

A TECTONIC STUDY OF THE POST-CAMBRIAN THRUSTS

of the

ASSYNT REGION

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In 1829, Murchison and Sedgwick correlated the red (Torridon) sandstones between Cape Wrath and Durness with outliers of conglomerate and sandstone near Tongue and hence with the Old Red Sandstone of Caithness. Ten years later, however, R.J.H. Cunningham described the red (Torridon) sandstones and the conglomerates and sandstones of Tongue and concluded that the two formations were not sufficiently alike to justify a correlation.

Cunningham's book, "The Geognosy of Sutherlandshire" (1839), contains a geological map of the county and gives an account of the distribution and relations of the rock-types in Assynt. The author confirmed Macculloch's observations on the unconformability of the red (Torridon) sandstones on the gneiss and the superposition of the eastern gneiss on the quartz-rocks and limestone. He considered that there was a conformable sequence from the quartz-rocks to the upper gneiss and postulated a 'Transition Series' to account for lateral variations in the succession. Cunningham maintained that "in Sutherland there are two systems of crystalline rock, one being older than conglomerate (Torridon), quartz-rock and limestone; and another which has been formed subsequently to all". (p. 28).

In his well-known book, "The Old Red Sandstone", published in 1841, Hugh Miller claimed that the red sandstones of Assynt were overlain successively by (1) a lower quartz-rock; (2) /

CONTENTS

<u>I. INTRODUCTION</u>	<u>Page</u>
1. REVIEW OF PREVIOUS RESEARCH	1
2. PURPOSE AND SCOPE OF THE STUDY	43
a. Statement of the Problems	43
b. Scope of the Study	45
c. Procedure	46
 <u>II. PRINCIPLES AND NOMENCLATURE</u>	
1. FABRIC AXES	48
2. TERMINOLOGY OF MYLONITIC ROCKS	54
3. KINEMATIC INTERPRETATION OF FABRICS OF DEFORMED ROCKS	69
 <u>III. MEGASCOPIC STRUCTURAL DATA</u>	
1. THE MOINE THRUST	76
a. Preliminary Survey	76
b. The Stack of Glencoul Area	79
c. The Cnoc a'Chaoruinn Area	91
d. The Loch Ailsh Area	99
e. The Knockan Crag Area	106
f. Summary	111
g. Discussion of the Movements	113
2. THE ZONE OF DISLOCATION	122
a. Introduction	122
b. Nomenclature of Thrusts and Nappes	123
c. Folding	130
d. Distribution and Style of Large-scale Folds	133
e. Lineations	136
f. Discussion of the Movements	137

IV. /

IV.	<u>MICROSCOPIC STRUCTURAL DATA</u>	
1.	GRAIN ORIENTATION IN THE DOLOMITE ROCKS	141
	a. Introduction	141
	b. Intragranular deformation in dolomite	143
	c. Fabric Data	151
	d. Interpretation and conclusions	161
2.	GRAIN ORIENTATION IN THE QUARTZ-BEARING ROCKS	175
	a. Introduction	175
	b. Petrography.	175
	c. Fabric Data	180
	d. Interpretation	188
V.	<u>TECTONIC SYNTHESIS</u>	
1.	INTRODUCTION	203
2.	STRUCTURAL CORRELATIONS	203
3.	DISCUSSION OF THE MOVEMENTS	208
4.	THE AGE OF THE MOVEMENTS	216
VI.	<u>ACKNOWLEDGEMENTS</u>	218
VII.	<u>LIST OF WORKS TO WHICH REFERENCE IS MADE</u>	219

I. INTRODUCTION

1. REVIEW OF PREVIOUS RESEARCH

The North-west Highlands have long attracted the notice of geologists and of this great tract of country the Assynt region has undoubtedly received more attention than any other of comparable size. The area has provided much of the critical evidence influencing the development of thought on the geological structure and origin of the Highlands. In the following paragraphs this development will be traced by brief reference to work in areas outside Assynt; the course of research carried out inside the area will be described in more detail.

The first noteworthy geological work in the North-west Highlands is contained in a series of papers published between 1814 and 1824 by J. Macculloch. He described a remarkable development of red sandstone, quartz-rock and limestone along the west coast of Sutherland and Ross-shire and maintained that the red sandstones rest unconformably on the western gneiss. The sandstones are overlain by the quartz-rocks and limestone, which alternate with and pass upwards into schists and gneisses characteristic of the types which form the greater part of the Highlands. On the eastern shore of Loch Eireboll Macculloch noted the superposition of the eastern gneiss on quartzite, while to the south in Skye and Glenelg he reported an upward gradation from the red sandstones into the gneisses and schists.

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(2) massive limestones with intercalated quartz-rocks near the base; and (3) an upper quartz-rock, which is exposed on Glasven and Ben More Assynt. Miller also correlated the red (Torridon) sandstones with those of the Moray Firth basin, which are of Old Red Sandstone age, thus supporting the contention of Murchison and Sedgwick.

In 1844, James Nicol suggested in his "Guide to the Geology of Scotland" that the crystalline rocks of the Highlands might be the metamorphic representatives of the Silurian rocks in the Southern Uplands. The search for faunal evidence was unproductive, however, until 1854, when C.W. Peach, Benjamin Peach's father, found Lower Palaeozoic fossils in the limestones of Durness. This discovery stimulated Murchison to visit the Durness-Eireboll area the following summer, accompanied by Nicol. Murchison (1855) separated the western gneiss from the eastern schists, which he considered, like Cunningham, to be younger than the fossiliferous limestones. He contended that the crystalline schists had originally been stratified deposits which recrystallised before the Old Red Sandstone period. The age of the fossils was thought by Murchison to be Lower Silurian, though Salter had provisionally referred them to Devonian genera.

Nicol returned to Sutherland in 1856 and extended his work into Assynt and southwards to Skye. He demonstrated (1857, p. 25) /

p. 25) that the quartzites rest unconformably on the red (Torridon) sandstones and established the following succession in the quartzite and limestone group:

- d. Limestones.
- c. Beds with cylindrical markings (Serpulite Grit).
- b. Brown slaty beds with fucoid markings.
- a. Quartzite with basal conglomeration.

That Nicol sensed the complexity of the structure in Assynt is shown by his section near the east end of Loch Assynt, where, as he indicates, the quartzite is repeated to the east of the limestone by faulting. He wrote of this section, "though less clear than at Ullapool, probably from having undergone greater disturbance, the relative positions of the formations appears to be essentially the same". Nicol considered that the superposition of the eastern schists on the quartzite and limestone might be accounted for in two ways: the schist might be either (a) the upper part of the fossiliferous succession converted into a newer metamorphic series; or (b) "merely a portion of the lower gneiss [Lewisian] forced up over it in some great convulsion".

In 1859 Murchison published a long paper on "The Succession of the Older Rocks in the Northernmost Counties of Scotland". In it he refuted Nicol's claim that in Assynt the quartz-rocks /

ROYAL CHARLES

quartz-rocks are repeated to the east of the limestones by faulting. He maintained that the quartzite of Conival and Braebag lies conformably on the limestone and concluded that there is a definite conformable sequence through a lower quartzite, limestone and upper quartzite to the upper gneiss. The whole sequence was considered to be of Lower Silurian age.

This period marks the opening of a lasting controversy between Nicol and Murchison; the disagreement dates from the 1859 meeting of the British Association, to which both contributed. In 1860 Murchison published a supplement to his 1859 memoir, based on his own observations and those of Ramsay and Harkness. These observations, extending over a great part of Assynt, engendered a further modification of Murchison's sequence; they confirmed the existence, at certain localities, between Cnoc a' Chaoruinn and the Stack of Glencoul, of an 'upper limestone' between the 'upper quartzite' and the younger gneiss. While admitting the existence of a fault between Cnoc na Droighinn and the Ben More range, east of Loch Assynt (see Nicol, above), Murchison claimed that it lay completely in the upper quartzite. He expressed definite disagreement with Nicol's suggestion that the eastern gneiss might be the older gneiss (Lewisian) brought over the sedimentary rocks by faulting. Nicol's view (1857) that intrusions of igneous rock in the quartzites /

quartzites and limestones are associated with planes of dislocation was also criticised by Murchison, who claimed that these masses do not disturb the general succession of the rocks.

In his final contribution to the geology of the Northwest Highlands (1861), Nicol presented further evidence against the conformable succession advocated by Murchison and his supporters. In Assynt he described in some detail sections near Loch Glencoul, Glasven, Ben Uidhe, Ben an Fhurain, Ben More, Glen Oykell, Loch Ailsh and Knockan Crag. He noted that the Glencoul gneiss, which Murchison considered to be conformable on the quartzite, was separated from it by a low hollow (now known to be the Glencoul Thrust) and that the foliation in the gneiss was almost vertical with a strike at right angles to that of the quartzite. In the mountains south of Glencoul he described a great development of syenite intermixed with granitic gneiss, which he considered to be continuous with the eastern gneisses. Nicol believed that the limestones in central Assynt, south-east of Inchmadamph, lay in a great syncline between the quartzite of Quinag and Canisp on the west and that of Ben an Fhurain and Ben More on the east. "The only obscurity in the sections", he stated, "arises from the synclinal fold in the limestone being conjoined with a great fault in the quartzite, which is thus brought up in enormous crushed masses, so broken that the lines of /

of stratification can hardly be detected; this is especially seen near the foot of Conival". The conspicuous line of fault referred to is now known as the Glencoul Thrust. In the corries of Ben More and on the hills south of Stronechrubie Nicol recorded red sandstones similar to those of the foreland. On Ben More these rest on gneiss and Nicol took this as final proof of the synclinal structure: "the synclinal is thus complete from the upper limestone to the lowest gneiss". He confirmed the existence of limestone at Loch Ailsh and suggested that it was merely a repetition of the Stronechrubie limestone on the eastern side of the Ben More anticline. In the section across Cnoc a' Chaoruinn (Cnoc Chaorinie) Nicol noted frequent breaks and omissions in the sequence, which could not possibly be explained on the basis of Murchison's 'conformable succession'.

The most important feature of Nicol's sections is that in every case the western limit of the eastern gneiss is marked by a fault. In addition, he recognised in the rocks signs of deformation which had been ignored by other investigators. He maintained that at Knockan Crag "the fracture and contortion of the beds, seen even in hand-specimens, and particularly the manner in which the limestone and fucoid beds are cut out, prove that there is, in this place, not 'conformable upward succession' but a line of fault with powerful lateral compression" (p. 102).
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The lithological similarity between the western Lewisian gneiss and some representatives of the "upper gneiss" series led him to conclude that the latter was, in reality, the old gneiss brought up by faulting. Nicol drew an analogy between the Scottish Highlands and the Alps, where the thrusting of crystalline masses over unmetamorphosed sediments was universally recognised, and claimed that "until some rational theory is produced of the mode in which an overlying formation, hundreds of square miles in extent and thousands of feet in thickness, can have ^{been} metamorphosed, whilst the underlying formation, of equal thickness and scarcely less in extent, has escaped, we shall be justified in admitting inversions and extrusions equal to those in the Alps". Nicol's paper, containing as it did the seeds of what is now known to be the correct interpretation of the complex structure of the Assynt region, is the most important contribution to our knowledge before the systematic work of the Geological Survey, which was begun in 1883.

In the same year (1861), however, Murchison and Geikie published a memoir embodying the results of their studies in the Highlands and Western Isles. In an appendix to this memoir, Murchison wrote a strong criticism of Nicol's work; he refused to accept the evidence of Nicol's sections and, consequently, his interpretation of the structures. He claimed: "to what-
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whatever 'old-established principles of Scottish geology' Professor Nicol may appeal, I maintain that the researches of my contemporaries and myself have necessarily led to the establishment of the new classification". It is probable that Murchison's censure, backed by the authority of Geikie, Ramsay and Harkness, was chiefly responsible for the official rejection of Nicol's views at the time. Nicol retired from the controversy and the theory of a conformable succession then remained unchallenged for the time being.

During the next twenty years no original research was carried out in the Assynt region. Crosskey (1865) and Hull (1880) re-examined a number of Murchison's sections and expressed agreement with Murchison's conclusions.

The Murchison-Nicol controversy was re-opened in 1878 with the publication of Hicks' investigations of the metamorphic rocks in the Loch Maree area. An account of this phase of the controversy is given by Horne (1907, pp. 23-25) and McIntyre (1954, p. 205). Another point of dispute arising from this work was the mode of origin of the so-called "Logan Rock" (Horne, 1907, p. 23 et seq.). Hicks regarded the mass of syenite and granitic rock in Glen Logan (Glen Cruchalie or Bruachaig) as an intrusion emplaced in the Silurian (Cambrian) sediments. Bonney (1880), however, examined the mass and showed that its junction /

junction with the quartzites, fucoid beds and limestones is faulted, and not intrusive. He drew attention to the presence of foliation in the rock and inferred that it was a granitic variety of the Hebridean gneiss. The fragmental structure in parts of the mass he attributed to crushing in situ.

In 1881 Heddle's Geological Map of Sutherland was published. The map shows the distribution of a formation referred to in the legend as '"Igneous Rock" of the Quartzite'. In a descriptive pamphlet on the map, published the following year, Heddle gave an account of the characters of the rock, which resembles the "Logan Rock", and reviewed the opinions of previous writers as to its origin. While admitting its similarity to the Lewisian gneiss, he referred it, as Cunningham had done, to the Upper Gneiss (Moine) Series. Heddle adhered to Murchison's hypothesis of a conformable succession throughout the district, but he recognised between the Upper Limestone and the Upper Gneiss "beds of quartz-rock" resembling "hornstone", which were later shown to be mylonites. An interesting feature of Heddle's map is that it shows the trend of large-scale folds in the sedimentary rocks of Assynt (cf. present author's diagram 22).

In the summer of 1880 C. Callaway re-examined the relationship of the quartzites and limestones on Cnoc na Droighinn /

Droighim and the ground to the east, and concluded (1881) that the formations were so disturbed that the section was quite unsuitable as the basis for a succession. He maintained, with Nicol, that the so-called 'Upper Quartzite' was the 'Lower Quartzite' brought up to the east by faulting. This view was also supported by W.H. Hudleston, in his "First Impressions of Assynt" (1882). This author disputed the existence of the Upper Quartzite, but accepted the conformability of the eastern gneiss on the quartzite and dolomite in the Knockan Crag section.

Callaway continued his work in the Assynt, Eireboll and Ullapool districts between 1881 and 1883 and his conclusions are contained in a long paper published in 1883. In this paper he described, with considerable care and accuracy, an area extending from Glencoul in the north to Knockan in the south and from Quinag, Canisp and Coul More on the west to the first exposures of the eastern or 'Caledonian' gneiss to the east. He noted the similarity between the 'Logan Rock' on Beinn Aird da Loch and Glasven and the 'Hebridean' gneiss, and maintained that the two were identical. This correlation was supported by the discovery of outliers of quartzite lying unconformably on the 'Logan Rock' of Beinn Aird da Loch; the quartzite is overlain by the normal succession of the 'Assynt Series' (Cambrian). From the intense crushing and alteration of the 'Logan Rock' at the /

the contact with the underlying, unmetamorphosed rocks of the Assynt Series at Loch Glencoul, Callaway inferred that the gneiss had been "overthrown" onto the Assynt rocks by earth movements.

Callaway discovered that the apparent conformable relationship of the eastern gneiss on the Cambrian rocks at Glencoul is deceptive. He observed that the 'brown flags' (furoid beds) and dolomite are frequently absent from the succession and that the quartzite, where it is in contact with the schists, shows signs of intense deformation: "the rock is intensely squeezed, so that a coarse cleavage is produced, the particles of quartz are flattened and there is a mineral change, the aspect being distinctly that of a partially metamorphosed rock". He noted also that the annelid tubes (= pipes) in the quartzite had suffered deformation. From these observations Callaway concluded that the eastern or 'Caledonian' gneiss had been brought over the gneiss and rocks of the Assynt Series by reverse faulting, "with excessive lateral pressure acting from the east" and that "the overthrow of Hebridean (onto the Cambrian) and the reversed faulting at the junction with the eastern gneiss are due to the same general cause".

Further to the south Callaway traced the outcrop of a major dislocation from the pass south of Conival, along the west side of Ben an Fhurain, Cnoc na Droighinn and Glasven to Loch Glencoul. This is the dislocation noted at several localities by /

by Nicol and subsequently named the Glencoul Thrust by Peach and Horne. Callaway demonstrated the inversion of gneiss over Torridonian grits and conglomerates on Conival and in the Oykell valley and cited this as absolute proof of the overthrow of Hebridean gneiss on to younger rocks. He also found considerable evidence of dislocation at Knockan Crag which led him to disagree with Murchison's interpretation of the section.

As these researches confirmed in most respects the conclusions of Nicol, Callaway paid a much-deserved tribute to Nicol's work: "I am glad to bear testimony to the accuracy of an author whose work has hardly received due recognition. It is certain that he made out many important points which escaped the observation of his distinguished rival".

In 1882 Charles Lapworth began work in the districts of Durness and Eireboll, and it was in the latter area that the key to the problems of the succession was eventually found. Lapworth mapped large areas of Durness and Eireboll in great detail during the summers of 1882 and 1883 and published his conclusions in a series of papers entitled "The Secret of the Highlands" (1883). This work confirmed a number of Nicol's conclusions: (a) that the Durness Limestone is the highest member of the fossiliferous sequence; (b) that the Upper Quartzite and Limestone are non-existent; (c) that there is no /

no conformable sequence from the quartzites and limestones to the eastern gneiss; (d) that the line of junction of the unaltered Palaeozoic rocks with the eastern gneiss is a line of faulting and overthrust. In the third paper of the series Lapworth developed the concept of overturned folds passing into overthrusts and referred to comparable examples in more recent mountain-chains, where the interrelation of folding and faulting is clearly visible.

In later papers (1884-5) Lapworth described the peculiar petrographic characters of the rocks along the great thrust-planes: "the most intense mechanical metamorphism occurs along the grand dislocation (thrust) planes, where the gneisses and pegmatites resting on these planes are crushed, dragged and ground out into a finely-laminated schist or mylonite (Gr. mylon, a mill) composed of shattered fragments of the original crystals of the rock set in a cement of secondary quartz, the lamination being defined by minute inosculating lines (fluxion lines) of kaolin or chloritic material and secondary crystals of a micaceous mineral". He recognised alternating layers of deformed gneiss, quartzite and limestone in the rocks and believed that the more highly crystalline flaggy mica-schists to the east of the mylonites might be formed from similar materials under somewhat different conditions. He considered the /

the schists to be a "metamorphic compound" formed by the re-crystallisation of a mechanical (mylonitic) mixture of Hebridean gneiss and Torridonian and Cambrian (Lapworth's Ordovician) rocks.

The work of Lapworth was one of the greatest contributions to the settlement of the 'Highland controversy'. It marked the climax to a sequence of researches, by Hicks, Bonney, Callaway and others, which entirely vindicated the reputation of Nicol; it is significant that all these authors commended Nicol's work. The Geological Survey, however, adhered to the views of Murchison until 1884. In 1883 Geikie, then Director of the Survey, sent B.N. Peach and J. Horne to commence a detailed survey of the western borders of Sutherland and Ross-shire

After the mapping of the Durness area in 1883, a party, under the direction of Peach, extended the work into Eireboll during the summer of 1884. North of the peninsula of Heilim, on the eastern shore of Loch Eireboll, Peach discovered what is now the classic locality for 'schuppen structure'. The surveyors were soon convinced that Murchison's interpretation was wrong and Geikie, who visited Eireboll and made a critical examination of the surveyors' work in the field, admitted that the evidence was 'altogether overwhelming against the upward succession which Murchison believed to exist in Eireboll'. In November, 1884, a short report on the results of /

of the investigations was published (Peach and Horne). This was accompanied by a communication from Geikie in which he abandoned the views which he had held in common with Murchison and acknowledged that Nicol and his protagonists had in some measure anticipated the conclusions reached by the Survey geologists.

The mapping was continued southwards along the zone of dislocation and by 1885 the surveyors had reached the north part of Assynt. In 1886 a preliminary survey was carried south as far as Ullapool and during the next two field seasons the mapping of the area covered by Sheets 101 (Ullapool) and 107 (Lochinver & Assynt) was completed. The delay in the publication of these sheets was prolonged by the discovery (in 1891) of Olenellus fragments in the fucoïd beds of Dundonnell Forest. The presence of these fossils proved beyond doubt that the lower part of the quartzite, shale and limestone succession, hitherto referred to the Lower Silurian (Murchison) or Ordovician (Lapworth), were of Cambrian age,^φ and the Torridonian Sandstones, therefore, pre-Cambrian. This important modification was incorporated in the two sheets, which were published in 1892.

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^φ More recently it has been shown that part of the Durness Limestone is of Arenig age, by correlation of the fauna with that in the Beekmantown rocks of NE America (e.g. Peach, 1913; Grabau, 1916; Peach & Horne, 1930). There is, however, considerable disagreement as to the relative thicknesses which should be referred to the Cambrian and Ordovician systems (see Phemister, 1948).

In 1888, a report on the "Recent Work of the Geological Survey in the North West Highlands", based on the work of Peach, Horne, Gunn, Clough, Hinxman and Cadell, was communicated to the Geological Society of London by Geikie. The paper contained a resume of the results which the Survey had obtained in mapping the ground between Eireboll and Ullapool. The structure of the Assynt area was described by Peach, Horne and Clough and illustrated by a number of sections drawn by Peach. The description is essentially that given in the Memoir (1907, see below).

The conclusions in this report differed from those in the earlier one (1884) in two important respects: (1) In the 1884 report it had been assumed that the thrusts developed by shearing of the overturned limbs of enormous overfolds. In the intervening period, however, it became evident to the surveyors that the overthrusts were not necessarily preceded by overfolds. (2) In the earlier work, reversed faults to the west of the major thrust in Eireboll (the Arnaboll Thrust) were represented as extending downwards into the unthrust basement. It was later shown, further to the south, that the strata broken by these faults had been driven along a major thrust-plane (the Sole) through the upper part of the rocks of the foreland.

H.M. Cadell, one of the surveyors, carried out a series of small-scale experiments in 'mountain-building' and succeeded in reproducing many of the structures found in the belt of dislocation. Cadell's results, published in 1888, corroborated the conclusions of the surveyors; they showed that the imbricate blocks in schuppen structure are generally carried on a major thrust (the Sole) and that thrust-planes are not invariably developed from overfolds.

The survey was extended southwards and by 1892 the major thrusts had been traced to their southern limit on the mainland. The mapping of the thrust-zone in the Loch Carron region and Skye was completed in 1896 and in that year Peach and Horne returned to Assynt to finish the survey of the zone of dislocation to the east of Ben More. This marked the completion of the survey of the thrust-zone.

