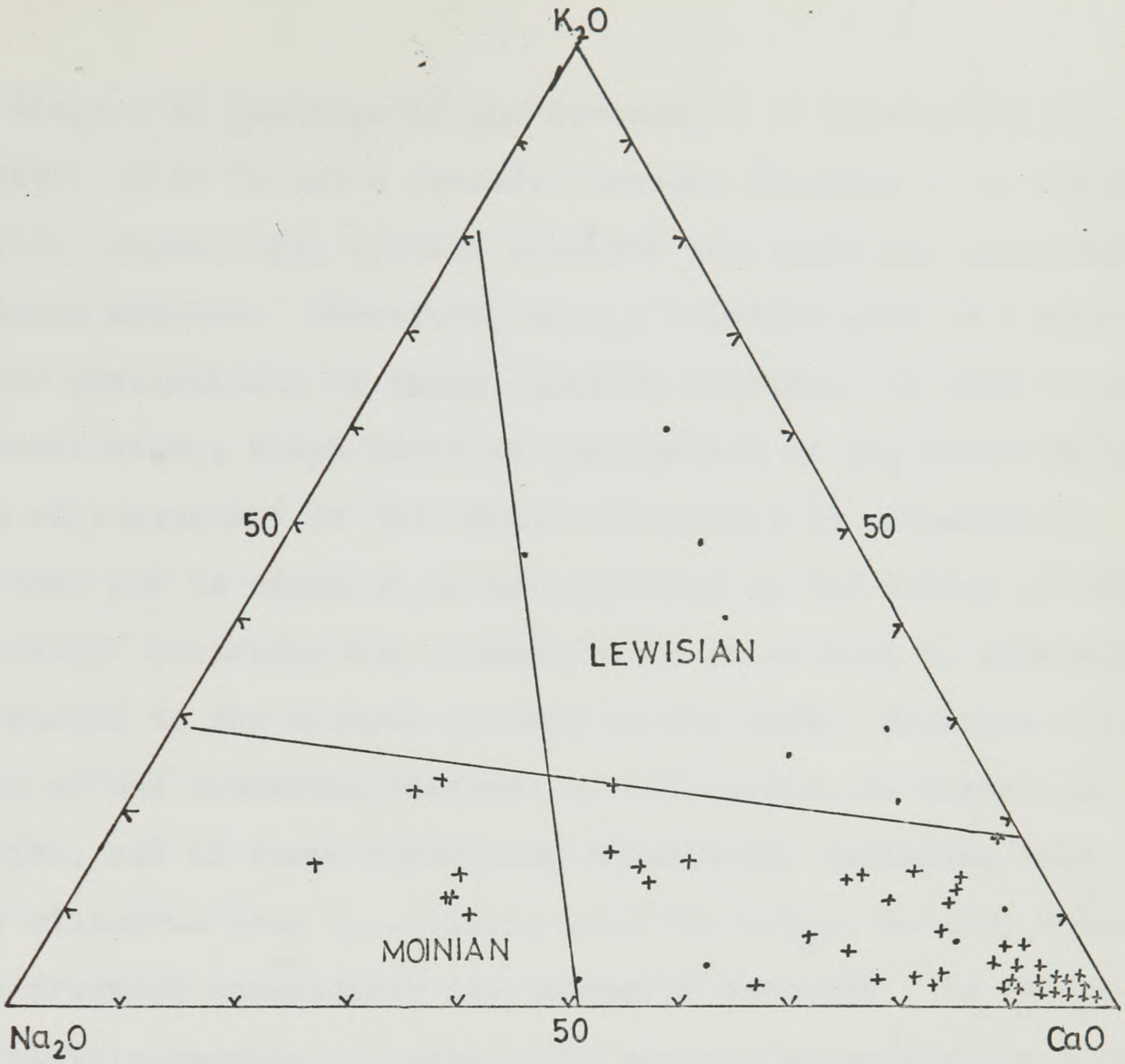


Figure 22. CaO - MgO contents of Moinian and Lewisian calc-silicates, showing the MgO depletion of the Sgurr Mor (Moinian) calc-silicates.



CaO - Na_2O - K_2O contents of Moinian and Lewisian calc-silicates, showing the K_2O depletion of the Sgurr Mor (Moinian) calc-silicates.

Figure 23.

the diagnostic reaction is the conversion of hornblende to biotite. This is not a reaction between minerals of essentially similar composition; biotite contains potassium and hornblende contains calcium. Therefore, such a reaction must be influenced by the availability of these elements outside. If this reaction proceeds alone, which detailed examination of the rocks denies, then an assessment of the ratios of calcium to potassium in the rock may be examined as an influence on the timing of the reaction. Certainly the element ratio of calcium to potassium is related to the mineral content of the rock. Averages were taken of the potassium contents of calc-silicates containing biotite, and of those containing hornblende, excluding only the very siliceous ones (containing over 72% SiO_2), as they would have produced anomalously low potassium contents. In these, the biotite-bearing calc-silicates contain an average of 0.94% potassium, while the hornblende-bearing ones averaged 0.47% potassium. But according to Reaction 12, the biotite forms partly at the expense of microcline derived from the country rock. Therefore, the greater potassium content of the biotite-bearing calc-silicates may be considered a result rather than a cause of the hornblende-biotite reaction. Moreover, a plot of calcium-potassium ratios of these rocks tends to highlight the ratio of biotite to zoisite in the rock rather than an invariant chemical composition controlling the timing of the

reaction. Alkali content of these calc-silicates, therefore, may be dependent on the amount of sodium or potassium derived from the country-rock as a result of the reactions, and therefore a diagram showing an alkali metal plotted against another element is not likely to throw light on the chemical conditions favouring the initiation of the hornblende to biotite reaction.

It has already been mentioned that a reaction forming zoisite from plagioclase occurs frequently in connection with the formation of biotite. This involves a change in the ratio of calcium to aluminium, and likewise a change in the ratio of calcium to aluminium occurs in the hornblende to biotite reaction. Overall, after both reactions have finished the calcium-aluminium ratio in the rock may not have changed, as neither element enters solution as readily as potash. Since it affects both visible reactions, and does not involve addition of calcium or aluminium from the country-rock, the calcium-aluminium ratio seems a significant index in assessing the effect of chemical composition upon the timing of these reactions.

Groups of calc-silicate rocks were collected from different parts of Fannich Forest (Fig.21), and then analysed (Tables 14-18). In certain parts of Fannich it was found that the reaction occurred in rocks with definite calcium-aluminium ratios, and that the critical ratio at which the reaction occurred, varied from place to place. These variations are considered

TABLE 14

Sgurr Mor Calc-Silicates:

(Hornblende-Zoisite; No Plagioclase)

	6871	6872	68718	68743	68744	68745	68756	68772	68773	69443a	69443b	69487
SiO_2	64.74	66.67	80.36	70.35	66.43	70.43	78.09	61.14	59.11	69.97	65.57	80.87
Al_2O_3	12.97	14.10	8.79	12.40	13.88	11.64	8.59	15.47	16.45	11.33	11.20	7.06
FeO(Tot)	5.84	3.35	2.00	3.03	3.67	3.32	3.25	5.45	5.87	2.82	5.20	2.77
MgO	2.61	1.25	0.66	1.05	1.65	1.51	0.85	1.74	1.91	0.97	2.91	0.58
CaO	12.24	13.56	7.27	12.30	13.24	12.13	7.80	14.45	14.74	13.78	13.03	7.83
Na_2O	0.14	0.12	0.22	0.20	0.43	0.22	0.14	0.43	0.40	0.20	0.71	0.16
K_2O	0.23	0.10	0.21	0.02	0.04	0.05	0.62	0.25	0.30	0.20	0.37	0.10
TiO_2	1.07	0.68	0.30	0.49	0.49	0.56	0.51	0.86	0.89	0.57	0.72	0.47
MnO	0.18	0.16	0.17	0.15	0.16	0.15	0.15	0.22	0.33	0.16	0.24	0.16
CaO/Al_2O_3	0.944	0.962	0.827	0.992	0.954	1.042	0.908	0.934	0.896	1.216	1.163	1.109

69443a: Pale, leucocratic core of the calc-silicate band.

69443b: Zone of calc-silicate on either side, with abundant hornblende.

TABLE 15

Sgurr Mor Calc-Silicates

(Biotite-Zoisite. No Plagioclase)

	68719	68736	68751	6977*	69710	69755
SiO_2	79.47	64.47	71.91	54.18	85.18	77.14
Al_2O_3	9.22	15.11	12.21	13.85	5.78	9.01
FeO(Tot)	1.88	4.23	3.19	3.63	1.98	3.19
MgO	0.77	1.21	0.88	2.99	0.48	0.31
CaO	7.73	13.47	10.69	22.17	5.71	8.94
Na_2O	0.24	0.21	0.18	0.30	0.21	0.31
K_2O	0.20	0.51	0.34	1.44	0.18	0.29
TiO_2	0.32	0.62	0.46	0.99	0.33	0.48
MnO	0.18	0.16	0.15	0.46	0.16	0.33
CaO/Al_2O_3	0.838	0.891	0.876	1.601	0.988	0.992

*contains calcite

TABLE 16 (a)

Sgurr Mor Calc-Silicates

(Hornblende - Plagioclase - Zoisite)

	68528	68615	68711	68724	68725	68726*	68738	68739	68740	68741	68742	68771	68778	68780
SiO_2	60.53	68.25	67.87	59.93	60.24	65.25	69.18	62.55	59.61	65.74	68.22	61.11	67.13	65.97
Al_2O_3	19.22	16.34	13.38	17.75	18.90	13.47	14.11	15.96	16.57	13.80	11.92	14.84	16.17	14.62
FeO(tot)	3.79	3.62	4.22	6.29	6.03	5.32	3.96	5.24	6.38	4.88	4.89	5.98	5.04	5.06
MgO	0.85	1.17	1.17	2.53	2.51	1.93	1.01	2.38	2.92	2.41	2.51	2.32	1.79	1.83
CaO	13.03	6.61	11.77	9.73	9.42	12.34	9.54	11.47	11.87	9.64	9.55	13.85	6.11	10.35
Na_2O	0.81	3.19	0.30	1.03	1.18	0.41	0.94	1.06	1.24	2.13	1.74	0.37	2.20	0.97
K_2O	0.96	0.24	0.19	1.56	1.33	0.35	0.43	0.31	0.32	0.30	0.35	0.28	0.65	0.32
TiO_2	0.65	0.43	0.91	0.95	0.92	0.73	0.56	0.87	0.89	0.91	0.65	0.95	0.75	0.70
MnO	0.16	0.15	0.20	0.22	0.17	0.20	0.27	0.16	0.19	0.19	0.17	0.30	0.16	0.18
CaO/Al_2O_3	0.677	0.405	0.879	0.548	0.498	0.916	0.676	0.719	0.716	0.699	0.811	0.933	0.378	0.708

TABLE 16 (b)

Sgurr Mor Calc-Silicates

(Hornblende - Plagioclase - Zoisite)

	68811	68813	68815	68816	68817	68818	68822	6978*	69738	69526	69744	69745*	69746	68810
SiO_2	63.64	62.64	62.96	68.31	61.94	62.78	65.08	64.62	64.67	64.01	62.51	64.69	71.34	61.16
Al_2O_3	16.42	18.03	17.02	14.79	17.42	17.77	14.99	12.36	16.65	16.04	16.96	15.76	12.80	16.88
FeO(tot)	6.00	5.80	6.40	5.48	6.49	6.14	4.30	3.35	3.70	4.66	3.28	6.07	3.20	5.84
MgO	1.84	1.69	1.98	1.66	2.59	2.57	1.13	2.84	1.02	1.47	1.83	2.71	0.80	1.77
CaO	8.43	7.05	7.58	5.55	7.18	5.67	13.22	10.46	11.45	9.78	12.96	5.05	5.63	11.35
Na_2O	1.67	2.77	2.21	2.45	2.96	3.61	0.31	0.96	1.16	2.51	0.91	3.30	4.31	1.60
K_2O	0.80	0.84	0.62	0.64	0.39	0.42	0.23	0.50	0.67	0.61	0.69	1.56	1.26	0.37
TiO_2	1.02	1.03	1.03	0.96	0.87	0.89	0.58	0.72	0.54	0.77	0.73	0.71	0.48	0.86
MnO	0.18	0.15	0.19	0.16	0.16	0.16	0.15	0.20	0.15	0.15	0.16	0.15	0.16	0.16
CaO/Al_2O_3	0.513	0.391	0.445	0.375	0.412	0.319	0.882	0.846	0.688	0.610	0.764	0.320	0.440	0.672

* contains calcite.

TABLE 17 (a)

Sgurr Mor Calc-Silicates

(Biotite - Plagioclase - Zoisite)

	68619	68620	68622	68625	68628	68623	68632	6873	6876	6878	68710	68721	68734	68749
SiO_2	77.93	63.25	68.59	85.96	69.83	65.24	77.14	70.02	68.10	69.42	65.81	73.61	63.54	68.29
Al_2O_3	11.74	16.92	16.46	7.75	15.52	16.00	13.16	14.74	16.29	13.02	13.82	14.33	15.84	14.93
FeO(tot)	2.99	5.63	3.35	1.98	3.68	6.60	2.42	4.42	5.15	4.36	4.47	3.81	4.79	3.25
MgO	1.56	2.81	0.57	0.30	1.64	3.20	0.70	2.47	1.95	0.99	1.71	1.45	1.13	0.59
CaO	0.91	7.22	7.47	1.18	4.20	4.79	2.01	3.84	1.99	8.81	12.49	2.78	12.59	10.88
Na_2O	3.63	1.67	2.23	1.93	3.08	1.59	3.17	2.73	3.70	2.36	0.14	2.31	0.48	0.90
K_2O	0.42	1.43	0.62	0.40	1.26	1.55	0.81	0.98	1.73	0.34	0.40	0.97	0.46	0.51
TiO_2	0.67	0.87	0.56	0.30	0.65	0.83	0.42	0.65	0.93	0.53	0.98	0.58	0.79	0.49
MnO	0.15	0.21	0.15	0.21	0.15	0.20	0.17	0.15	0.15	0.15	0.17	0.15	0.37	0.15
CaO/Al_2O_3	0.077	0.427	0.454	0.152	0.271	0.299	0.152	0.261	0.227	0.181	0.904	0.194	0.795	0.729

TABLE 17 (b)

Sgurr Mor Calc-Silicates

(Biotite - Plagioclase - Zoisite)

	68750	68752	68753	68754	68755	68763	68764	68765	68766	68767	68769	68770	68782	68783	68764
SiO_2	69.15	70.85	85.68	86.62	73.76	65.42	67.13	71.56	66.12	65.79	76.09	76.05	70.86	72.18	71.70
Al_2O_3	14.69	11.92	7.31	7.12	13.90	15.70	13.17	14.04	13.80	15.57	13.76	13.72	13.49	13.51	14.24
FeO(tot)	3.75	3.14	2.80	2.29	3.98	4.72	5.34	3.42	4.83	6.46	2.50	2.41	4.96	4.35	3.38
MgO	0.75	0.85	0.68	0.45	1.25	0.74	1.17	0.66	2.13	3.37	0.57	0.44	1.60	1.17	0.55
CaO	9.44	11.32	0.73	0.57	3.21	9.13	9.05	8.29	10.74	7.66	2.36	2.26	5.03	4.04	5.26
Na_2O	0.96	1.03	1.55	1.91	1.89	1.91	1.43	0.64	0.44	0.21	3.55	3.78	1.93	2.62	3.39
K_2O	0.54	0.30	0.65	0.43	0.91	1.38	1.74	0.64	0.92	1.71	0.62	0.79	1.10	1.21	0.56
TiO_2	0.55	0.45	0.46	0.45	0.95	0.86	0.82	0.58	0.87	1.06	0.40	0.39	0.88	0.78	0.78
MnO	0.17	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.15	0.16	0.16	0.16	0.15	0.15	0.15
CaO/Al_2O_3	0.643	0.950	0.100	0.080	0.231	0.582	0.687	0.590	0.778	0.492	0.172	0.165	0.373	0.299	0.369

TABLE 17 (c)

Sgurr Mor Calc-Silicates

(Biotite - Plagioclase - Zoisite)

	68785	68786	6881	6971*	6972*	69717	69720	69721*	69722*	69747	69750	69757
SiO_2	66.06	71.52	66.61	69.79	69.47	73.18	75.94	73.84	63.16	78.03	76.11	74.30
Al_2O_3	13.64	13.10	14.81	10.45	11.61	12.30	10.14	10.31	6.56	8.44	10.63	9.11
FeO(tot)	5.96	4.28	4.18	3.17	3.23	3.24	3.25	2.08	3.66	3.36	2.48	3.71
MgO	2.87	1.02	1.40	2.03	1.35	1.61	1.16	0.43	0.64	0.80	0.25	3.25
CaO	8.25	6.68	10.58	11.34	9.97	5.37	5.40	9.54	22.72	6.60	9.26	8.13
Na_2O	0.58	1.74	0.69	1.18	2.25	2.38	2.32	2.68	1.42	1.11	0.39	0.34
K_2O	1.62	0.69	0.92	1.35	1.36	1.07	1.13	0.47	0.47	0.98	0.27	0.41
TiO_2	0.88	0.83	0.62	0.55	0.65	0.74	0.55	0.48	0.47	0.51	0.46	0.50
MnO	0.15	00.15	0.20	0.17	0.13	0.12	0.13	0.17	0.89	0.18	0.14	0.27
CaO/Al_2O_3	0.605	0.510	0.714	1.085	0.859	0.437	0.533	0.925	3.460	0.782	0.871	0.892

* contains calcite.

TABLE 18 (a)

Sgurr Mor Calc-Silicates

Rocks containing both Hornblende and Biotite

	68627	68629	68630	68631	6877	6879	68717	68735	68737	68776
SiO_2	63.87	67.34	69.42	67.22	69.28	71.19	75.42	62.15	67.67	62.25
Al_2O_3	13.45	13.02	13.38	13.51	14.68	13.74	11.96	14.58	14.77	14.50
FeO(tot)	6.05	4.06	3.28	3.87	5.52	3.51	3.66	5.86	4.11	6.29
MgO	2.34	1.34	0.64	1.43	2.40	1.52	1.41	2.98	0.95	3.50
CaO	13.05	12.70	12.11	12.65	2.92	7.28	4.69	12.41	9.02	10.40
Na_2O	0.26	0.16	0.16	0.19	2.37	0.68	1.23	0.15	1.38	0.64
K_2O	0.38	0.23	0.32	0.19	1.58	1.28	0.90	0.67	0.90	1.08
TiO_2	0.33	0.93	0.53	0.78	1.10	0.63	0.59	0.95	1.01	1.14
MnO	0.26	0.21	0.16	0.16	0.15	0.16	0.15	0.24	0.19	0.19
CaO/Al_2O_3	0.970	0.975	0.905	0.936	0.199	0.530	0.392	0.851	0.611	0.717

TABLE 18 (b)

Sgurr Mor Calc-Silicates

Rocks containing both Hornblende and Biotite

	68777	68779	68748	6884	69441	6979*	69713	89742	69753
SiO_2	63.06	65.99	65.54	70.15	74.03	69.36	78.29	68.52	71.05
Al_2O_3	14.40	14.94	14.29	12.35	8.48	11.79	8.36	13.97	11.96
FeO(tot)	5.96	4.66	5.51	3.37	4.20	3.21	1.89	3.23	3.91
MgO	2.69	1.37	2.06	1.01	1.57	2.36	0.25	1.66	0.54
CaO	11.26	10.82	9.38	11.78	9.70	11.54	10.39	9.49	11.20
Na_2O	0.40	1.05	1.80	0.19	0.25	0.58	0.28	1.06	0.17
K_2O	0.97	0.36	0.26	0.35	0.68	0.33	0.08	0.99	0.42
TiO_2	1.09	0.64	1.02	0.65	0.90	0.66	0.31	0.87	0.61
MnO	0.16	0.16	0.15	0.15	0.18	0.18	0.14	0.23	0.16
CaO/Al_2O_3	0.782	0.724	0.656	0.954	1.143	0.979	1.243	0.679	0.936

* contains calcite

to be the direct result of differences of metamorphic grade. The increasing abundance of hornblende indicates increasing metamorphic grade; this parallels Kennedy's replacement of biotite by hornblende with increasing grade. In rocks with a CaO/Al_2O_3 ratio of less than 0.300, hornblende was not seen; rocks containing less than this ratio are not considered to be calc-silicates, as the calcium content is too low, and they do not seem to develop the distinctive mineralogy. Chemically and lithologically they are semipsammites. Where a critical ratio for the reaction from hornblende to biotite occurs, hornblende is always preserved in the more calcic rocks. Therefore, the more calcic the rock in which hornblende is replaced by biotite, the lower is its metamorphic grade.

By plotting the points at which a hornblende biotite reaction was observed, and noting the critical CaO/Al_2O_3 ratio at which this reaction proceeded, it was possible to plot variations in metamorphic grade, as indicated by these ratios, on a map. Around Carn na Criche (Fig.24), abundant calc-silicate bands, and mountainous terrain enabled an assessment of the variation of metamorphic grade in three dimensions. With a height difference of over 400 metres in a small area it was possible to plot planes of equal metamorphic grade, in addition to ordinary isograds. Calc-silicates were collected from similar elevations both north and south of Carn na Criche, so

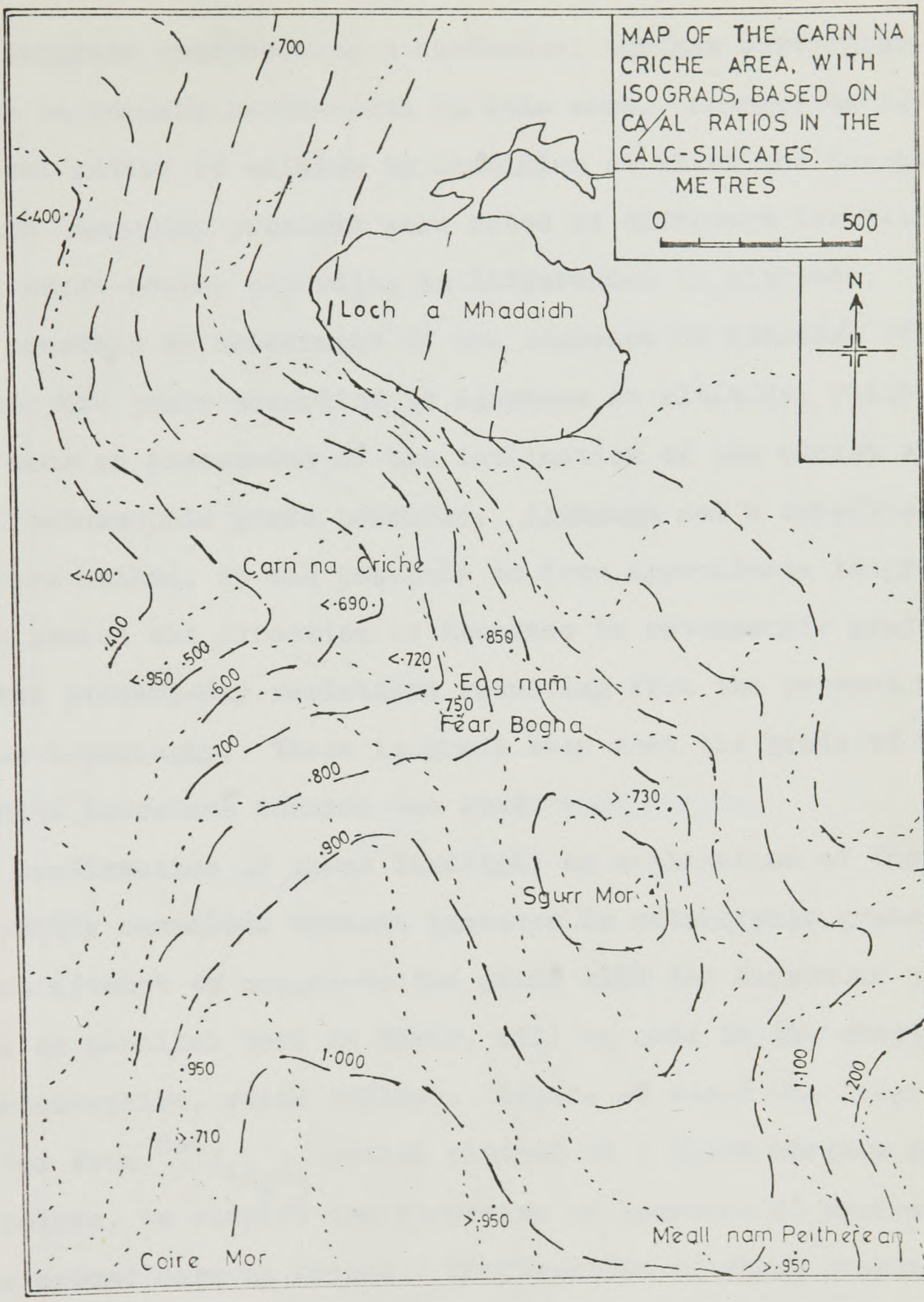


Figure 24. Topographic contours are at 100 metre intervals.

that isograds intersecting a horizontal surface were interpreted as running north-south in this area. Changes in the critical ratios of calcium to aluminium at which the hornblende-biotite reaction proceeds were noted at different localities lying north-south, according to differences in altitude. This made possible an assessment of the increase or decrease of metamorphic grade according to increase in altitude, which in turn made an assessment of the inclination of the planes of equal metamorphic grade possible. Although not a completely accurate method, it was possible to draw approximate isograds which showed the direction of increase in metamorphic grade and the present-day variations resulting from the present mountainous topography. These isograds show that the grade of metamorphism increases towards the west.