The Memoir on the "Geological Structure of the North-West Highlands of Scotland", published in 1907, ranks as one of the greatest texts on structural geology ever produced. The work was edited by Sir Archibald Geikie, although he had retired from the Survey several years earlier, and the majority of the sections were drawn by Peach, who had also retired from the Service before the publication of the Memoir. The area under consideration in the present work was described by Peach, Horne /

Horne, Clough and Hinxman. The greater part of the ground was jointly surveyed and described by Peach and Horne, while Clough dealt with the area to the north of Loch Glencoul and Hinxman the area to the south of Knockan and the Cromalt Hills. The structure of the region and the sequence of the movements, as described in the Memoir, are summarised below.

The region is traversed by three great planes of dislocation, each with a general dip towards the east-south-east. From east to west, these are

1. The Moine Thrust
2. The Ben More Thrust
3. The Glencoul Thrust.

The Moine Thrust is the most important of these structures. The trend of the thrust, so remarkably constant from Eireboll to Skye (NNE-SSW), varies in Assynt, giving rise to a great embayment, 15 miles long from north to south, and approximately 7 miles wide. In the north of Assynt the thrust dips at low angles to the north-east while in the south it has a gentle south-easterly dip. It carries the crystalline schists of the Moine Series, which cover the greater part of the Highlands.

The Ben More Thrust to the west carries a great slice (the Ben More Nappe) of Lewisian, Torridonian and Cambrian rocks /

rocks, showing their normal unconformable relations. The thrust has been folded and a number of outliers of the nappe lie far to the west of the present outcrop of the thrust.

These masses of Lewisian, Torridonian and Cambrian rocks outcrop on Beinn na Cnaimseag, Beinn an Fhuarain and on the ground between Ledbeg and Loch Urigill; they represent structural outliers or "klippen", isolated from the parent nappe by erosion.

The Glencoul Thrust is the most westerly of the great planes of disruption and carries a slice of Lewisian gneiss, with a maximum thickness of at least 1500 feet, capped by Cambrian sediments. No Torridonian Sandstones are exposed in the Glencoul Nappe.

The rocks of the area are broken by countless lesser thrusts and faults, the most important of which are the Sole, the Sgonnan Beag Thrust, which carries the Loch Ailsh syenite mass, and an unnamed thrust between Ben Uidhe and Glasven. Imbricate structure or "Schuppen Struktur" is frequently associated with the thrusts. In imbricate systems the Cambrian strata are repeated by reversed faults which generally dip towards the east-south-east at steeper angles than the strata themselves. Imbricate zones are particularly well developed below the Glencoul Thrust north and south of Loch Glencoul and below the Moine Thrust.

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ROYAL CHARLES

Each of the thrusts is overlapped in turn by the overlying one: the Ben More Thrust overlaps the Glencoul Thrust south of Conival and appears to be truncated by the Moine Thrust near the Stack of Glencoul and at a number of localities in the south of Assynt. A remarkable feature of the Moine Thrust is its successive overlap of all the underlying thrusts, until, south of Knockan Crag, it rests on the undisturbed Cambrian sediments of the foreland. It follows that movement on the Moine Thrust outlasted that on all the other thrusts, while the Ben More Thrust was active after movement on the Glencoul Thrust had ceased. The authors consider that the Moine Thrust was probably the first of the great planes of movement to be produced (pp. 471-2).

The Eastern or Moine Schists are represented in the area by (1) mylonised rocks, (2) puckered grey and green schists like those described at the Stack of Glencoul by Clough (pp. 502-5), and (3) granulitic siliceous flagstones with thin mica-schists. The following comment on the orientation of fold-axes in the Moine Schists appears in the Memoir (p. 601):

"A striking feature of the Eastern Schists is presented by the double system of folding which they possess. One system has a NNE and SSW strike, the inclination of the axial planes being ESE, thus harmonising with the strike and direction of dip of the /

ROYAL CHARLES

the Moine thrust-plane and of the divisional planes of the mylonised rocks in association with that displacement. This plication may be regarded as an obvious accompaniment of the movement of the thrust masses in a WNW direction. The other system strikes generally WNW and ESE as if produced by forces acting at right angles to this trend This second system of folding is to be regarded as one of the structures that have resulted from the post-Cambrian movements". No definite information is given as to the relative age of the two groups of fold-structures.

It is possible to determine the geological age of the movements within certain limits. The igneous rocks of the Loch Ailsh and Loch Borolan masses and the numerous minor intrusions of post-Cambrian age are cut by thrust-planes, crushed and sometimes foliated by the movements. In Central and North Sutherland, moreover, the Moine Schists are overlain unconformably by Middle Old Red Sandstone sediments. The movements, therefore, appear to be of post-Cambrian and pre-Middle Old Red age.

A geological model of the Assynt Mountains on a scale of six inches to the mile was constructed after the publication of the Memoir under the direction of Peach and Horne; the Guide to this model (the 'beloved penny guide' of Bailey), published in 1914, is an excellent summary of the tectonics of the district.

The systematic survey of the central parts of Sutherland and Ross-shire, initiated by Hugh Miller and Edward Greenly while the main Survey party was working on the belt of dislocation, was continued by C.B. Crampton, M. McGregor, G.V. Wilson, H.H. Read, G. Ross, E.M. Anderson and others. Sheets 102 and 108 were not completed and published until 1925 and 1931 respectively, but a composite geological map of the Assynt district, comprising parts of Sheets 101 and 107 and the uncompleted Sheets 102 and 108, was published in 1923. The geology of the areas covered by Sheets 102 and 108 is described in two memoirs: "The Geology of Strath Oykell and Lower Loch Shin" (Read, Phemister and others, 1926) and "The Geology of Central Sutherland" (Read, 1931).

These two works are very similar with regard to their scope and conclusions. They contain detailed notes on the petrography of the Moine Schists (1923, p. 132 et seq.; 1931, pp. 36-43), the mylonites (1926, p. 21; 1931, pp. 48-50) and the microscopic effects of the post-Cambrian movements on the Lewisian, Torridonian and Cambrian rocks (1926, pp. 19-20; 1931, pp. 25-26).

At the time when the North-west Highland Memoir was published there was not universal agreement among members of the Survey as to the relative ages of the Moine metamorphism and the thrust-movements. The subject is cautiously treated by /

by Teall in the Memoir (p. 600): "In these rocks immediately above the Moine Thrust cataclastic structures are not uncommon, and the question has arisen as to whether they represent crystalline schists more or less broken down or sedimentary rocks which are on the way, so to speak, to become Moine-schist. Both views have been held by different members of the Survey, and both views may be right, though not, of course, as applied to one and the same rock. The age and origin of the rocks that have been mapped as Moine schists is a complicated problem which has not been finally and definitely solved, but abundant evidence has been accumulated to show that under the influence of the post-Cambrian movements rocks of diverse age and origin have acquired a common type of structure, and that true crystalline schists have been simulated if not actually produced".

The conflicting hypotheses implicit in this statement have been more fully stated in later publications (e.g. Read, 1934, pp. 302-4; Peach and Horne, 1930). Peach regarded the Moine schists as altered Torridonian rocks and considered that "the clean-cut thrust-planes, the deformation of the Torridon sandstone and the regional metamorphism of the Moine Series were produced by the same set of movements in post-Cambrian time" (1930, p. 200). Horne, on the other hand, regarded the Moine Series as "sedimentary schists of pre-Torridonian age, modified by the post-Cambrian movements, which developed, along the /

the outcrop of the Moine Thrust, a complex of mylonites, greenschists, phyllites, lenticles of Cambrian quartzite, of schistose Torridon Sandstone ... and deformed Moine Schists, with common planes of schistosity determined by these movements" (1930, p. 201). Plemister (1926) concluded, like Horne, that the general Moine metamorphism was earlier than, and distinct from, the post-Cambrian thrust-movements. This hypothesis was developed by Read (1931), after he had made a more complete investigation of the Moine schists close to the Moine Thrust. He observed that in a broad belt the schists had undergone a "marked dislocation-metamorphism" which was superposed upon the "normal Moine metamorphism". Close to the thrust, in a zone varying in width from a few feet to almost a mile, the schists are converted to mylonite, but dislocation effects, notably granulation of minerals and development of "slickensides", are recognisable in a zone up to three miles wide.

In 1934 Read published a stimulating paper on "Age-problems in the Moine Series of Scotland", in which he stated briefly the various views on the origin and metamorphic history of the Moine schists and discussed the evidence bearing on the problem. Two lines of evidence led him to conclude that there was a substantial time-interval between the general Moine metamorphism and the thrusting: (1) in 1931 he had correlated /

correlated the Ben Loyal syenite, which is later than the folding and general metamorphism of the Moine schists, with the Loch Borolan and Loch Ailsh alkaline rocks in Assynt, which were emplaced before the thrusting; (2) the superposition of the dislocation metamorphism on the regional Moine metamorphism, as described above. He considered that the similarity in texture and composition between the low-grade Moine schists close to the Thrust and the sheared Torridonian sandstones (probably the best evidence for the correlation of the two series) was due to a 'metamorphic convergence', since metamorphism affecting rocks of the same bulk composition, whatever the original texture, will tend to give similar products.

Read drew attention to a similarity, amounting in many cases to complete identity, between the orthogneisses, paragneisses and ultrabasic and basic intrusions in (a) the 'rocks of Lewisian type' in the Moine Series and (b) the Lewisian gneiss of the foreland. Apparently identical intrusions occur also in the Moine Schists and the rocks of Lewisian type in the schists. Read correlated these intrusions with the pre-Torridonian dykes in the Lewisian gneiss of the foreland and concluded that the Moine Series and its general metamorphism are of pre-Torridonian, and probably Lewisian, age.

It will be more convenient now to consider the course of research on the tectonic problems of the Assynt area under two headings, according to the methods employed. On the one hand (A), the work of E.B. Bailey and P.A. Sabine in the zone of dislocation has led to some slight modification of the conclusions of Peach and Horne. On the other (B), F. Coles Phillips, Gilbert Wilson, D.B. McIntyre and others, have made a totally different approach to the problems; their application of more modern techniques of geometric and kinematic analysis to the study of small-scale structures in the Moine Schists and mylonites has brought to light new aspects of the tectonic history of these rocks.

A. Bailey and Sabine

In 1934, Bailey led a party consisting of members of the Pre-Cambrian Association to localities of geological interest in the Scottish Highlands; the party spent several days in Assynt. In the report of the excursion (Bailey & McCallien, 1934), Bailey drew attention to certain sheets of sheared intrusive rock in the mylonite zone above and below the Moine Thrust (see also Phemister, 1926, pp. 106-7); they are intruded along the foliation planes in the mylonites and are themselves sheared by the movements, suggesting that they were intruded after the inception of the movements, and not entirely /

entirely before, as had been assumed. Eskola noted that the sheared borolanite in the Allt a' Mhuillin is cut in places by relatively unshaped pegmatite; since the shearing of the borolanite "may have been produced by the post-Cambrian movements", Bailey concluded that the pegmatite was possibly intruded after the movements and that this evidence favours the inference drawn above, that the periods of intrusion and movement overlapped to some extent.

In 1935 Bailey published a paper on "The Glencoul Nappe and Assynt Culmination", containing the results of his observations in the area during the previous six years. He felt that Peach and Horne had "ascribed too great persistence to some of their main structures" and proposed a number of changes in the mapping and interpretation of some of the major thrusts:

(1) After revising the mapping of area at the base of the Glencoul Nappe, NNE of Inchnadamph, Bailey concluded that the Glencoul Thrust dies out at the Allt Poll an Droighinn; the major thrust extending from this point to Conival he considered to be the Ben Uidhe Thrust (Fig. 1, p. 152) and not the Glencoul Thrust, as shown by Peach and Horne. This raises an important problem in the interpretation of the Glencoul Thrust. Clough's correlation of the Glencoul Lewisian with that /

that of the foreland in the Laxford-Loch Stack area (Clough, 1907, p. 501; Horne, p. 469) indicates a minimum distance of 6 miles, with a more probable figure of 13 miles, for the amount of displacement of the Glencoul Nappe. It is not easy to reconcile such a considerable displacement with the disappearance of the thrust at the Allt Poll an Droighinn. Bailey considers, however, that the distribution of the movement throughout the schuppen-zone below the thrust, near the southern limit of its outcrop, might provide "a possible escape from the difficulty".

(2) Following a suggestion by Clough (1907, p. 506), Bailey also modified the course of the Ben More Thrust (see fig. 1, Bailey). From the distribution of the Lewisian gneiss in the nappe complex he inferred that the Ben More Thrust is not an important dislocation, the Glencoul and Ben More Nappes being, in reality, parts of a single tectonic unit.

(3) During the 1912 B.A. Excursion to Assynt, Maurice Lugeon had suggested that the Loch Ailsh syenite might represent an extension of the Loch Borolan mass exposed as a "window" through the Ben More Thrust. Having examined the Sgonnan Beag Thrust, which was thought to carry the Loch Ailsh syenite, Bailey concluded that it was not a thrust at all, but the original intrusive contact of the syenite, modified to a small extent by shearing.

In conclusion, Bailey drew an analogy between the Glendhu and Assynt 'bulges' and the Aulloch massif in Provence, implying /

implying that they are axial culminations which developed concurrently with the thrust-movements. The use of this term will be discussed in one of the following chapters (p. 205).

Sabine, in his petrological study of the minor intrusions of Assynt, observed a number of interesting features in the distribution of different types of hypabyssal intrusive rocks and he has discussed the structural significance of his observations (1952). The gneisses are of widespread occurrence in the Glencoul and Ben More nappes and are also represented in the "klippen of the Ben More Thrust". They are not present, however, in the mass between the Sole and the Glencoul and Ben More Thrusts. Sabine inferred that "the Glencoul and Ben More Thrust-masses appear, on this evidence and as previously suggested by Bailey (1935), to be parts of a single tectonic unit. If this be so, then the Ben More thrust-plane south of Conival has a considerably greater significance than to the north, where it merely sub-divides the major tectonic unit. I suggest, therefore, that the name 'Ben More Thrust-plane' should be restricted to the ground north of the Braebeg Tarsuinn, and that that part of the Ben More Thrust-plane (old usage) south of Braebag and now considered of equal importance to and continuing southwards the effect of the Glencoul Thrust should be called the Assynt thrust-plane. The major tectonic unit between Loch Glendhu and Elphin may thus conveniently, in view of /

of the geographical location, be referred to as the "Glencoul-Assynt thrust-masses". Following this suggested change of terminology the klippen to the west of the Ben More thrust (old usage) are referred to by Sabine as "klippen of the Assynt thrust-plane", though it should be noted that they belong to the same tectonic unit as the Glencoul and Ben More nappes.

From the distribution of certain other types of intrusive rocks Sabine drew further conclusions regarding the displacement on the Sole. The 'Canisp porphyry' outcrops only in Torridonian and Cambrian rocks on the foreland. In view of the extensive development of other intrusive rocks in the zone of the thrust masses, Sabine considers this to be evidence of considerable displacement on the Sole. A ledmorite dyke outcrops at intervals in a straight line extending for 20 miles from Rhu More Coigach to Elphin; this line, if prolonged eastwards into the zone of dislocation, passes through the Loch Borolan mass, in which the type rock occurs (at Ledmore). Sabine cites this as evidence of little displacement along the Sole in a north-south direction. The existence of other intrusions of this type in the foreland further north (at Achmelvich), however, weakens this argument to some extent.

B. Structural Analysis

Since the beginning of the present century new techniques have been developed for the study of rock fabrics (i.e. textures and structures on all scales) and principles have been evolved for the interpretation of these fabrics. The so-called 'Alpine geologists' (notably Lugeon, Argand and Wegmann) developed a procedure of tectonic analysis involving megascopic structural features, while the Austrian geologists (Becke, Schmidt, Sander and others) concerned themselves mainly with analysis on a microscopic scale. The first successful study of the optical orientation of minerals in a rock was carried out with the aid of the Universal Stage by Schmidt in 1925. Since then the methods of 'petrofabric analysis' have been employed and developed in many parts of the world. F.C. Phillips was the first, and for many years the only, geologist to use these techniques in Britain.

Phillips' first work (1937) took the form of a regional study of the microfabric of the Moine Schists and rocks from the zone of the thrusts and the foreland. He measured the orientation of quartz, muscovite and biotite in the schists and found a remarkable consistency in the results over a very wide area. The optic axes of quartz showed a constant tendency to lie in a more or less well-defined girdle -- that is, the /

the rocks are B-tectonites in the terminology of Sander. The micas, also, showed a strong preferred orientation; the poles of $\{001\}$ cleavages generally lie in a strong point-maximum, defining the foliation, but there is every gradation to a girdle, which coincides with the girdle of quartz-axes. Attention was directed in this paper to the parallelism of the b-axes (normal to the plane of the girdles) with such megascopic linear structures as lineation, fold-axes, rodding and mullions. The b-axes plunge towards the south-east over the whole area of outcrop of the schists.

Frequently the quartz diagrams show extension of the poles in such a way as to form not a single (ac) girdle, but intersecting (Ok1) girdles. Phillips considered that such patterns might have been produced by either (a) a "crossed strain" causing rotation in a plane normal to the first girdle, or (b) the influence of later movements on simple girdle patterns. After discussing the principles governing the production of girdle-fabrics, Phillips concluded that "b-axes over a given area have a similar significance to fold-axes, and it can safely be asserted that the deformation has acted in a plane more or less perpendicular to them". He considered that the fabric evidence indicated that the "Moine Schists were brought into their present state of regional /

regional metamorphism by a deformation acting along approximately south-west and north-east lines prior to the dislocation phase of the Caledonian movements".

Phillips examined the effects of the 'dislocation metamorphism' on the Moine schists and found that the later movements appear to have had little, if any, constructive effect on the schist fabrics. In the partially crushed and mylonised rocks, the larger relict grains of strained quartz always give the typical girdle and b-axis with the same orientation as in the undeformed schists. The Cambrian and Torridonian rocks of the foreland and the region of the overthrusts show little evidence of preferred orientation of quartz. However, in a few of the rocks collected near the major thrusts an incipient girdle of quartz axes was found; this had a north-west to south-east trend, "normal to the outcrop of the (Moine) thrust, with its b-axis perpendicular to the direction of movement in the post-Cambrian dislocations." Phillips concluded that this fabric data lent support to Read's contention that the "Moine series and its metamorphism are of pre-Torridonian date, whilst a Lewisian age is not excluded."

In an extension of this work (1945) Phillips demonstrated very strikingly, by means of composite diagrams, the homogeneity of the fabric over the total area of outcrop of the /

the Moines. While the b-axes in the Moine schists plunge consistently to the south-east, the Torridonian and Cambrian below the Moine Thrust yield weak girdles with a NW-SE trend. The author inferred from this contrast in the fabrics that the fabric of the schists was not imprinted during the overthrust phase. He now ascribed the "crossed-girdle" patterns to 'overprinting' on simple B-tectonite girdles by the thrust-movements; the slight divergence in orientation of the quartz- and mica-girdles in some specimens was also attributed to this cause.

Later (1947, 1949, 1951) Phillips drew attention to certain similarities between Moine and Lewisian fabrics. The lineations in much of the Lewisian gneiss of the foreland plunge to the SE, parallel to those in the Moines. The orientation of quartz and mica in some of the Lewisian rocks, moreover, resembles that in some of the Moines. While hesitating to press the identity of these fabrics, Phillips emphasised that this 'coincidence' appeared to favour even more strongly the hypothesis that the general Moine metamorphism was of Lewisian age (1951, pp. 234-5).

Since the existence of the Moine Thrust was first established, the parallelism of the thrust outcrop with the general strike of the Moine schists throughout the Highlands had /

had led the investigators to assume that the thrusting and the tilting and folding of the schists were caused by the same large-scale movements. The down-dip lineations in the schists were considered to be a type of slickensides produced by the movement of the Moines towards the north-west. Thus Phillips' interpretation of the schist fabrics, though conforming to the tradition of the Austrian structural petrologists, was contrary to the accepted doctrines and stimulated a brisk controversy on the relationship between fabric girdles, lineations and deforming movements. Structural workers in Norway (Strand, 1945, Kvale, 1945, 1948) and elsewhere (Martin, 1935, E. Cloos, 1946) have expressed the view that girdles may be produced by shearing in a direction either parallel to, or normal to, the girdle plane. E.M. Anderson (1948) went further than this to suggest that the 'orthodox' interpretation (Schmidt, Sander, Phillips and others) of girdles was erroneous and that the axes of girdles (b-axes of Phillips) and lineations are invariably parallel to the direction of shear movement. This view was in agreement with Cloos's interpretation of the lineations in the Moines to the south of Assynt (Cloos, 1946), and was supported by Kennedy and Shackleton (Discussion of Anderson, 1948).

In 1952 Wilson described a spectacular example of quartz-filled tension-gashes in the Moine schists near Melness.
His /

His kinematic analysis of the structures revealed a "south-south-eastward direction of movement" which "shows no relationship to the Caledonian thrusting five miles away to the west". This direction of movement approximates to that invoked by Phillips to account for the micro-fabric in the neighbouring rocks and Wilson concluded that the evidence supported Phillips' argument that "the Moine lineation in this area is in 'b' and not in 'a'". In a later publication (1953), the same author adduced a large body of megascopic field data to show the widespread occurrence of fold-axes and other B-structures (lineations, mullions and rodding) with east-west or NW-SE trend in the Moine schists. The fold-structures on all scales show monoclinic symmetry and Wilson considered that they "owe their forms primarily to tectonic movements which acted in directions perpendicular to the elongation of the structures". The direction of overturning of the recumbent folds and the geometry of the rodded structures, moreover, suggested to the author that the "predominant tectonic movement around Oykell Bridge, was from the north-east towards the south-west"; at Ben Hutig "the tectonic translation was from the north towards the south".

Wilson drew attention to the contrast in tectonic style between the recumbent fold-structures in the Moine Series and/

and the dislocations in the thrust-zone and stressed the independent origin of the two sets of phenomena. He was of the opinion, however, that the "spectacular development of mullions was probably assisted by movements associated with the Caledonian Moine thrust acting along the lengths of the earlier-formed corrugated structures." (cf. Read, 1926, p. 121; Phillips, 1937, p. 596). The evidence to hand, he concluded, was in favour of a pre-Torridonian age for the Moine schists; the Moine orogenic phase, for which he suggested the term Sutherlandian, was probably to be correlated with the Laxfordian phase of deformation in the gneisses of the foreland (Sutton and Watson, 1951).

D.B. McIntyre, while applying the methods of Argand and Wegmann in various parts of the Scottish Highlands, found that prominent lineations were almost universally parallel to the axes of folds, determined on every scale (1950, 1951 a, b, c: 1952), and he stated that he was "in whole-hearted agreement with Dr Coles Phillips's conclusion that the fold-movements in the Highlands took place in planes normal to the dominant lineations". McIntyre also emphasised the contrast in tectonic style between the Moine schists and the rocks in the thrust-zone: "the comparative kinematics of the folds in the schists and the thrusts show that they cannot be directly correlated in a single /

single movement picture. Of even greater importance than the movement-directions is the striking difference in style between the folded schists and the mylonites The mylonite-zone has its own tectonics of overfolds, overthrusts and lineations which have never been adequately described or contrasted with those of the Moine schists". (McIntyre, in discussion of Wilson, 1953, p. 148).

More recently, in an important paper on "The Moine Thrust - its discovery, age and tectonic significance" (1954), McIntyre reviewed the history of research on the Thrust and re-examined the evidence for dating the movements. He showed clearly how the importance of the thrusts, once their existence had been established, was exaggerated to such an extent that they were considered to have controlled the structural development of the whole Highlands. "Generalised strike was confused with axial trend and B-structures in the schists were not distinguished from a-lineations in the mylonites." (p. 216). McIntyre concluded, like Read, Phillips and Wilson, that there is no genetic significance to be attached to the parallelism of linear structures in the mylonites and the Moine Schists: "it may ultimately be possible to correlate the folds and the thrusts in a single movement-picture, but with our present knowledge we must assume that they constitute two separate tectonic events which were separated by an interval of time of unknown length".

On /

On the subject of the relative age of these two events, McIntyre had previously stated (Discussion of Wilson, 1953) that "the folding of the Highlands may prove to be post-Cambrian. If this is indeed the case he, Dr McIntyre, would put forward for consideration that the Moine Thrust could be Middle Old Red, Hercynian or even Tertiary, for all that is known to the contrary". In the intervening period, however, a re-examination of the evidence bearing on the age of the thrust showed that it was definitely older than a monchiquite-fourchite dyke, probably of Permian age, which cuts the mylonites of A'Mhoine.

In 1953 McIntyre (Discussion of Kvale, 1953) reported the presence of B-lineations (parallel to the axes of small-scale folds) in the mylonites of the Knockan Crag and at other localities near the thrusts, but did not record the orientation of these lineations. At the same time (July, 1953) the present writer began a study of the tectonics of the mylonite zone in Assynt, the full results of which are incorporated in the present work. It was discovered that many of the lineations in the rocks of the mylonite zone, previously taken to be a-structures, were in fact B-lineations similar to those described in the Moine Schists.

Following this discovery, a joint study was made of a number of exposures of the thrusts between Skye and Eireboll by Dr McIntyre, Dr L.E. Weiss and the present writer. This investigation /

investigation was completed before McIntyre's "Moine Thrust" paper was read in June, 1954, and a summary of the results was presented in the form of an Appendix to the paper.

A number of the conclusions in the Appendix are at variance with the hypothesis favoured by Read, Phillips and Wilson on the connexion between the folding and thrust-movements.

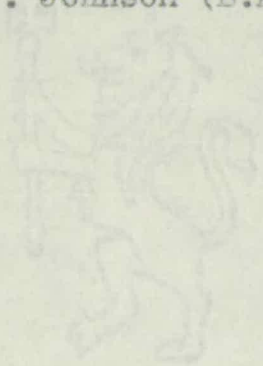
"1. There has been a single penetrative movement about a common B-axis in the Moine Schists, the mylonites above the Moine Thrust and the deformed Lewisian, Torridonian and Cambrian rocks below The conspicuous B-axis must have been imprinted in post-Cambrian time.

"3. Repeated movement is indicated locally by brecciation, movement on joints, and even mylonitisation of the older mylonites of the Moine Thrust. An upward age-limit for these movements has not yet been determined.

"6. The symmetry of the fabric both of the Moine Schists and of the rocks intimately associated with the thrust seems to be characteristically nearly orthorhombic. The association of these fabrics with large-scale transfer of Moine over Cambrian raises fresh problems."

In the discussion of this paper P. Wilkinson stated that his findings on the ground east of Loch Eireboll were in harmony with these conclusions. His results had been presented /

presented in the discussion of Wilson's paper on mullion and rodding structures (1953), but an ambiguity in the statement had led to a misunderstanding of their significance. The presence of a south-easterly-plunging B-axis in the Moine Series and the mylonites has been further corroborated by Wilkinson and M.R.W. Johnson (B.A., 1955; report in press).



ROYAL CHARLES

2. PURPOSE AND SCOPE OF THE STUDY

a. Statement of the Problems

The Survey Memoirs contain a full and detailed description of the large-scale structures in the Assynt area, but references to small-scale features such as minor folds and lineations are few and brief. Two systems of folding in the Moine Schists are mentioned in all three Memoirs dealing with the area (1907, p. 468; 1926, p. 121; 1931, pp. 10, 28), and the authors of the North-west Highland and Central Sutherland Memoirs (Clough, 1907, pp. 506-7; Read, 1931, p. 10) make specific reference to folds in the mylonitic rocks. Subsequent investigators (e.g. Phillips, 1936, 1945; Wilson 1953; McLachlan, 1953) have described the geometry of small-scale structures in the Moine Schists and recently (Wilson, 1953; McIntyre, 1954) the "plastic" style of folding in the schists has been contrasted with the "brittle" style of deformation in the mylonites. As McIntyre has emphasized, however, the tectonics of the thrust-zone have never been adequately described, and such allusions are necessarily vague.

The authors of the North-west Highland Memoir claimed that the two systems of folding in the Schists were "evidently produced by the same series of earth-stresses" in post-Cambrian times (1907, pp. 468, 601). Read, on the other hand, considered (1926 /

(1926, p. 121) that they were formed during two distinct phases of deformation: the east-south-east trending folds were produced during an early phase and the north-north-east trending folds originated with the thrust-movements during a later phase. Read developed this interpretation (1934) and concluded that the east-south-east trending folds were contemporaneous with the general Moine metamorphism and of pre-Torridonian age. This view has been supported by Phillips (1936, 1949, 1951), Wilson (1953), and McIntyre (Discussion of Wilson, 1953; 1954). However, the evidence presented by Bailey, Kennedy and MacGregor (see MacGregor, 1951) suggests that the Moine metamorphism and folding were entirely "Caledonian" (=post-Cambrian), a conclusion which is in harmony with the views expressed in the Northwest Highland Memoir on the origin of the folds. These closely related issues are the main subject of dispute in the present day 'Highland controversy'. The problems involved in these issues may be summarized in the following way:

1. What is the relationship between the two groups of folds?
2. What is the relationship of each group of folds to
(a) the regional metamorphism of the Moine Schists,
and (b) the thrust-movements?

b. /

b. Scope of the Study

The primary purpose of the present study is to give a detailed account of the tectonics of a part of the thrust-zone embracing large- and small-scale structures, and to develop a kinematic interpretation of the structures on all scales. The following phenomena, listed in order of decreasing scale, have been investigated during the course of the work:

- (1) The orientation and mutual relations of the major thrusts and faults, and the form of large-scale folds associated with these structures;
- (2) The orientation and form of small-scale folds and lineations in the mylonitic rocks along the major thrusts and in the Moine Schists;
- (3) The grain orientation in deformed rocks, notably in the mylonitic rocks and Moine Schists.

The importance of minor structures, such as folds and lineations, in determining the nature of rock deformation is now generally recognized and particular attention was paid to these structures during the investigations. The relationships between the folds plunging to the east-south-east in the Moine Schists and the structures associated with the Moine Thrust were investigated with special care in order to determine the sequence of the metamorphic and tectonic events. It was hoped that the study might also give some information on the significance of the Assynt "culmination", as indeed it has done.

c. Procedure

A preliminary survey was made of the structures in the mylonites along the Moine Thrust in order to determine the course to be followed in the later stages of the study. On the basis of this survey certain critical areas were selected for detailed examination, which included mapping on a scale of 6 inches to the mile. The Moine Schists were examined in these areas and also along a number of traverses extending up to three miles eastward from the Moine Thrust.

In the area between the Sole and the Moine Thrust (referred to as the "zone of dislocation") the Torridonian and Cambrian rocks are folded on a large scale. The orientation and symmetry of these folds were investigated in a number of selected areas. Except in a few isolated areas (Sutton and Watson, 1951; King, 1955), the fabric of the Lewisian gneiss of the foreland has never been studied in detail, so that an investigation of the effects of the post-Cambrian movements on the fabric of these gneisses would be premature at the present time. For this reason, no attempt has been made to study the fabric of the Lewisian gneiss in the zone of dislocation.

Petrofabric analyses of a large number of rocks, including quartzites, dolomites, mylonitic rocks, and Moine schists, have been made. The analyses were carried out in close /

close association with the study of megascopic structural features, in order to supplement the information obtained from the field studies. For convenience in the presentation of structural data, the megascopic and the microscopic data are described separately, but the writer wishes to emphasize that the synthesis and final conclusions are based on a joint consideration of both aspects of the fabric.

Most of the techniques employed in the study are standard procedure in structural petrology. The operations involved in the measurement of megascopic data, the collection of oriented specimens, the preparation and examination of thin sections, and the presentation of data are described by Ingerson (1938, pp. 211-262) and Fairbairn (1949, pp. 241-292). Orientation data throughout the thesis are recorded on the lower hemisphere of an equal-area projection.

II. PRINCIPLES AND NOMENCLATURE

1. FABRIC AXES

Several systems of notation have been suggested for fabric axes (Cloos, 1946, pp. 5-6), but that proposed by Sander is now almost universally adopted by structural petrologists. Some confusion still exists, however, as to the exact significance of Sander's terms (a, b, B, c) and much of the controversy in structural problems is due to the lack of uniformity in the usage of these terms. Sander first defined the three orthogonal axes a, b and c in the following way (1926): b is the direction of the fold-axis; a is perpendicular to b in the slip-plane; and c is normal to the ab plane. This definition is not purely descriptive, as the use of the term '~~movement~~^{slip}-plane' introduces an element of interpretation into the statement. Later, however, in "Gefugekunde der Gesteine" (1930), Sander modified the definition, placing it on a descriptive basis. The axes were defined thus for fabrics with monoclinic symmetry: ab is the principal fabric plane; ac is the plane of symmetry in the fabric; and c is normal to ab.

Round any flexural-slip fold with monoclinic symmetry (Fig. 2 a) the orientation of a and c varies, while b, which is the axis of symmetry, retains a constant orientation; b is the principal fabric axis and is generally designated B. The notation b or b = B is frequently used in the description of
small /

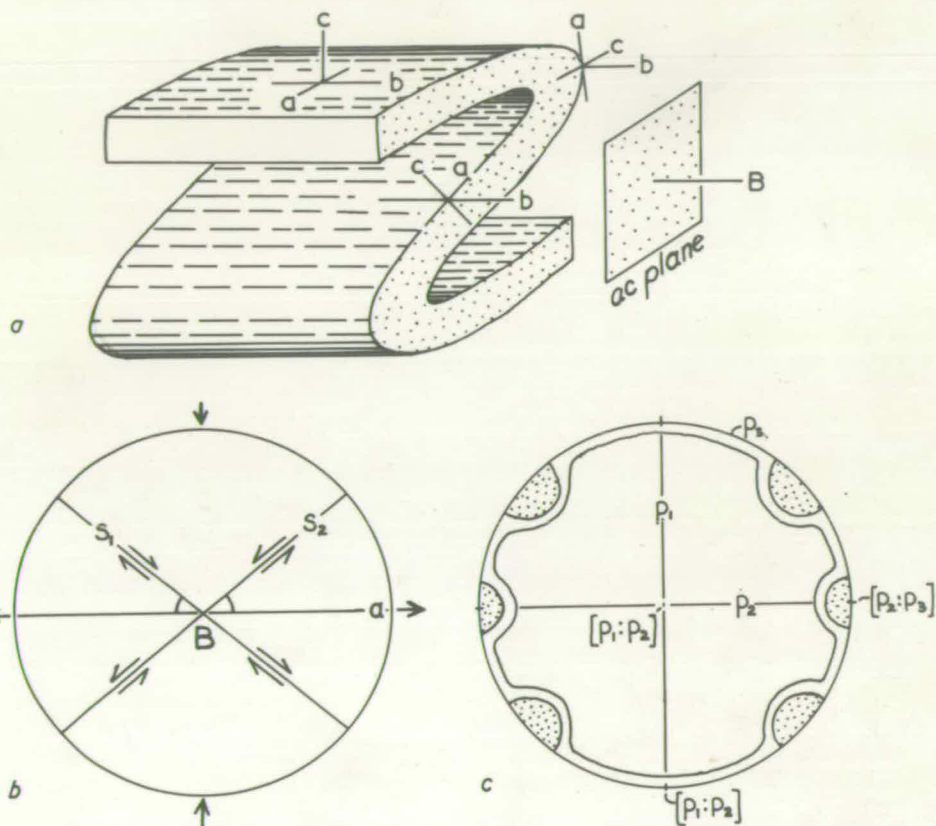


Figure 2.

a. Flexural-slip fold showing the orientation of fabric axes in monoclinic fabrics.

b. Diagram showing fabric axes in orthorhombic fabrics, after Sander. S_1 and S_2 are equivalent slip-planes. Arrows indicate axes of flattening and extension.

c. Reference coordinates used in the present work for the description of orthorhombic fabrics. p_1 , p_2 and p_3 are planes of symmetry.

small structural units, such as hand-specimens, while B is used, with a regional significance, in referring to bodies of greater dimensions, and in discussing the kinematic interpretation of fabrics. Weiss (1955, pp. 229-30) has discussed the significance of these terms and distinguishes fabric axes, which are descriptive and defined in terms of the geometrical relations of the elements in a fabric, from kinematic axes, which are defined in terms of a movement-system: "The kinematic axes are defined for rotational strain involving slip on one s-plane. The slip-plane is ab, the deformation plane is ac, and the normal to the plane of deformation is b." The notation B is adopted in the present study to denote the principal kinematic axis and also the principal fabric axis, irrespective of scale.

This definition of fabric axes, it must be noted, holds only for fabrics with monoclinic symmetry and cannot be transferred to fabrics with another order of symmetry. Sander extended the usage of the term B-axis to fabrics with triclinic and orthorhombic symmetry. He relates the orientation of all the fabric elements in tectonites to 's-planes' (a descriptive term signifying any type of planar structure in a rock, visible or statistically determined; 's' denotes 'sedimentation', 'shear', /

'shear' 'schistosity' and so on). Described in terms of these fabric planes, the B-axis in monoclinic fabrics is the axis of intersection of two or more s-planes — $s_1, s_2, s_3 = (h0l)$. (Sander, 1948, p. 81; Case III). In fabrics with orthorhombic symmetry (Ibid., Case II), one or more pairs of equivalent s-planes — s_1 and s_2 , or s_1^a and s_2^a , s_1^b and $s_2^b = (h0l)$ — intersect in an axis which Sander calls B, by analogy with the fabrics with monoclinic symmetry. Sander refers to Cases II and III as "Orthorhombic B-tectonites" and "Monoclinic B-tectonites" respectively and states that the latter is the commonest type of tectonite. Another important type of symmetry in natural rock fabrics is exhibited by the "B-tectonites of the Second Order" (Ibid., Case IV). In these rocks a-planes intersect in each of two mutually perpendicular axes, which Sander designates B and B'. Where both B and B' have the characteristics of the B-axis in orthorhombic B-tectonites (Case II), the overall symmetry of the fabric is orthorhombic, or very rarely tetragonal or cubic; the latter cases are of no practical significance. Where B has the properties of a B-axis /

The indices (hkl) are used as in crystallography to describe the orientation of a surface or plane with reference to the fabric axes.

B-axis in an orthorhombic B-tectonite and B' of a B-axis in a monoclinic B-tectonite, the symmetry of fabric is monoclinic. In the final instance where both B and B' have the characters of monoclinic B-axes, the resultant symmetry is triclinic. Sander describes rocks with fabrics of these three types respectively as orthorhombic, monoclinic and triclinic $\underline{B} \perp \underline{B}'$ tectonites and considers B and B' to be syngenetic in such rocks. There is a further group of triclinic tectonites in which two mutually oblique B-axes are recognisable (the $\underline{B} \wedge \underline{B}'$ tectonites), but this group, according to Sander, has not the same significance as those described above, as he believes that the B and B' axes are not syngenetic in $\underline{B} \wedge \underline{B}'$ tectonites, but have been produced by the superposition of two unrelated deformations.

In fabrics with orthorhombic symmetry there are at least two, and generally three, mutually perpendicular planes of symmetry and consequently two or three symmetry axes which have the same 'symmetrological' significance as B in a monoclinic fabric. Sander has defined one of these as a in orthorhombic B-tectonites. He considers that the orthorhombic B-tectonites have originated by slip on one or more pairs of slip-planes intersecting in the B-kinematic axis (Fig. 2 b),
in /



in response to a flattening or squeezing (Turner, 1948, p. 166). In a body subjected to such a deformation there is a resultant elongation in a direction normal to the axis of flattening in the plane containing this axis and the poles of the slip-planes. Sander designates this axis a. This a-axis is not, however, strictly analogous to a in monoclinic fabrics, for although it is the direction of maximum elongation in the body, it is not a direction of slip movement, since the aB plane is normal to the axis of flattening and differential movement along this plane is impossible. Moreover, it is not possible, with our present imperfect knowledge of the mechanism of deformation of minerals such as quartz, to identify slip-planes in many orthorhombic tectonites as, for example, in the lineated quartzites described on pages 185-6. Consequently, it is impossible in these rocks to fix the orientation of the B and a axes, as defined by Sander. In discussing orthorhombic fabrics the present writer will adopt the descriptive notation employed by Weiss (1956, Structural Analysis of the Basement System at Turoka, Kenya. In press); the planes of symmetry are designated p_1 , p_2 and p_3 and it follows that the symmetry axes are the intersections of these planes - $p_1:p_2$, $p_2:p_3$, and $p_1:p_3$ (Fig. 2 c). This system of notation is adequate for reference and does /

does not necessitate the selection of a B-axis from two or three similar axes of symmetry. Thus the use of the terms a and c is confined, in the present work, to monoclinic fabrics or to those elements of a fabric which have monoclinic symmetry.

According to the terminology adopted here the expression "folds in a" is meaningless; the fold-axis is B in monoclinic fabrics. "Non-cylindroidal" folds are triclinic structures and an a-axis has never been defined for fabrics with this order of symmetry. In rocks which are folded about two mutually perpendicular axes ("Querfaltung", Sander; Koark, 1952; "cross-folds", King, 1956) the fabric should be described with reference to two B-axes (B \perp B' tectonites).

2. THE TERMINOLOGY OF MYLONITIC ROCKS

Before an attempt can be made to describe the structures in the rocks of the thrust-zone, it will be necessary to examine the terminology of mylonitic rocks. Since the term mylonite (from the Greek 'mylon' - a mill) was first proposed by Lapworth (1885) for certain types of crushed rock along the thrust-planes in Eireboll, it has been widely applied to supposedly similar rocks in many parts of the world. A study of the literature shows that there is considerable confusion as to the exact meaning of the term. Although the characters of the original mylonites were precisely and fully defined by Lapworth, later investigators have not adhered to his definition; the term has been redefined by some of the later authors with meanings which depart considerably from the original. In addition, certain authors have been unaware of Lapworth's term or have preferred to introduce new terms for rocks with essentially the same characters as the North-west Highland mylonites, thereby causing unnecessary duplication in the terminology. Perhaps the ultimate source of the confusion, however, lies in the existence of a great many varieties of crushed and "milled-down" rocks, with properties varying according to the physical conditions under which they were produced. Numerous classifications have been devised (e.g. Termier & Boussac /

Boussac, 1911; Staub, 1915; Quensel, 1916; Shand, 1916; Raguin, 1925) which separate some of these varieties under new terms, but nevertheless the word mylonite has frequently been used (with a genetic rather than a descriptive connotation) for almost any rock which is the product of severe mechanical metamorphism. The extreme expression of this tendency is seen in a paper by Termier and Maury (1928):

"Comme tous les tectoniciens, nous appelons mylonite toute roche écrasée, quelle qu'ait été sa nature originale et quel que soit le type de son écrasement."

The original definition of 'mylonite' (Lapworth, 1885) is "a microscopic pressure-breccia with fluxion-structure in which the interstitial dusty, siliceous and kaolinitic paste has only crystallised in part" (see also p. 14). Lapworth observed a complete gradation from the mylonites to the typical schists of the Moine Series and referred to all the finely laminated, colour-banded rocks above the Thrusts as 'variegated schists'. For a certain type of variegated schist which shows considerable recrystallization he used the term "augen schist"; this is a fine-grained, laminated rock containing augen or fragments of the original rock with cataclastic textures, set in "a secondary crystalline matrix of quartz and mica arranged in fluxion-planes." He considered that the mylonites and augen schists were formed contemporaneously with the more coarsely crystalline Moine schists, under different conditions of /

of differential movement and 'chemical change': "The mylonites were formed along the thrust-planes, where the two superposed rock-systems moved over each other as solid masses; the augen schists were probably formed in the more central parts of the moving system, where the all-surrounding weight and pressure forced the rock to yield somewhat like a plastic body." The variegated schists "differ locally in composition according to the material from which they have been derived, and in composition according to the special physical accidents to which they have been subjected since their date of origin - forming frilled schists, veined schists, glazed schists, &c., &c."

Teall (1918) has described and figured a rock which might be called the 'type' mylonite. This was collected in 1883 near a thrust-fault on Arnaboll Hill (Eireboll) in the presence of Lapworth, who indicated that it would show all the structures characteristic of mylonites. By means of a series of photomicrographs, Teall illustrated the development of the mylonite texture from the holocrystalline texture of the parent rock (in this case, Lewisian gneiss).

Three important conditions are implied in Lapworth's definition of mylonite. Firstly, the rocks must be fine-grained; secondly, they must possess a well-defined "fluxion-structure" or lamination; and thirdly, the constituent minerals must show the effects of cataclastic breakdown or granulation with /

with only a minor amount of recrystallization or neo-mineralization (Knopf, 1931; p. 5; footnote). Apart from the extreme case of the Alpine tectonicians cited above, the usage of the term by most subsequent writers does not differ greatly from that of Lapworth. All agree that almost complete granulation is an essential property of the rocks, but some (e.g. Quensel, Holmes and Knopf) have extended the meaning of the term to include rocks which do not show well-developed lamination.