Confirmation of these findings, an explanation of the apparently anomalous upwards increase in metamorphic grade, and an attempt to correlate the grade with the Barrovian zones, based on parallel work in Morar, will be made in the chapter on metamorphism, which follows. Figure 25 shows the isograds derived from $^{CaO}/_{Al_2O_3}$ ratios plotted on a plane surface at 500 metres, to clarify the direction of increase of metamorphic grade around Carn na Criche. Confirmation of these general findings will be discussed in the next chapter.

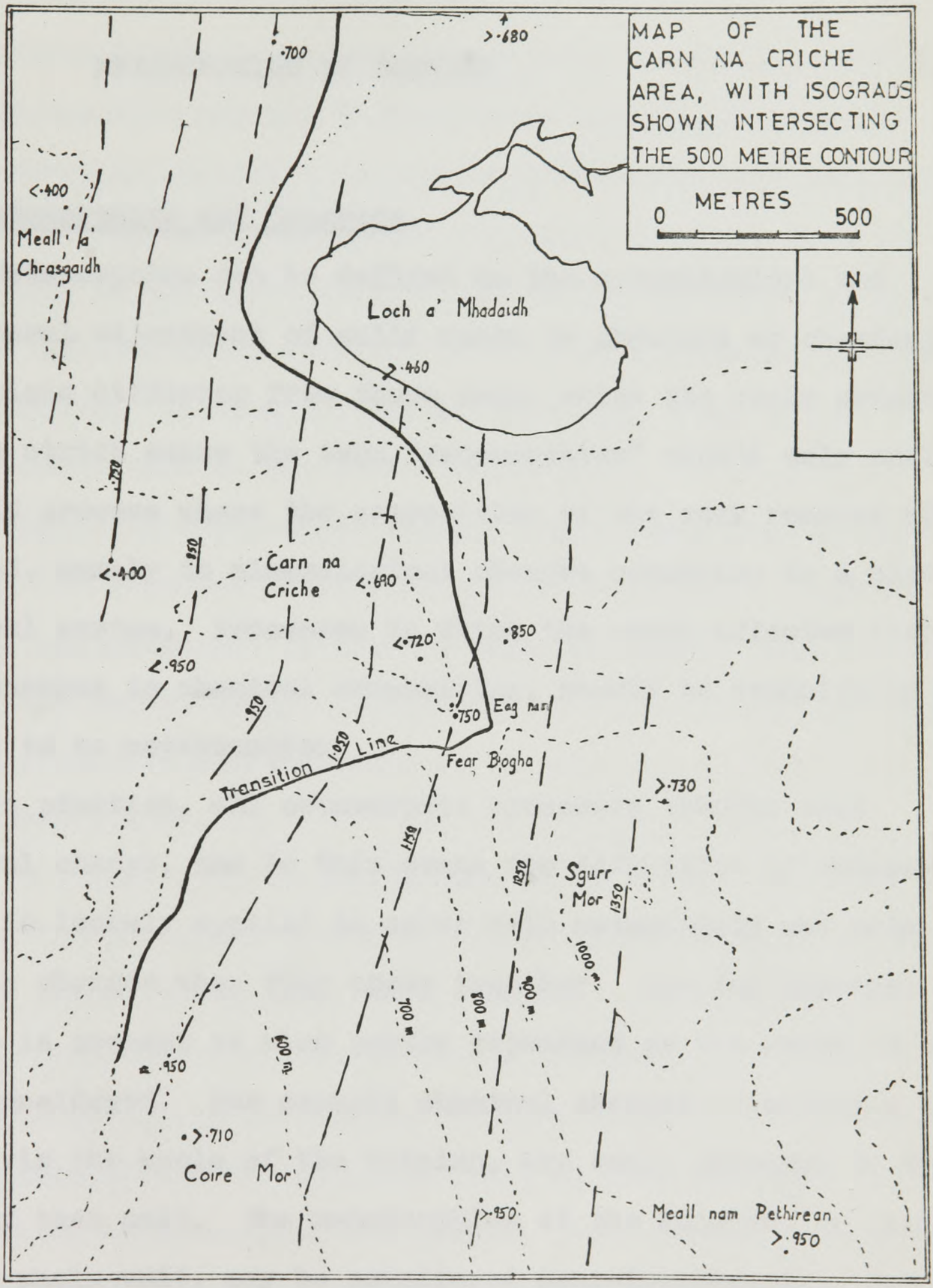


Figure 25. Topographic contours are at 100 metre intervals.

8

METAMORPHISM IN FANNICH

1. Metamorphism and Isograds.

Metamorphism can be defined as the mineralogical and structural adjustment of solid rocks to physical or chemical conditions differing from those under which the rocks originated. In the strict sense the term "metamorphism" should only apply to this process where the composition of the rock remains unaltered, namely to mineralogical changes occurring in a closed chemical system. Processes in which the rocks affected also show changes in chemical composition, should be technically referred to as metasomatism.

In practice, all metamorphic processes involve some chemical change, and in this sense the definition of metamorphism is loosely applied to cover both metamorphic and metasomatic changes when they occur together. How far chemical change is present is also partly dependent on the scale of the unit considered. For example chemical changes affecting a large unit, viz the whole of the Moinian, are small compared to the bulk of that unit. The metamorphism of the Moinian, as applied to the whole unit, may be considered near-isochemical. But

if a small part of the same unit is considered, subjected to the same conditions of metamorphism, for example one of the calc-silicate strips in the Sgurr Mor Pelite, with the interchange of elements between calc-silicate and country rock, the metamorphism affecting the calc-silicate can only be allochemical. With, for example, the transfer of potash from the country rock to the calc-silicate during the formation of biotite, the calc-silicate affected must be considered as part of an open system. In this particular reaction, local potash metasomatism occurs in the strict sense.

But such small-scale examples of metasomatism are ~~normal~~ normal in the regional metamorphism of a large unit. Therefore the term "metamorphism" is used in this thesis to cover all the chemical and mineralogical changes in the rocks in Fannich that apparently reflect their adjustment to changing physical and chemical conditions.

But the definition of metamorphism itself, and the understanding of 'grade of metamorphism' as the measure of the intensity of the metamorphic processes, do not sufficiently convey the complexity of the processes involved. With the addition of energy to the system, usually in the form of heat, more and more processes can be invoked, as more and more elements become mobile components of the system. For example, "grade of metamorphism" is recognized in the diagnostic residual

mineral assemblages of rocks that have been subjected to certain partial pressures of water, oxygen, carbon dioxide, and of other volatile components, which increase in number as the temperature is raised. It can be used as a measure of the intensity of metamorphism. In the Barrovian suite of progressive metamorphism, increase of metamorphic grade is usually reflected in the dehydration of the system, with the replacement of hydrous minerals by anhydrous ones, and the migration of the water, thus liberated, from the system.

Turner (1968) states that the influence of increasing temperature was considered to overshadow that of increasing pressure, but that now the reaction is visualised simply as the result of progressive dehydration or decarbonation under increasing temperature. But in Fannich dehydration may occur simultaneously with recarbonation or vice versa. Can these reactions be considered as indicating changes of metamorphic grade? But since most metamorphic reactions show that dehydration is more dominant that decarbonation in the higher grades, it is dehydration which is taken here as indicative of increasing metamorphic grade.

By this criterion most reactions in Fannich indicate that metamorphism is retrogressive. Most reactions involve the formation of a new mineral assemblage on addition of water into the system. In Fannich, therefore, the indications that

the metamorphism is retrogressive are based on the increased water content of the system after the visible reactions have been completed.

But for retrogression to have occured in Fannich, there must have been an earlier progressive metamorphism to account for the breakdown of the pre-existing minerals diagnostic of higher grade, such as kyanite. That retrogression has occurred is also indicated by reversed zoning in garnets. These sources of information will be discussed below under separate headings.

The grade of metamorphism in an area is usually shown by drawing isograds to denote the variations, and delimit points where the intensity of metamorphism was equal. Tilley (1924) defined an isograd as "a line joining points of similar pressure /temperature values in metamorphic rocks." But the appearance of an index mineral must also depend on the composition of the rock, while the timing of its appearance must also depend upon the chemistry. This is admirably shown in the timing of the appearance of biotite in the Sgurr Mor calc-silicates. But in these the additional influences of temperature and pressure are hard to assess except by studying the relative stabilities of zoisite and plagioclase in the same rocks.

Atherton (1965) divides isograds into two main types: those based on the first entrance of a mineral or polymorph, and those based on the disappearance of a phase previously

present. Nearly all the isograds commonly used belong to the first type. But isograds of this type, as defined by Tilley, can only be drawn with accuracy in areas of homogeneous rock composition. In Fannich, even with individual units, there is considerable compositional variation, and so the isograds shown are drawn on the understanding that they connect areas of only approximately equal grade.

Isograds of the first type outlined by Atherton include all Barrow's classical isograds. Atherton divides isograds of this type into six groups, of which only three have been used to assess the grade of metamorphism in Fannich. These three include:

1. Isograds based on Polymorphic Transitions.
2. Isograds based on the appearance of a Single Mineral of non-variable composition.
3. Isograds based on the appearance of a single mineral with a composition found to vary systematically with metamorphic grade.

These will be briefly discussed in turn:

1. Polymorphic Transitions: Aluminosilicate minerals are rare in Fannich, because the CaO/Al_2O_5 ratio in the pelitic rocks is usually too high to permit their formation. In this the Fannich pelites are typical of the Moine Series. But the presence of kyanite does enable some idea of the pressure-

temperature environment to be gained, by reference to the experimental work on the stability fields of the main aluminosilicate polymorphs.

2. Single Mineral Isograds: These are based on the appearance of a mineral with a non-variable composition, for example, staurolite. No staurolite was seen in Fannich, although other indicators of metamorphic grade suggest that the pressure-temperature conditions were favourable to its formation. Williamson (1953) believed that staurolite only develops in rocks with a low MgO content, and a Fe_2O_3/Al_2O_3 ratio around, or less than 0.40, and Atherton's work in the Dalradian supports this. Since the Fe_2O_3/Al_2O_3 ratios of pelites from Fannich usually exceed this figure, and since much of the alumina occurs in plagioclase, as a result of the higher CaO content of the Fannich pelites, staurolite has not developed. Nevertheless the first appearance of kyanite in Fannich could be taken as an example of a Single-Mineral Isograd. Although the only kyanite seen is now breaking down, the fact that it formed at all indicates that Fannich has been subjected to kyanite-grade metamorphism.

3. Isograds based on the appearance of a single mineral which varies in composition systematically with the variation in metamorphic grade.

Garnet is the best-documented example of a family of

minerals in which the substitution of certain ions occurs systematically with grade. Hornblende and biotite also vary systematically when present in association with garnet. Research by Miyashiro (1953), Lambert (1959), Sturt (1962) Atherton & Edmunds (1966), and Atherton (1968) shows a direct variation of garnet composition with grade, while Atherton also discusses variation in garnet composition related to the CaO and MnO bulk compositions of the host-rock.

Garnets are ubiquitous in Fannich, and those analysed from the Meall an t-Sithe Pelite were used to assess the metamorphic grade in the centre of the area mapped. Although the grade of metamorphism is shown in Figure 26 in terms of Barrovian Zones, the 'isograds' used are based on correlations between garnet composition and metamorphic grade as derived by Sturt (1962), and Nandi (1967) and also on the evidence derived from calc-silicates in Fannich. These will be discussed in greater detail below.

8.2 Previous Research in Fannich

After mapping in Fannich, Gunn concluded that the grade of metamorphism in the Meall an t-Sithe Pelite and the Lewisian Gneisses was higher than in the underlying units. Finding no evidence for a tectonic break, he concluded that the Lewisian and the pelite were really inverted, and this explained their

higher metamorphic grade. The evidence for this conclusion is not clearly set out; Gunn apparently based it upon the grain-size of the constituent minerals in the psammites, and partly on the abundance of pegmatites. The mention of these pegmatites by Horne (1913) was interpreted by later geologists as implying that an injection complex exists at Fannich, thereby suggesting that the area with the highest concentration of pegmatites had been subjected to the most intense metamorphism.

Sutton and Watson (1954) reported the occurrence of sillimanite in the Meall an t-Sithe Pelite. That much of Fannich covered by the pelite was subjected to sillimanite-grade pressure-temperature conditions at the peak of metamorphism is also suggested by garnet compositions, but the greatest concentration of pegmatites, just west of Coire Breac, does not appear to coincide with the area subjected to the most intense metamorphism, suggested by garnet composition.

In the remainder of this chapter the evidence derived from recent fieldwork will be critically discussed and assessed. Pelite mineralogy, amphibolite mineralogy, the mineral assemblage and chemical composition of Sgurr Mor calc-silicates, and the composition and zonation of garnets were all used to assess the metamorphic grade and these lines of evidence will be discussed in turn.

8.3 Pelites and Amphibolites

Fannich lies north of the part of Scotland where pelite-based Barrovian grades of metamorphism have been drawn. Further south, Barrovian zones were drawn according to the mineral assemblages of Dalradian pelites, but Moinian pelites, containing a higher CaO content, tend not to develop staurolite or aluminosilicate minerals. Projecting higher-grade Barrow isograds further north is therefore difficult.

Garnet is abundant in all but a few muscovite-rich pelitic strips, and occurs scattered throughout the pelites of Fannich Forest. It also occurs in every other rock-type recorded in the area, so the whole region must have been subjected to Barrovian garnet grade, or more intense metamorphism.

Staurolite was not seen in Fannich, but kyanite occurs in Meall an t-Sithe Pelite, breaking down to form muscovite (Plate 15). Barrow (1893) defined his kyanite zone by the presence of kyanite, but since it is rare in high-grade Moinian pelites, as in eastern Morar, its absence does not imply that the pressure-temperature conditions did not reach the intensity characteristic of the kyanite grade as defined in the Dalradian. Therefore, in spite of the scarcity of kyanite, parts of Fannich may have been subjected to kyanite-grade metamorphism. The observed breakdown of kyanite indicates that subsequent retrogression also occurred. Sillimanite has been reported from

Fannich (Sutton and Watson 1954), but was not seen in samples recently collected.

Wiseman (1934) used mineral assemblages in amphibolite to assess metamorphic grade. He interpreted the presence of almandine as indicating garnet-grade conditions, the absence of biotite as indicative of kyanite grade. All amphibolites in Fannich either contain garnet or occur close to a garnet-bearing amphibolite. Biotite occurs in all Moinian amphibolites, but appears to result from a later period of growth when it occurs in Lewisian ones, possibly a result of the percolation through the Lewisian of potassic solutions derived from the Moinian. By suggesting that Fannich falls within the garnet or kyanite zones, amphibolites add little to the evidence supplied by the pelites.

8.4 Calc-Silicates and Metamorphic Grade

The conversion of hornblende to biotite, usually occurring in association with the breakdown of plagioclase to form zoisite, was discussed in the chapter on calc-silicates. According to Kennedy's zonation, this reaction is retrograde, and preservation of hornblende in a calc-silicate of a given composition indicates that it has preserved a higher metamorphic-grade assemblage than a chemically identical calc-silicate containing biotite. As already stated, the CaO/Al_2O_3 ratio provides a

useful indicator of metamorphic grade when used in connection with the mineral assemblage. By collecting calc-silicates in the Carn na Criche area a local picture of the variations in metamorphic grade was built up. This will now be described in more detail (see Figs 24, 25).

In Coire Mor, at an elevation of 600 metres, the critical CaO/Al_2O_3 ratio, in which rocks containing a lower ratio than the critical one contain biotite formed at the expense of hornblende, is approximately 1.050. Around Loch a' Mhadaidh, at an elevation of 560 metres, no calc-silicates containing a ratio of over 0.680 were seen, and all contained biotite. Therefore the Critical Ratio is higher than 0.680 around the loch. At a height of 800 metres on Carn na Criche, both biotite -bearing and hornblende-bearing calc-silicates occur. In some rocks the hornblende was unstable, and from the whole-rock compositions of these rocks the Critical Ratio was placed at 0.850. At about 900 metres on the saddle between Carn na Criche and Sgurr Mor, named Eag nam Fear Bogha, a sample with a ratio of 0.806 contained chloritized hornblende, and another containing biotite rimming relict amphibole cores showed a ratio of 0.611. The Critical Ratio was estimated to be about 0.750 here, while at an elevation of 960 metres on Carn na Criche, but situated further west, hornblende shows no sign of instability in a calc-silicate with a ratio of 0.699. To the west of Carn na Criche

on Am Burach at a height of 850 metres, hornblende remains stable in a sample with a ratio of only 0.405. The Critical Ratio must therefore be even lower at this point. From these findings, it was clear that the Critical Ratio becomes lower towards the west, and hornblende is the typical ferromagnesian mineral in the more westerly calc-silicates. By analogy with Kennedy's work, the greater dominance of hornblende to the west also indicates that grade of metamorphism increases westwards.

To the north of Carn na Criche, at an altitude of 650 metres, on the north-east spur of Meall a' Chrasgaidh, a collection of hornblende-bearing, and biotite-bearing calc-silicates showed the Critical Ratio to be 0.700, but to the south-west at a height of 750 metres, the Critical Ratio is less than 0.400. This occurrence of higher Critical Ratios in Coire Mor and around Loch a' Mhadaidh, and lower Critical Ratios, as observed in between on Carn na Criche suggested that present-day elevation also affects the configuration of isograds based on the Critical Ratio. With lower Critical Ratios on the higher ground, by analogy with Kennedy, the grade of metamorphism also appears to increase upwards. According to the observations on Carn na Criche, the Critical Ratio is reduced along the "strike" of the isograds by approximately 0.100 for every 100 metres gained in height. In Figure 25, the isograds are drawn reduced to a plane surface at 500 metres above sea-level. If the correction

for altitude is wrong, the figures gained from different heights would not fit the isograd pattern as well as they do. No hornblende-bearing calc-silicates were seen on Sgurr Mor or Meall nan Pethirean, but according to the Critical Ratio isograds, as drawn in Fig.24, they could occur on Sgurr Mor, where at a height of 1000 metres, no calc-silicates containing a ratio of over 0.730 were collected. This is interpreted as the reason why no hornblende was seen, but more calcareous examples from the same locality should contain hornblende.

The 'isograds' reduced to a plane surface in Fig.25 are placed about 220 metres apart over much of the district. Therefore the Critical Ratio increases by 0.100 for every 220 metres at a constant elevation towards the east. By simple trigonometry, the elevation corrections, and the rate of increase of the Critical Ratio along a horizontal surface, show that the planes of equal metamorphic grade in the Carn na Criche area dip at about 25° west, and strike approximately 10° east of True North. Thus, although many small variations of the metamorphic grade may occur in this area, the isograds drawn in Figure 25 can be considered as the intersects of the present land-surface with the planar isograde surfaces just described.

Also drawn on Figure 25 is the 'Transition Line'. This is the 0.800 CaO/Al_2O_3 Critical Ratio Isograd. As 0.800 is an average ratio for calc-silicates in Fannich, this line divides

the area in which hornblende is dominant from that where biotite is the dominant ferromagnesian mineral. Exceptions do occur, as a result of the compositional variations already described.

The lines on the map connecting points of equal CaO/Al_2O_3 Critical Ratio have hitherto been described as isograds. Reaction 15, incorporating both the hornblende-biotite, and plagioclase-zoisite reactions, involves hydration. Earlier in this chapter, it was concluded that dehydration is an essential feature of progressive metamorphism. The calc-silicate isograds are therefore iso_grads of retrogressive metamorphism.