In a well-known paper on mylonitic rocks (1916), Quensel defined two sub-varieties of mylonite: "mylonite im engeren Sinn" (mylonite in the restricted sense) is a micro-breccia in which there is no laminar structure; for rocks of this texture which do exhibit banded structure he used the term "mylonitschiefer" (mylonite-schist). Where there is a considerable degree of neo-mineralization in the comminuted matrix of the rock, as in Lapworth's augen schists, Quensel used the term "mylonitgneiss". In the same category as the latter are the rocks which Tyrrell calls "flaser rocks" (flaser gneiss, flaser gabbro, &c.). Associated with mylonites of various types /

Footnote:

From the German 'Mineralneubildung'; neo-mineralization implies growth of new minerals from the old constituents of the rock, not merely recrystallization of the pre-existing minerals.

types in Scandinavia are microbrecciated rocks which exhibit rigidly parallel banding and a variable degree of neo-mineralization. These are the 'hartschiefer' of the Swedish geologists (Holmquist, 1910; Quensel, 1916; see also Tyrrell, 1926).

The neo-mineralization in these rocks is variable and independent of the layering (Knopf, 1931, p. 13), unlike that in most of the partially crystallised mylonitic rocks. For rocks in which neo-mineralization has proceeded so far that their cataclastic origin can be recognised only with difficulty, Sander introduced the term "blastomylonite" (1912). In blastomylonites even the lenticles show recrystallization, although they are probably of a porphyroclastic nature. They have been produced "by a deformation which is partly ruptural and partly crystalloblastic, not by a rehealing crystallization of a previously mylonitised rock" (Knopf, 1931, p. 14) and are thus equivalent to some of Lapworth's variegated schists.

A number of terms have been employed to denote the extreme products of dynamic metamorphism; rocks in which the degree of cataclastic breakdown is very great and recrystallization is at a minimum. Termier and Boussac (1911) have used the apt expression "puree parfaite" to describe compact, finely-ground microbreccias in which the particles are so fine-grained that the rocks resemble chert or hard wax. Staub (1915) and Quensel /

Quensel (1916) refer to such rocks as "ultramylonite". The "cataclasites" of Grubenmann' and Niggli (1924) and Tyrrell (1926) are closely related to these: "when the product is a structureless rock powder, in which a few porphyroclasts may have survived, the term cataclasite is used in preference to mylonite, as the latter connotes a rolling out or milling of the material with resulting parallel structure" (Tyrrell). Thus the cataclasites lie in the ultramylonite-mylonite range of Quensel.

The term "kakirite" was first used by Svenonius for the cataclastic rocks in the Lake Kakir region of Finnish-Lapland. He appears to have included under the term all rocks which show signs of crushing on any scale, including possibly the hartschiefer (Waters & Campbell, 1935). The term was later used by Holmquist (1910), with a meaning approximating to that of Lapworth's 'mylonite'. In order to distinguish the microscopically crushed rocks from megascopic fault-breccias and other broken and shattered rocks, Quensel redefined the term as follows: 'A megascopically brecciated rock in which the fragments of the original material are surrounded on all sides by shear- and fracture-surfaces, along which intense granulation and some neo-mineralization have occurred'. Other expressions which have been used to denote coarse megascopic breccias /

TABLE 1

1. VARIED USAGE OF THE SAME TERM:-

Mylonite - (a) Lapworth, 1885; (also Staub, 1915; Grubenmann & Niggli, 1924; Tyrrell, 1926; Waters & Campbell, 1935; Turner, 1948)

(b) Quensel, 1916; (also Holmes, 1920; Knopf, 1931; Crickmay, 1933)

Kakirite - (a) Holmquist, 1910

(b) Quensel, 1916

2. SYNONYMOUS USAGE OF DIFFERENT TERMS:-

- | | |
|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| (a) Mylonite, (Lapworth)
Mylonite schist, (Quensel)
Kakirite, (Holmquist) | A microbreccia with subordinate neo-mineralization and conspicuous lamination |
| (b) Mylonite, (Quensel)
Cataclasite in part,
(Grubenmann & Niggli;
Tyrrell) | As above, with or without lamination |
| (c) Ultramylonite, (Staub,
Quensel)
Cataclasite in part
"Puree parfaite", (Termier
& Boussac) | Intensely granulated rock with little neo-mineralization and no lamination |
| (d) Augen schist, (Lapworth)
Mylonite gneiss, (Quensel)
Flaser rock, (Tyrrell) | Porphyroclasts show cataclastic texture: matrix is almost completely crystallised |
| (e) Kakirite, (Quensel)
Protomylonite, (Backlund)
Nodular mylonite, (Raguin) | Megascopically brecciated rocks with or without neo-mineralization |

breccias are "protomylonite" (Backlund, 1918) and "nodular mylonite" (Raguin, 1925). Table 1 (~~Fig.~~) shows some of the ambiguous usage and the duplication of terms in the literature on mylonitic rocks.

Under certain conditions of cataclastic deformation a dark, glassy material is produced, which frequently occurs as veins and stringers, apparently intrusive in the rocks. "Flinty crush-rock" (Clough, 1888; Jehu & Craig, 1923), "trap-shotten gneiss" (King & Foote, 1864; Holland, 1900) and "hyalomylonite" (Scott & Drever, 1954) are some of the terms which have been suggested for rocks of this type. Most authors consider that the amorphous material has developed either by the ultimate mechanical breakdown of the mineral particles by grinding or by local fusion under the influence of intense frictional heat. Shand's term "pseudo-tachylyte" has frequently been confused (e.g. by Tyrrell, 1924; Knopf, 1931; also, to some extent, by Waters & Campbell, 1935) with mylonitic materials of this type. The pseudo-tachylytes of the Parijs region (Shand, 1916) occur as dykes and ramifying veins traversing the granitic country rocks and showing an apparently intrusive relationship to them. The veins are not related to shear-planes and there is no evidence of large-scale displacement of the sides of the veins. The evidence presented by Shand /

Shand on the microscopic characters of the veins also indicates a complete absence of shearing in the walls of the veins. He concluded that the pseudo-tachylytes had originated by shock - "sudden rupture of the granite without long-continued friction or shearing", or alternatively by "the outrush of incandescent gases through all the fissures of the granite". D.L. Reynolds has recently (1954) discussed the mode of origin of the pseudo-tachylytes of the Vredefort area (Shand, 1916; Hall & Molengraaff, 1925; Willemse, 1936) in the light of up-to-date knowledge on the behaviour of solid-gas reaction systems. The textural characters of the dykes and veins of pseudo-tachylyte indicate that they have originated in "fluidized" systems (footnote); the author recognises evidence of both "fluidized" bed reaction and entrainment of particles and concludes that the pseudo-tachylytes were not all formed as a result of a single act: "they were formed through a period of time during which gas streams flowed along structural breaks to the surface with varying velocities and perhaps intermittently." (p. 593).
The /

Footnote:

"Fluidization" is an industrial process in which gas is passed through a bed of fine-grained solid particles in order to facilitate chemical reaction. A number of stages are recognisable in such systems, depending on the rate of flow of the gas: (1) expanded bed stage; (2) fluidized stage when bubbles of gas pass through the expanded bed; (3) ultimate stage when solid particles are entrained and transported by the gas.

The flinty crush-rocks, trap-shotten gneisses and hyalomylonite differ significantly from the texturally similar pseudo-tachylytes in being closely associated with shear-planes, generally thrust-planes. Glass-bearing mylonitic rocks have not been found in the Assynt region by the present writer but the above discussion of these rocks is included with a view to correcting a widespread misconception as to the significance of the term 'pseudo-tachylyte'.

In an excellent paper on "Retrogressive Metamorphism and Phyllonitisation" E.B. Knopf discussed the terminology of mylonitic rocks and introduced Sander's term "phyllonite" (Sander, 1912, p. 301) into English-speaking geological literature. Phyllonite or phyllite-mylonite is a rock of phyllitic composition which has been produced by the mylonitic degradation of a coarser-grained rock by differential movements working along a pre-existing set of S-planes. Knopf lists the following criteria for the recognition of phyllonites:

- "1. Phyllitic appearance accompanied by the characteristic lenticular structure, either megascopic or microscopic.
- "2. A completely phyllonitised rock does not show cleavage that cuts the old S-planes because its phyllitic texture is the result of a refolding and transposition of the old S-planes of the rock.
- "3. Adjacent lenses are of different sizes but the individuals in each lens are of similar grain-size.
- "4. All the individuals in one lens show sub-parallel optical orientation." (p. 19).

She further states that "in regional phyllonitization different specimens will show all transitions from incipient phyllonitization where the transverse character of the relict S-structure can be seen between the folded limbs to a complete new phyllitic texture where the old S is completely sheared out"

Another clear and comprehensive discussion of the nomenclature of mylonitic rocks is given by Waters and Campbell (1935). They recognised that mylonites (in the unrestricted sense of Quensel) may grade into a great many different types of tectonite, with change in the conditions of deformation: (a) by decrease in coherence they grade into ordinary gouge and finely pulverised fault-breccia; (b) by decrease in the degree of crushing into megascopic, coherent breccias; (c) by increase in the degree of recrystallization (neo-mineralization) into varieties of crystalline schist; (d) by fusion due to frictional heat into the glassy varieties of tectonite. These authors consider that the limitations in existing classifications of mylonitic rocks (see above) spring partly from the fact that each was designed to fit the rocks of a specific area in which not all the gradations occur.

In the course of the field examination of the mylonitic rocks along the Moine Thrust and subsequent microscopic study of thin sections in the laboratory, the present writer has /

has found abundant evidence confirming the gradation to which Lapworth directed attention, i.e. from mylonites through augen schists and other varieties of finely-laminated schist to the more coarsely crystalline Moine schists (c.f. Quensel; Knopf; Waters & Campbell). In this sequence the rocks which show cataclastic textures conform to Lapworth's definitions of mylonite and augen schist and the present writer prefers to retain these terms, with their original meaning, rather than adopt newer terms or amended definitions introduced at a later date. Sander's term "blastomylonite" will be used for rocks in which evidence of cataclastic breakdown is almost completely masked by neo-mineralization.

Of the three properties which characterise Lapworth's mylonites, namely (1) fine grain due to granulation, (2) well-developed lamination and (3) lack of neo-mineralization, only the first two can be detected in hand specimen, and it was these two characters which the Survey geologists used for identifying mylonites while mapping the thrust-zone. Fine-grained rocks exhibiting marked evidence of crushing and well-developed laminar structure were distinguished from the more coarsely crystalline, often slabby, Moine Schists to the east and are represented on the maps by the symbols 'μ' and 'μ'. The present writer has found that much of the finely-laminated rock along the Moine /

Moine Thrust in Assynt (μ on the One-inch Map) shows a considerable degree of neo-mineralization and frequently lacks even the vestiges of cataclastic texture which characterise the augen schists. They are chiefly blastomylonites and in many cases could be adequately described as fine-grained quartz-schists and chlorite-schists (see p. 177). Since there is no means of distinguishing between the true mylonites and the blastomylonites and banded schists in the field, it is difficult to map their distribution accurately. However, there is in general a gradation, with increasing crystallinity, from the Moine Thrust upwards into the typical Moine Schists. In addition, at many localities there is complete structural continuity from deformed Cambrian rocks below the Thrust into the Moines (see pp. 111-2). Thus the mylonites, blastomylonites and laminated schists differ only in the degree of recrystallization and development of new minerals. To avoid needless repetition of terms and to distinguish these rocks from other types of cataclastic rock (see below - Secondary Mylonitic Rocks) they will be referred to collectively as Primary Mylonitic Rocks.

At certain localities along the Thrust, notably at Knockan Crag and to the north of Loch nan Caorach, the laminated schists and mylonites themselves show evidence of cataclastic /

cataclastic deformation of a somewhat different type. There is local development of megascopic breccias made up of dis-oriented fragments of Primary Mylonitic Rocks in an extremely fine-grained matrix of rock-dust (= Kakirite of Quensel). The Moine Schists are also affected by this crushing near the same localities. The final product of this process, seen only in the Knockan Crag vicinity, is an unlaminated microbreccia, which carries few porphyroclastic mineral fragments and shows no trace of neo-mineralization. Staub and Quensel have used the term 'ultramylonite' for rocks of this type. The term implies that the properties and origin of the rocks are similar to those of ordinary mylonites. The ultrabrecciated rocks, however, are unlaminated and must have been produced under conditions differing considerably from those under which the mylonites (Lapworth's usage) originated; it would thus be misleading to refer to them as ultramylonites. Instead, Grubermann's term 'cataclasite' will be used.

The kakirites and cataclasites are, in general, formed from competent, quartzo-feldspathic schists and mylonites. Where more incompetent pelitic rocks are affected by the secondary deformation, they have been converted to phyllonite. The kakirites, cataclasites and phyllonites will be referred to as Secondary Mylonitic Rocks, the word 'mylonitic' being given a genetic /

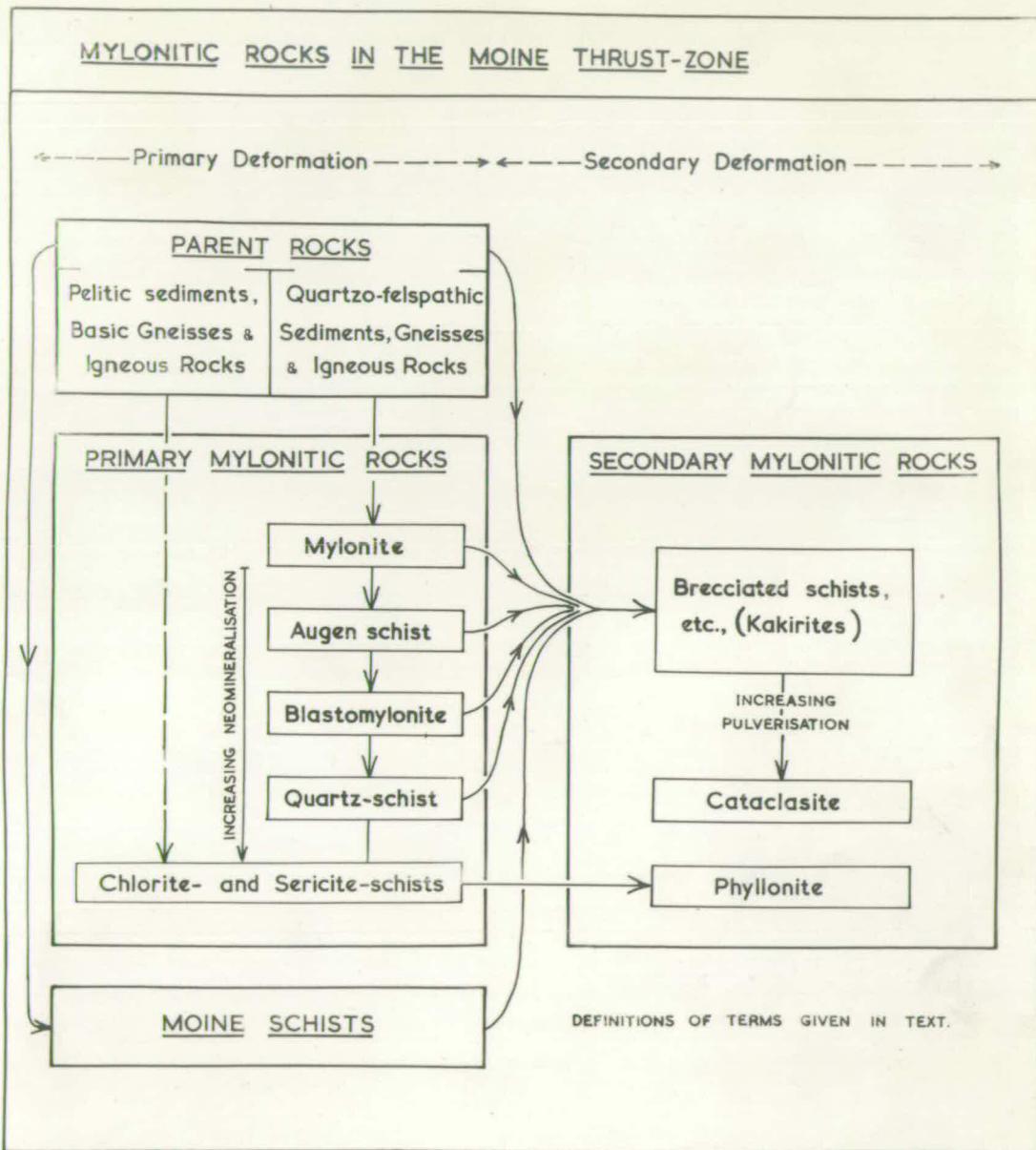


Figure 3. Diagrammatic representation of the relationship between different types of mylonitic rock in the Moine Thrust-zone.

genetic connotation, since they are products of "milling" or "grinding". It should be noted, however, that they are texturally and structurally (see pp. 176-8, 112) unrelated to the mylonites of Lapworth.

The relationship between these numerous types of 'mylonitic' rock is shown diagrammatically in Fig. 3.

3. KINEMATIC INTERPRETATION OF FABRICS OF DEFORMED ROCKS

The first stage in any tectonic study is the determination of geometry, that is, the spatial arrangement of all the structural elements in a deformed body. This part of the study must include an analysis of the components on every scale within the range of field and laboratory observation, since a geometrical picture based on either megascopic data or microscopic data alone is incomplete. An integrated picture of the geometry of structural elements on all scales constitutes the fabric of the body. Some degree of selection of data is inevitable in a geometrical analysis of this type, but the effects of selection are minimised by the use of statistical methods in the organisation and evaluation of data.

In the second stage of a tectonic study the nature and sequence of the movements which have affected the body are reconstructed from the fabric data. The earliest structural investigators were concerned primarily with the forces which produced such structures as folds and cleavage in rocks (Knopf, 1938, p. 11), but since the beginning of the present century emphasis has shifted from the dynamic to the kinematic aspects of /

of rock deformation. As Knopf has stated, "regardless of any information about the forces that caused the movements, a descriptive analysis of the movement will give a picture of the conditions under which the rock was deformed" (1938, pp. 29-30).

The principle which forms the basis for the kinematic interpretation of rock fabrics was first formulated by Sander from the evidence of his studies of rock structures. In its original form, it is contained in a paper 'On the connexion between rock fabric and the interrelated movements of component parts' (translation by Knopf, 1938, p. 11), published in 1911. In this work, which marks the birth of the science of Structural Analysis, Sander demonstrated that the orientation of the elements in the fabric of a rock records the interrelated movements of component parts during the formation of the rock in much the same way as a photograph of grass bent by a wind records the movement of the grass. After further investigation Sander developed this theory and evolved the principle that the symmetry of the fabric of a tectonite reflects the symmetry of the movements that produced the fabric. Anderson (1948) has referred to the principle as the 'argument from symmetry'; in the following pages it is called the 'principle of symmetry'. For many years it has been accepted by structural petrologists and Turner states (1948, p. 188) that it "has been so well substantiated /

substantiated by the accumulated results of petrofabric analysis that it now has the status of an established law of structural petrology."

Three types of symmetry - orthorhombic, monoclinic and triclinic - are common in the fabrics of tectonites (Sander, 1930, 1948) and Sander has interpreted each of these types of fabric in terms of strain with the same order of symmetry. Some authors, however, have not mentioned symmetry in discussing the significance of fabric diagrams and there has been a tendency to interpret all tectonite fabrics in terms of monoclinic movements, notably simple shear.

The validity of the principle of symmetry has recently been questioned, especially by Kvale (1946-47, 1953) and Anderson (1948). Both authors cite areas, Kvale in Norway and Anderson in Scotland, in which they claim that the principle does not hold. According to the authors, the dominant lineation in these areas is normal to a single plane of symmetry in the fabric and also represents the direction of tectonic transport.

Kvale stated that:

"the real testing areas of Sander's hypothesis are those in which there is no doubt as to the direction of the movements involved and as to the symmetry of the structures that resulted from these movements. The structures of two such areas /

areas, one in eastern Norway and the other the Bergesdalen quadrangle, have now been studied sufficiently to show that a modification of the principle, based on plane of symmetry and direction of movement, must be seriously considered" (1953, p. 53).

It is obvious that there can be "no doubt as to the direction of the movements" in a rock-mass only when the movements have been directly observed. In the two areas cited by Kvale the direction of movement has been inferred from selected field evidence. From the data given by Kvale it is evident that, on the scale considered, the fabric in these areas is inhomogeneous (Turner, 1948, p. 192); yet he considers that the fabrics have been produced by simple shear with a single 'direction of movement'. He has attempted to interpret the fabric of a body that has suffered complex strain in simple kinematic terms.

Anderson's paper contains a useful account of the principles underlying the interpretation of fabric data. The main thesis of the paper is that lineation (parallel to a fold-axis or axis of symmetry) is parallel to a direction of shear. Anderson's criticisms of the principle of symmetry are indirect, but in the course of the discussion he states that to Sander "the argument from symmetry seemed so convincing that a more direct proof of the supposed relation was unneeded." Anderson, like /

like Kvale, has approached the problem with the view that such a "proof" is possible on the basis of theoretical reasoning or geological evidence. The principle is a physical hypothesis and as such can only be "proved" or "disproved" by direct observation of both movements and resulting structures in a large number of deformations. It is clear that no direct evidence of movements can be obtained from geological studies: only the effects of movement may be studied in rock fabrics.

The only reliable evidence of the validity of the principle of symmetry comes from experimental studies of the deformation of rocks, metals, plasticine and other substances. All the evidence so far obtained from this source confirms the principle (e.g. Griggs, Turner et al., 1951, p. 905). In view of this fact the present writer considers that the controversial question at the present time is not whether the principle of symmetry is valid, but whether it should be given the status of a hypothesis or a natural law.

The experiments on Yule marble show that the symmetry of movement, and thus of fabric, produced by a given stress depends upon the predeformational fabric. Weiss (1955) has discussed the influence of the predeformational fabric on the final fabric in rock deformation and concluded that the principle of symmetry /

symmetry, as cited above, is only valid under one of three conditions:

- "1. If the deformed fabric was statistically isotropic before deformation.
2. If the deformation was sufficiently prolonged or intense to remove by transposition all traces of structures in the original fabric.
3. If structures^x inherent in the fabric before deformation agreed in symmetry with the deforming movements" (Weiss, 1955, p. 230).

Fabric analysis of a triclinic tectonite from Anglesey revealed asymmetrically oriented girdles of quartz [0001] and mica [001] axes. Weiss interpreted the fabric in terms of a single monoclinic deformation involving slip on a single set of slip-surfaces which did not coincide with a pre-existing s-plane in the fabric; he attributed the triclinic symmetry of the fabric to the fact that the B-axis did not lie in the original s-plane.