So far, calc-silicate isograds have only been described from around Carn na Criche. But groups of samples delimiting the hornblende to biotite inversion were collected from numerous localities in and around Fannich (Fig.21). Among these were the River Cuileig, the Allt an Fas Bhig, the headwaters of the Allt Coire nam Fear Ribhaich, the Allt a' Bhraighe, the eastern outliers of the Fannich Range and Lochluichart. Using the same method as around Carn na Criche, isograds based on the Critical CaO/Al_2O_3 Ratio variations can be drawn. Because of the distances between some of the collecting sites, the accuracy of these isograds is proportionately less than in the Carn na Criche area. As indicated in Figure 26 only the extremely calcic rocks at Lochluichart retain hornblende; at the other

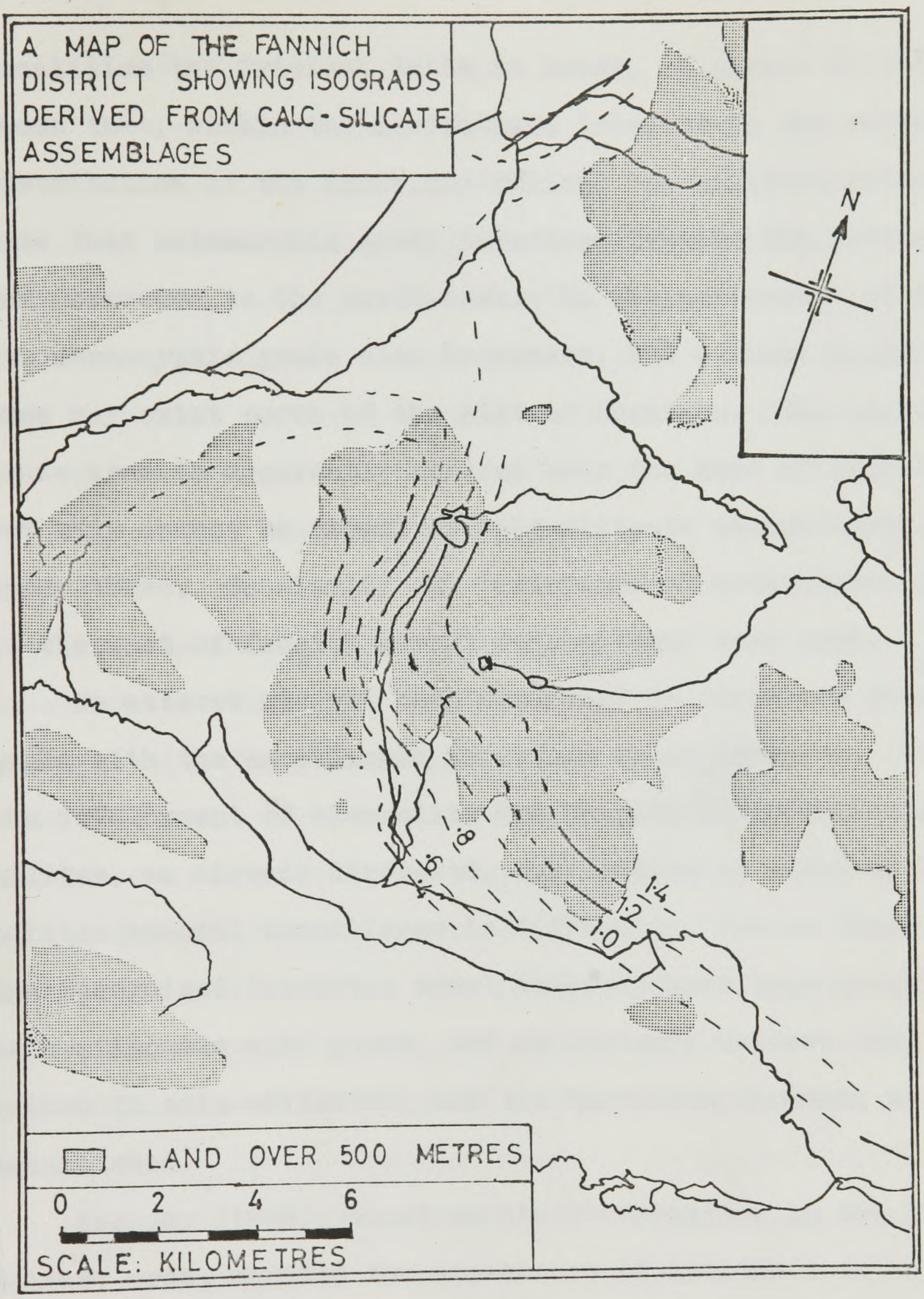

A MAP OF THE FANNICH DISTRICT SHOWING ISOGRADS DERIVED FROM CALC-SILICATE ASSEMBLAGES
N
1·8
1·6
1·4
1·2
1·0
LAND OVER 500 METRES
0 2 4 6
SCALE: KILOMETRES

Figure 26.

localities the Critical Ratio is lower. A glance at the map shows that, within the limitations inherent in the restricted distribution of the Sgurr Mor Pelite, the critical ratios indicate that metamorphic grade increases towards the south-west, and decreases to the north-east. To the north-west of Fannich the metamorphic grade also decreases, but a local higher grade area may exist north of the Allt a' Bhraighe. The highest grade area is apparently centred near the head of Loch Fannich, but this cannot be proved by calc-silicate assemblages, as none occur there. To clarify the variations of metamorphic grade in the west of Fannich garnet compositions were used.

No attempt has yet been described to correlate these retrogressive isograds with the established Barrovian zonal isograds. Since the development of staurolite and kyanite is rare in Moinian pelites, as already discussed, correlation by means of local pelitic mineral assemblages is difficult. But in Morar, where the recognized Barrovian zonal isograds have been roughly plotted calc-silicates also occur, and an analogy, between CaO/Al_2O_3 ratios in calc-silicates, and the Barrovian isograds can be established.

Kennedy (1949), based on his observations in the Knoydart-Moidart area, equated the appearance of anorthite in calc-silicates with the kyanite isograd. Poole (1962), suggested that anorthite is not developed in the calc-silicates until

the metamorphic grade falls well within the kyanite zone. Based on his observations in North-East Morar, Poole placed the Biotite-Hornblende reaction in the middle of the Garnet Zone. As already discussed, fieldwork in Fannich has shown that the biotite-hornblende reaction is strongly influenced by the rock composition. Poole (pers. comm.) shows that analysed calc-silicates from the head of Loch Ailort and from the western end of Loch Beoraid contain a CaO/Al_2O_3 Ratio of approximately 0.400, and show the hornblende-biotite reaction. A calc-silicate from east of Tarbet in North-East Morar also showed this reaction, but had a CaO/Al_2O_3 ratio of about 0.500. These ratios can therefore be taken as the Critical Ratios at these places, and compared with the Barrovian Zonal Isograds in the same area. Thus, while the Tarbet calc-silicate is shown as occurring within the Garnet Zone, the other two calc-silicates occur very close to the Kyanite Isograd. Accepting that the exact lines of the Kyanite Isograd in Morar may not be perfectly known, because of the scarcity of kyanite in Moinian pelites, a CaO/Al_2O_3 Critical Ratio of 0.400 in calc-silicates probably lies along the same line as the Kyanite Isograd. In drawing the map showing the metamorphic grade of Fannich in terms of Barrovian Zones (Fig.27), the Kyanite Isograd has been drawn along the line of the 0.400 Critical Ratio Isograd. The 1.200 Critical Ratio Isograd is taken as an arbitrary division distinguishing higher-

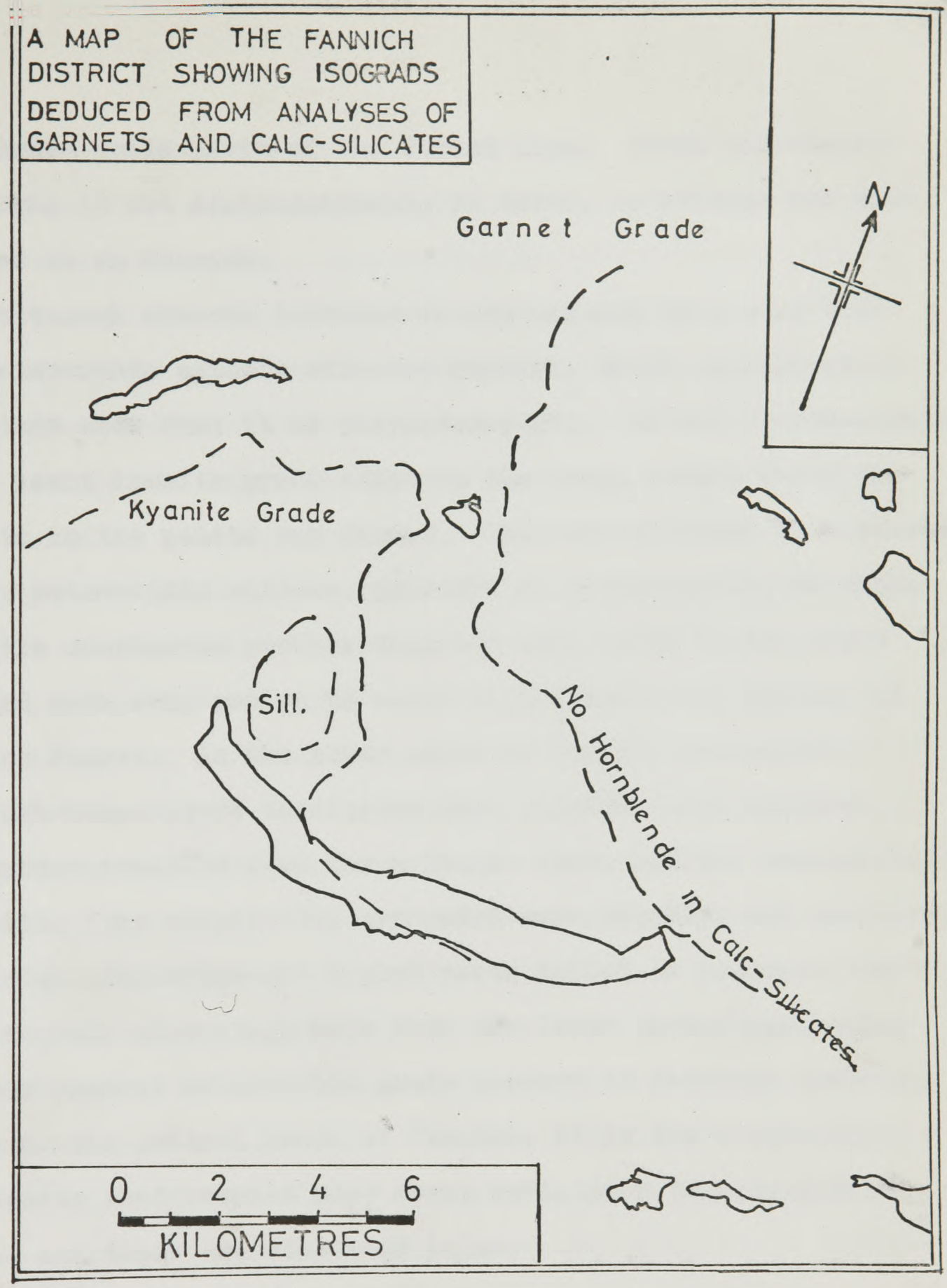

A MAP OF THE FANNICH DISTRICT SHOWING ISOGRADS DEDUCED FROM ANALYSES OF GARNETS AND CALC-SILICATES
N
Garnet Grade
Kyanite Grade
Sill.
No Hornblende in Calc-Silicates
0 2 4 6
KILOMETRES

Figure 27.

and lower- grade parts of the Garnet Zone. Since the Staurolite Zone is not distinguishable in Morar, no attempt was made to show it in Fannich.

Although mineral textures do not suggest that more than one metamorphic episode affected Fannich, these retrogressive reactions show that it is polymetamorphic. An early metamorphism of at least kyanite grade affected the area, during which the kyanite in the pelite was formed. This was followed by a second, milder metamorphic episode, possibly of garnet-grade, in which volatile components perhaps expelled from lower in the crust allowed some rehydration to occur at the level now exposed in Fannich Forest. In the lower parts of Fannich metamorphic pressure-temperature conditions were slightly more intense, the system remained open for a longer time, and the retrogression resulting from rehydration proceeded more rapidly, and was more complete. Therefore the higher parts tended to preserve their higher-grade mineralogy more than the lower parts, explaining why the present metamorphic grade appears to increase upwards. But over the central parts of Fannich, it is the composition of garnets that reveals most about variations in metamorphic grade, and these are discussed below.

8.5 Garnet Analyses

Garnets were selected for analysis in Fannich because

they are among the best-documented minerals showing compositional change related to metamorphic grade, and because they are abundant in Fannich. The variation in the composition of almandine and its relation to metamorphic grade has been described by several geologists. Miyashiro (1953), working in the Gosaisyo-Takanuki district of Japan showed that the MnO content of garnet decreased with increasing metamorphic grade, while a higher overall MnO content indicated that the garnet was closer to a thermal aureole. Experimental work conducted by Yoder and Keith (1951) showed that MnO-rich garnet could be synthesized at atmospheric pressure; therefore the MnO content of garnet may be directly proportional to the pressure of formation. But in Morar, Lambert (1959) did not find a consistent variation of MnO with theoretical increasing grade in garnet. He noted an increase in MgO and a decrease in CaO with increasing grade. This difference may reflect a different heat to pressure ratio in the two metamorphic provinces. Sturt (1962) confirmed the findings of both Miyashiro and Lambert, and suggested that the ratio of CaO + MnO to FeO and MgO could be used as an index of metamorphic grade. Using as a guide, garnets collected from Dalradian pelites near Pitlochry, he showed that their compositions varied systematically with metamorphic grade.

But so far, little mention has been made of host-rock compositional control on garnet composition. Atherton (1964)

concludes from a study of MnO-rich garnets in South-West England and the Dalradian pelites that the MnO content of the host-rock has a direct influence on the MnO content of the garnet. He points out that MnO rich garnet is not confined to low metamorphic grades, and quotes the example of a spessartite garnet dexcribed by Clifford (1960) from sillimanite-grade rocks in New Hampshire. Miyashiro (1956), and Chinner (1960) plotted garnet-biotite analyses from adjacent different host-rocks, and noted the differences in composition possible in rocks of essentially the same metamorphic grade. At Glen Clova, Chinner interpreted this variation as a function of the oxygen content of the rock, but Atherton (1965) suggests that the variation can be more simply interpreted in terms of host-rock composition. Atherton (1968) confirmed that MnO and CaO decrease, and FeO and MgO increase with increasing grade, but concluded that the CaO content of garnet is also affected by host-rock composition. But the FeO content of the garnet was not so dependant on the host-rock FeO content as on the combined MnO and CaO variation. These studies show that garnet is a reliable indicator of metamorphic grade, provided that the garnets are selected from host-rocks with similar CaO and MnO contents.

In Fannich, garnets were analysed by means of Electron Probe Microanalyser from 19 rocks. Their geographical

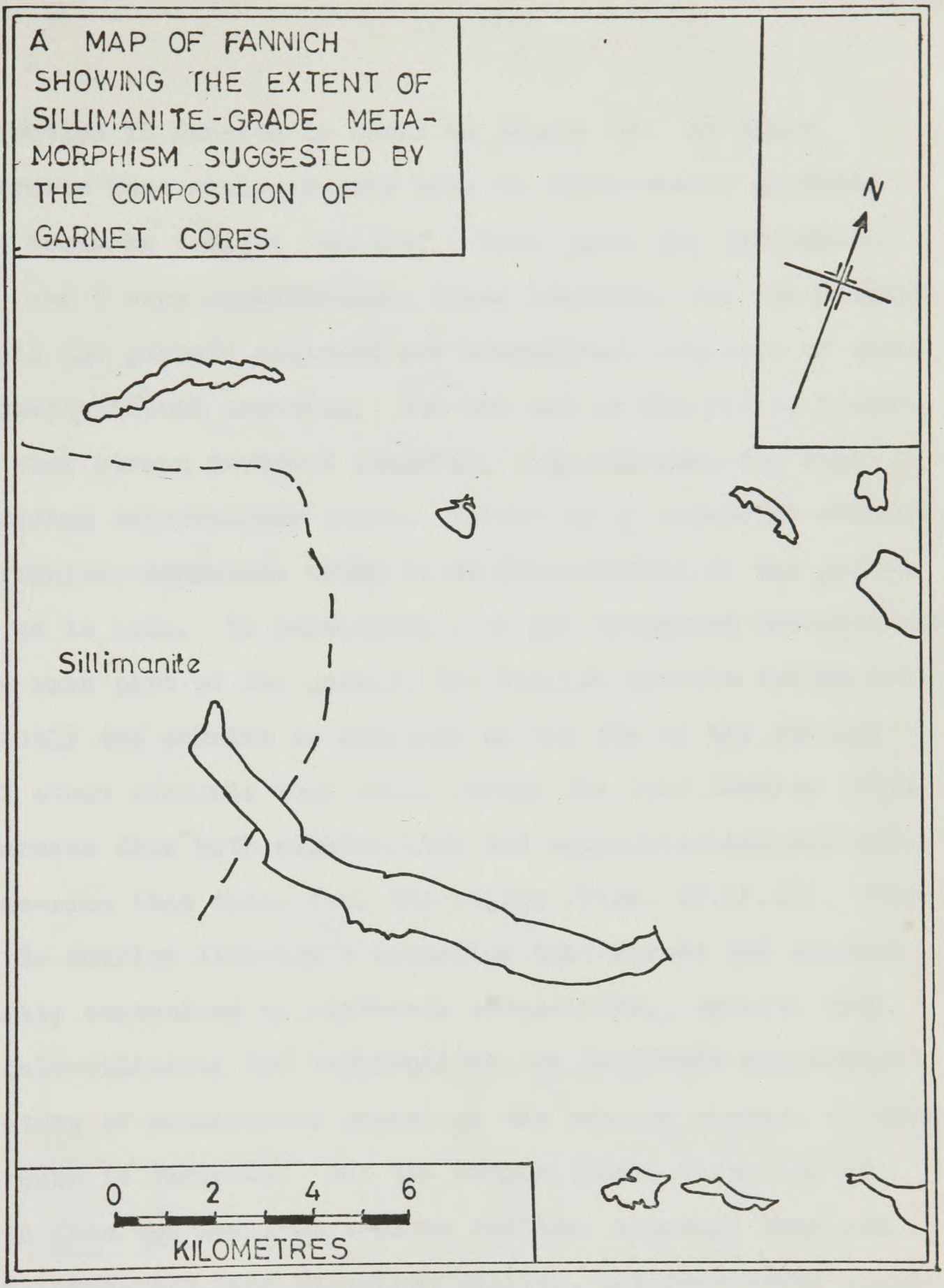
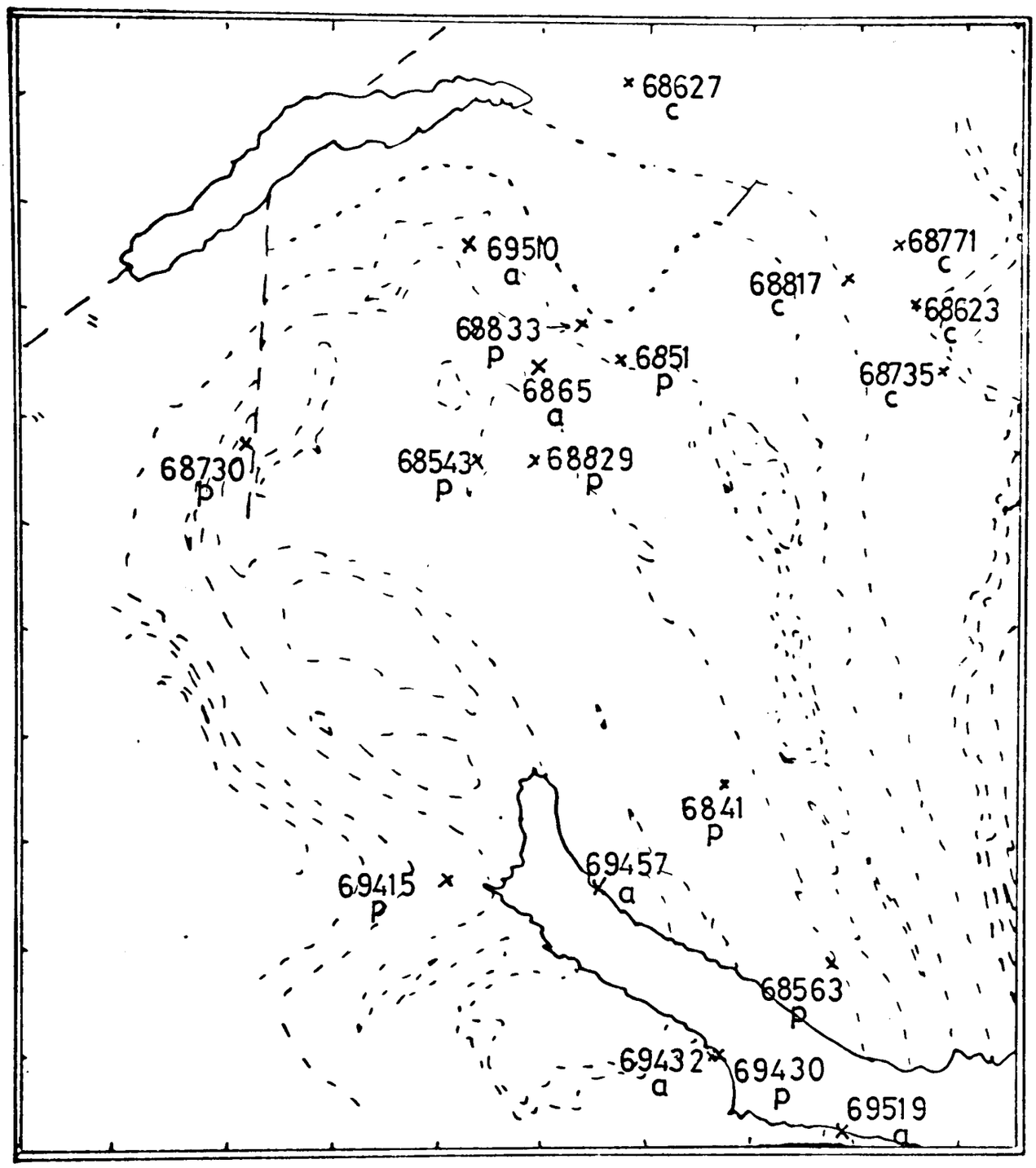

A MAP OF FANNICH SHOWING THE EXTENT OF SILLIMANITE-GRADE METAMORPHISM SUGGESTED BY THE COMPOSITION OF GARNET CORES.
N
Sillimanite
0 2 4 6
KILOMETRES

Figure 28.

distribution in Fannich is shown in Figure 29. At least two garnets were analysed from most of these rocks, of which 9 were Meall an t-Sithe Pelites, 5 were Sgurr Mor calc-silicates, and 5 were amphibolites, three Lewisian, and two Moinian.

All the garnets analysed are almandines, and most of them show compositional zonation. All but one of the pelite almandines show strong reversed zonation, with calcium-rich rims surrounding calcium-poor cores. Variation in magnesium content is irregular; manganese tends to be concentrated in the garnet core, as is iron. In containing iron and manganese concentrated in the same part of the garnet, the Fannich garnets are unusual; apparently the calcium is enriched in the rim at the expense of all other elements that could occupy the same lattice sites. The garnets from both amphibolites and calc-silicates are more calcium-rich than those from the pelite (Figs. 30,31,32); this tends to confirm Atherton's assertion that garnet CaO content is partly controlled by host-rock composition. Garnets from both calc-silicates and amphibolites are therefore unreliable indicators of metamorphic grade, as the calcium content of their host-rocks is variable. But the compositional variation of garnets from the Meall an t-Sithe Pelites, although they are more calcium-rich than Dalradian Pelites, was considered significant, and the CaO and MnO contents of these garnets was plotted against their combined FeO + MgO contents, in a diagram



A MAP OF FANNICH FOREST SHOWING THE POINTS FROM WHICH ANALYSED ALMANDINES WERE COLLECTED.
a: from amphibolite, c: calc-silicate, p: pelite

Figure 20.

GARNETS FROM MEALL AN T-SITHE PELITE

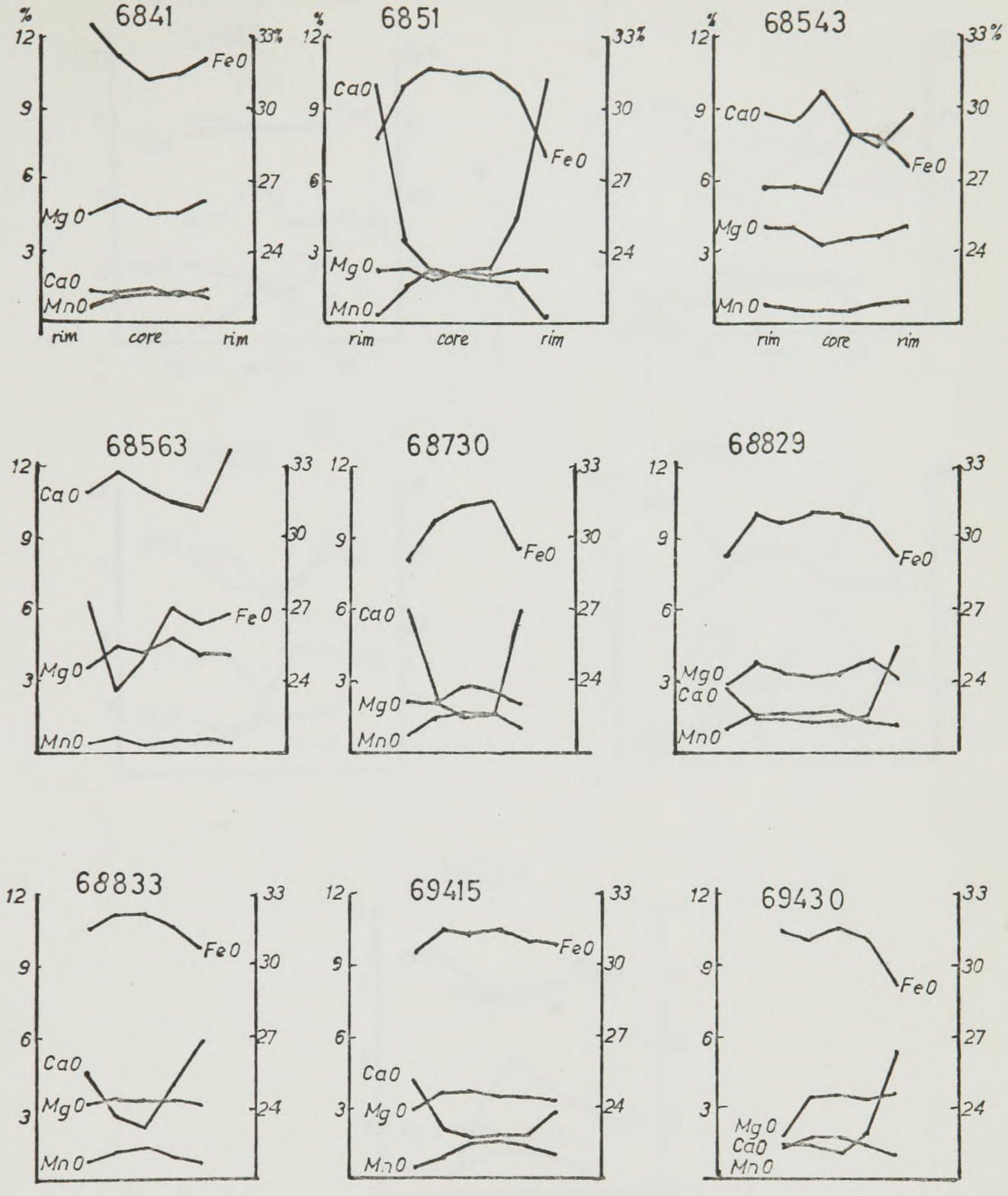


Figure 30.

GARNETS FROM SGURR MOR CALC-SILICATES

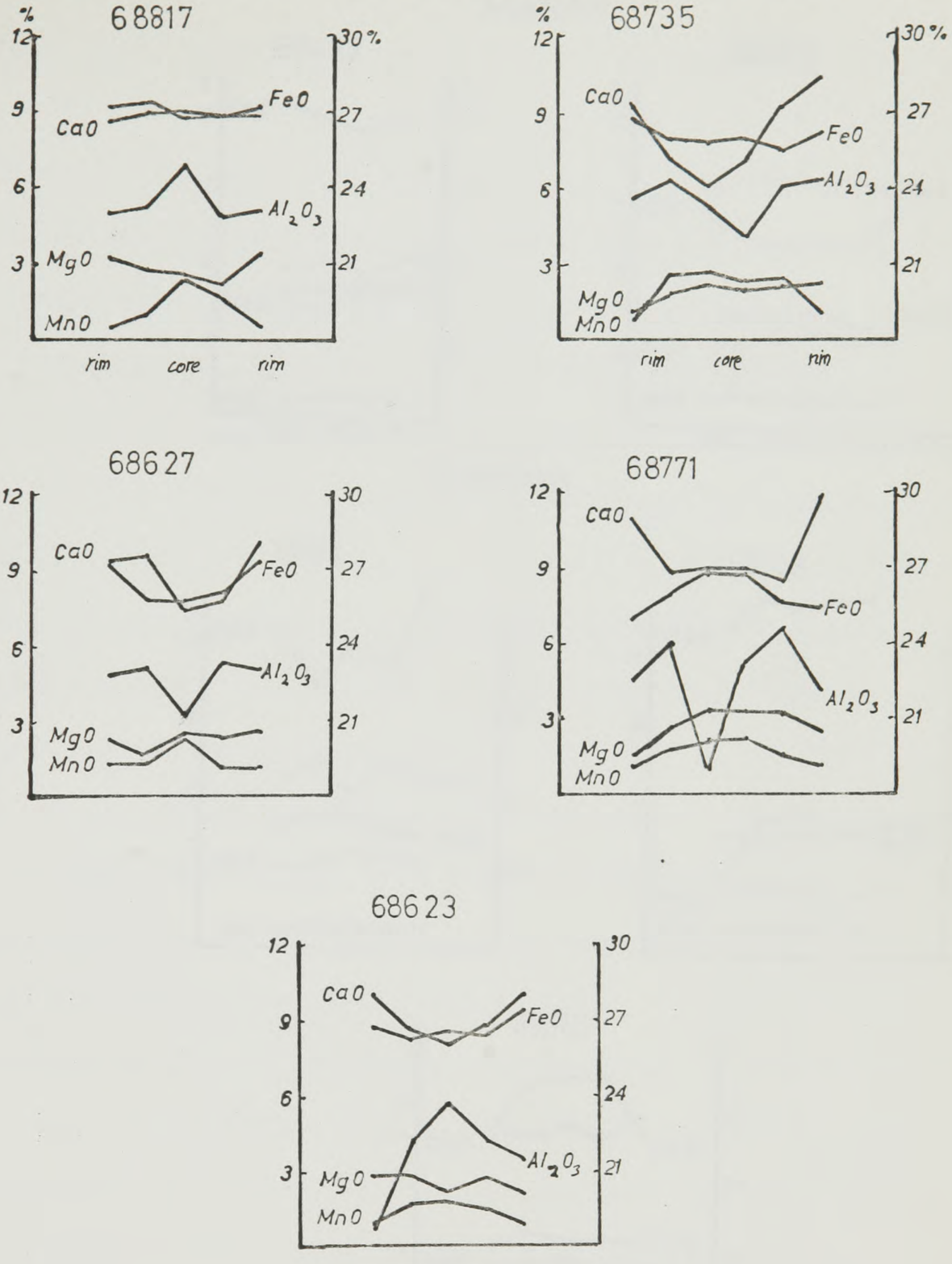
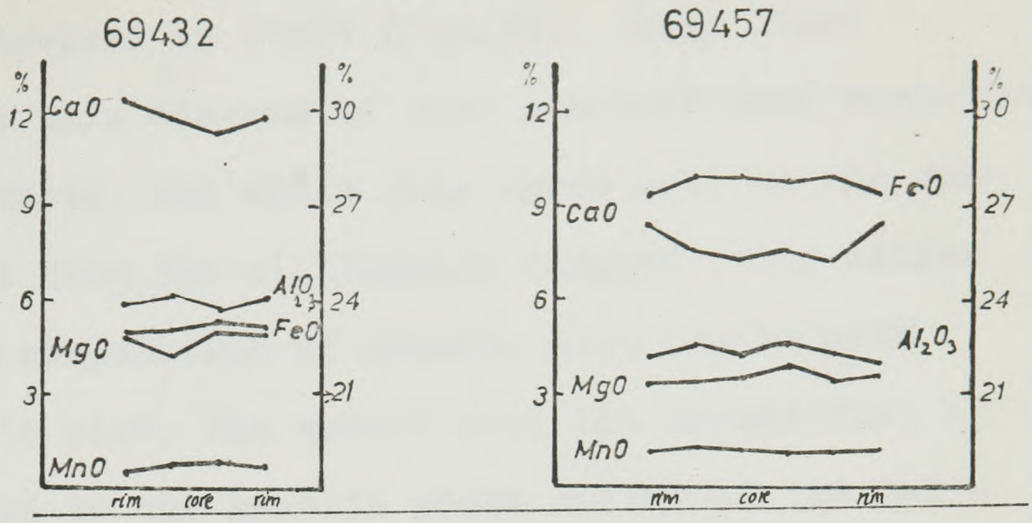


Figure 31.

GARNETS FROM AMPHIBOLITE

MOINIAN



LEWISIAN

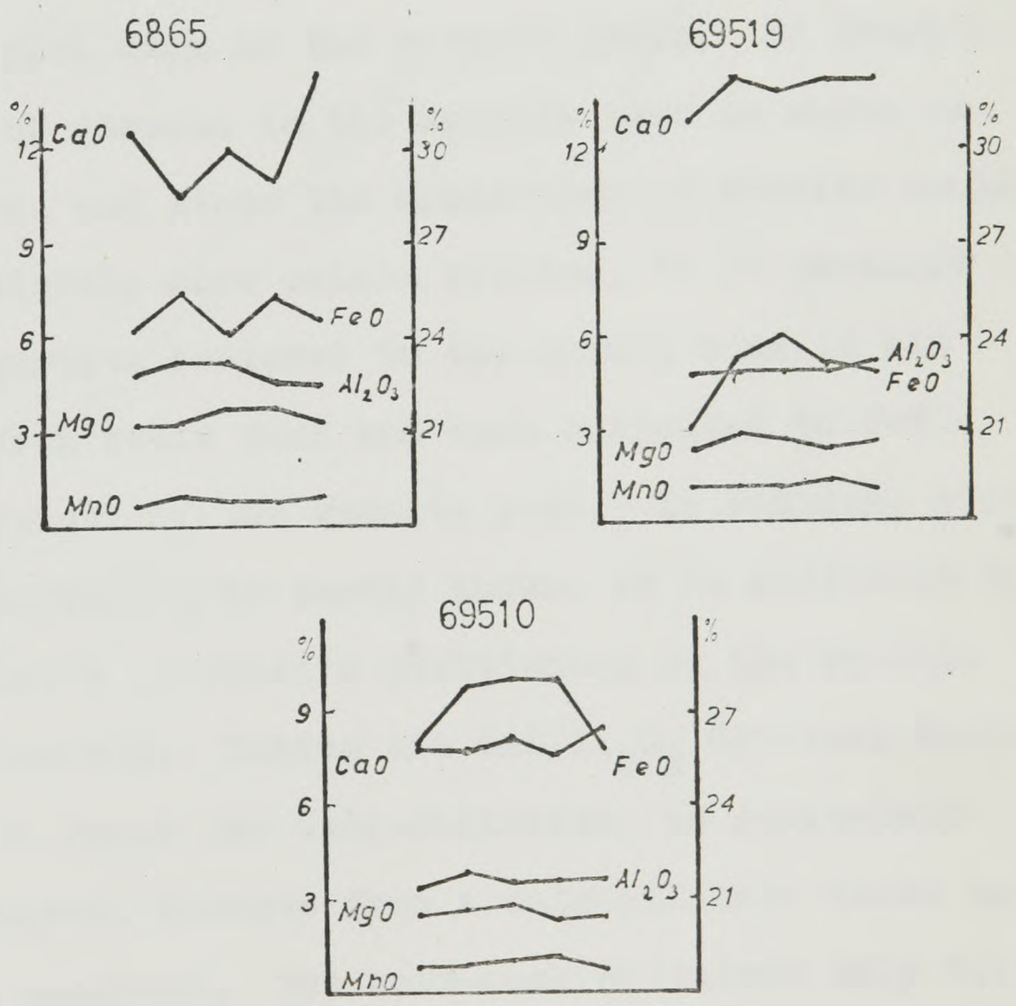


Figure 32.

analogous to that devised by Sturt (Fig.33). Both Sturt and Nandi(1967) use this diagram to show compositional variation in calcium-poor garnets, and while they agree well in the composition of garnets from the sillimanite isograd, they differ radically over the composition of garnets from the kyanite isograd. In Sturt's plot, the garnet with the lowest FeO + MgO content assigned to the kyanite grade contained 33% FeO + MgO and only 4% CaO + MnO. According to Nandi's diagram the same garnet would plot high in the kyanite grade. In Sturt's diagram the range of garnets in the kyanite zone is shown to be extremely narrow, and since the appearance of kyanite could be prevented in slightly more calcic pelites, it is possible that some of the garnets assigned to the garnet zone in his diagram, do come from rocks that had been subjected to P-T conditions more typical of the kyanite zone. In Fannich, since the grade of metamorphism is poorly known, it is difficult to assess whether Sturt's or Nandi's positioning of the kyanite isograd is more accurate. Taking the CaO/Al_2O_3 Critical Ratio of 0.400 isograd in Sgurr Mor Calc-Silicates, as equivalent to the Kyanite isograd, garnets from a calc-silicate close to this isograd were analysed. The host-rock contained only 7.18% CaO, and the final composition of the garnets, as shown by analyses of their rims consisted of: CaO + MnO : 9.1%, FeO + MgO : 30.4%. This composition falls within the kyanite grade,

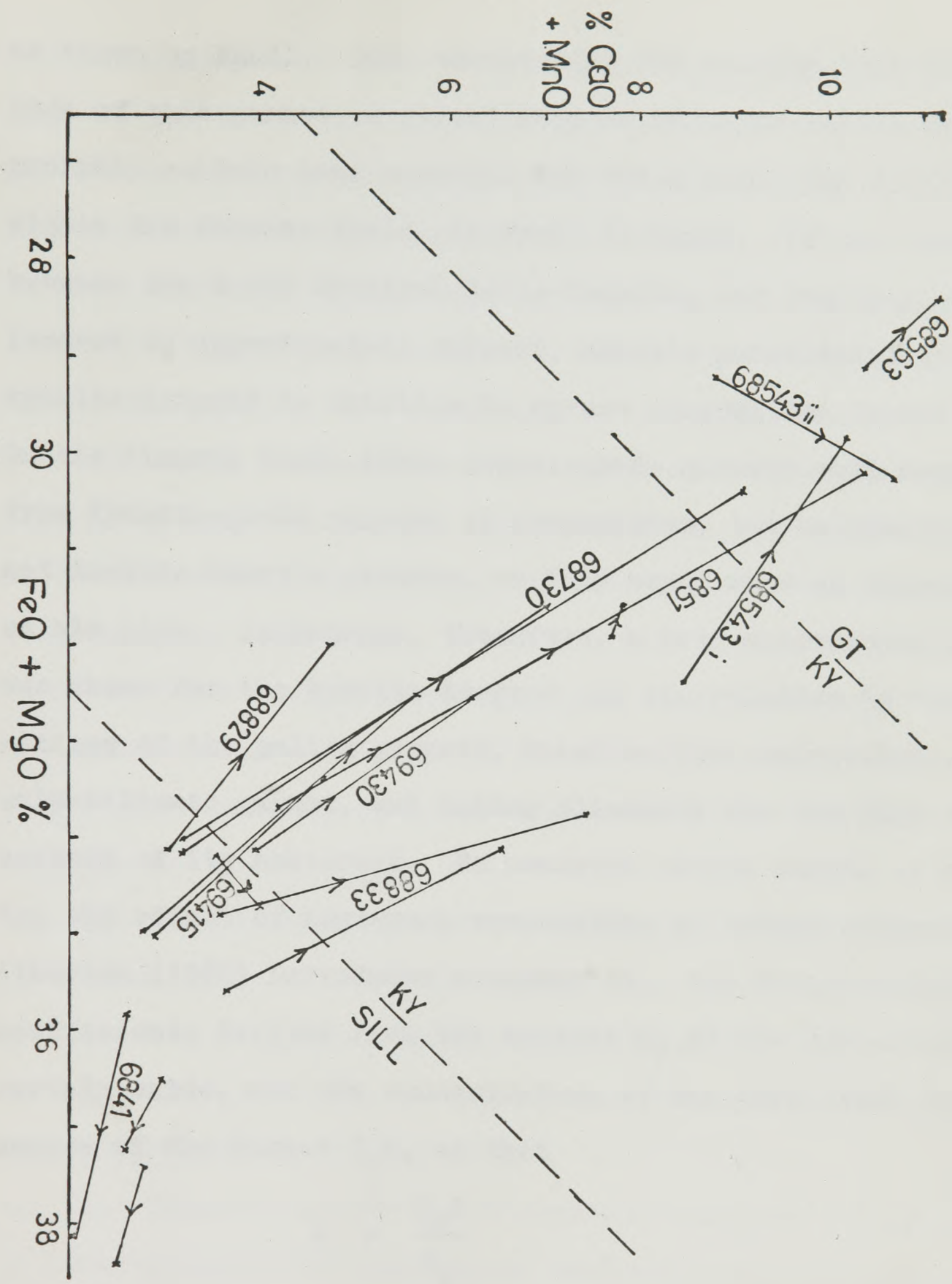


Figure 33. Compositional variations in garnets from the Moall an t-Sithe Polite; CaO + MnO against FeO + MgO, after Sturt 1962.

as shown by Nandi. But, considering the calcium-rich host-rock of this garnet, a garnet from an adjacent pelite would probably contain less calcium, and would plot even further within the kyanite field, as drawn by Nandi. If the analogy between the 0.400 Critical Ratio Isograd, and the Kyanite Isograd is approximately correct, Nandi's positioning of the kyanite isograd in relation to garnet composition is too calcic. On his diagram Nandi shows Garnet-grade garnets well separated from Kyanite-grade garnets in composition, but he clearly does not include Sturt's garnets, or they would show as exceptions on his plot. In Fannich, therefore, a very approximate position was shown for the kyanite isograd and its relation to the compositions of the pelite garnets, based on the composition of this calc-silicate garnet, and making allowance for the high calcium content of its host-rock. No accurate method exists of assessing the effect of host-rock composition on garnet composition. Atherton (1968) introduces a factor (k), the distribution coefficient, derived from the content C_o of the host-rock of a certain oxide, and the concentration of the same oxide at the centre of the garnet $C_o k$, so that

$$k = \frac{C_o k}{C_o}$$

He suggests that k CaO, and k MnO diminish with increasing grade, and that the factor k partly eliminates anomalous CaO

and MnO contents in garnets taken from host-rocks with different CaO and MnO contents. This may work within the pelitic rocks, but when applied to radically different rocks, containing utterly different minerals which absorb calcium, for example clinozoisite and hornblende, k values cannot be used as grade indicators. However, k values may be usable in rocks, other than pelites, which contain the same mineralogy. But because of the lack of other ties between k values and metamorphic grade, this method could not be used in Fannich to discover the metamorphic grade of the rocks from which the garnets were analysed. Any map showing the positions of Barrovian Isograds derived from garnet analyses in Fannich cannot be taken as accurate, but must only be treated as indicating relative differences in metamorphic grade. Reasons for its lack of accuracy are threefold:

1. The shortcomings of the Sturt-Nandi diagram in not accounting for CaO + MnO variations in garnet composition related to the host-rock composition.
2. The difficulty in fixing the position of the kyanite isograd on this diagram.
3. Inaccuracies in the microprobe analyses stemming from the presence of microscopic inclusions in the garnet, and from the lack of adequately analysed almandine standards covering the whole range of garnets analysed.

The kyanite isograd, as drawn approximately for Fannich, falls well between the positions postulated for it by Nandi and Sturt, as shown in Figure 33. Taking this line as approximately marking the kyanite isograd, a map of Fannich was drawn, showing the final position of the isograds after the later metamorphic episode, using the composition of the garnet rims as a guide to the intensity of the final metamorphic event.

Given the composition of garnets on the sillimanite isograd, as suggested by both Sturt and Nandi, Figure 33 shows that several garnets from the pelite contain cores with compositions indicating growth under sillimanite grade conditions. These garnets come from the south and west of Fannich; east of a line drawn from the mouth of the Allt na h'Ara to the Allt Breabaig, no garnet cores with compositions indicating growth under sillimanite grade conditions were seen. An attempt to define from this evidence the maximum extent of Sillimanite-grade conditions in Fannich is shown in Figure 28.

In certain samples different garnets did not show the same composition. In a sample from south of Loch Fannich, a small euhedral garnet was more calcic than the calcic rim of the large garnet analysed. This apparent anomaly is explained by the small garnet resulting from a later episode of garnet formation, which was only partly represented on the rim of the larger garnet. Figure 28 shows the former extent of the

sillimanite isograd in Fannich, as indicated approximately by the compositions of garnet cores in the Meall an t-Sithe Pelite.

The garnet rims in the pelites are often calcium-rich; some contain over 10% CaO. On the Nandi-Sturt diagram the compositions of four garnet rims suggest that retrogression into the garnet grade has occurred. In all the other calcic-rimmed garnets, retrogression into the kyanite grade is suggested, always considering the probably inaccurate placing of the kyanite isograd on this diagram.

In suggesting that retrogression has occurred, therefore, these almandines support the evidence supplied by the calc-silicates and pelite and amphibolite mineral assemblages. They also suggest that the second metamorphic episode was of garnet grade, accounting for the later growth of almandine.

Calc-silicate garnets were analysed both to establish their composition, and to examine the compositional variations suggested by the strong optical zoning that is frequently visible. All proved to be calcic almandines, and the use of grossular as a component in calc-silicate reactions was therefore considered unjustifiable. To establish whether garnet was affected by the other reactions in the calc-silicates the analysed garnets were taken from calc-silicates with the different characteristic mineral assemblages. In the garnets from the

kyanite isograd already mentioned, the rims are less calcic than the cores, indicating that the garnets formed during a time of increasing metamorphic grade. Plagioclase and hornblende are both stable constituents of the same rock.

But in the other calc-silicates from which garnets were analysed, either zoisite or biotite have formed by means of reactions already described, and the compositional variations of garnets in these rocks are more complex. (Fig. 34). Both Reaction 12 and Reaction 15 produce calcic-almandine, while the changes in oxidation state of the iron are reflected in the apparently anomalous fluctuations in the alumina content of the garnets. While no attempt was made to unravel the exact causes of each fluctuation in garnet composition, the only garnets in which the zonation varied in the conventional manner noted by other geologists, came from a rock in which neither zoisite nor biotite had formed. The complex chemical variations (see Fig.34) of the other calc-silicate garnets are therefore considered to result in the interaction of two processes:

1. Fluctuations of the temperature-pressure conditions during metamorphism.
2. The manner in which garnet is affected by other chemical reactions taking place in the calc-silicates.

Inaccuracy in some of the microprobe analyses has already been mentioned; this probably did not clarify the situation.