Where evidence of the mechanism of deformation of minerals is available from experimental studies, as for calcite and dolomite, it is possible to make a dynamic interpretation of fabric data (twin-lamellae, &c.). In the present work lamellar /

^xThis should read - "3. If passive structures inherent "; Weiss, 1956, personal communication.

lamellar structures in dolomite rocks are interpreted dynamically in the light of information derived from experimental deformation; all other fabric data are interpreted kinematically on the basis of the principle of symmetry, with due regard to the conditions outlined above.

ROYAL CHARLES

III. MEGASCOPIIC STRUCTURAL DATA

1. THE MOINE THRUST

a. Preliminary Survey

The strike of the Moine Thrust, which is so remarkably constant over most of its outcrop, varies considerably in Assynt, giving rise to the embayment in the outcrop known as the 'Assynt Bulge'. Round the southern part of the 'bulge', east of Knockan Crag, the strike of the Thrust is approximately east and the dip is towards the south at low angles; along the eastern margin of the 'bulge' the strike of the Thrust is north-north-east and the dip to the east-south-east, while to the north, from the head-waters of the River Cassley to the Stack of Glencoul, the strike becomes north-west with dip towards the north-east. Mylonitic rocks of various types are developed both above and below the horizon mapped as the Moine Thrust. The commonest of these are the finely-laminated, colour-layered primary mylonitic rocks which occupy a zone of variable thickness above the Thrust. Overlying the mylonitic rocks are the low-grade quartzo-feldspathic schists of the Moine Series.

Where the trend of the outcrop of the Thrust is north-north-east the mylonitic rocks form a well-marked scarp-feature which generally affords good exposures. In the northern and southern portions of the 'bulge', however, where the outcrop trends /

trends north-west and east, the scarp-feature is not so distinct and the rocks are poorly exposed. The outcrop of the Thrust itself is generally obscured by peat or scree. Only at a few localities, notably at Knockan Crag and the Stack of Glencoul, is the Thrust well exposed. The Moine Schists throughout the area are very poorly exposed; they give rise to rounded, featureless hills, which are thickly covered with peat, and the only available exposures are in the beds of comparatively large streams and at widely-scattered localities where the peat is deeply eroded.

The foliation in the primary mylonitic rocks and Moine Schists is parallel to the Moine Thrust. East of Knockan Crag the strike of the foliation is east and the dip is towards the south. The strike swings round the south-east corner of the 'bulge' and becomes north-north-east, parallel to the regional strike of the Moine Schists. In the northern part of the area the strike of the foliation is generally north-west and the dip towards the north-east. There is no evidence of large-scale folding of the foliation in the mylonitic rocks or in the Moine Schists within at least a mile of the Thrust, but small-scale folds are conspicuous in the mylonitic rocks. A fine penetrative lineation is present in the primary mylonitic rocks /

rocks and Moine Schists and also in some deformed Cambrian and Torridonian rocks below the Moine Thrust^{*}. The orientation of small-scale folds and penetrative lineations measured in a survey of the thrust-zone extending from Knockan Crag to the Glencoul River is shown in figure 4. There is a marked preferred orientation of fold-axes (Fig. 4a) with a strong maximum plunging at a low angle to approximately N100E and a sub-maximum with north-south trend. The lineations (Fig. 4b) show a higher degree of preferred orientation than the fold-axes; they define a strong maximum which coincides with the maximum of fold-axes. The lineation is therefore a B-lineation. The east-south-east plunging folds and lineations are present in the mylonitic rocks along the whole extent of the outcrop of the Moine Thrust, but the majority of the folds with north-south trending axes occur in two small areas. The larger of these areas is in the north of Assynt, near the Stack of Glencoul, and the other is in the south-east on Cnoc a' Chaoruinn (Cnoc Chaornaigh on the 1" Geological Map of Assynt). It is significant that these are the two areas in which the Survey geologists reported the greatest development of mylonites in the Assynt region (Clough, 1907, pp. 502-7; Phemister, 1926, p. 21).

The /

*This lineation, defined by the elongation of quartz grains and a preferred orientation of chlorite and sericite, is continuous throughout the rock and is described as penetrative to distinguish it from superficial streaking on foliation and shear-surfaces, such as slickensides.

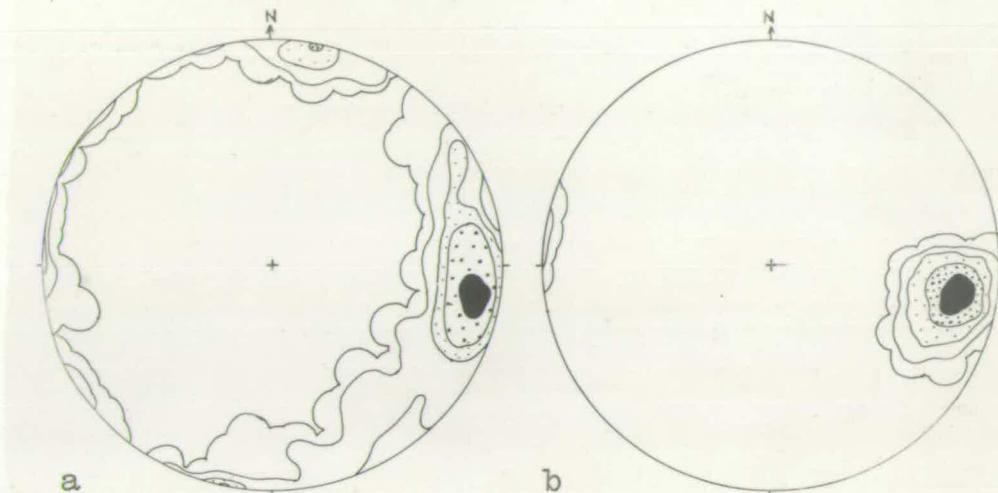


Figure 4. Orientation of minor structures measured in the preliminary survey of the mylonitic rocks associated with the Moine Thrust.

a. Axes of 166 small-scale folds. Contours: $\frac{3}{5}$, 2, 4, 6, 12% per 1% area.

b. 112 penetrative lineations. Contours: 1, 5, 10, 20, 30% per 1% area.

The distribution of the minor folds has been mapped in these two areas and the relationship of the two groups of folds to each other and to the thrusts investigated. The fabric of a third area, at Benmore Lodge, north of Loch Ailsh, has also been studied in detail. Certain other sections across the thrust-zone and the overlying schists, notably in the vicinity of Knockan Crag, have also been subjected to a detailed investigation. The results of these studies are described below.

b. The Stack of Glencoul Area

General Description of Area. Figure 5 is a structural map of the Moine Thrust-zone between Beinn Aird da Loch and the Fionn Allt. The outcrops of Lewisian, Torridonian and Cambrian rocks to the west of the Moine Thrust are based on the Geological Survey maps. The data recorded on the map represent only a small proportion of the measurements made by the writer in the area. The data are recorded more fully in the fabric diagrams (Figs. 6).

The outcrop of the Moine Thrust in the area is sinuous but the general trend of the outcrop is north-west. To the west of the Thrust Lewisian and Cambrian rocks forming parts of /

of the Glencoul and Ben More Nappes are exposed. In the western part of the area the Lewisian gneiss and Cambrian quartzites belong to the upper part of the Glencoul Nappe. The Ben More Thrust outcrops to the south-east of Loch nan Caorach and the rocks to the east of the Thrust - Cambrian quartzites, Fucoid Beds, Serpulite Grit and limestones - represent the most northerly exposures of the Ben More Nappe. Thrust slices of Cambrian quartzite and Torridonian rocks, carried on other important, but unnamed thrusts, outcrop immediately below the Moine Thrust: a small lenticle of quartzite outcrops at the base of the Stack of Glencoul and a considerably larger slice of Cambrian quartzite and Torridonian sediments extends from Loch an Eircill south-eastwards beyond the limits of the map. The Cambrian rocks to the east and south-east of Loch nan Caorach are broken by a complex of reverse faults which form an imbricate zone. The outcrop of the faults is parallel to that of the Ben More Thrust and the faulting is most intense in the vicinity of the Thrust. It is evident that the imbricate zone is related to the Ben More Thrust rather than the Moine Thrust. The orientation of the Ben More Thrust and a number of the related faults, determined by stratum contoured, is shown in figure 6a^T. The strike of the Thrust is approximately N 10°W and the dip between 30° and 40° towards the east. The /

The faults have approximately the same strike but the dip is variable and considerably steeper.

For a considerable distance above the Moine Thrust and for several feet below it the rocks are intensely mylonitised. The mylonitic rocks form a distinctive scarp, which is most marked where the outcrop of the Thrust trends north-south: it is especially well developed on the west side of the Stack of Glencoul (Plate Ia) and to the north of the Glencoul River, where the rocks form a precipitous cliff, locally approaching 200 feet in height.

Both primary and secondary mylonitic rocks are present above the Moine Thrust. Primary mylonitic rocks form a zone of variable thickness above the Thrust; to the north of Loch nan Caorach this is between 150 and 200 feet thick, thinning towards the south-east. Secondary mylonitic rocks occupy a zone, approximately half a mile wide, to the east of the Moine Thrust and the primary mylonitic rocks associated with it. They comprise slightly crushed rocks, still recognisable as primary mylonitic rocks and Moine Schists, and more intensely deformed rocks showing varying degrees of phyllonitization. To the east of this zone, there is a second zone of undeformed primary mylonitic rocks, considerably thinner than that described above, extending for a mile north-north-east from Loch an /

an Eircill. The primary mylonitic rocks of the eastern zone grade upwards into normal granulitic Moine Schists. The gradational boundary between the primary mylonitic rocks and Moine Schists can be traced southwards from Loch an Eircill towards the Moine Thrust but in this area both types of rock have suffered severe secondary deformation.

Structural Data. The position of the Moine Thrust can be determined within a few feet along most of its outcrop although it is seldom exposed. The Thrust has a north-westerly strike and dips at approximately 20° to the north-east. Plate Ia shows the position of the Thrust at the base of the Stack of Glencoul, viewed from the west; the apparent dip of the thrust-plane is towards the north. Plate Ib is a view of the area from the south, showing the position of the Thrust; the apparent dip of the Thrust in this section at the Stack of Glencoul (left middle-distance) is towards the east. East of Loch nan Caorach the Thrust is warped into a gentle antiform so that on the ridge south-east of the loch it is at the same topographic level as at the west side of the Stack of Glencoul. This gentle fold in the thrust-plane was noted by the Survey geologists (1907, Fig. 30, p. 505; p. 506). Peach considered, moreover, that the eastern zone of primary mylonitic rock (μ) was due to a fold affecting the Moine Thrust, so that the mylonitic /

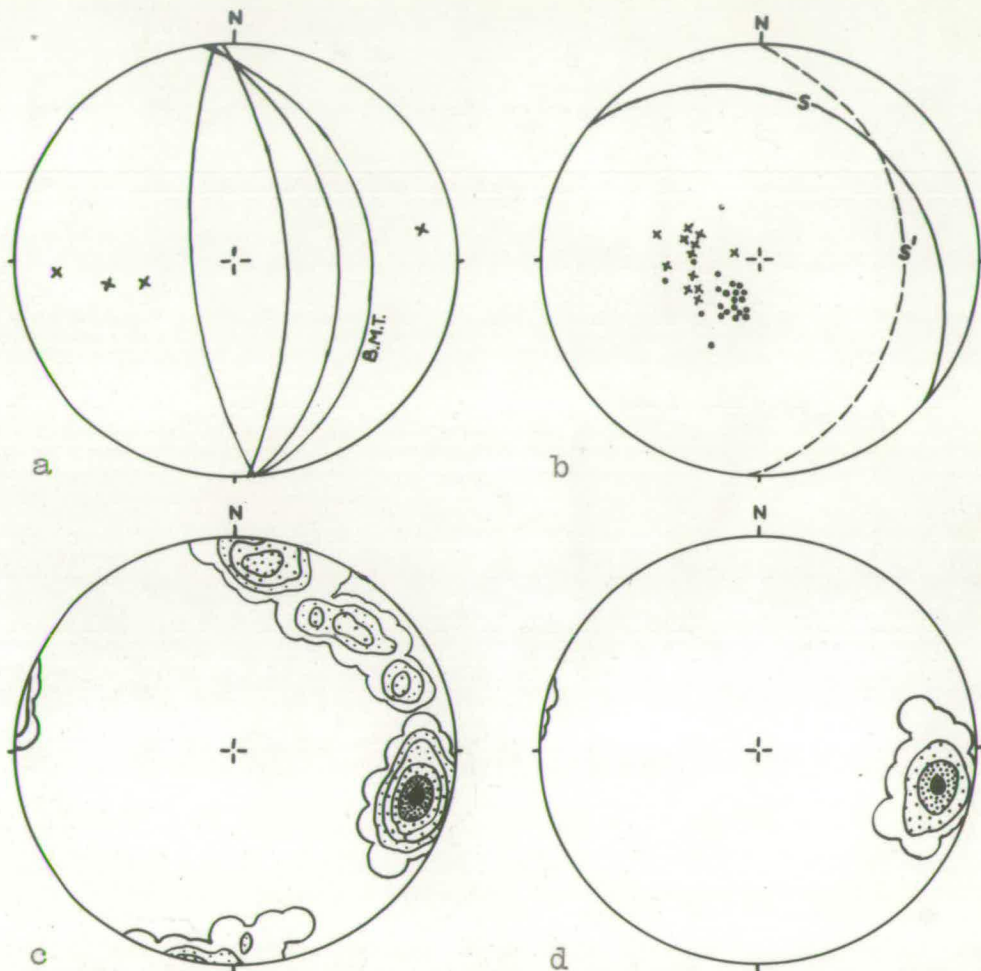


Figure 6. Structural data from the Stack of Glencoul area.

a. The orientation of the Ben More Thrust and three reverse faults associated with the Thrust. Crosses represent the poles of the planes.

b. Foliation planes in the primary mylonitic rocks (dots) and phyllonites (crosses). \underline{S} and \underline{S}' represent the mean orientation of the foliation in the primary mylonitic rocks and phyllonites respectively.

c. Axes of 97 small-scale folds in the area. Contours: 1, 3, 5, 10, 15, 20% per 1% area.

d. 70 penetrative lineations measured in the area. Contours: 1½, 10, 30, 50% per 1% area.

mylonitic rocks were warped upwards along this zone (see sketch diagram "explaining B.N.P.'s views" on Clough's field maps). It should be noted that the antiform is just above the Ben More Thrust, an important fact which apparently escaped the notice of the Survey geologists.

The Moine Thrust is exposed only on the west side of the Stack of Glencoul and due east of Loch nan Caorach. At both localities there is an alternation between mylonitized Cambrian quartzites and colour-layered primary mylonitic rocks through a vertical distance of between ten and twenty feet. There is no well-defined surface representing the Thrust. The quartzite in the thrust slices below the Thrust is foliated and lineated (and locally folded) like the primary mylonitic rocks. The horizon mapped as the Moine Thrust in the area, then, is not a fault surface but a boundary between rocks of different composition and similar fabric.

The orientation of the foliation (S) in the primary mylonitic rocks, where they are not affected by the secondary deformation, is shown in figure 6B. The foliation dips consistently towards the north-east, parallel to the Moine Thrust. The strike of the foliation in the secondary mylonitic rocks (Fig. 6b, S') is slightly east of north and the dip is approximately 35° towards the east. Figures 6c and d show the orientation /

orientation of all the small-scale folds and penetrative lineations measured in the mylonitic rocks and Moine Schists in the area. There is a strong maximum of fold-axes plunging towards the east-south-east (\underline{E}) and a sub-maximum with north-south trend (\underline{E}_n); there is a slight spread of the axes in a great-circle parallel to the regional foliation (\underline{S}). The lineations are consistently parallel to the maximum of fold-axes (\underline{E}) and show a very high degree of preferred orientation.

The partial diagrams in figure 7 show that all the folds and lineations in the deformed rocks below the Moine Thrust, in the primary mylonitic rocks and in the Moine Schists plunge towards the east-south-east, whereas the \underline{E}_n folds are confined to the zone of secondary mylonitic rocks. Folding is comparatively rare in the Moine Schists but very common in the rocks in the vicinity of the Thrust. The style of the folding in the Cambrian rocks (Fig. 8b), the primary mylonitic rocks (Plate II; Fig. 8c) and the Moine Schists (Fig. 8a) is remarkably similar. The folds are generally overturned, with closely appressed limbs and the style suggests considerable mobility. The majority of the folds are overturned towards the south-south-west. Thus there appears to be a common \underline{E} -axis in the Cambrian rocks, the primary mylonitic rocks and the Moine Schists.

Along /

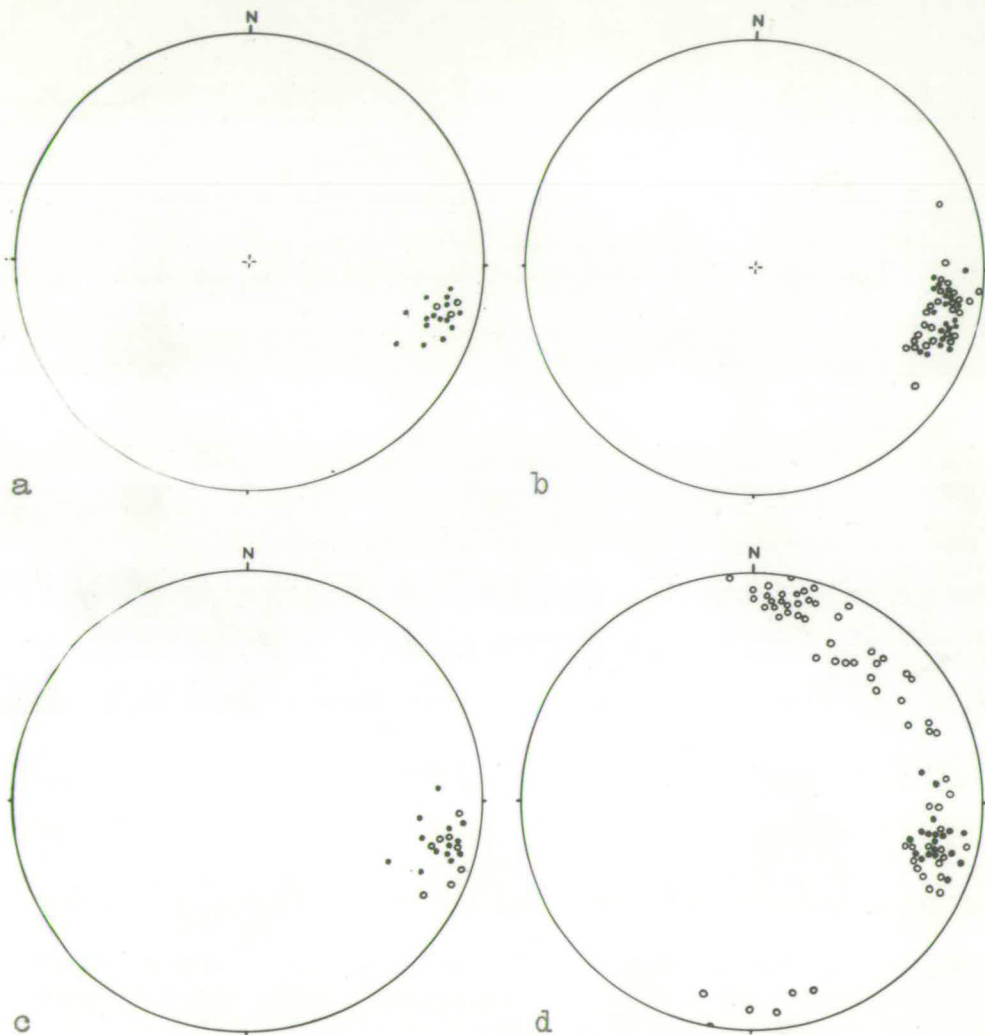


Figure 7. Partial diagrams constructed from the data in Figure 6c and d, showing the orientation of fold-axes (circles) and lineations (dots) in a, Cambrian and Torridonian rocks below the Moine Thrust, b, the primary mylonitic rocks, c, the granulitic Moine Schists and d, the secondary mylonitic rocks.

NNE

SSW

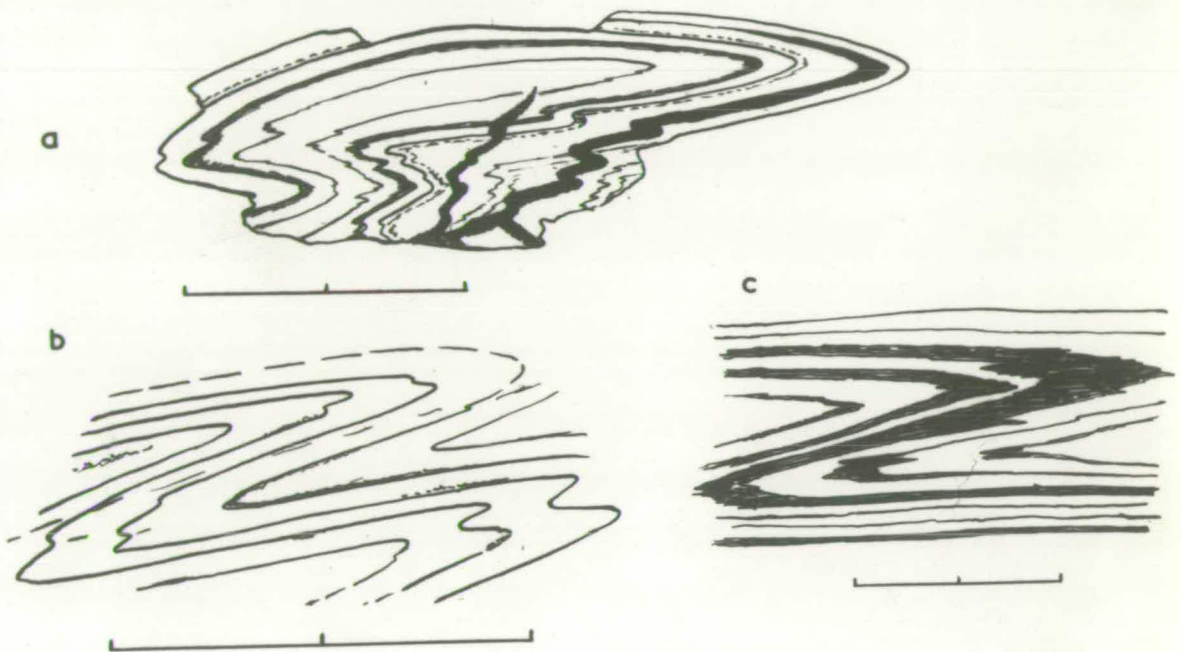


Figure 8. The style of folding in the Stack of Glencoul area.

a. Profile of a fold in the Moine Schists, Fionn Allt. Black layers are quartzose. Scale in inches.

b. Profile of a fold in deformed Cambrian quartzite below the Moine Thrust east of Loch nan Caorach. Scale in inches.

c. Profile of a fold in primary mylonitic rock, Cnoc an Fhuarain Bhain. Shaded layers are chloritic. Scale in inches.