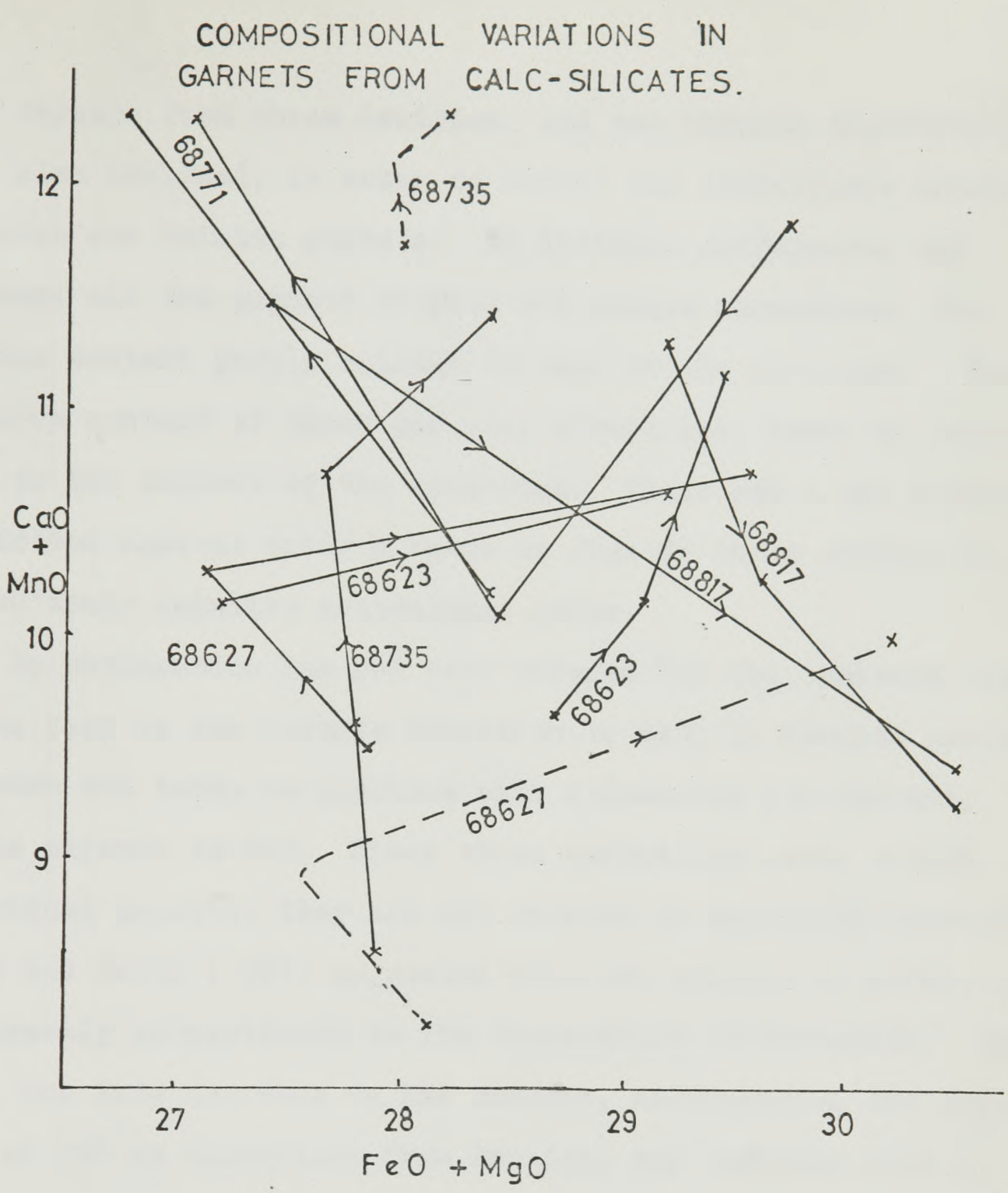

COMPOSITIONAL VARIATIONS IN
GARNETS FROM CALC-SILICATES.
68771
68735
68623
68627
68735
68817
68817
68623
68627
12
11
CaO
+
MnO
10
9
27
28
29
30
FeO + MgO

Figure 34.

Garnets from three Lewisian, and two Moinian amphibolites were also analysed, in order to detect any differences between Lewisian and Moinian garnets. No distinct differences can be seen; all the garnets studied are calcic almandines, the calcium content partly related to that of the host-rock. The titanium content of these garnets, always low, bears no relation to the content of the host-rock. Their FeO + MgO content is plotted against their k value in Fig. 35 in an attempt to assess their relative metamorphic grade.

No explanation has yet been offered for the tendency for MnO to vary in the reverse direction to CaO, in Fannich garnets. Likewise MnO tends to increase with increasing FeO content, at the expense of CaO. Since these variations occur within individual garnets, they are not related to host-rock control. Yoder and Keith (1951) suggested that MnO content of garnet may be directly proportional to its temperature of formation. Therefore, the late decrease in MnO content, accompanying the enrichment of CaO in almandines from Fannich, may indicate that a reduction in temperature occurred towards the end of the metamorphic event, during which the garnets were formed. This supports the contention that a regional retrogressive event affected Fannich.

In this discussion on almandines, the reasons for their distinctive colouring have not been mentioned. The garnets

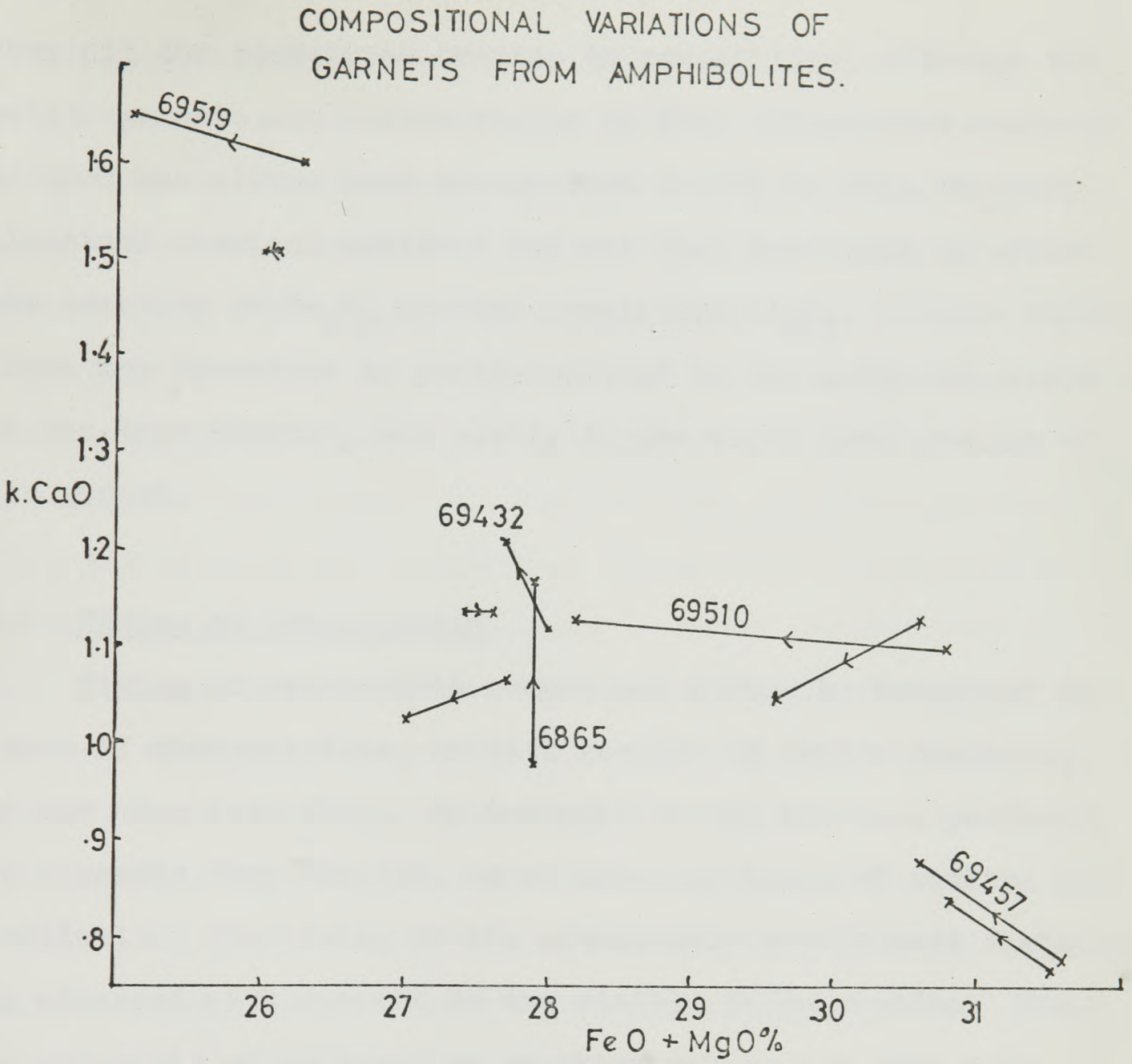


Figure 35. The k.CaO value is plotted against FeO + MgO in order to eliminate as far as possible compositional variations stemming more from the host-rock composition than the metamorphic grade.

from all the rock-types overlap in composition, although the pelite garnets are mostly richer in FeO. Microprobe analysis of iron has always been interpreted as FeO in this chapter; classical chemical analysis has not been performed to assess the quantity of Fe_2O_3 present, replacing Al_2O_3. Colour variations may therefore be partly related to the oxidation state of the iron present, and partly to the total iron content of the garnet.

8.6 Timing of Metamorphism

Timing of metamorphic events can either be described in terms of absolute time, or with respect to events occurring in the area described. No isotopic dating has been performed on minerals from Fannich, so no absolute dates of cooling are available. The timing of the metamorphic events must therefore be assessed with respect to the visible fold-episodes. The relationship of deformation to metamorphism has been more thoroughly investigated in the Dalradian than in the Moinian. Bailey (1923) considered that the regional metamorphism accompanied the isoclinal folding, while Tilley (1925) and Elles and Tilley (1930), considered the regional metamorphism to have preceded recumbent folding. More recently, Rast (1958) has suggested that in the Schichallion complex the regional metamorphism can be divided into a series of events, approximately

synchronous with deformational episodes. In most of the Dalradian areas described, three fold episodes similar to those observed in Fannich are described. In the Loch Tummel area, Sturt and Harris (1961) note that mild retrogressive metamorphism accompanied the late F_3 fold-episode. A similar relationship occurs in Fannich, where the open F_3 folds deform a pre-existing foliation. No extensive recrystallization accompanied this event, and Fannich does not show polymetamorphic textures as seen elsewhere; the evidence later retrogression is seen only in the calc-silicates, and in the reversed zoning of the almandines. Yet even in the calc-silicates, polymetamorphic textures do not occur, as the minerals have recrystallized instead of being deformed.

No visible structural evidence suggests that the formation of the present foliation preceded the F_2 fold-episode. Although two earlier fold-episodes F_1 and F_2 must be invoked to explain the visible structures in Fannich, there is no definite evidence for two corresponding peaks of metamorphic activity. But the peak of metamorphism must either be synchronous with, or just after the F_2 fold episode, as mineral textures do not betray the existence of F_2 deformation. The garnets from Fannich do not throw light on earlier metamorphic events, as most garnets nucleated at the peak of metamorphism, and show reversed zonation. Probably the relationship of metamorphism

to folding is similar to that suggested by Rast (1958) for Schichallion, and Ramsay (1963) for the Moinian, based on evidence from Glenelg and Monar.

To summarize, it is postulated that in Fannich:

1. The F_1 and F_2 deformational events were accompanied by strong recrystallization, during a period of increasing metamorphic grade.

2. The peak of metamorphism, reaching sillimanite grade in the west of Fannich, probably accompanied, or slightly postdated the F_2 movements.

3. Garnet-grade metamorphism, accounting for retrogression in parts of Fannich, slightly preceded, or accompanied the open F_3 folds, which deform pre-existing foliation planes. The tendency of the present isograds to run subparallel to the unit boundaries may indicate that the folding slightly post-dates the retrogressive metamorphism, and occurred when the system was no longer open. During the F_1, F_2 and F_3 fold phases, the Lewisian basement, already metamorphosed, was recrystallized so that it contains mineral assemblages typifying the same grade of metamorphism as the Moinian. Only in the banded texture, and the strong folding of the banding in the silicic gneisses, is there any suggestion of metamorphism in the Lewisian preceding the sedimentation of the Moinian.

8.7 Conditions of Metamorphism in Fannich

An accurate assessment of the temperature-pressure conditions under which the rocks of Fannich Forest were metamorphosed is difficult for three reasons:

1. The minerals on which experimental data is available are either scarce or absent.

2. Minerals with variable composition exist in Fannich, in which the stability fields of the pure end-members only, are known.

3. The different minerals on which experimental data about their stability fields is available occur in rocks of different composition, often in different parts of Fannich, where the pressure-temperature conditions may have been different.

The minerals which occur in Fannich on which experimental data is available are kyanite (from one locality only), almandine, and zoisite, formed from plagioclase in the calc-silicate strips.

Yoder (1955) has determined the upper thermal stability curve of almandine at water vapour pressures of up to ten kilobars. His univariant equilibrium curve for almandine breakdown to form cordierite, fayalite and hercynite passes through the points 830°C at 2 kilobars, and 930°C at 6 kilobars. No sign of thermal breakdown of almandine occurs in Fannich. Hsu

(1968) has investigated experimentally the conditions of almandine formation. The lower thermal stability range for almandine derived from ferro-chlorite and quartz is 550°C approximately (see Fig 36) for fluid pressures exceeding 1.5 kilobars. But Hsu's data is based on the stability of pure almandine, while all the garnets in Fannich were calcic almandine, some containing over 10% CaO. Hsu's data therefore can only be used as an approximate guide to temperature-pressure conditions in Fannich at the time of metamorphism.

Newton (1965) plots five experimentally determined univariant equilibrium curves for zoisite stability. Two of these reactions involve corundum, and two more involve sillimanite, but as neither of these minerals took part in reactions involving zoisite in Fannich, the fifth of Newton's reactions calculated by Winkler and Nitsch was the only one considered relevant. But Newton says that, depending on which mineral assemblage resulting from zoisite breakdown is most stable, the temperature and pressure at which zoisite breaks down is also variable. This may suggest that the stability field of zoisite is greatly affected by variations in the composition of the host-rock. The curve for Winkler and Nitsch's reaction demands the breakdown of zoisite at a higher temperature or lower pressure than is characteristic of Barrovian metamorphism. But the stability field of zoisite may be restricted to a higher-pressure, lower-

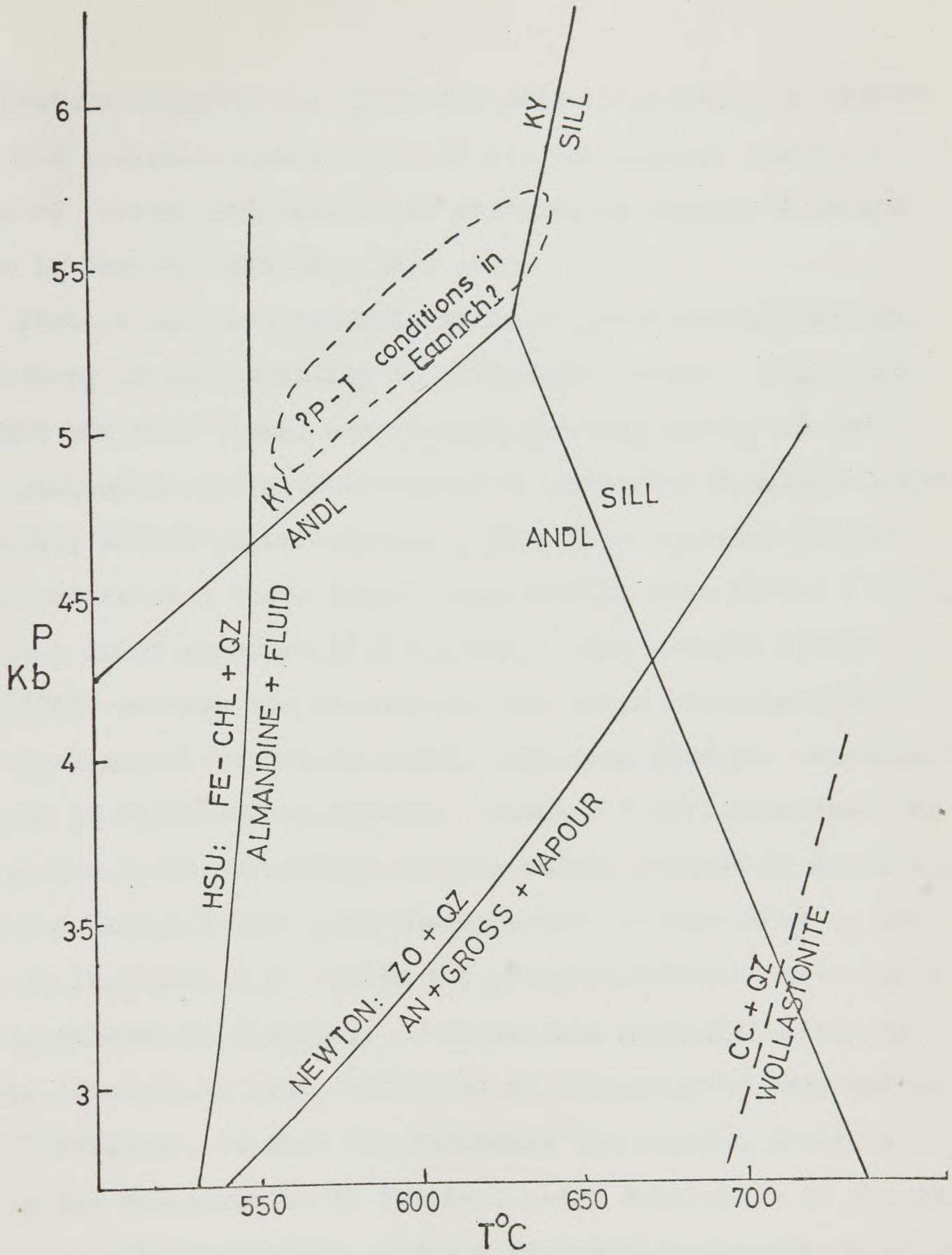


Figure 36. Pressure - Temperature diagram attempting to show the conditions under which the regional metamorphism of Fannich Forest took place.

temperature range in the Sgurr Mor calc-silicates as a result of their overall composition. If so, the zoisite stability curve of Winkler and Nitsch may represent a minimum pressure range in Fannich (see Fig. 36).

Perhaps the most reliable guide to pressure-temperature conditions is the stability of aluminosilicates. Richardson, Gilbert and Bell (1969) are amongst the most recent of the many geologists who have attempted to determine aluminosilicate stability curves experimentally. They show that the triple point occurs at a lower temperature (630°C) than Newton (1966), and at a lower pressure (5.3 kilobars) than Althaus (1967). Zen (1969) reviews the reasons for the large disagreement about the location of the triple point, resulting from the experimental work of different geologists. Althaus (1967) dismisses the low pressure and temperature triple points defined by Weill and Holm and Kleppa (1966) from thermodynamic calculations on the grounds that they fall within the pyrophyllite stability field (as calculated by Althaus). Outside this stability field no triple points have been calculated as occurring at pressure less than 5 kilobars, so this may represent the minimum pressure during the metamorphism of Fannich, where andalusite is absent. The occurrence of kyanite, and the reported occurrence of sillimanite suggest that the temperature probably did not greatly exceed 650°C if the total pressure did not exceed 6 kilobars.

Turner (1968) mentions that at depths of a few kilometres, there is a strong tendency for the fluid pressure to approach the load pressure in value. In Fig. 36 therefore, the pressure shown can be interpreted either as fluid pressure or total pressure. Assuming that rock undergoing metamorphism is essentially viscous, he suggests that at depths exceeding 10 kilometres, the fluid pressure is approximately equal to the load pressure. The presence of kyanite indicates that total pressures may have exceeded 5 kilobars, and that the metamorphism occurred at a depth exceeding 15 kilometres.

But Turner mainly based his evidence on the observed behaviour of fluid pressure and total pressure in deep drilling for oil and gas. After the early expulsion of fluids in the initial stages of metamorphism, the fluid pressure may drop to a somewhat lower value than the total pressure, even at considerable depth. It is possible that in the earlier metamorphic event in Tannich, fluid pressure was substantially below the total pressure, but in the later event, a rise in fluid pressure induced the breakdown of plagioclase to form zoisite, possibly accompanied by a fall in temperature.

Also, the kyanite was only seen in a locality over two kilometres from the nearest place where the plagioclase-zoisite reaction occurred, and pressure-temperature conditions could have differed between the two places.

However, as shown in Figure 36, the scanty evidence available generally suggests that the rocks exposed in Fannich were metamorphosed at temperatures of approximately 650°C and total pressures between 5 and 6 kilobars.

9

CHEMICAL DISTINCTIONS IN FANNICH

1. Reasons for attempting to discover chemical differences

Lewisian Inliers have been postulated as existing in the Moinian of North-West Scotland ever since the area was first mapped. In Fannich Peach et al. (1913), as elsewhere suggested that Lewisian rocks occurred on lithological grounds only. No further proof that these rocks are Lewisian has been forthcoming in Fannich, although in Glenelg (Ramsay 1958) the field-relations, showing the Moinian to rest unconformably on silicic gneisses, supported the hypothesis. It was felt that if fundamental chemical differences, unlikely to be eliminated by all but the most intense metamorphic episodes, between Lewisian and Moinian rocks were found, chemical evidence would provide proof of their origin.

Chemical differences were also sought between the different amphibolites and the different calc-silicates, as it was believed that such differences, if they exist, can help distinguish different units, or support the chemical evidence distinguishing Lewisian and Moinian.

While it was appreciated that many other chemical

differences between Moinian and Lewisian could be discovered, on the analysis of more rocks for more minor elements, the object of this thesis, as the "Geology of Fannich Forest", is to establish that compositional differences occur, rather than to execute a major geochemical study of Moinian and Lewisian rocks. But the differences that have emerged from this study do apparently suggest that certain distinctions are retained in spite of metamorphism after the Moinian deposition, and that these distinctions can be used to identify Lewisian Inliers in the Moinian, when the field relations prove inconclusive.

9.2 Distinctions between Lewisian and Moinian and amphibolites

Whole-rock analyses of 64 rocks from the Fannich Lewisian Inlier and 61 whole-rock analyses (excluding those of calc-silicates) from the Moinian units, were carried out for 9 major elements. The samples selected for analysis embraced the whole range of rock-types seen in both Lewisian and Moinian. Any detectable chemical distinctions were therefore likely to consist of differing ratios between element pairs. While it was appreciated that amphibolites, whether Moinian or Lewisian, would tend to contain high CaO, FeO and MgO contents, compared to silicic rocks, it was also realised that certain elements tend to occur together, and different ratios between these can be considered more significant.

Titanium and iron are two elements that occur in similar minerals, and which apparently occur in an almost constant ratio throughout the crust. Certain minerals are carriers of titanium in almost all magmatic and metamorphic rocks: ilmenite, rutile, sphene, and to a more limited extent, the amphiboles and biotite. Although single minerals, other than garnets, have not been analysed in Fannich, the titanium present probably occurs distributed among the last three minerals named. Holland (1965) plotted the percentage of TiO_2 against the percentage of Fe_2O_3 for various members of the grey gneiss suite in the Lewisian, which showed a marked coherence of the two elements.

Goldschmidt (1958) calculated that the iron content of the upper lithosphere is 7.0% Fe_2O_3(total); a figure smaller than Taylor's (1964) calculated value of 7.9% Fe_2O_3, but greater than the figure of 4.8% estimated by Vogt (1931). In the Lewisian the average Fe_2O_3 content of the Laxfordian grey gneiss suite is 3.5%, while that of the Scourian granulites is 8.8%, as calculated by Holland.

Goldschmidt (1958) calculated the crustal average content of titania to be 0.73%. Taylor calculated that it was 0.94%. Holland states that the average titania content of the Laxfordian grey gneisses is 0.49% of the whole-rock composition, while that of Scourian pyroxene granulites is 0.70%.

According to Goldschmidt's figures the crustal ratio of

iron, calculated as FeO, to titania is 9.6 : 1, while according to Taylor it is 8.4 : 1. More recently Ronov and Yaroshevsky (1969) suggest a FeO/TiO_2 crustal ratio of 7.9 : 1, and also quote figures estimated by other geologists for continental shields: for the Canadian Shield 8.2 : 1 (Shaw et al. 1967), for the South-West Australian Shield 8.8 : 1 (Lambert and Heier 1968), for the Russian Platform 8.0 : 1 (Ronov and Yaroshevsky). Compared to these figures, the Lewisian is titania-depleted, relative to iron. From Holland's average figures, although the FeO/TiO_2 ratio for the Laxfordian is 7.1 : 1, that of the Scourian pyroxene-granulites is 12.6 : 1. These ratios are tabulated in Table 19, together with the K/Rb ratios and zirconium contents. The FeO/TiO_2 ratios for igneous rocks range on either side of the average crustal figures. The average granite ratio was calculated as 9.1 : 1 (Taylor 1964), that of average tholeiites 6.4 : 1, and of olivine-basalts, 4.9 : 1 (Manson 1967). Compared to these igneous or shield ratios, the range of ratios seen in detrital sediments is low. Shaw (1967) quotes an average composition of shale from which the FeO/TiO_2 ratio emerges as 6.9 : 1. Gad, Catt and Leriche (1967) quote figures for Whitbian shales, in which the FeO/TiO_2 ratio averages 5.8 : 1. Arenaceous sediments are apparently more enriched in titania relative to iron. Thus averages taken from analyses of Torridonian show a ratio of 5.8 : 1 (Kennedy

TABLE 19

Element ratios and contents in various rock-groups

	Crustal Average	Granite	Olivine-Basalt	Quartz-Basalt
FeO/TiO_2	7.9	9.1	4.9	6.4
Zr p.p.m.	165	180	138	108
K/Rb	232	223	288	484

	Scourian	Laxfordian	Fannich Inlier	Moinan	Australian Shield	Canadian Shield
FeO/TiO_2	12.6	7.1	10.4	5.6-6.6	8.8	8.2
Zr p.p.m.	101	125	178	345	-	-
K/Rb	1500	292	318	238	216	218

	Average Shale	Whitbian	Torridonian	Old Red Sandstone	Carboniferous S.s.t.n.s
FeO/TiO_2	6.9	5.8	5.8	4.8	2.8
Zr p.p.m.	200	180	-	900	600
K/Rb	-	-	-	-	-

1951), of the old Red Sandstone 4.8 : 1 (Sabine 1969), and of Carboniferous sandstones in England 2.8 : 1 (Sabine 1969). The average ratio for the Moinian basal psammite at Morar (Poole 1962) is 5.6 : 1, while averages from Moinian metasediments in Fannich range from 6.5 : 1 in the pelites to 5.8 : 1 in the psammites, the latter are identical with the Torridonian ratio. These Moinian figures are very similar to those for unmetamorphosed sediments, but different from those from the Lewisian Foreland. For this reason, FeO/TiO_2 ratios were selected as significant in attempting to establish the identity of the controversial 'Lewisian' Inlier at Fannich. Since the average FeO/TiO_2 ratio from the inlier rocks at Fannich was 10.4 : 1, more titania-depleted than all but the Scourian, the individual rock ratios were plotted, in order to see how reliable this distinction is. In Figure 37, iron and titania values for Moinian metasediments, derived from Fannich, Poole's (1962) basal psammites from Morar, and Butler's (1965) analyses from scattered Moinian localities, have been plotted against Lewisian gneisses from west of the Moine Thrust, selected from the whole range of rock-types analysed by Holland (1965), from the Lewisian near Torridon (Lambert pers. comm.), and from selected analyses by Park (1966) and Ghaly (1966) from the Lewisian near Gairloch. With strikingly few exceptions, rocks analysed from the Lewisian contain a FeO/TiO_2 ratio exceeding

Figure 37. Diagram showing the strikingly different FeO - TiO$_2$ ratios which help to distinguish Lewisian and Moinian rocks. All rock-types for both units are plotted.

7:1, while Moinian rocks contain ratios of less than 7:1. The division between the two rock units is therefore almost complete. Out of approximately 400 rocks plotted, only 17 proved exceptional (mostly Laxfordian gneisses) in plotting across the line dividing Moinian ratios from Lewisian ones.

Since the FeO/TiO_2 ratio division is so striking between Moinian and Lewisian, rocks from the supposed Fannich Lewisian were plotted on a diagram on which the dividing line marked by the 7:1 ratio had already been drawn. This diagram (Fig.38) shows that out of 64 rocks, only 13 plot within the 'Moinian' field, strongly suggesting that the rock suite is Lewisian, although casting doubt on the affinities of these rocks falling within the Moinian field which also have dubious field-relations.

One chemical distinction was not considered sufficient data to decide on the nature of the Fannich Inlier, so, out of 64 rocks taken from it, 24 were also analysed for five minor elements: Strontium, Rubidium, Zirconium, Nickel and Niobium. These elements were selected for various reasons. They can be rapidly analysed quantitatively by X-Ray Fluorescence spectometry. Rubidium-Strontium, and Potassium-Rubidium ratios had proved significant elsewhere, for example within the Lewisian (Holland 1965). Zirconium was selected because the frequent presence of zircons in the Moinian metasediments suggests that the zirconium content of the Moinian is significantly higher than that

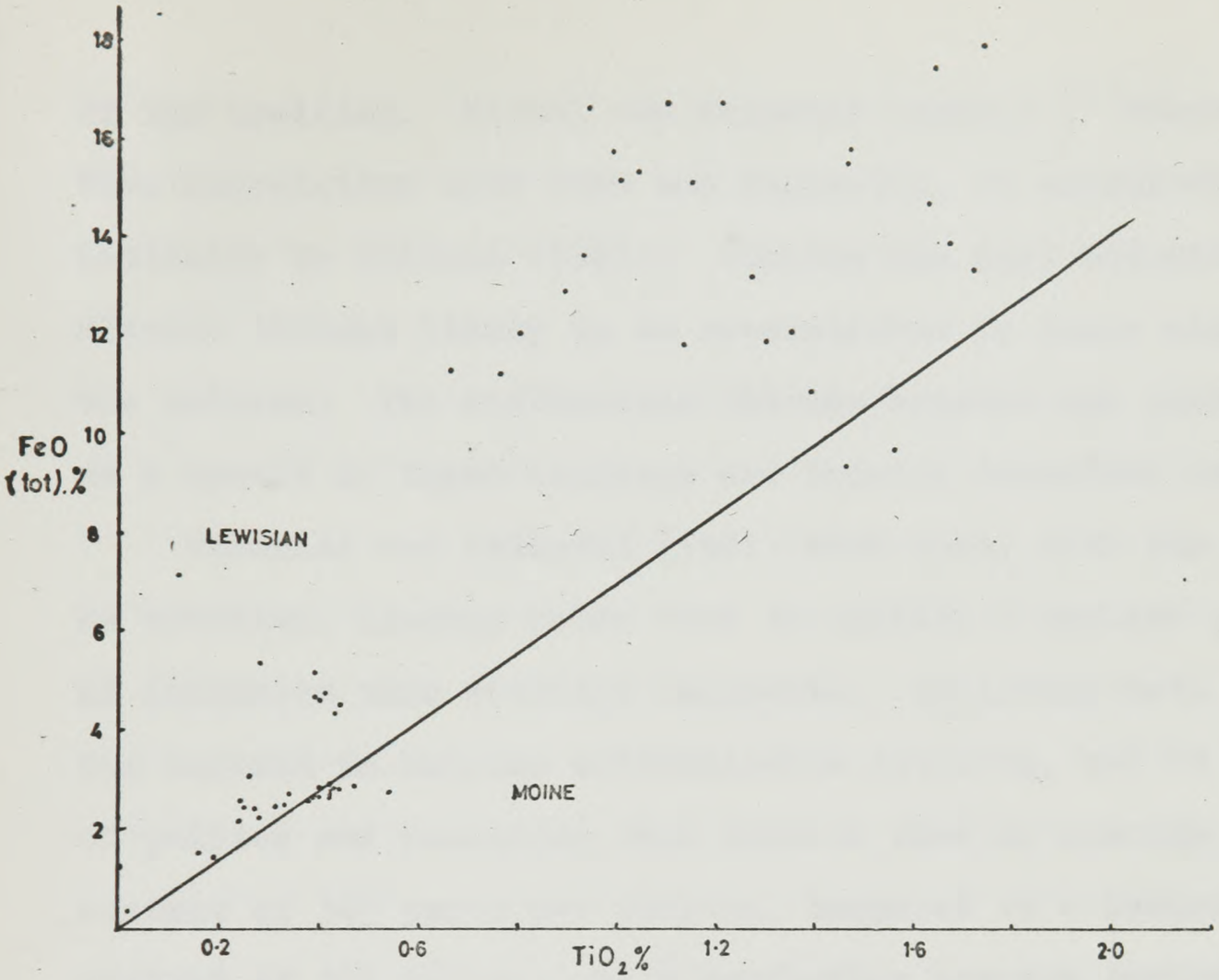


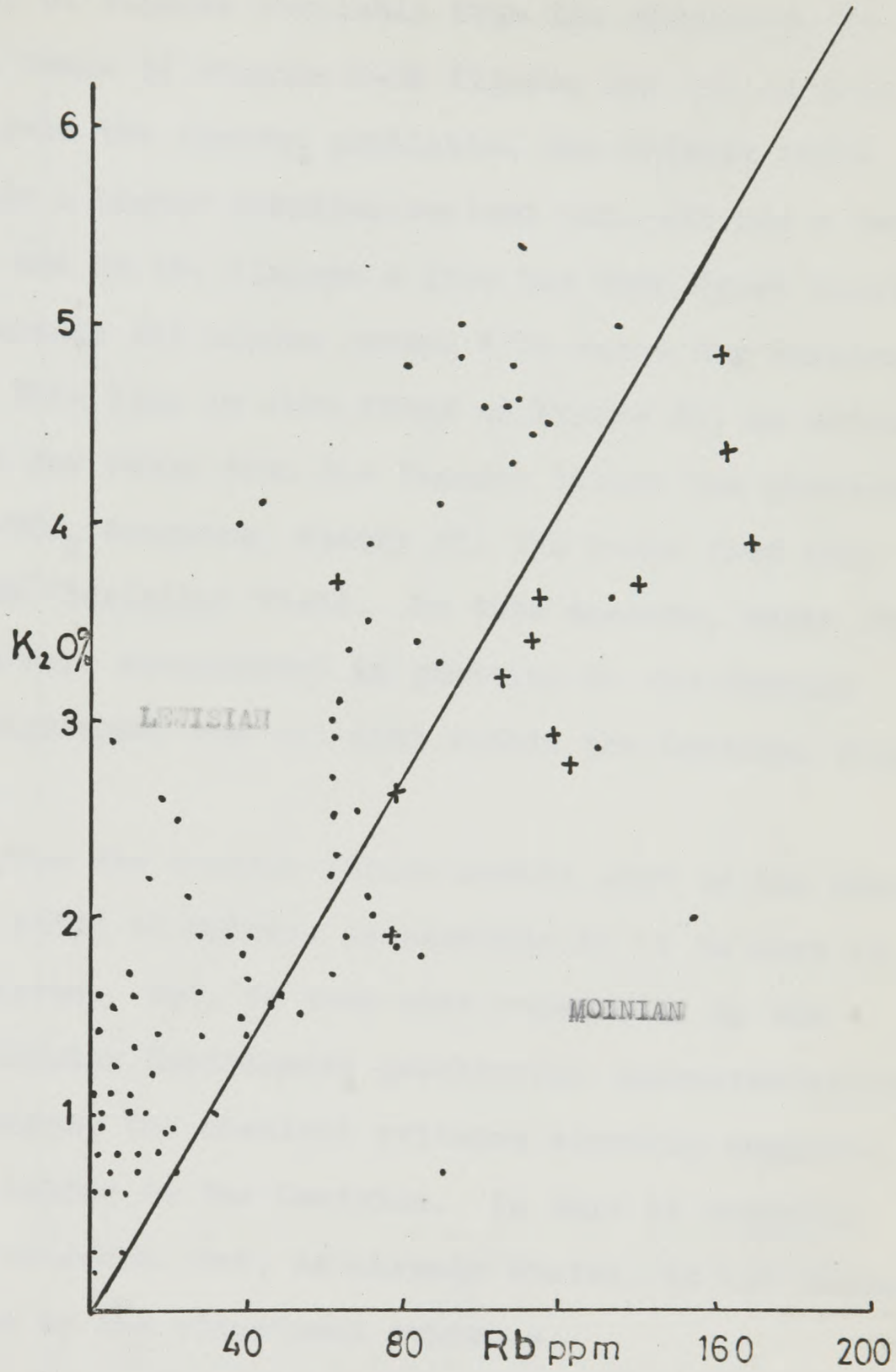
Figure 38. Diagram showing the FeO - TiO_2 ratios of rocks from the Fannich Inlier. Nearly all plot within the Lewisian 'field' as identified in Figure 37.

of the Lewisian. Nickel was selected because it shows a positive correlation with iron and magnesium, as calculated statistically by Holland (1965). Niobium was also selected as an element thought likely to be concentrated in heavy minerals in the Moinian. The differences between Moinian and Lewisian noted as a result of these analyses are briefly described below.

Turekian and Wedepohl (1961) show that, with the exception of syenites, igneous rocks tend to contain a smaller quantity of zirconium than detrital sediments. Available data of zirconium content in Moinian metasediments is scarce, but 12 samples of pelites and psammites from Fannich show an average zirconium content of 345 parts per million, compared to a Scourian average content of 101 p.p.m., and a Laxfordian average content of 125 p.p.m. (Holland 1965). But the range of zirconium contents in individual samples from Moinian and Lewisian shows considerable overlap, so the zirconium content can only be used as a significant distinguishing feature if average contents are used. Taylor (1964) estimates the crustal average content as 165 p.p.m; the contents of detrital sediments tend to be higher. Sabine (1969) quotes an average zirconium content of the old Red Sandstone as 900 p.p.m.; Shaw (1967) quotes an average content in shale of 200 p.p.m. Igneous rocks have lower contents. An average granite content (Taylor 1964) is 180 p.p.m., while Prinz (1967) quotes an average content of only 108 ppm. in quartz-

basalts. Compared to the Moinian zirconium contents, the average content of the Fannich inlier is low; only 178 p.p.m., although still high compared to the content of Lewisian rocks from the Foreland.

Holland (1965) investigated the geochemistry of the alkali metals within the Lewisian, and found that the average potassium /rubidium ratio of the Scourian pyroxene-granulites is, at 1500, very different from that of the Laxfordian grey gneisses, at 292. He drew attention to the very low rubidium content of the granulites, averaging only 5 p.p.m. Taylor (1964) quotes the crustal average rubidium content as 90 p.p.m., based on a survey by Heier and Adams (1964). According to Taylor's figures the average K content of the crust is 2.09%, so that the average crustal K/Rb ratio is 232. If so, then both Scourian and Laxfordian rocks have higher K/Rb ratios than average, while the K/Rb ratio of the Moinian, at 238, is very close to the average. Figures for shield areas elsewhere (see Table 19) differ from the Lewisian in containing lower ratios than the average; the low rubidium content of the Scourian is therefore exceptional. In Fannich an average K/Rb ratio was obtained from the inlier rocks; this, at 318, was again significantly higher than the Moinian average. In view of this difference, rubidium contents are plotted against potassium percentages in Fig.39 for Foreland Lewisian rocks from Holland's analyses, and for Moinian metasediments from Fannich.


6
5
4
3
2
1
$K_2O\%$
LEWISIAN
MOINIAN
40
80
Rb ppm
160
200

Since the number of figures available from the Moinian is so small, the full range of Moinian K-Rb figures may not be represented. But, given the figures available, the Moinian rocks generally contain a higher rubidium content than all but a few Lewisian rocks, and on the diagram a line has been drawn representing approximately the maxium normal K/Rb ratio for Moinian metasediments. This line is also drawn on Figure 40, on which the K-Rb figures for rocks from the Fannich Inlier are plotted. As with the FeO-TiO_2 diagrams, nearly all the rocks from this group plot in the 'Lewisian' field. In this diagram, rocks from the inlier which were exceptional in plotting in the Moinian field, are distinguished, and all plot within the Lewisian field on this diagram.

That rocks from the Fannich Inlier should plot in the Lewisian field, yet still be Moinian is possible if it is seen in only one such diagram. But, if they plot repeatedly in the Lewisian field, showing Lewisianoid geochemical characteristics, as happens in Fannich, the chemical evidence strongly suggests that these rocks belong to the Lewisian. In this it supports the petrological evidence, and, as already stated, is not necessarily contradicted by the structural evidence.

Holland also notes the Sr/Ca ratio increases from the Scourian pyroxene-granulites to the Laxfordian grey gneisses, explaining that this concentration is quite consistent with a sedimentary link between the two. Taylor's figures indicate

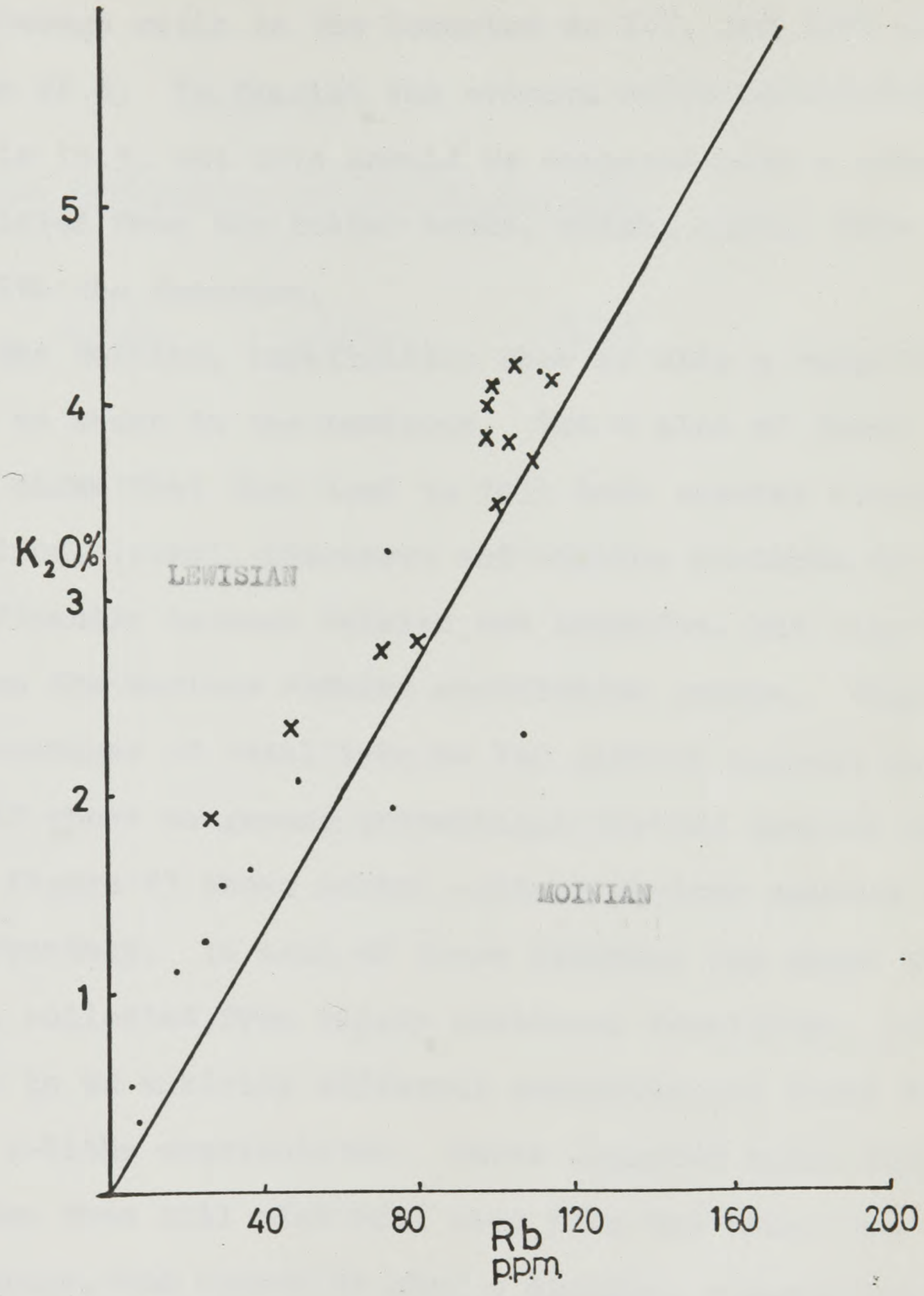


Figure 40. Diagram showing the Rb - K_2O ratios of rocks from the Fannich Inlier. Nearly all plot within the Lewisian field as identified in Figre 39. Crosses distinguish those rocks which plotted in the Moinian field in Figure 38.

that the average Sr x 10^3/Ca ratio in the crust is 9.1. Holland quotes the average ratio in the Scourian as 6.7, and that of the Laxfordian as 21.8. In Fannich the average ratio calculated for the Moinian is 19.3, but this should be compared with a ratio of 6.6 calculated from the inlier rocks, which, again, show affinities with the Scourian.

Within the Moinian, amphibolites show as wide a range of compositions as those in the Lewisian. But a plot of their compositions shows that they tend to fall into several discrete groupings. Iron, nickel, manganese and niobium contents do not differ significantly between Moinian and Lewisian, but they do differ between the various Moinian amphibolite groups. Figure 41 shows percentages of total iron as FeO plotted against manganese, figure 42 shows manganese percentages plotted against nickel content, and figure 43 shows nickel content plotted against the magnesium percentage. In each of these diagrams the Sgurr Mor amphibolites, collected from widely scattered localities, always plot together in an entirely different compositional field from the Meall an t-Sithe amphibolites. Three analyses taken from the Moinian Ben Hope Bill plot well away from the other two Moinian groupings, and appear to show a distinct compositional trend, possibly related to magmatic differentiation at the time of intrusion. The significance of these distinctions is discussed in the following sections.