Along the margins of the zone of secondary deformation fold-structures plunge to the east-south-east and towards the north. The east-south-east plunging folds are similar in style to those in the primary mylonitic rocks and are obviously relict \underline{E} -structures which have survived the secondary deformation. In the central parts of the zone, however, only \underline{E}_n folds are present (Fig. 5, inset, top right) and this will be called the \underline{E}_n zone. There is a small area of \underline{E}_n folds, isolated from the main \underline{E}_n zone, above the Moine Thrust south of Loch an Eircill.

Certain types of mylonitic rock are characteristic of each of these structural zones. The primary mylonitic rocks (with \underline{E} -structures) show the whole range of textures from true mylonites to quartz- and chlorite-schists. Mylonites are present near the thrust-plane but neomineralization is extensive and most of the rocks are augen-schists and blastomylonites. Even some of the mylonitized quartzites below the Moine Thrust are completely recrystallized. The rocks in the zones of relict \underline{E} -structures show the first stages of phyllonitization and near the eastern margin of the zone there is considerable brecciation. At the localities marked by crosses (Fig. 5, inset, bottom left) kakirites are developed. The rocks in the \underline{E}_n zone are chiefly dark-coloured phyllonites (p) but in the northward /

northward extension of the zone (p') the rock is similar to the quartzo-feldspathic Moine Schists in appearance and composition. On weathered outcrops, however, the rock develops a carious surface due to the isolation of small lenticles. This lenticular texture is not found in normal Moine Schists, but is characteristic of phyllonitic rocks.

There is an increase in the effects of phyllonitization from the margins of the zone of secondary deformation towards the centre. Near the margins of the zone the lineation on the s-surfaces is obscured and the surfaces assume a dull, uneven appearance which has been aptly described as "diseased" (Knopf, 1931, p. 6). In some pelitic layers a new s-surface, parallel to \underline{S}' (Fig. 6b), defined by the orientation of chlorite flakes, is produced; this is steeply inclined to the old \underline{s} -surfaces (\underline{S}). Near the centre of the zone the s-surfaces (\underline{S}) are intensely folded, but in the most intensely phyllonitized rocks the old foliation (\underline{S}) has been completely transposed. These rocks bear a superficial resemblance to phyllites but close examination reveals that the \underline{s} -surfaces are uneven or wavy, as in the "frilled schists" and "oyster-shell rock" of the Survey geologists (1907, pp. 481, 598). Lineations are not common in the phyllonites, but in some there is a faint streaking /

streaking on the \underline{g} -surfaces, resembling slickensides. This lineation is normal to the axes of \underline{B}_n folds - that is, it is an \underline{a} -lineation. In some of the quartzite layers the old penetrative lineation (\underline{B}) is preserved and is locally folded about north-trending axes (\underline{B}_n).

Although many of the rocks which show phyllonitic textures are of pelitic composition, some are highly siliceous. The factor controlling the development of these textures appears to be the presence of a well-defined lamination in the rocks before deformation. While the lamination is most marked in the chlorite-rich varieties of primary mylonitic rock, it is also present in the more siliceous members.

The unusual nature of the rocks in the Stack of Glencoul area was recognised by Clough, who named them "Stackschists" (1907, pp. 502, 505). He described them as "crumpled schists" and "puckered schist with thin siliceous streaks". With customary attention to detail, Clough recorded evidence of late-stage deformation: "The shear-planes [i.e. foliation-planes] are contorted and crossed by many almost horizontal fault-planes, which also cross the red mylonised stripes, and must have been formed after the rock was in a mylonised condition". (1907, p. 502; present writer's italics).

The /

ROYAL CHARLES

W

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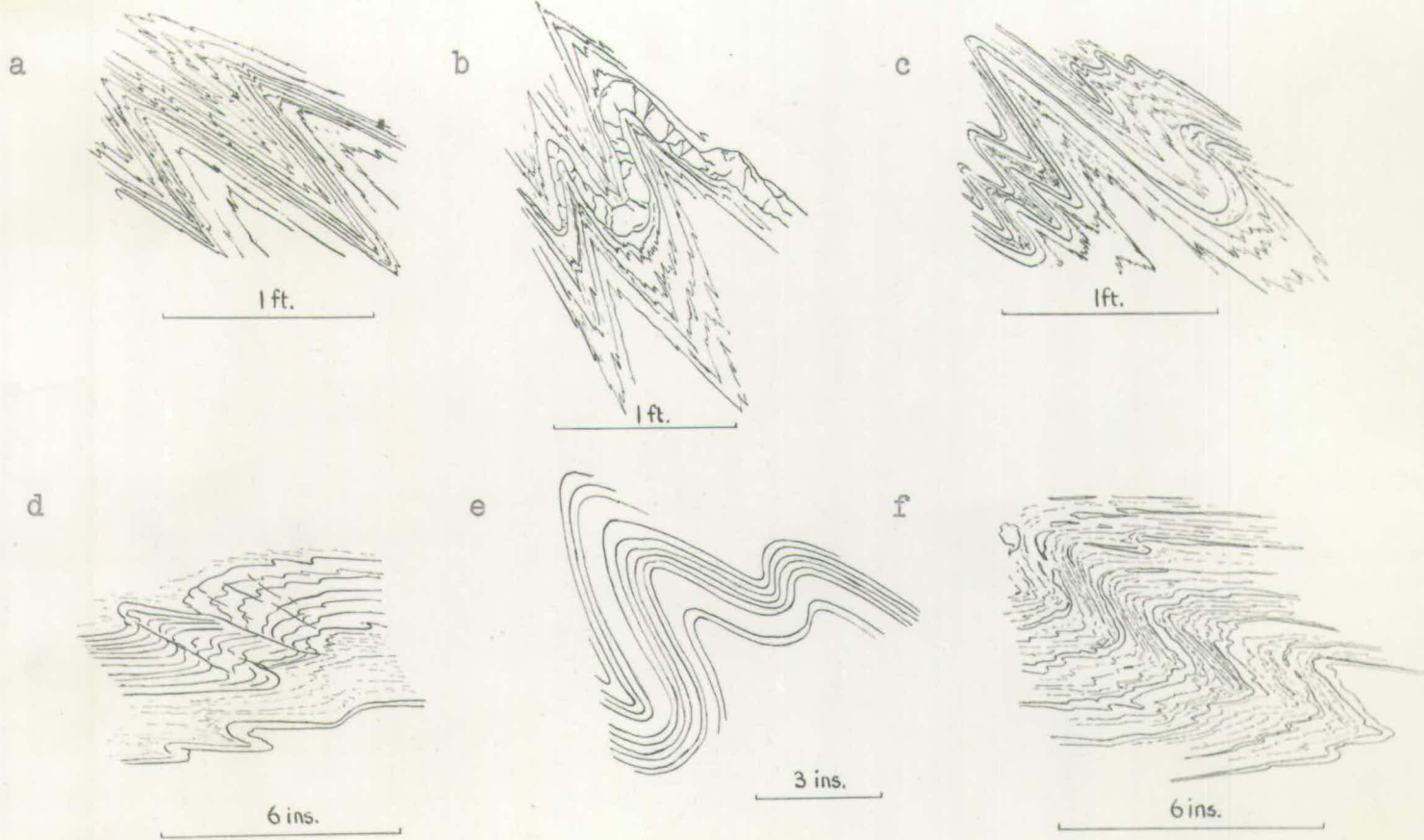


Figure 9. Profiles of folds in the zone of north-plunging folds.
Stack of Glencoul area

The style of the B_n folds is shown by the profiles in figure 9 and Plate III. The simplest type is illustrated by the fold in Plate IIIa, on an outcrop near the eastern margin of the zone of secondary deformation. The s -surfaces (S) are sharply folded as shown in the Plate, so that the steeper limbs define regular layers which dip between 30° and 60° to the east. The more complex folds are angular, with axial planes dipping invariably towards the east. The folds show all the properties of flexural-slip folds (Knopf, 1938, pp. 160-2): in competent siliceous and pegmatitic layers the folds have rounded profiles, whereas in adjacent incompetent layers the folds are smaller and more angular. In general, the complexity of the folding varies with the composition of the rocks, the quartzites showing the simplest and the pelitic rocks the most complex style. The folds frequently show attenuation along the limbs and thickening at the crests.

Folds of the type shown in Plate IIIa have been described by German writers and are variously termed "Knitterung", "Knickbänder", "Zerknitterung", "Verschiebungsflächen" and "Knickzonen" (Hoeppener, 1956, pp. 34-5). The structures are analogous to the so-called "kink-bands" in deformed crystals (Turner, Griggs and Heard, 1954, p. 896). They are referred to /

to below as kink-zones.

Figure 10b is a diagrammatic section across the Stack of Glencoul area showing the relationship between the Moine and Ben More Thrusts and the structural zones (Fig. 5, RB and B_n). Peach and Horne (1907, pp. 471-2; 1914, p. 19) considered that the Ben More Thrust was overlapped by the Moine Thrust in this area, indicating that the movement on the Moine Thrust outlasted that on the Ben More Thrust. It is clear, however, that the Moine Thrust has suffered a displacement of between 500 and 1000 feet above the Ben More Thrust and the associated system of faults and it is also in this zone that the primary mylonitic rocks and Moine Schists have suffered the most intense secondary deformation. Thus the evidence suggests that the displacement of the Moine Thrust and the secondary deformation were produced by movement on the Ben More Thrust. Movement on the Ben More Thrust, then, must have taken place, at least in part, after movement on the Moine Thrust had ceased. In the kink-zones in the zone of relict B-structures (Fig. 10a) the movement-picture is exactly the same as that in the rocks below the Moine Thrust: the g-surfaces (S₁) are "kinked" along layers (S₂) which the present writer considers are genetically related to the Ben More Thrust and associated reverse faults.

Combined /

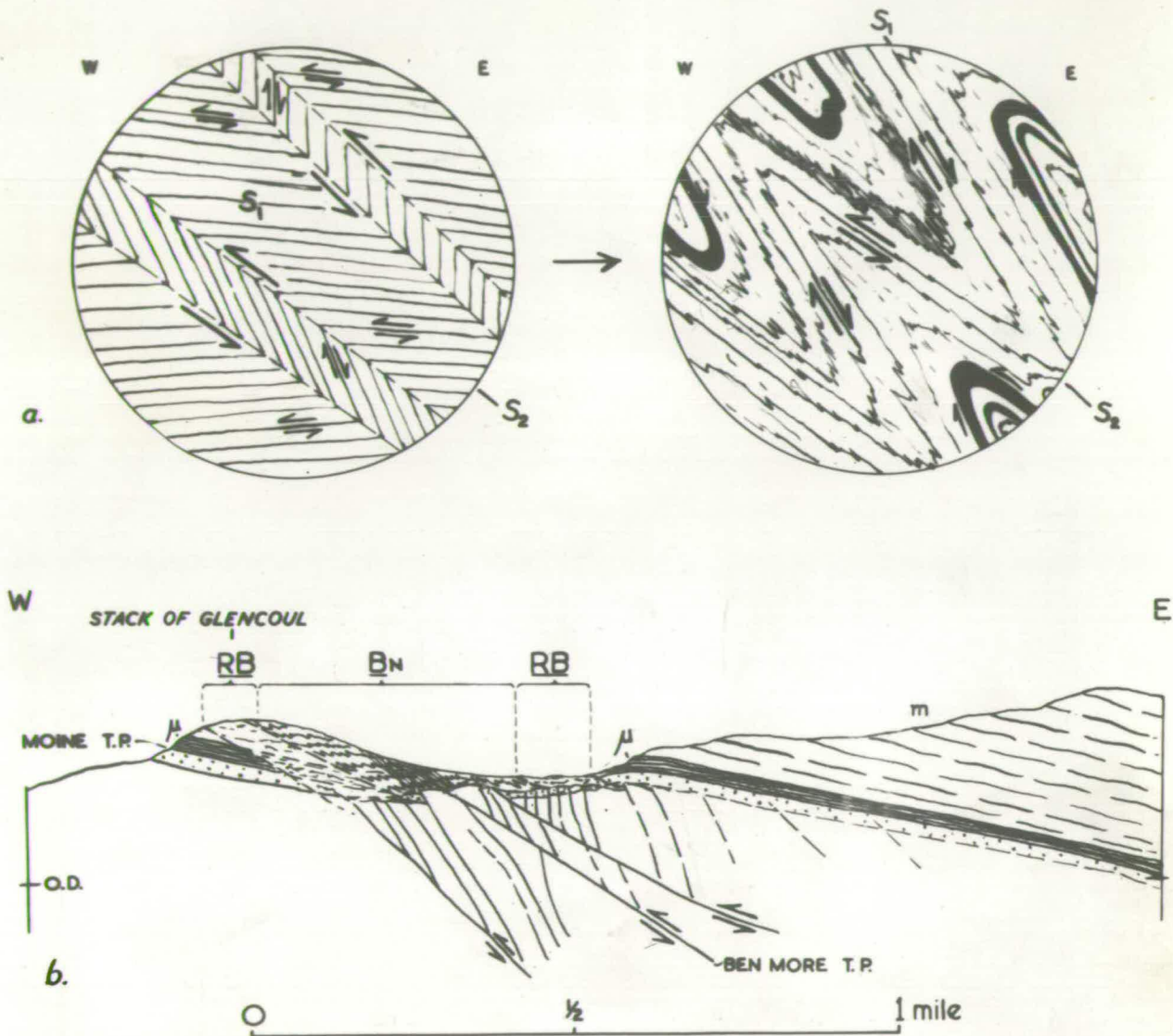


Figure 10.

a. Diagrams showing the development of B_n folds in the zone of secondary deformation in the Stack of Glencoul area. S_1 is the foliation in the primary mylonitic rocks; S_2 is the new s -plane produced during the secondary deformation.

b. Diagrammatic section across the Stack of Glencoul area, showing the relationship of the structural zones (RB and B_n) to the Ben More Thrust.

Combined with the slip-movement parallel to \underline{S}_2 there is slip on the foliation \underline{S}_1 . The parallelism of the axial planes of more complex folds with \underline{S}_2 suggests that they have originated in a similar fashion. The folds probably originated as kink-zones and evolved into the more complex forms by continued slip on \underline{S}_1 . The presence of the competent layers of quartzite and pegmatitic rocks (in black) has probably had some influence on the formation of the folds, as there appears to be complete transposition of \underline{S}_1 to \underline{S}_2 where no competent layers are present.

At certain localities the primary mylonitic rocks and Moine Schists near the Moine Thrust are traversed by parallel systems of planar quartz veins. The veins, which are generally between 1 and 5 mms. thick, are approximately normal to the foliation and to the lineation in the rocks, that is, they are almost vertical and the strike is slightly east of north. These veins are also present locally in the secondary mylonitic rocks, notably in the brecciated schists south of Loch an Eircill. In these rocks the veins are considerably sheared and dip at variable angles towards the east. The veins must have originated by the infilling of tension fissures at some period before the phase of secondary deformation. The writer considers that they were internally (see below pp. 145-50) rotated by /

by slip on the s-planes during the phase of secondary deformation. The sense of slip on the s-planes must have been such that the upper layers moved over the lower from east to west.

c. The Cnoc a' Chaoruinn Area

General description of the area. Figure 11 is a structural map of the area between Loch Ailsh and the Allt Ealag, in the south-east corner of the Assynt 'Bulge'. The ground is comparatively well exposed in the vicinity of the Moine Thrust, where the mylonitic rocks form the customary scarp-feature, but to the west of the thrust-zone and over the Moine Schists to the east there is a thick covering of peat and the rocks are poorly exposed.

The map (Fig. 11) differs in a number of important respects from those published by the Geological Survey. The Ben More Thrust is shown on the Survey maps crossing the peat-covered area south of Strathsheaskich and following the course of the Benmore Lodge road north of Cnoc a' Chaoruinn. The Thrust is supposed to extend westward from the area covered by Figure 11 and to carry the klippen of Lewisian, Torridonian and Cambrian rocks which rest on the limestones and marble south of Loch Urigill and Knockan village. The field observations made by /

by the present writer indicate that the Thrust follows another course in the area under consideration. Calcareous rocks with basic intrusions outcrop in a number of knolls projecting from the peat south-south-west of Strathsheaskich. In the most prominent of these knolls an important dislocation separates the coarsely crystalline dedolomitised marble (λ) along the margin of the Loch Borolan syenite mass from unmetamorphosed limestone and dolomite with fragments of basic sills to the east. This dislocation may be traced southwards towards the Lairg-Lochinver road, where it is associated with a complex zone of imbrication (Fig. 11; inset map). The line of outcrop of this dislocation crosses that of the Moine Thrust south of the road. The present writer interprets this dislocation as the southward extension of the Ben More Thrust from Sgonnan Beag, north of Strathsheaskich.

Another thrust carries the Cambrian quartzite which overlies the limestones at Strathsheaskich and the quartzite, Fucoïd Beds, Serpulite Grit and limestones on the north and west slopes of Cnoc a' Chaoruinn. It is the westerly continuation of this thrust which carries the klippen south of Loch Urigill and Knockan. Sabine (1953, pp. 151-2) proposed the term "Assynt thrust-plane" for this thrust, which he believed to /

ROYAL CHARLES

to be, in effect, an extension of the Glencoul Thrust. The present writer is in agreement with this interpretation and the term Assynt Thrust will be retained for this dislocation. The relationship of the thrusts will be discussed in more detail below.

The rocks above the Assynt Thrust are Cambrian quartzites, Fucoid Beds, Serpulite Grit and limestones, with numerous sills of felsite and hornblende porphyrite. The rocks show a considerable degree of cataclastic deformation and the intrusive rocks are generally foliated. The stratigraphic sequence from quartzite to limestone is recognisable only in the small area immediately to the west of the Ben More Thrust. East of the Ben More Thrust the succession consists of a repetition of Serpulite Grit, acid and basic sills and limestones; there are at least two Serpulite Grit horizons in the succession, indicating that it has been repeated by folding or thrusting. In the Oykell valley this repeated succession is gently folded about an axis trending slightly north of east, while on the north slope of Cnoc a' Chaoruinn the beds dip consistently towards the south. Here the succession, already repeated by folding or thrusting, is further disturbed by a number of reverse faults of slight throw. These faults dip steeply towards the east. The faults become more numerous towards /

towards the Ben More Thrust and it is evident that they belong to a zone of imbrication associated with the Thrust.

On both sides of the Oykell valley a slice of foliated and lineated quartzite, similar to those in the Stack of Glencoul area, outcrops below the Moine Thrust.

The primary mylonitic rocks occupy a zone between 100 and 150 feet thick above the Moine Thrust. They show a high degree of neo-mineralisation and grade upwards into low-grade granulitic Moine Schists. A lenticle of quartzite, represented on the Survey maps as quartz-schist, outcrops in the zone of primary mylonitic rocks in the Allt nan Sleagh. The quartzite is similar to the Cambrian quartzites below the Moine Thrust and contains similar structures. Since there are no pure quartzites in the Lewisian, Torridonian or Moine, the lenticle probably represents a fragment of Cambrian quartzite which has been isolated at some stage in the thrust-movements and included in the colour-layered mylonitic rocks.

There is widespread secondary deformation of the primary mylonitic rocks and Moine Schists. The degree of deformation is slight in the schists along the southern and eastern margins of the area covered by the map; locally there has been slight movement of joints but there is no brecciation. The /

The effects of secondary deformation increase towards the Moine Thrust. The incompetent layers near the Thrust have been converted to phyllonite and at some localities (e.g. in the Allt na Cailliche) there has been movement of joints and slight brecciation in more competent primary mylonitic rocks. Secondary deformation is most intense in two zones (Fig. 11), one on the west slope of Cnoc a' Chaoruinn and the other in the River Oykeall. In these zones the primary mylonitic rocks are phyllonitized and the Moine Schists are severely brecciated. The larger of the two zones outcrops above the fault-system associated with the Ben More Thrust, as in the northern area at the Stack of Glencoul. The smaller zone, in the River Oykeall, cuts across the Moine Thrust and the boundary between the primary mylonitic rocks and Moine Schists. At the southern end of the smaller zone the schists are penetrated by discordant veins and stringers of granitic material, which are also sheared and brecciated.

Structural Data. The foliation in the primary mylonitic rocks and Moine Schists throughout the area dips consistently towards the south-east (Fig. 12a). In the secondary mylonitic rocks the strike of the foliation is generally north-north-west and the dip, though variable, is generally towards the east-north- /

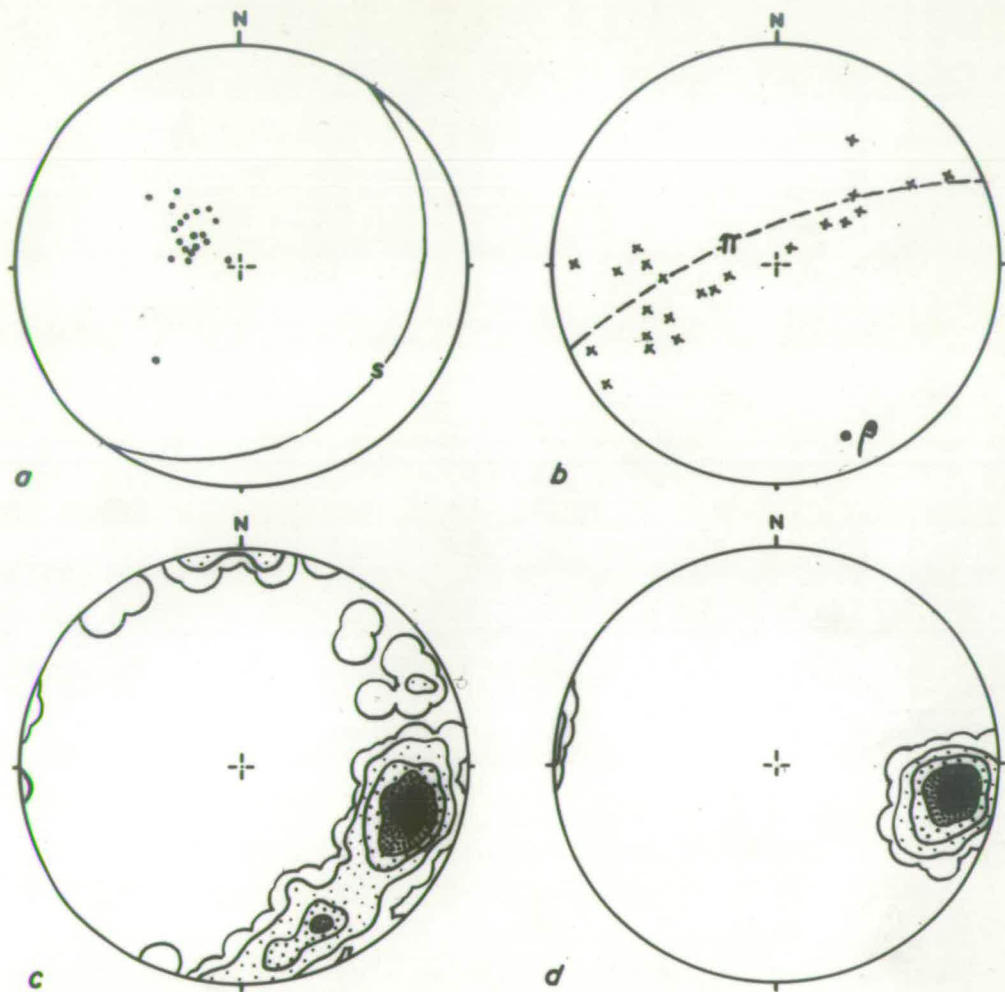


Figure 12. Structural data from the Cnoc a' Chaoruinn area.

a. Orientation of the foliation in the primary mylonitic rocks and Moine Schists in the area. Dots represent poles of foliation planes. S represents the mean orientation of the foliation in the area.

b. Poles of foliation planes in the phyllonites on Cnoc a' Chaoruinn, showing π -circle and β -axis.

c. Axes of 143 small-scale folds. Contours: 2, 3, 2, 6, 10, 14% per 1% area.

d. 80 penetrative lineations. Contours: 1, 4, 5, 10, 20, 30% per 1% area.