TABLE 20

Analyses of Amphibolites from the Ben Hope Sill

	B.H.4	B.H.2	B.H.8
SiO_2	52.32	59.70	57.22
Al_2O_3	13.75	11.67	13.59
FeO(Tot)	12.30	11.10	10.63
MgO	6.64	4.75	5.08
CaO	8.88	7.41	5.71
Na_2O	3.84	2.42	4.15
K_2O	0.59	0.48	0.37
TiO_2	1.41	2.04	2.71
MnO	0.27	0.43	0.55
Sr p.p.m.	362	155	170
Rb "	2	6	2
Zr "	115	274	246
Nb "	n.d	10	9
Ni "	106	71	57

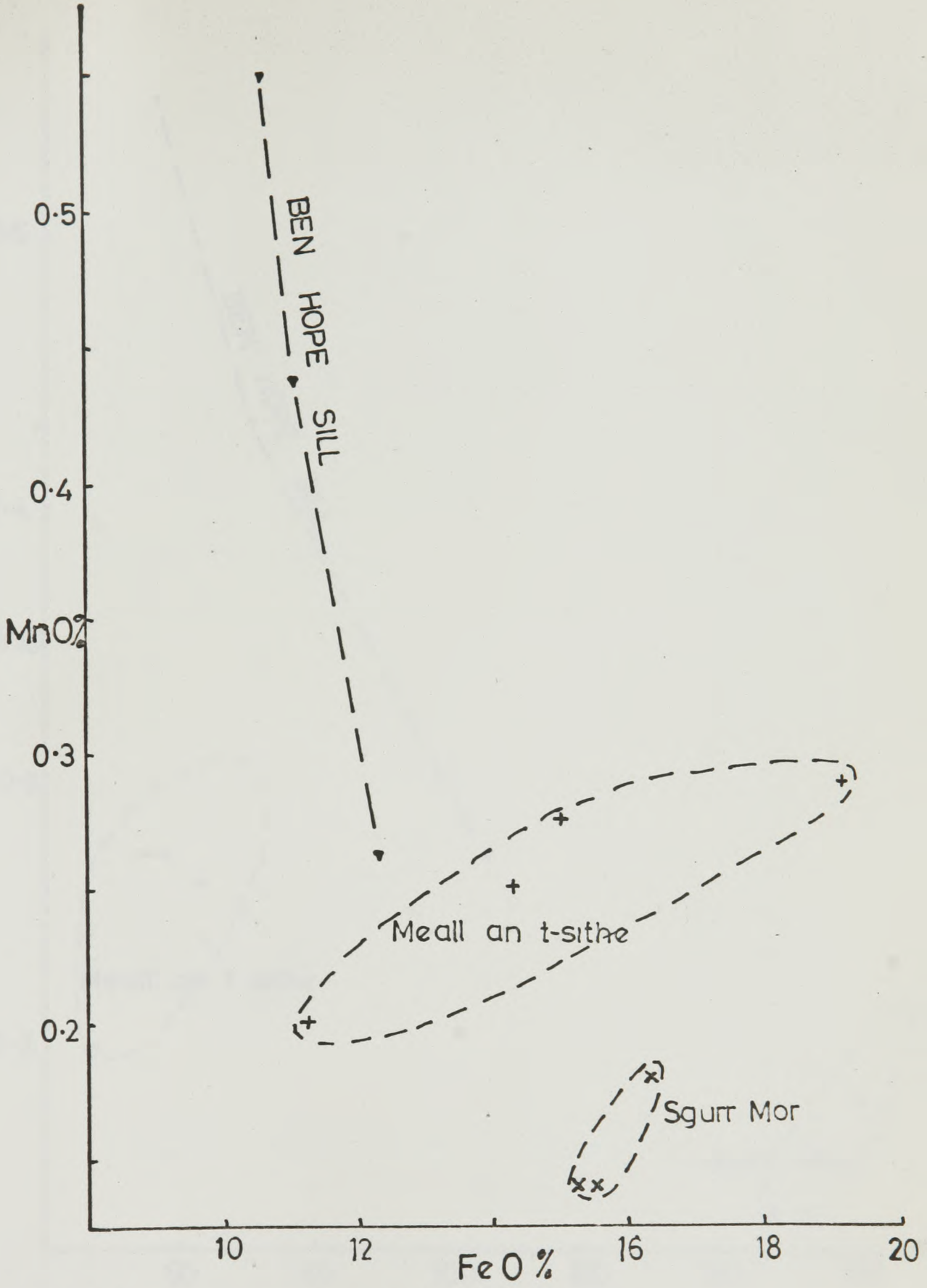


Figure 41. Diagram showing the different MnO - FeO proportions of different Moinian amphibolite suites.

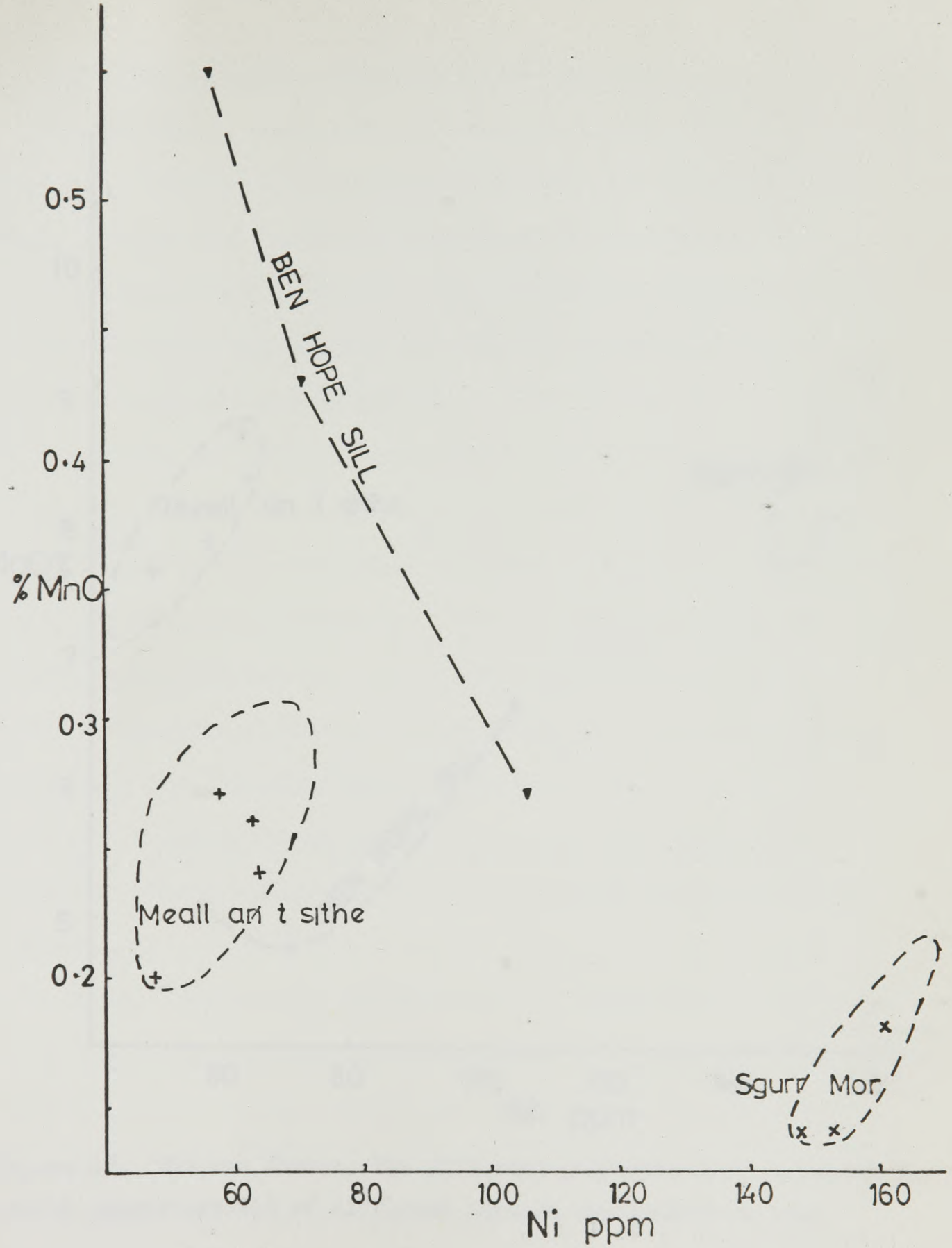


Figure 42. Diagram showing the different proportions of manganese to nickel characteristic of different Moinian amphibolite suites.

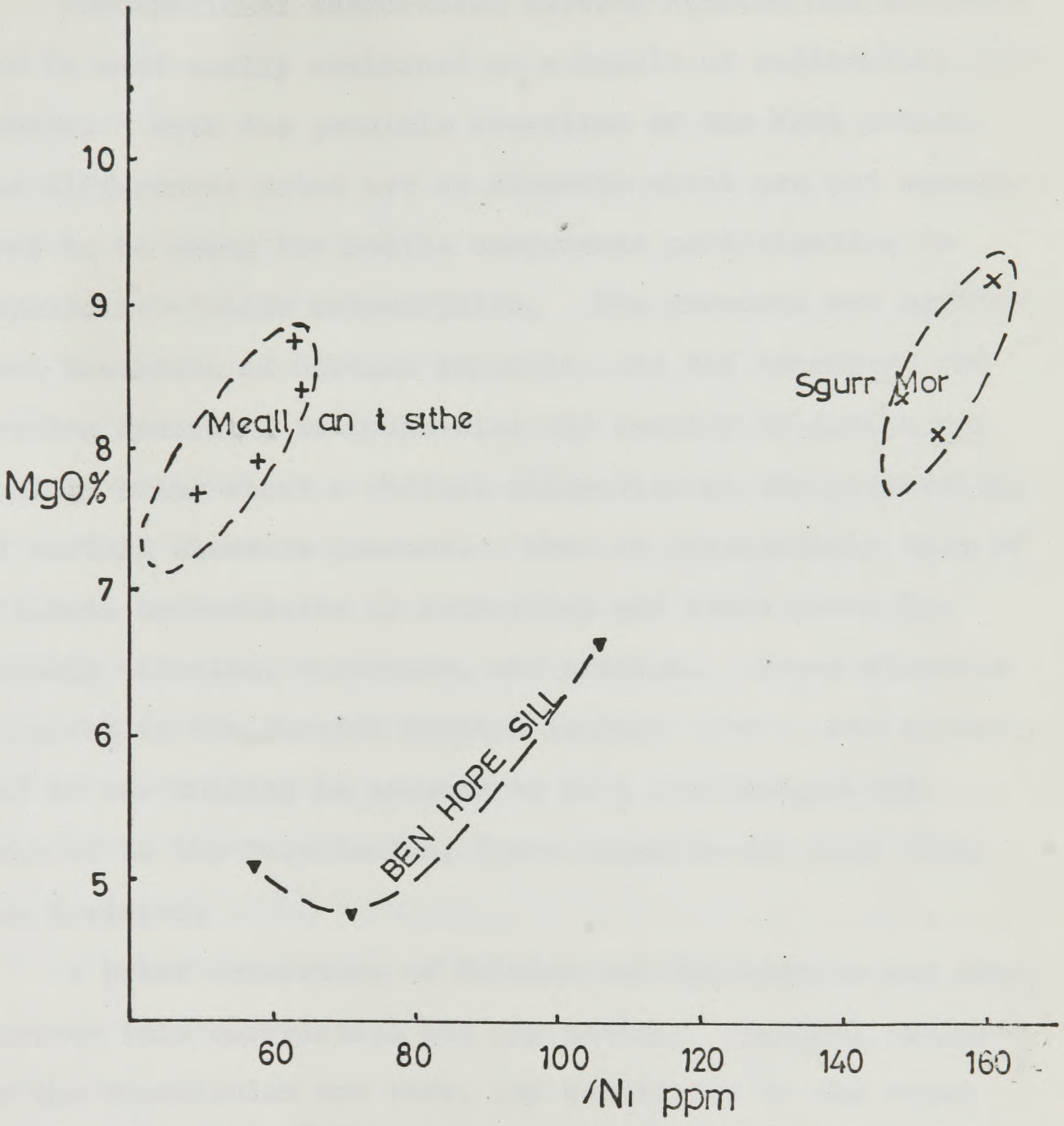


Figure 43. Diagram showing the different proportions of magnesium to nickel characteristic of different Moinian amphibolite types.

9.3 Chemical Changes caused by Sedimentation

Compositional differences between Moinian and Lewisian can be most easily explained as a result of sedimentary processes. With the possible exception of the K/Rb ratios, the differences noted are in elements which are not considered to be among the mobile components participating in amphibolite-facies metamorphism. The chemical and mechanical breakdown of certain minerals, and the transport and sorting according to grain-size and density of grains can rapidly bring about a radical alteration in the proportions of certain elements present. This is particularly true of elements concentrated in refractory and heavy minerals, notably titanium, zirconium, and uranium. Heavy minerals observed in the Fannich Moinian include sphene and zircon, and if the Moinian is assumed to be a sedimentary unit related to the Torridonian, these minerals may come from the Lewisian.

A brief comparison of Moinian and Torridonian may show whether this correlation has any basis. Chemical analyses of the Torridonian are rare, and restricted to the major elements, but the $^{FeO}/_{TiO_2}$ ratios are similar to those of the Moinian. Both rock units are remarkably free from calcareous facies, and both contain rare heavy mineral seams (Butler 1965, Stewart 1962). Selley (1966) remarks

that heavy mineral content decreases in the higher Torridonian beds; no such comparison was possible in the Moinian. Kennedy (1951) considered that the two units were contemporaneous, but were deposited further apart than they are now, being brought into juxtaposition by the movement of the Moine Thrust.

Mackie (1920) studied the reasons for heavy mineral concentration, and decided that the specific gravity of the grains, and selective sifting by water are the most important factors. In fluviatile deposits running water could sift the grains; while in marine sediments undersea currents can sort the particles. In view of the chemical breakdown of certain minerals derived from the original rock, the average content of heavy minerals should be slightly higher in detrital sediments than in average igneous rocks, and this appears to be so. Also, with the reworking of sediments, further concentration of heavy minerals could result, in the manner used to explain the formation of economic placer deposits (Park & McDiarmid 1964).

That detrital sediments tend to contain more heavy minerals is supported by the zirconium contents of Lewisian, Moinian, and Old Red Sandstone; respectively 113 p.p.m., 345 p.p.m., and 900 p.p.m. (Sabine 1969), the

Old Red Sandstone probably being partly derived from pre-existing detrital sediments. A similar relationship can be seen in the $^{FeO}/_{TiO_2}$ ratios for the same units; respectively 9.8, 5.6, and 4.8. Subsequent metamorphism has not visibly changed the ratio of heavy minerals, accumulated during sedimentation., of the Moinian.

Deposition of the Moinian, as detritus possibly derived from the Lewisian can adequately explain the difference in $^{FeO}/_{TiO_2}$ ratio and zirconium contents of the two units.

Rankama and Sahama (1950) state that strontium readily enters into the sedimentary cycle, and when reprecipitated during hydrolysate sedimentation the $^{Srx10^3}/_{Ca}$ ratio increases relative to that of the source area. The ratio in the Moinian is much higher than that of the Scourian, but lower than that of the Laxfordian; the Moinian could be derived by sedimentation from a Scourian source area. Also, the very low ratio in the Fannich Inlier rocks cannot be adequately explained by claiming that its rock-units come from a different source; their ratio is almost identical with that in the Scourian.

Both potassium and rubidium may have had limited mobility during metamorphism. Local migration of potassium occurs in the formation of biotite from hornblende in calc-silicate bands; therefore some introduction of

potassium and rubidium into the alkali-depleted Lewisian rocks during post-Moinian metamorphism may have occurred, the amounts introduced depending upon the mobility of the element, and how depleted it was in the original Lewisian. In view of the extreme rubidium depletion characteristic of the Scourian, rubidium would be concentrated relative to potassium by this process. But hydrolysate sedimentation can also result in the concentration of rubidium relative to potassium; therefore the K/Rb ratio is lower in hydrolysate sediments than in their source rocks. The K/Rb ratio in the Moinian is lower than in the Lewisian of the Foreland, and lower than in the Fannich Lewisian. This difference can be explained by sedimentation. But the K/Rb ratio of the Fannich Lewisian is also much lower than that of the Scourian, and this can be explained by rubidium enrichment by solutions during metamorphism. The growth of biotite in Lewisian amphibolites supports the suggestion that potassium, and probably rubidium were introduced. The possibility of alteration of element ratios in the Fannich Lewisian as a result of weathering are discussed in the next section.

9.4 Chemical Changes caused by weathering

No attempt has yet been made to explain why certain

rocks in the Fannich Inlier plot within the Moinian compositional field. The field-evidence shows they belong to the inlier. Nothing suggests that metamorphism in Fannich was sufficiently intense to cause wholesale mobilization of the elements discussed, except for potassium and rubidium, although changes in oxidation state, water content and carbon dioxide content almost certainly occurred. Inlier rocks containing an $^{FeO}/_{TiO_2}$ ratio of less than 7:1, were collected almost exclusively from close to the junction with the Moinian. This could suggest either contamination during metamorphism, by aqueous solutions removing iron in solution from the Lewisian, or removal of iron in solution during weathering before Moinian deposition.

Williams (1968) studied the geochemical effects of pre-Torridonian weathering on Laxfordian gneiss, and found that, with the breakdown of biotite, iron was leached out and depleted, except in the topsoil, rarely preserved, where iron was concentrated. In the lower weathered gneisses, therefore, the $^{FeO}/_{TiO_2}$ ratio was lower, and it is suggested that the lower $^{FeO}/_{TiO_2}$ ratios noted near the Moinian junction in Fannich might also result from weathering.

Williams also shows that the potassium content of the rock increases with weathering, with the breakdown of

plagioclase and concentration of microcline, but he does not provide data on the rubidium contents of the rock. Holland (1965) states that the K/Rb ratio in biotite from the Laxfordian dark gneisses is about 150, and in microcline from the Laxfordian grey gneisses it is about 500. With the concentration of microcline with weathering the K/Rb ratio should rise; therefore the samples from the Fannich Inlier close to the Moinian junction should have higher K/Rb ratios. This is not obvious; therefore the K/Rb ratio in the marginal Lewisian may have been initially increased by weathering, but subsequently reduced by the action of solutions derived from the Moinian. If the Moinian in Fannich rests uncomfortably on the Fannich Lewisian, chemical alteration by weathering cannot be ignored.

9.5 Is the Fannich Lewisian Scourian or Laxfordian ?

Table 20 shows that the average $^{FeO}/_{TiO_2}$ ratio in the Fannich Inlier is considerably higher than that of the Laxfordian, but lower than that of the Scourian. Since its ratio is so much higher than that of the Moinian it is more likely to have been reduced by the action of solutions, than increased. If so, it is more likely to be Scourian, rather than Laxfordian.

Also, the K/Rb ratio is slightly higher than that of

the Laxfordian. Percolation through the system during metamorphism, of solutions enriched in potassium and rubidium from the Moinian should tend to lower the Lewisian K/Rb ratio to a figure more similar to the ratio in the Moinian. That some enrichment in alkalis has occurred is suggested by the later growth of biotite in amphibolites; that the K/Rb ratio remains higher than that of the Laxfordian suggests that the inlier rocks originally had an even higher ratio. The only known rocks with a much higher ratio in the district are Scourian.

How far does petrological evidence support the chemical evidence? Pyroxene and sphene are preserved in one of the inlier amphibolites within garnet. This is believed to reflect an original mineralogy reminiscent of post-Scourian dykes. The abundance of amphibolite is greater in the Fannich Inlier than it usually is in the Laxfordian. None of this petrological evidence proves that the Fannich Inlier is Scourian, but it does not contradict the chemical evidence in suggesting that it is not. Therefore the rocks of the Fannich Inlier are probably re-metamorphosed Scourian gneisses.

9.6 The significance of geochemical differences between Moinian amphibolites.

Geochemical differences between Moinian amphibolites suggest that they do not originate from identical igneous bodies. One dyke-swarm is unlikely to account for the range of compositions shown by the Meall an t-Sithe amphibolites, the Sgurr Mor amphibolites and the Ben Hope Sill. Both Fannich amphibolite groups, with low silica contents, were probably derived from basalts, but compared to the "normal" basalts quoted by Nockolds (1954) and Manson (1967), they are alumina-depleted and iron-rich, although not as iron-rich as the ferrogabbros from Skaergaard (Wager 1960). But the higher MgO and Ni contents, and lower CaO content of the Sgurr Mor amphibolites may suggest that they originated from alkali-basalts rather than alkali-tholeiites, which are compositionally closer to the Meall an t-Sithe amphibolites.

Amphibolites from the Ben Hope Sill are more silicic. While it is appreciated that few reliable conclusions can be drawn from only three analyses (Table 20), the most basic sample has the composition of an average tholeiitic andesite (Nockolds 1954). The other two samples indicate that a differentiation trend occurs within the sill, producing rocks with higher contents of SiO_2, TiO_2 and MnO, and lower contents of FeO, CaO and Ni. The more silicic rocks, occurring as coarse-grained segregations in the sill

tend towards a ferro-tonalitic composition. Although local element migration may have occurred during chemical reactions along the junctions of these basic bodies during metamorphism, it is considered that most of the ferromagnesian elements have been preserved in their original proportions. Different element ratios in the Ben Hope Sill suggest that it is a metamorphosed differentiated sill.

There exist in the Moinian, therefore, several distinct suites of pre-orogenic minor intrusive rocks, and two quite separate suites occur in the Moinian of Fannich Forest.

In conclusion, the geochemical evidence supports the petrological evidence that a Lewisian Inlier exists in Fannich, and that its junction with the Moinian is unconformable. This strengthens the assumption that the Lewisian forms the core of an isoclinal fold rather than a thrust-slice, and supports both the structural and stratigraphic interpretations proposed in this thesis.

APPENDIX

METHODS OF ANALYSIS.

1. Whole-Rock Analysis

X-ray Fluorescence analysis was chosen in preference to chemical methods because of its rapidity and because the same method can be used for both major and trace elements. The object of analysing rocks from Fannich was to discover any trends in the compositions of certain rock-types, and any chemical changes to which mineralogical differences could be related. Since the number of analyses required for this purpose is large, speed in analysis is extremely valuable. Thus, while it is accepted that minor errors present in the chemical analyses quoted in this thesis may have been avoided by using classical chemical analysis, their accuracy is nonetheless considered sufficient.

Over 230 rocks from Fannich have been analysed. The techniques employed, and the potential sources of error have been described in detail by Liebhafsky et al. (1960) and Norrish and Chappell(1967).

Preparation of the samples requires the production of a homogeneous compacted rock-powder, which is exposed to X-rays of an appropriate intensity and wavelength. To prepare these

powders, the rock-samples were first split into smaller blocks, which were further reduced in size by jaw-crusher. The coarse powder produced by this crushing was finally powdered in a Tema swing-mill to a uniform grain-size entirely less than 200 mesh. The use of tungsten carbide ring in the Tema Mill instead of agate reduced the possibility of silica contamination. 100-150 grams of rock-powder were usually produced by this method. These powders were compressed at 4 tons pressure into 2.5 cm. tablets without containing rims; siliceous powders were mixed with 1-2 drops of aqueous Mowiol cement solution for greater cohesion. The same tablets were used for both major and minor element analyses.

This method of analysis depends on the fact that, subject to certain assumptions about the sample and excitation conditions, the intensity of the fluorescent radiation I is directly proportional to the concentration of the analysed element.C, divided by the mass absorption coefficient of the unknown sample U.

$$I = \frac{kC}{U}$$

The mass absorption coefficient of a sample is related to the relative concentrations of the major elements present. Thus, if the fluorescent intensities of all the major elements are measured, the mass absorption of the sample at a given wavelength may be determined. From this the concentration of an element

may be calculated by means of a repetitive calculation. To calculate the mass-absorption at a given wavelength U, the following equation is used:

$$U = U_a Ca + U_b + Cb + \ldots$$

where U_a is the mass absorption coefficient of element a at wavelength , and Ca is the concentration of element a. Dr. J.G. Holland kindly loaned a computer programme for this calculation (Holland and Brindle 1966).

50 samples, already analysed for major elements, were also analysed for trace elements. For trace element analysis, in a method described in detail by Pankhurst (1968), the total mass absorption U can be determined directly by measuring the attenuation of the X-ray beam through a thin film of rock-powder, according to the equation:

$$U = \frac{2.915}{M} \cdot \log. \frac{I_o}{I_1}$$

where M is the weight of the rock powder in grams, I_o is the time taken for the count to reach a pre-set figure with the rock-powder present, while I_1 is the time taken for the count to reach the same figure with the disc absent. The mass absorptions were determined at the Sr K wavelength, and the same values were used for the traces Sr, Rb, Zr, Nb and Ni. Using these mass-absorptions, corrected for Dead Time statistical

counting error, and accurately analysed standard powders of other rocks determined by independent methods, a linear calibration, passing through the origin, was obtained for each of these elements. The results for Zr have been corrected for interference from Rb K_α (16%Rb K_α). Results for concentrations greater than 20 p.p.m. should be accurate to within 5%, but in the lower concentrations obtained in some rocks for Rb and Nb the error may be much greater.

In major element analysis four main sources of error exist, namely mass absorption, variations of grain-size of powders, interference between elements, and statistical counting error.

Error in the calculated mass absorption coefficients is the greatest single source of error. The accuracy of the available tables is only about 2-5%, which must therefore be the maximum precision possible with this method. The mass absorption tables of Heinrich have been used as they have been found to give distinctly better results than the older tables of Liebhafsky, particularly in the determinations for SiO_2, Al_2O_3 and MgO.

The grain-size of the sample influences the homgeneity of the tablet to X-Rays, particularly at long wavelengths, where excitation is essentially a surface phenomenon. Grain orientation, which becomes increasingly important with coarser-grained powders, may also cause error. For example sheet silicates,

chlorite or micas tend to become oriented parallel to the tablet surface during compression, thus presenting an above average surface area to the beam. Only fine grinding can eliminate this.

Interference between elements is another source of error, but usually in major element analysis, concentrations of minor elements that may cause interference are usually too small to be significant.

For most elements the peak count-rates are sufficiently large compared to those of the background, to keep statistical counting error to a very low level, but for Mg and Na statistical error may be significant. As far as possible this was minimised by running the sample several times and subtracting the background values obtained.

A final source of error may be described as the selection of inappropriate standard rocks. As far as possible the standards used were derived from comparable rocks. I am indebted particularly to Dr. Butler for supplying Moinian standards from Ardnamurchan, Dr. Muecke for supplying analysed Scourian powders, and Dr. Poole for supplying analysed powders from Moinian calc-silicates from Morar.

All these sources of error have been kept at a minimum by using a consistent grinding method, fine grain size and comparable standards. I am grateful to Dr. M.P. Martineau and

and Mr. C.R. Fagg for assistance and advice in the chemical analyses conducted by this method.

2 Garnet Analysis

Garnets from 19 rocks were analysed by Mr. C.R. Fagg using the electron microprobe. The electron microprobe was used because it could analyse minute areas of a sample, and thus reveal variations of composition within garnet grains. The use of the microprobe is described in detail by McKinley et al. (1964).

But since microscopic inclusions were frequently present in the garnets analysed, and since a few of the garnets were richer in iron than any of the standards against which they were run, the results obtained were used more as a guide to the fluctuations in garnet composition, rather than as accurately determined analyses. To minimize inaccuracies in the analysis of the most iron-rich samples, one was analysed by Mrs. J. Wigley using classical chemical methods. The garnet standards used are unzoned Lewisian garnets chemically analysed by Dr. Muecke.

As the presence of inclusions rendered a continuous scan of the garnet difficult to interpret, the garnets were analysed by performing separate analyses at different points in the grain. At least three measurements were made at each point to

eliminate statistical counting error as far as possible, but in view of the large fluctuations that still occurred, further corrections were considered unlikely to improve the accuracy of the readings.

The samples were prepared as thin-sections without cover-slips, the surface highly polished and coated with a thin layer of carbon to prevent an electric charge accumulating.

In view of the use to which these garnet analyses have been put, in revealing compositional variations within garnet grains, this method has proved sufficiently accurate, and I am indebted to Mr. C.R. Fagg for performing these analyses.

REFERENCES

Althaus, E. 1967 The Triple Point Andalusite-Sillimanite -Kyanite. Contr. Min. Pet. 16, pp.29-44.

Atherton, M.P. 1964 The Garnet Isograd in Pelitic Rocks and its relation to metamorphic facies. Amer. Min. 49, pp.1331-1349.

Atherton, M.P. 1965a The Chemical Significance of Isograds. in 'Controls of Metamorphism', edited by W.S. Pitcher and G.W. Flinn, Oliver & Boyd, Edinburgh and London.

Atherton, M.P. 1965b The composition of Garnet in regionally metamorphosed rocks. in 'Controls of Metamorphism', edited by W.S. Pitcher and G.W. Flinn. Oliver & Boyd, Edinburgh and London.

Atherton, M.P. 1968 The variation in Garnet, Biotite and Chlorite Composition in Medium Grade Pelitic Rocks from the Dalradian, Scotland, with Particular Reference to the Zonation in Garnet. Contr. Min. Pet. 18, pp.347-371.

Atherton, M.P. and Edmunds, W.M. 1966 An electron microprobe study of some zoned garnets from metamorphic rocks. Earth and Planet Sci. Letters 1, pp.185-193.

Bailey, E.B. 1922 The structure of the South-West Highlands of Scotland. Quart. J. Geol. Soc. Lond. 78, pp.82-127.

Barrow, G. 1893 On an intrusion of Muscovite-Biotite Gneiss in the South-eastern Highlands of Scotland, and its accompanying metamorphism. Quart. J. Geol. Soc. Lond. 49, pp.33-358.

Barth, T.F.W. 1936 Structural and Petrologic Studies in Dutchess County, New York. Bull. Geol. Soc. Amer. 47, pp. 775-850.

Bence, A.E. and Albee, A.L. 1968 Empirical correction factors for the electron microanalysis of silicates and oxides. J. Geol. 76, pp.382-403.

Bosworth, T.O. 1925 in The Geology of South-west Mull. Mem. Geol. Surv. Sheet 43.

Buddington, A.F. 1963 Isograds and the role of H_2O in Metamorphic Facies of Orthogneisses of the North-West Adirondack Area, New York. Bull. Geol. Soc. Amer. 74, pp. 1155-1182.

Butler, B.C.M. 1960 The structure and petrology of Ardnamurchan, Argyllshire. Cambridge Ph.D. Thesis (unpublished).

Butler, B.C.M. 1962 Biotite- and Sphene-rich rocks in the Moine Series of Ardnamurchan, Argyllshire Geol. Mag. 99, pp.173-182.

Butler, B.C.M. 1965 A chemical study of some rocks of the Moine Series of Scotland. Quart. J. Geol. Soc. Lond. 121, pp.163-208.

Chinner, G.A. 1960 Pelitic Gneisses with varying Ferrous/Ferric ratios from Glen Clova, Angus, Scotland. J. Petrol. 1, pp. 178-217.

Clifford, P. 1960 The geological structure of the Loch Luichart area, Ross-shire. Quart. J. Geol. Soc. Lond. 115, pp. 365-388.

Clifford, T.N. 1957 The stratigraphy and structure of part of the Kintail district of southern Ross-shire: its relation to the Northern Highlands. Quart. J. Geol. Soc. Lond. 113, pp.57-92.

Clifford, T.N. 1958 A note on kyanite in the Moine Series of southern Ross-shire, and a review of related rocks in the Northern Highlands of Scotland. Geol. Mag. 95, pp.333-346.

Crampton, C.B. 1913 in The Geology of Central Ross-shire. Mem. Geol. Surv. Sheet 82.

Crampton, C.B.	1956	Loch Shin Limestone: Comparison of Dolomite and Calcite Fabrics. Trans. Edin. Geol. Soc. 16, pp.334-337.
Deer, W.A., Howie, R.A. and Zussman, J.	1962	Rock-forming minerals. Longmans, London.
Elles G.L., and Tilley, C.E.	1930	Metamorphism in relation to structure in the Scottish Highlands. Trans. Roy. Soc. Edin. 56, pp.621-646.
Flett, J.S.	1902	in The Geology of Lower Strathspey. Mem. Geol. Surv. Sheet 85.
Flett, J.S.	1912	in The Geology of Ben Wyvis, Carn Chuinneag, Inchbae and the surrounding country. Mem. Geol. Surv. Sheet 93.
Fleuty, M.J.	1961	The three fold-systems in the Metamorphic Rocks of Upper Glen Orrin, Ross-shire and Inverness-shire. Quart. J. Geol. Soc. Lond. 117, pp.447-476.
Francis, G.H.	1858	The Amphibolite of Doir' a' Chatha (Durcha), Sutherland. Geol. Mag. 95, pp.25-40.
Ged, M.A., Catt, J.A. and LeRiche H.H.	1968	Geochemistry of the Whitbian (Upper Lias) sediments of the Yorkshire Coast. Proc. Yorks. Geol. Soc. 37, pp.105-139.
Ghaly, T.S.,	1966	The Lewisian Geology of the area between Loch Shieldaig and Loch Braigh Horrisdale, Gairloch, Ross-shire. Scot. J. Geol. 2, pp.282-305.
Goldschmidt, V.M.	1954	Geochemistry. Alex. Muir, Oxford.
Grant-Wilson, J.S. and Teall, J.J.H.	1899	in Summ. Prog. Geol. Surv. U.K.
Guppy, E.M. and Thomas, H.H.	1931	Chemical Analyses of Igneous Rocks, Metamorphic Rocks and Minerals. H.M. Stationery Office, London.

Guppy, E.M. and Sabine, P.A.	1956	Chemical Analyses of Igneous Rocks, Metamorphic Rocks and Minerals, 1931-1954. H.M. Stationery Office, London.
Heier, K.S. and Adams, J.A.S.	1964	The Geochemistry of the Alkali Metals. Physics and Chemistry of the Earth, 5, pp. 253-381.
Holland, J.G.	1965	Geochemical Studies in the Lewisian. Oxford D. Phil Thesis (unpublished).
Holland, J.G. and Brindle, D.W.	1966	A self-consistent mass-absorption correction for silicate analysis by X-ray Fluorescence. Spectrochim. Acta 22.
Holm, J.C. and Kleppa, O.J.	1966	The thermodynamic properties of the aluminium silicates. Am. Min. 51, pp. 1608-1622.
Hsu, L.C.	1968	Selected Phase Relationships in the Systems Al-Mn-Fe-Si-O-H. A Model for Garnet Equilibria. J. Petrol. 9, pp. 40-83.
Johnson, M.R.W.	1960	The structural history of the Moine Thrust Zone at Lochcarron, Wester Ross. Trans. Roy. Soc. Edin. 64, pp.139-168.
Johnson, M.R.W. and Stewart, F.H.	1963	The British Caledonides. Oliver & Boyd, Edinburgh & London.
Johnstone, G.S., Smith, D.I. and Harris, A.L.	1969	The Moinian Assemblage of Scotland. Am. Assoc. Petroleum Geologists. Mem.12, pp.159-180.
Kennedy, W.Q.	1949	Zones of Progressive Regional Metamorphism in the Moine Schists of the Western Highlands of Scotland. Geol. Mag. 86, pp.43-56.
Kennedy, W.Q.	1951	Sedimentary Differentiation as a Factor in the Moine-Torridonian Correlation. Geol. Mag. 88, pp.257-266.
Lambert, I.G. and Heier, K.S.	1968	Estimates of the Crustal Abundances of Thorium, Uranium and Potassium. Chem. Geol. 3, pp.233-238.

Lambert, R.St.J. 1955 The structure and petrology of the Moine Schists and associated gneisses of the Morar and Knoydart Districts of Inverness-shire. Cambridge Ph.D. Thesis (unpublished).

Lambert, R.St.J. 1959 The mineralogy and metamorphism of the Moine Schists of the Morar and Knoydart districts of Inverness-shire. Trans. Roy. Soc. Edin. 63, pp.553-588.

Lambert, R.St.J. 1968 Isotopic studies relating to the Pre-Cambrian history of the Moinian of Scotland. Proc. Geol. Soc. Lond. 1652 pp.243-245.

Lambert, R. St.J. and Holland, J.G. in press A geochronological study of the Lewisian of the Laxford area, north-west Scotland.

Liebhafsky, M.A., Pfeiffer, H.G., Winslow, E.H. and Zemany, P.E. 1960 X-ray absorption and emission in analytical chemistry. Wiley. pp.357

Mackie, W. 1920 The Principles that Regulate the Distribution of Particles of Heavy Minerals in Sedimentary Rocks, as illustrated by the Sandstones of North-East Scotland. Trans. Edin. Geol. Soc. XI, pp.128-164.

Manson, V. 1967 Geochemistry of Basaltic Rocks. Major Elements. in The Poldervaart Treatise on Rocks of Basaltic Composition, edited by Hess, H.H. and Poldervaart, A.

McGregor, A.G. 1948 Resemblances between the Moine and 'Sub-Moine' Metamorphic Sediments in the Western Highlands of Scotland. Geol. Mag. 85, pp.265-275.

McIntyre, D.B. 1952 The tectonics of the Beinn Dronaig Area, Attadale. Trans. Edin. Geol. Soc. 15, pp.258-264.

McKinley, T.D., Heinrich, K.F.J., and Wittry, D.B. 1964 The Electron Microprobe. John Wiley, New York, London, Sydney.

Miyashiro, A.	1953	Calcium-poor Garnet in relation to metamorphism. Geochim. Cosmochim. Acta 4, pp.179-
Miyashiro A.	1956	Data on garnet-biotite equilibria in some metamorphic rocks of the Kyoke zone. J. Geol. Soc. Jap. 62, pp.700
Muecke, G.K.	1969	Petrogenesis of granulite-facies rocks from the Lewisian of North-West Scotland. Oxford D.Phil. Thesis (unpublished).
Nandi, K.	1967	Garnets as indices of progressive regional metamorphism. Min. Mag. 36, pp.89-93.
Newton, R.C.	1965	The Thermal Stability of Zoisite. J. Geol. 73, pp. 431-441.
Newton, R.C.	1966	Kyanite-Sillimanite Equilibrium at 750°C. Science 151, pp.1222.
Nockolds, S.R.	1954	Chemical Compositions of Igneous Rocks. Bull. Geol. Soc. Amer. 65, pp.1007-1032.
Norrish, K. and Chappell B.W.	1967	X-Ray Fluorescence Analysis, in Physical Methods in Determinative Mineralogy, ed. Zussman, J. Academic Press, London, pp.161-214.
Pankhurst R.J.	1968	Strontium isotope and age studies in North-East Scotland. Oxford D.Phil. Thesis (unpublished).
Park, R.G.	1966	Nature and Origin of the Lewisian basic rocks of Gairloch, Ross-shire. Scot. J. Geol. 2, pp.179-199.
Park, C.F. and McDiarmid, R.A.	1964	Ore Deposits. Freeman & Co., San Francisco, London.
Peach, B.N., and Gunn	1897	in Summ. Prog. Geol. Surv. U.K.
Peach, B.N. and Gunn	1898	in Summ. Prog. Geol. Surv. U.K.
Peach, B.N. and Gunn	1899	in Summ. Prog. Geol. Surv. U.K.

Peach, B.N. et al.	1910	in The Geology of Glenelg and South-East Skye. Mem. Geol. Surv. Sheet 71.
Peach, B.N. et al.	1913a	in The Geology of Central Ross-shire. Mem. Geol. Surv. Sheet 82.
Peach, B.N. et al.	1913b	in The Geology of the Fannich Mountains and the country around Upper Loch Maree, and Strath Broom. Mem. Geol. Surv. Sheet 92.
Phillips, F.C.	1937	A Fabric Study of some Moine Schists and Associated Rocks. Quart. J. Geol. Soc. Lond. 93, pp.581-620.
Poole, A.B.	1962	The Structure and Petrology of the Metamorphic Rocks of Eastern Morar, Inverness-shire. Oxford D.Phil. Thesis (unpublished).
Powell, D.	1964	The Stratigraphical Succession of the Moine Schists around Lochailort (Inverness-shire) and its Regional Significance. Proc. Geol. Ass. Lond. 75, pp.223-250.
Prinz, M.	1967	Geochemistry of Basaltic Rocks: Trace Elements. in The Poldervaart Treatise on Rocks of Basaltic Composition. ed. Hess, H.H. and Poldervaart, A., pp.271-321.
Ramsay, J.G.	1957	Superimposed folding at Loch Monar, Inverness-shire and Ross-shire. Quart. J. Geol. Soc. Lond. 113, pp.271-305.
Ramsay, J.G.	1959	Moine-Lewisian Relations at Glenelg, Inverness-shire. Quart. J. Geol. Soc. Lond. 113, pp.487-520.
Ramsay, J.G.	1963	Structure and Metamorphism of the Moine and Lewisian Rocks of the North-West Caledonides. in The British Caledonides ed. Johnson, M.W., Stewart, F.H., pp. 143-175.
Ramsay, J.G. and Spring, J.	1962	Moine Stratigraphy in the Western Highlands of Scotland. Proc. Geol. Ass. Lond. 73, pp. 295-326.

Rankama, K. & Sahama, Th.G.	1950	Geochemistry. Univ. Chicago Press.
Rast, N.	1958	Metamorphic History of the Schichallion Complex. (Perthshire). Trans. Roy. Soc. Edin. LXIII, pp.413-431.
Read, H.H., Phemister, J., and Ross G.	1926	The Geology of Strath Oykell and Lower Loch Shin. Mem. Geol. Surv. Sheet 102.
Read, H.H.	1931	The Geology of Central Sutherland. Mem. Geol. Surv. Sheets 108 and 109.
Read, H.H.	1934	Age-Problems of the Moine Series of Scotland. Geol. Mag. 71, pp.302-317.
Richardson, S.W., Gilbert, M.C. and Bell, P.M.	1969	Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the aluminium silicate triple point. Amer. J. Sci. 267, pp. 259-272.
Richey, J.E. and Kennedy, W.Q.	1939	The Moine and Sub-Moine Series of Morar, Inverness-shire. Bull. Geol. Survey Gt. Brit. 2, p.26.
Ronov, A.B. and Yaroshevsky, A.A.	1969	Chemical Structure of the Earth's Crust. in Geochem. Int. 4, pp.1041-1066.
Rutledge, H.	1952	The structure of the Fannich Forest Pelitic Belt. Trans. Edin. Geol. Soc. 15, pp.317-321.
Sabine, P.A.	1969	Geochemistry of Sedimentary Rocks. Natural Environment Research Council Report No.69/1. H.M. Stationery Office, London.
Selley, R.C.	1966	Petrography of the Torridonian Rocks of Ramsay and Scalpay, Inverness-shire. Proc. Geol. Ass. Lond. 77, pp.293-313.
Shaw, D.M.	1956	Geochemistry of Pelitic Rocks; Major elements and General Geochemistry. Bull. Geol. Soc. Amer. 67, 919-934.

Shaw, D.M. Reilly, G.A. Muysson, J.R. Pattenden, G.E. Campbell, F.E.	1967	An estimate of the chemical composition of the Canadian Precambrian Shield. Can. J. Earth Sci. 4, pp. 829-853.
Spring, J.S.	1960	The stratigraphy and structure of the Moine and Lewisian rocks of Knoydart, Inverness-shire. Imperial College Ph.D. Thesis (unpublished).
Stewart, A.D.	1962	On the Torridonian Sediments of Colonsay and their Relationship to the Main Outcrop in North-West Scotland. Lpool. Manchr. Geol. J. 3, pp.121-156.
Sturt, B.A.	1962	The Composition of Garnets from Pelitic Schists in relation to the Grade of Regional Metamorphism. J. Petrol. 3, pp.181-191.
Sturt, B.A. and Harris, A.L.	1961	The Metamorphic History of the Loch Tummel area, Central Perthshire, Scotland. Lpool. Manchr. Geol. J. 2, pp. 689-711.
Sutton, J. and Watson, J.	1954	The structure and stratigraphical succession of the Moines of Fannich Forest and Strath Bran, Ross-shire. Quart. J. Geol. Soc. Lond. 110, pp.21-54.
Sutton, J. and Watson, J.	1962	An Interpretation of Moine-Lewisian Relations in Central Ross-shire. Geol. Mag. 99, pp.527-541.
Tanner, P.W.G.	in press	The Sgurr Beag Slide - a major tectonic break within the Moinian of the western Highlands of Scotland.
Tanner, P.W.G., Johnstone, G.S., Smith, D.I. and Harris, A.L.	1970	Moinian Stratigraphy and the Problem of the Central Ross-shire Inliers. Bull. Geol. Soc. Amer. 81, pp.299-306.
Taylor, S.R.	1964	Abundance of Chemical Elements in the Continental Crust: a new table. Geochim. et Cosmochin. Acta 10, pp.245-296.

Tilley, C.E.	1924	The Facies Classification of Metamorphic Rocks. Geol. Mag. 61, pp. 167-171.
Tilley, C.E.	1925	Metamorphic zones in the southern Highlands of Scotland. Quart. J. Geol. Soc. Lond. 81, pp.100-112.
Turekian, K.K., and Wedepohl, K.H.	1961	Distribution of the Elements in some major units of the Earth's crust. Bull. Geol. Soc. Amer. 72, pp.175-192.
Turner, F.J.	1968	Metamorphic Petrology. McGraw-Hill. New York, San Francisco, London
Vogt, J.H.L.	1931	On the average composition of the Earth's Crust, with particular reference to the contents of phosphoric and titanic acid. Skrifter Norske Videnskaps-Acad. Oslo I. Mat.-naturv. Klasse N.7.
Wager, L.R.	1960	The Major Element Variation of the Layered Series of the Skaergaard Intrusion and a Re-estimation of the Average Composition of the Hidden Layered Series, and of the Successive Residual Magmas. J. Petrol. 1, pp.364-398.
Weill, D.F.	1966	Stability Relations in the Al_2O_3-SiO_2 system calculated from solubilities in the Al_2O_3-SiO_2-Na_3AlF_6 system: Geochim. et Cosmochim. Acta 30, pp.223-237.
Williams, G.E.	1968	Torridonian weathering, and its bearing on Torridonian palaeo-climate and source. Scot. J. Geol. 4, pp.164-183.
Williamson	1953	Petrology of Chloritoid and Staurolite Rocks, North of Stonehaven, Kincardineshire. Geol. Mag. 90, pp.353-361.
Winchester, J.A. and Lambert, R. St.J.	1970	Geochemical distinctions between the Lewisian of Cassley, Durcha and Loch Shin, Sutherland, and the surrounding Moinian. Proc. Geol. Assoc. 81,(Lond.)
Winkler, H.G.F.	1967	Petrogenesis of Metamorphic Rocks. 2nd Edn. Springer-Verlag, Berlin, Heidelberg, New York.

Wiseman, J.D.H. 1934 The Central and South-West Highland Epidiorites: A study in Progressive Metamorphism. Quart. J. Geol. Soc. Lond. 90, pp.354-417.

Yoder, H.S. 1955 Role of Water in Metamorphism. Bull. Geol. Soc. Amer. 62, pp.505-524.

Yoder, H.S. and Keith, M.L. 1951 Complete substitution of Aluminium for Silicon: The System: $3MnO-Al_2O_3-3SiO_2-3Y_2O_3-5Al_2O_3$. Amer. Min. 36, pp.519-533.

Zen, E-an. 1969 The Stability Relations of the Polymorphs of Aluminium Silicate: A survey and some comments. Amer. J. Sci. 267, pp.297-309.