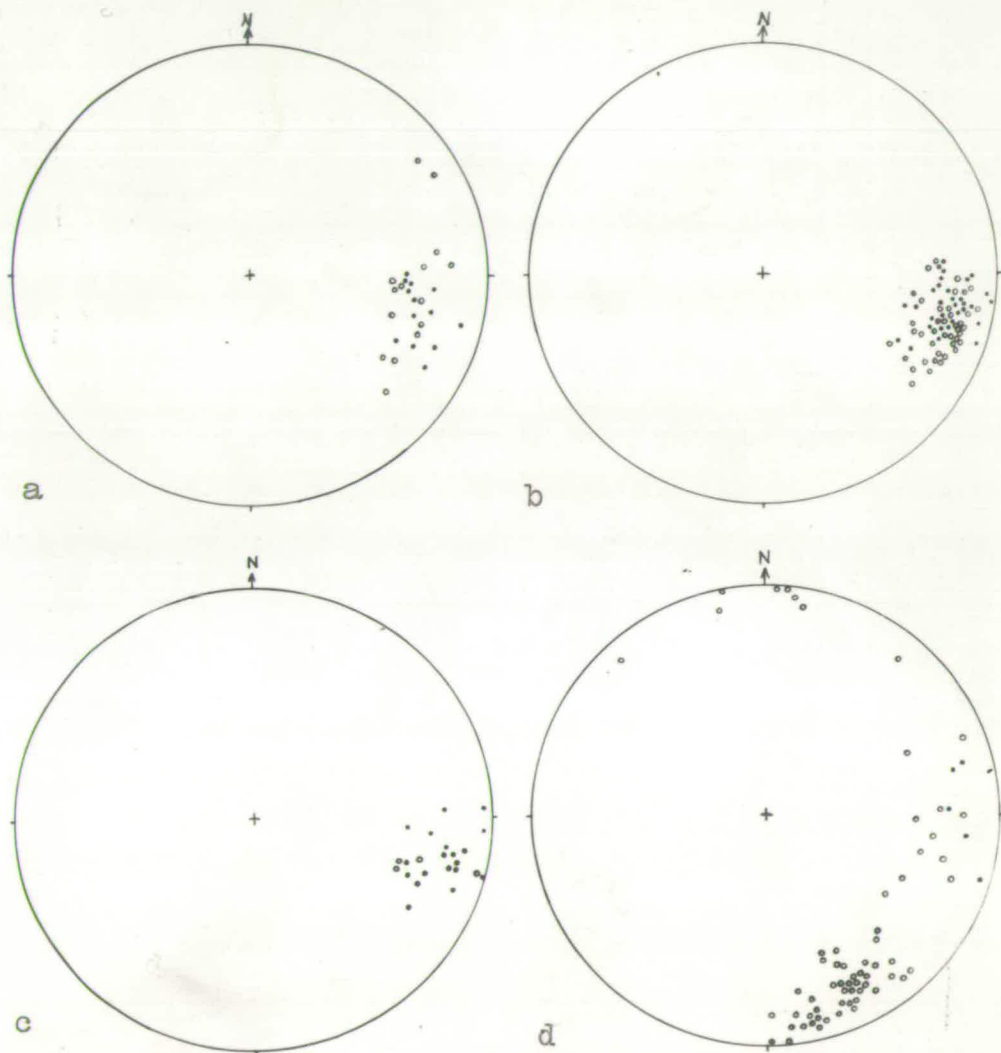


Figure 13. Partial diagrams constructed from the data in figure 12c and d, showing fold-axes (circles) and lineations (dots) in a, the Cambrian quartzites below the Moine Thrust, b, the primary mylonitic rocks, c, the granulitic Moine Schists and d, the secondary mylonitic rocks.

north-east at approximately 45° . The fold-axis (β , Fig. 12b) plunges at 15° to the south-south-east. Small-scale folds are common in the quartzites below the Moine Thrust and in the primary and secondary mylonitic rocks. The Moine Schists, on the other hand, are unfolded except at a few widely-scattered localities. Figure 12c shows the orientation of small-scale folds measured throughout the area. The majority of the folds plunge to the east-south-east (\underline{E}), but there is a sub-maximum in the diagram, representing folds which plunge towards the south-south-east (\underline{E}_S). A persistent lineation, plunging to the east-south-east, is common to the quartzites below the Moine Thrust, the primary mylonitic rocks and the Moine Schists (Fig. 12d). The partial diagrams in Figure 13 show the orientation of folds and lineations in the quartzites, the primary mylonitic rocks, the Moine Schists and the secondary mylonitic rocks. The folds and lineations in the quartzites, primary mylonitic rocks and schists plunge, with few exceptions, to the east-south-east, while the \underline{E}_S folds are confined to the phyllonites in the two zones shown on the map. These zones are analogous to the \underline{E}_N zones in the Glencoul area and will be referred to as the \underline{E}_S and \underline{E}'_S (smaller) zones.

In certain layers in the \underline{E}_S zone deformation is slight and /

and the rocks in these layers retain the B-folds and lineations (Fig. 13d). Where phyllonitization is more intense the lineation is obliterated, but in quartzose layers it may be preserved and the relict lineation is locally seen folded about south-south-east (B_s) axes. As in ~~the phyllonites of~~ the northern area the only new lineation in the phyllonites is a faint, inconstant streaking, approximately normal to the fold-axes.

Figure 14 shows in profile a number of typical folds in the mylonitized quartzites below the Moine Thrust, the primary mylonitic rocks and the Moine Schists. In the quartzite below the Thrust east of the Oykell and in the lenticle of quartzite in the zone of primary mylonitic rocks small folds with closely appressed limbs, like that in figure 14b, are common. Intrafolial folds (Fig. 14d, e) are frequent in the primary mylonitic rocks, though the style of the folds is variable. At some localities in this zone closely-spaced kink-zones (Fig. 14c) and slip-surfaces ("strain-slip cleavage") steeply inclined to the foliation, cut slightly phyllonitized rocks. Kink-zones and slip-surfaces were recorded dipping to the east and to the south.

The only two folds observed in the Moine Schists are shown in Figure 14e and f. They are medium-scale, open folds, overturned towards the south-south-west.

The /

NNE

SSW

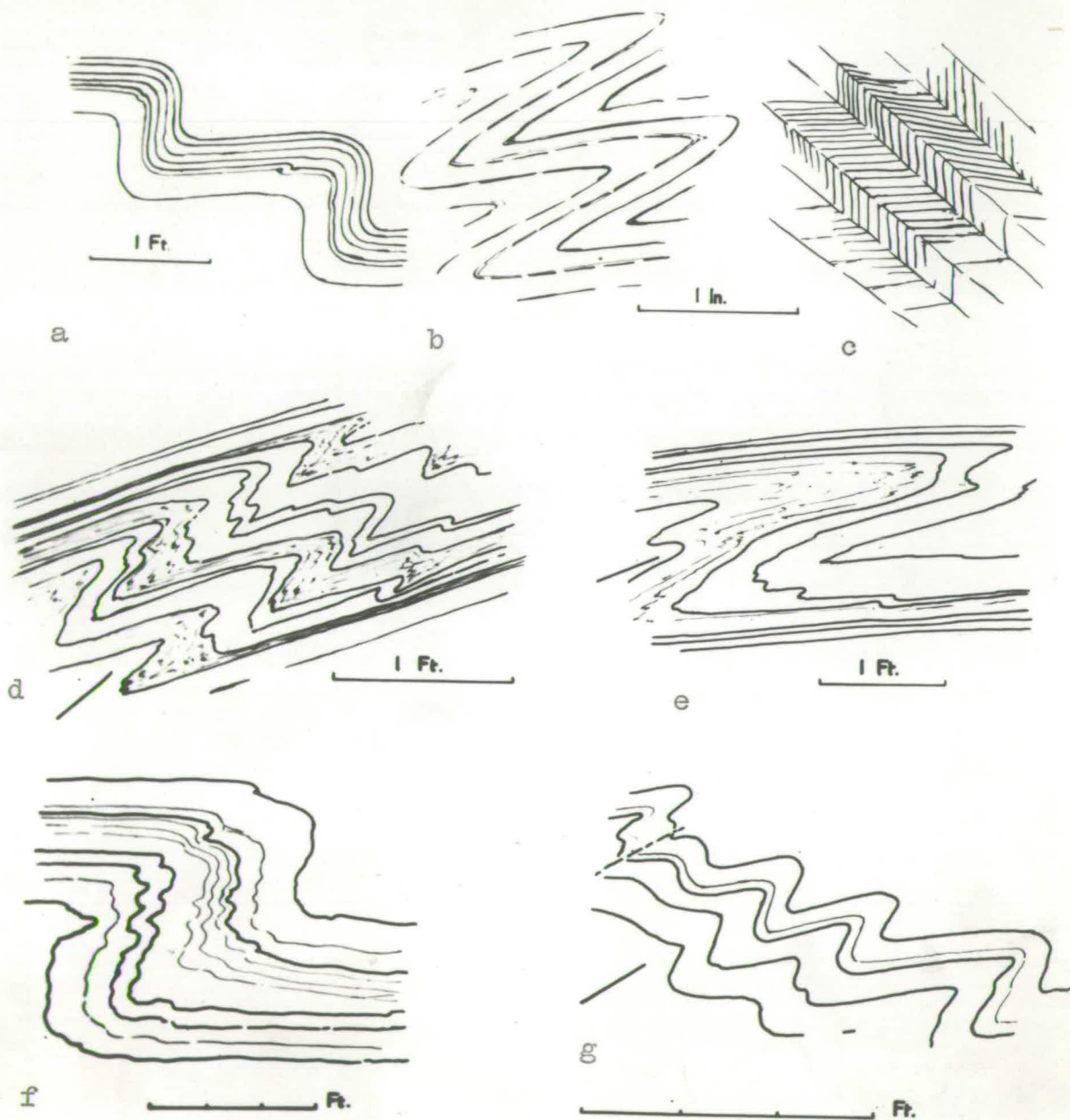


Figure 14. The style of folding in the Cnoc a' Chaoruinn area
 a, b. Profiles of folds in Cambrian quartzite below the Moine Thrust, River Oykeil.
 c, d, e. Profiles of folds in the primary mylonitic rocks, Cnoc a' Chaoruinn.
 f, g. Profiles of folds in the Moine Schists, River Oykeil approximately two miles below Loch Ailsh.

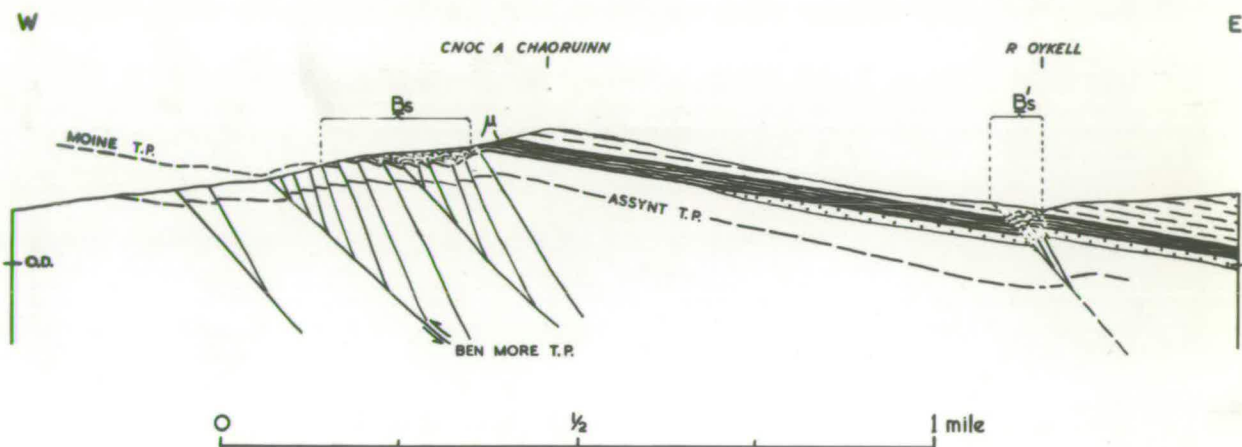


Figure 15. Diagrammatic section across the Cnoc a' Chaoruinn area, showing the relationship between the structural zones (B_s and B'_s) and the major thrusts and faults in the area.

The style of the folding in the quartzites, primary mylonitic rocks and schists is so similar that they must reflect similar conditions of deformation. From the parallelism of the fold-axes and the similarity in style, the writer infers that the folds in all these rocks date from the same phase of deformation. Of the folds in which it is possible to determine the direction of overturning, either from the form of the complete fold or the orientation of the axial plane, approximately 80% are overturned towards the south-south-west and the remainder towards the north-north-east.

The folds in the zones of phyllonite (\underline{B}_s and \underline{B}'_s) are closed and angular, similar to those in the \underline{B}_n zone, with axial planes dipping consistently towards the east. The structures in Plate IV show the characteristic style of folding. The diagrammatic section in figure 15 illustrates the relationship between the zones of \underline{B}_s folds and the major thrusts and faults in the area. The \underline{B}_s zone is situated above the zone of imbrication associated with the Ben More Thrust. The axial planes of the folds are sub-parallel to the underlying dislocations, suggesting that the folding is probably related to movements on the Ben More Thrust and the reverse faults in the same way as the \underline{B}_n folds in the Stack of Glencoul area. It is probable /

probable that the smaller zone of phyllonite (B'_s), which also contains B_s folds, overlies another thrust or reverse fault which is not exposed east of the Moine Thrust.

The Moine Thrust is displaced by the Ben More Thrust west of Cnoc a' Chaoruinn: the Moine Thrust is at a considerably higher level on the hill to the east of the Ben More Thrust than to the west. It is not possible to estimate the displacement accurately, because the Moine Thrust is so poorly exposed, but the amount is less than 500 feet.

d. The Loch Ailsh Area

General Description of the Area. The structural relationship of the rocks in the Loch Ailsh area is shown in the map (Fig. 16). The outcrop of the Moine Thrust extends from the north-east extremity of the Loch with a north-easterly trend. The Thrust gives rise to a marked topographic feature, the resistant mylonitic rocks and schists to the east forming a steep scarp approaching 200 feet in height, and the more soluble calcareous rocks to the west giving low-lying ground. The Thrust is poorly exposed, as the hollow at the base of the scarp is largely peat-filled, but the unexposed belt is sufficiently narrow /

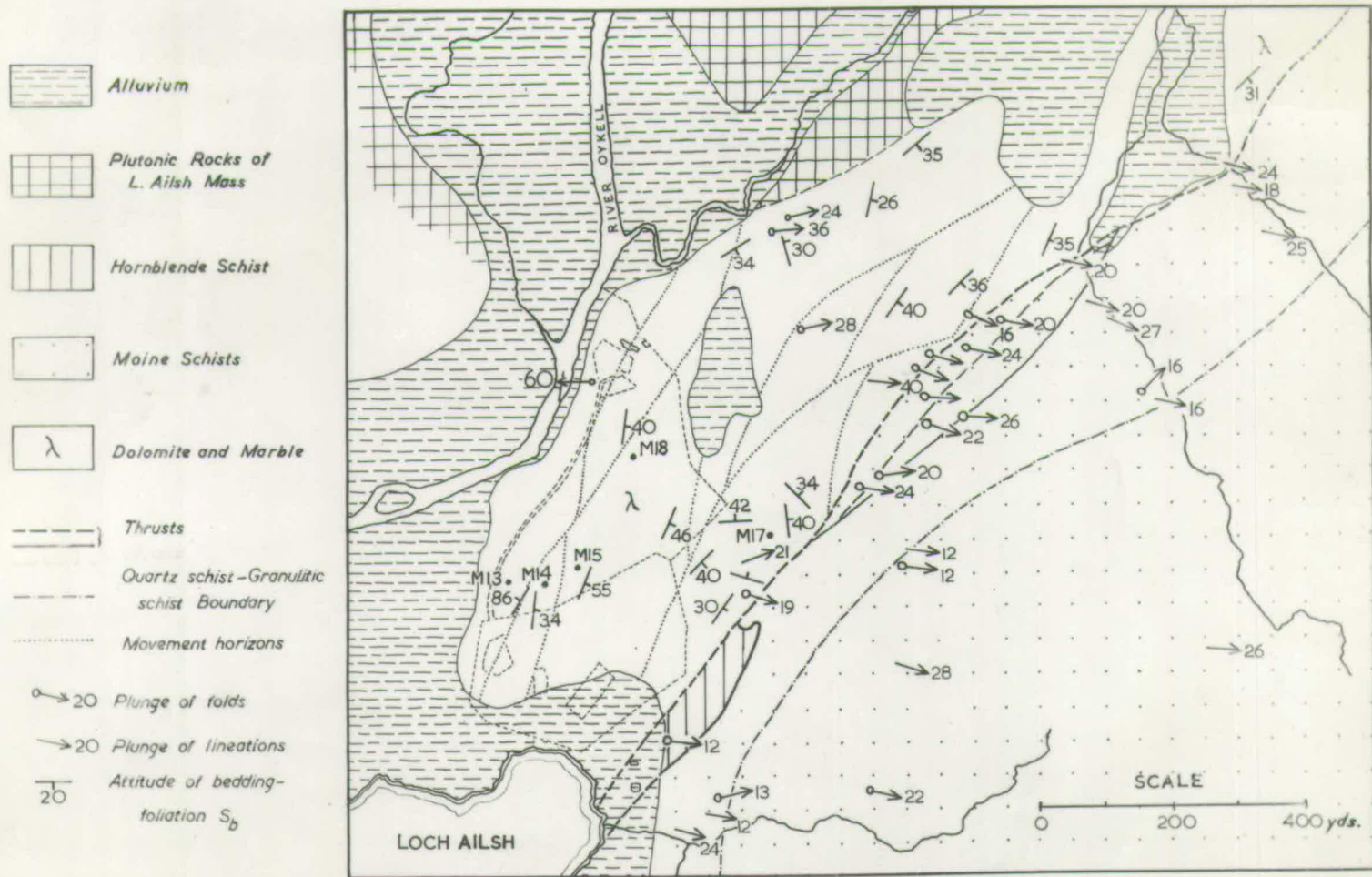


Figure 16. Structural Map of the Loch Ailsh area.

narrow for the position of the thrust to be determined within a few feet along most of the outcrop. Exposures are frequent in the calcareous rocks and the mylonitic rocks but much of the Moine Schist in the area is covered with peat and few exposures are available.

The calcareous rock is, for the most part, yellowish crystalline dolomite. Near the centre of the outcrop are lenticles, a few feet in thickness, of dark, micaceous marble. The low-lying ground, in which the dolomite is exposed, is traversed by a number of ridges which are sub-parallel to the outcrop of the Moine Thrust. These features appear to reflect the structure of the underlying rocks and it is probable that the ridges represent large lenticles of dolomite separated by movement horizons in the intervening hollows.

Above the Moine Thrust there is a zone of primary mylonitic rocks, chiefly quartz-schists and blastomylonites, approximately 200 feet thick. The mylonitic rocks are dominantly quartzo-feldspathic, but slices and lenticles of more pelitic composition are locally present. Near Loch Ailsh, a large body of hornblende-schist outcrops immediately above the Thrust. Further to the north-east, a thick lenticle, shown on the map (Fig. 16), is represented on the Geological Survey maps /

maps as foliated acid and basic igneous rocks with Cambrian sediments. These rocks are texturally and structurally similar to other rocks in the zone of primary mylonitic rocks and are considered here as a part of this zone. There is a gradual transition from the primary mylonitic rocks into the more typical granulitic Moine Schists. The transition is marked by an increase in the grain size and a decrease in the fissility of the rocks; the granulitic schists are more slabby and lack the colour-layering which is a conspicuous feature of the mylonitic rocks.

There is no evidence of appreciable secondary deformation in the primary mylonitic rocks or the schists. Locally the granulitic schists have suffered slight crushing but over most of the area the rocks are devoid of cataclastic structures.

Structural Data. Two types of planar structure are recognisable in the dolomite: one is sedimentary bedding and the other is a schistosity induced by deformation. The two types of s-surface are easily distinguished and do not occur together. The bedding-foliation (S_b) is marked by thin, fine-grained or cherty layers which are more resistant to solution than the more coarsely granular dolomite and stand out on weathered surfaces. /

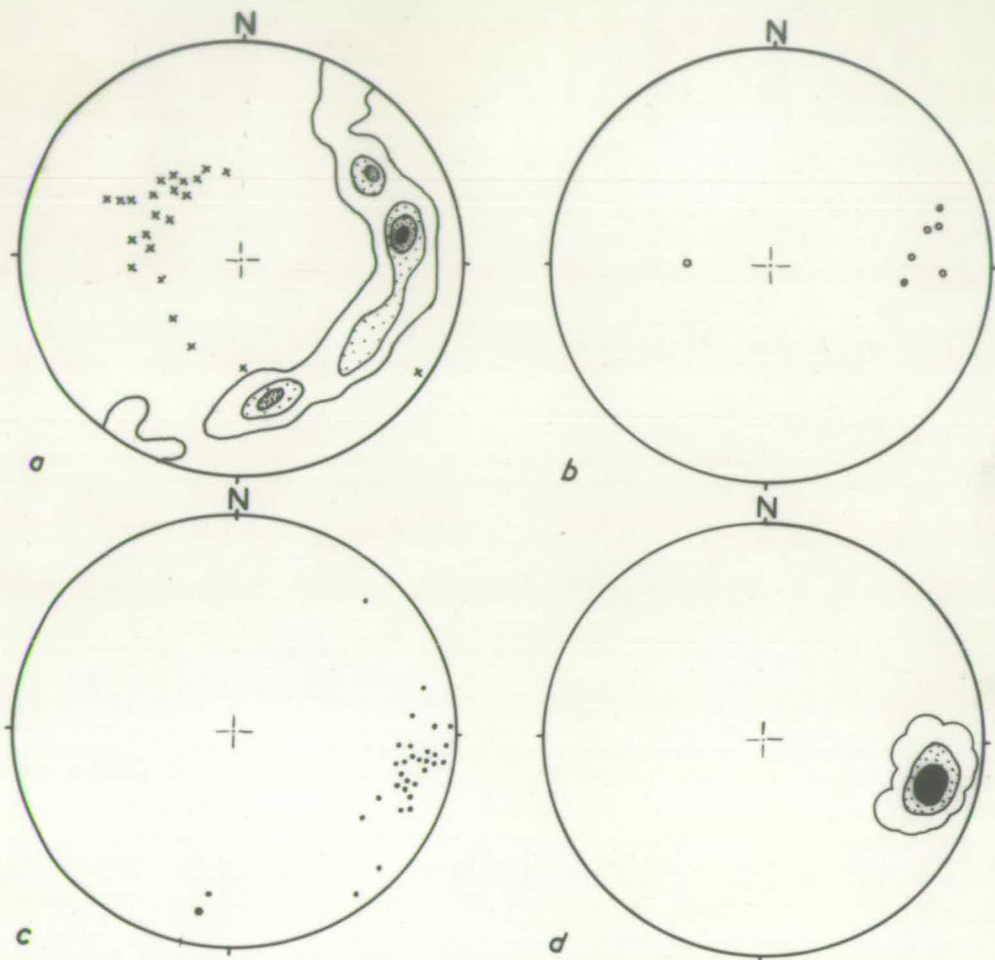


Figure 17. Structural data from the Loch Ailsh area.

- a. Orientation of S_b in the dolomite. Crosses represent poles of foliation-surfaces. Contours of P -intersections: 2, 5, 8, 10% per 1% area.
- b. Fold-axes (circles) and penetrative lineations (dots) in the dolomite.
- c. Fold-axes (32) in the primary mylonitic rocks.
- d. Penetrative lineations (40) in the primary mylonitic rocks and granulitic Moine Schists. Contours: 2½, 20, 40% per 1% area.

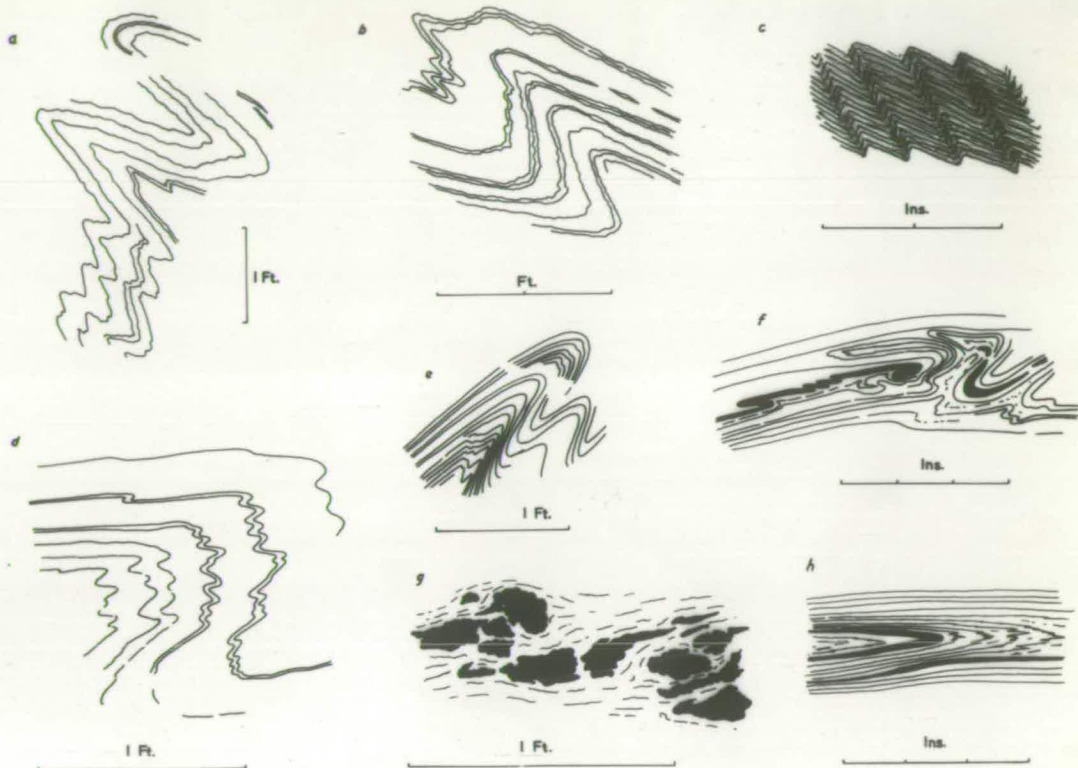


Figure 18. The style of folding in the Loch Ailsh area.

a, b. Profiles of folds in the dolomite, viewed in profile towards the east.

c, d, e, f. Profiles of folds in the primary mylonitic rocks. Folds plunge to east-south-east. Viewed down plunge.

g. Profile of quartz-rodding in the Moine Schists, viewed down plunge.

h. Profile of south-plunging fold in the primary mylonitic rocks, viewed down plunge.

surfaces. These layers may be closely spaced, several occurring in a thickness of one inch, but commonly the rock is massive, with no trace of this foliation. Figures 17a show the attitude of S_b measured at 24 localities. The dip of the beds, though generally at low angles to the east and south-east, is locally variable. The β -maximum indicates that S_b is folded about an eastward-plunging axis, but the β -intersections show a marked tendency to spread along a great circle, containing strong sub-maxima. This spread reflects the lack of diversity in the orientation of the foliation. In the western part of the area the dip becomes steeper until in the River Oykell at the old footbridge and to the south of this the bedding dips steeply towards the west. Visible folding of S_b is not common, but at three localities medium-scale folds were recorded. The orientation of the folds and the only penetrative lineations observed in the area is shown in Figure 17b. Most of the folds and lineations plunge to the east, parallel to the β -axis, but at the locality in the River Oykell mentioned above, there are folds which plunge steeply to the west. The folds are all closed and overturned to the north (Fig. 18a and b). The westward-plunging folds are of similar style to those at the other localities and there can be /

be little doubt that they originated during the same phase of deformation.

Close to the Moine Thrust S_b is obliterated and the second type of foliation is developed. The orientation of this foliation is very uniform, dipping at 20-30° towards the east-south-east, parallel to the Moine Thrust. It is a very fine lamination defined by layers and lenticles of quartz and by slip-surfaces coated with chlorite. Within a few feet of the Thrust it is plicated on a very small scale.

The foliation in the primary mylonitic rocks and the granulitic schists is remarkably uniform, dipping at low angles to the east-south-east. Folding of the foliation is very common throughout the zone of primary mylonitic rocks but decreases upwards and is absent in the slabby schists. The axes of a representative number of folds are shown in Figure 17c. The majority of the folds plunge towards the east and east-south-east (B), but there is a spread of the axes round the great circle corresponding to the foliation, and a few folds are inclined almost at right angles to the maximum. At one horizon in the granulitic schist, exposed in the burn which flows into Loch Ailsh, quartz-rodding (Fig. 18g) is developed. The long axes /

axes of the quartz rods plunge slightly south of east, parallel to the axes of folds in the primary mylonitic rocks. There is a single faint lineation on the g-surfaces in the primary mylonitic rocks and the Moine Schists. The lineations show a very high degree of preferred orientation (Fig. 17d) and define a single strong maximum plunging slightly south of east, parallel to the maximum of fold-axes (B).

The style of the folding in the primary mylonitic rocks is illustrated by the profiles in Figure 18 (c-f, h). The commonest type is a simple recumbent fold (d, e, h) with or without minor drag folds on the limbs, but more complex types (f) occur. On a few folded outcrops the orientation of the axial planes of folds varies from place to place over the outcrop. This type of folding is not unlike that illustrated by Greenly from Anglesey (1919, pp. 190-1) and referred to by him as polyclinal. Many of the smallest-scale folds are intra-folial and appear to have suffered a considerable degree of flattening normal to the foliation (Fig. 18f, h). On a few exposures small-scale kink-zones are visible (Fig. 18c), the planes of the kink-zones dipping steeply to the south. Although there is considerable diversity in the style of the folds, the general impression obtained is one of extreme mobility /

mobility during the deformation of the rocks; this is the style of deformation which has been loosely described as 'plastic'. A few folds, such as the kink-zones illustrated, indicate less mobile conditions. Of the folds examined, approximately 70% were overturned towards the south, 20% towards the north and the remainder were polyclinal.

The parallelism of the \underline{E} -axes in the dolomite and the mylonitic rocks and schists above the Moine Thrust suggests that they were produced during the same period of deformation. Whereas the majority of the folds in the primary mylonitic rocks are overturned to the south, the folds in the dolomite are consistently overturned towards the north, as are a few of the folds in the mylonitic rocks. While it is conceivable that the folds overturned to both north and south were produced during the same act of deformation, it is more probable, in the writer's opinion, that in the deformation which produced the \underline{E} -structures there were separate phases of movement, during which the sense of movement was different. This problem will be discussed more fully below. The dolomite body is heterogeneous with respect to the orientation of \underline{S}_b . In the vicinity of the Thrust \underline{S}_b is gently folded about an eastward-plunging axis (β), but to the west, near the Oykeell, it becomes steep, with /

with northerly strike. The folds which plunge towards the west at the old footbridge are probably of the same age as the other folds in the dolomite, as noted above. The orientation of the bedding-foliation and folds in the western part of the dolomite could be explained by postulating warping of the rocks about a north-trending horizontal axis after the folding about B, but in the absence of more folds with a greater diversity of orientation this can only be regarded as a possible hypothesis.

e. The Knockan Crag Area

General Description of the Area. In the southern part of Assynt the Moine Thrust overlaps the thrust slices in the zone of dislocation and at Knockan Crag the Thrust carries the mylonitized rocks and schists directly on to the limestones in the undisturbed Cambrian succession of the foreland. At the north end of the crag a thin slice of heavily-deformed white limestone, carried on the Sole, rests on the dark limestones of the foreland succession, and this is overlain by the mylonitic rocks above the Thrust. Near the southern end of the crag, this slice is pinched out and the Moinian rocks rest directly on the limestones of the foreland.

The Moine Thrust, which is well exposed for some distance along the crag and to the east, towards Druim Poll Eoghainn, is a sharply defined surface separating the calcareous rocks from the intensely mylonitized siliceous rocks above. Immediately above the Thrust is a layer, two or three feet thick of cataclasite and kakirite, containing fragments of primary mylonitic rock. The degree of cataclastic deformation decreases rapidly upwards until a few feet above the Thrust the laminated primary mylonitic rocks show only a slight degree of brecciation. The primary mylonitic rocks show the normal transition into slabby granulitic schists to the east. The transition is so gradual that it would be impossible to place a boundary between the two rock-types. Except in the narrow zone immediately above the Moine Thrust, there is little secondary deformation of the primary mylonitic rocks and schists in the vicinity of Knockan Crag; there is slight brecciation associated with some of the folding in the mylonitic rocks but the schists are undeformed for some distance to the east of the crag. Approximately 400 yards west of Loch Odhar, however, there is a zone of intense secondary deformation in which the schists are brecciated and locally slightly folded.

Structural /

Structural Data. The foliation in the primary mylonitic rocks east of Knockan Crag has an easterly strike and dips at angles up to 10° towards the south. The strike swings at the crag and becomes north-north-east and the dip is at low angles towards the east-south-east. Folding of the rocks, though not so common as in the other areas described, is by no means uncommon. Some of the folds are symmetrical (Fig. 19a, d, e) and others (Fig. 19b, c) are asymmetrical but not overturned. The folding is frequently associated with shear-surfaces and some degree of brecciation (Plate Va), that is, the style of folding is less 'plastic' than in the other areas described. The shear-surfaces dip to both north and south at variable angles. The sense of shear on the shear-surfaces in a number of characteristic folds is shown in figure 19 (a, b, c). The intensity of the folding decreases upwards towards the summit of Cnoc an t'Sasunnaich and the highest folds are small symmetrical corrugations in the s-planes (Fig. 19e). Whereas the folds elsewhere along the Moine Thrust in Assynt are generally recumbent and consistently overturned in the same direction, at Knockan many of the folds are symmetrical (Fig. 19a, d, e) and the axial planes of asymmetric folds are not consistently overturned in one direction. The overall movement-picture suggested by the folds is one of slight shortening parallel to the foliation and normal to the fold-axis (B).

The /

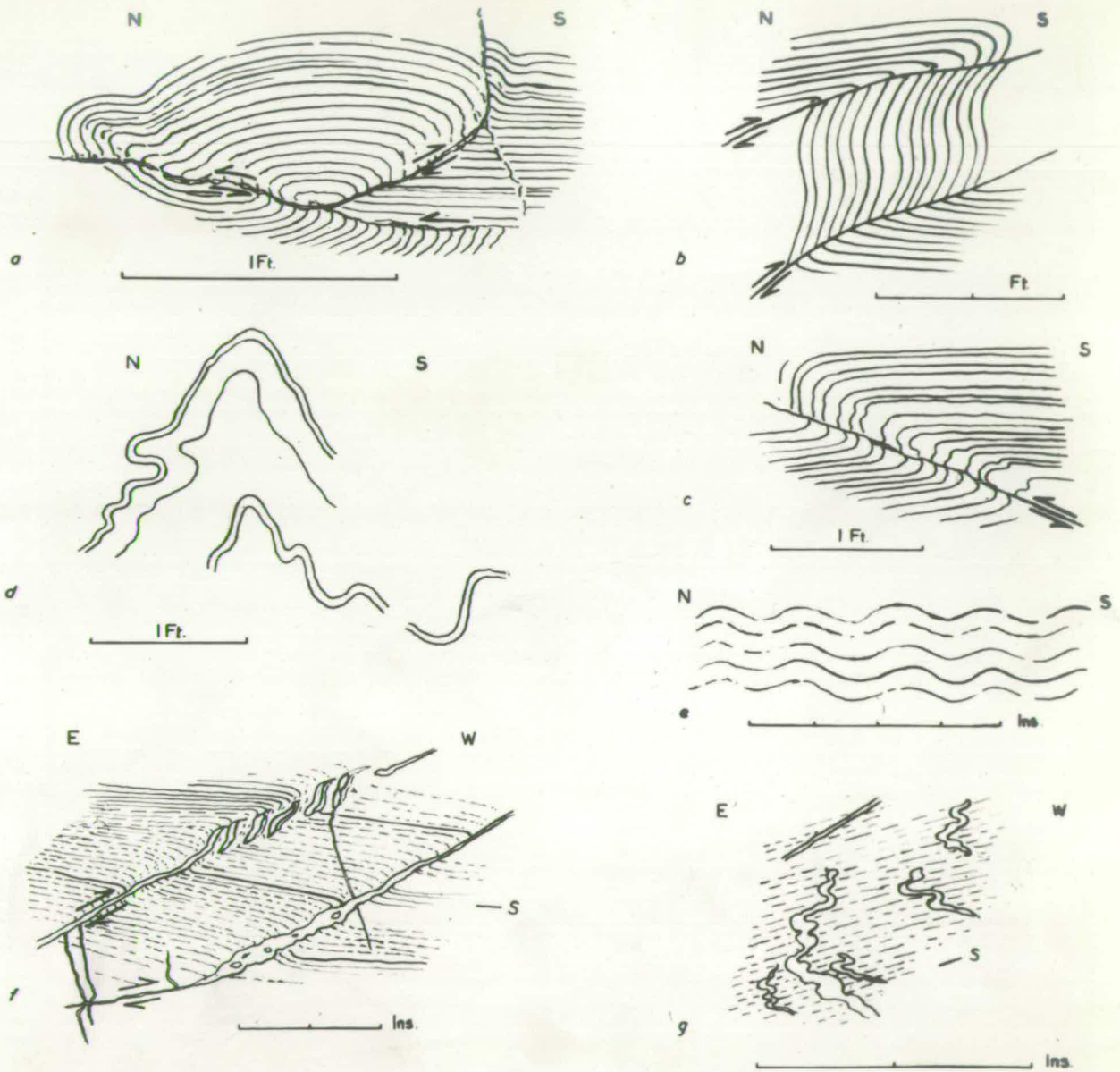


Figure 19. The style of folding in the Knockan Crag area.

a, b, c, d, e. Profiles of folds in the primary mylonitic rocks at Knockan Crag.

f. Rodded quartz vein in deformed Moine Schist south-east of Knockan Crag. Note bending of the foliation (S).

g. Folded quartz veins in deformed Moine Schist near Loch Odhar. S - foliation.

Arrows indicate the sense of movement on the shear-surfaces.

The Moine Schists between Knockan Crag and Meall nan Dearcag Mor are massive slabby rocks with a well-developed system of joints (Plate Vb). The grade of metamorphism is extremely low and the rocks appear to have suffered little deformation during regional metamorphism. The foliation is a bedding-foliation, and at several localities current-bedding is preserved. At the only locality examined where this was sufficiently well preserved to determine the direction of younging, the beds young upwards. There is no folding of the foliation but a faint lineation (B), plunging to the east or east-south-east, is visible locally.

Secondary deformation of the schists is not widespread and does not decrease uniformly away from the Moine Thrust. The schists immediately to the east of the primary mylonitic rocks are unbrecciated, but the degree of cataclastic deformation increases further east until, approximately 400 yards west of Loch Odhar, it is intense: the foliation is distorted and there is considerable brecciation of the rocks in this area. The rocks are traversed by complex systems of quartz veins, with strike varying between north and north-north-east. The thickest veins intersect the bedding at low angles and dip towards the east at angles between 20° and 40° (Plate Vc; Fig. 19f). These veins show marked evidence of shearing and the bedding /

bedding is bent along some of the veins, showing a sense of movement such that the upper layers moved to the west over the lower. On the exposure illustrated in figure 19f one of the veins has been rodded by the shearing movement; the trend of the rods is slightly east of north. Branching outwards at right angles from the thick veins are thinner veinlets, which are relatively undeformed (Plate 19c). The origin of the veins is problematical but it is clear that they define a E-axis with northerly trend and their present disposition appears to be due to slip movement in which the upper layers moved towards the west. In the above cases the main movement has been along the veins, but elsewhere (Fig. 19g) the foliation appears to have been the most important slip-plane as the veins are themselves folded on a small scale about north-trending axes. The veins have been folded by internal rotation due to slip on S, a process analogous to that postulated to account for the eastward-dipping quartz-veins near the Stack of Glencoul.

f. Summary

A number of important facts emerge from the study of the Moine Thrust-zone in the above areas:

1. There is a common B-axis, defined by the megascopic elements of the fabric, in the Moine Schists, the primary mylonitic rocks along the Moine Thrust and some of the Cambrian rocks below the Thrust. The rocks all belong to a single structural unit which must obviously have suffered penetrative deformation in post-Cambrian times.

2. The Moine Thrust varies considerably in character along its outcrop in Assynt, but at all the localities studied, with the exception of Knockan Crag, the movements have been distributed through a zone of considerable thickness. The Moine Thrust is merely a lithological boundary within this zone, separating rocks which are recognisable as Cambrian or Torridonian from mylonitic rocks of unknown origin.

3. After the deformation which produced the B-axis, the rocks locally suffered a secondary deformation which was not generally related to movements on the Moine Thrust; the deformation was most intense in zones which cut across the Moine Thrust, the primary mylonitic rocks and the Moine Schists. Late movement on or near the Thrust is indicated by intense cataclastic /

cataclastic deformation immediately above the Thrust at Knockan and by phyllonitization of pelitic layers near the Thrust at other localities (e.g. Allt nan Sleagh).

4. During the phase of secondary deformation the Moine Thrust was displaced to the extent of approximately 500 feet by the Ben More Thrust at the Stack of Glencoul and at Cnoc a' Chaoruinn. The imbricate structure in these two areas is related to the Ben More Thrust and not the Moine Thrust.

5. The so-called "double system of folding" in the 'Eastern Schists', described by Horne (1907, p. 468) does not exist in the Assynt area. The E_n and E_s folds form two distinct maxima, neither of which trends "N.NE and S.S.W." They were produced, moreover, during the secondary phase of deformation and not synchronously with the E structures.

6. The widespread lineation, plunging to the east-south-east, in the competent rocks near the Moine Thrust, is not an a -lineation, as has previously been assumed, but a E -lineation. A faint a -lineation (slickensides) is also present, however, in some of the phyllonitized rocks near the Thrust; this also plunges at low angles to the east and east-south-east.

g. Discussion of the Movements

The first fact cited above is of paramount importance as it clarifies the controversial issue of the age of the general Moine metamorphism and deformation. The deformation which produced the E-structures in the Moine Schists, the primary mylonitic rocks and the Cambrian rocks must obviously be of post-Cambrian age. The widespread folding about east-south-east and south-east plunging axes in the Moine Schists was contemporaneous with the regional metamorphism of the rocks (see e.g. Phillips, 1937). It is clear, then, that the hypothesis favouring a pre-Torridonian age for the general Moine Metamorphism (Read, 1934; Phillips, 1937; Wilson, 1953) is untenable; the Moine metamorphism and deformation took place in post-Cambrian times, as claimed by Bailey (1950), Kennedy (1951) and A.G. MacGregor (1951).

The east-south-east-plunging lineations in the vicinity of the Moine Thrust are universally assumed to be a-lineations, marking the direction of movement on the Thrust, and they have frequently been referred to as 'slickensides' (e.g. Read, 1931; Bailey, 1935). They are thoroughly penetrative, however, and cannot be confused with the true slickensides which are present in some of the phyllonitized rocks. Throughout the Assynt area the penetrative lineations are statistically parallel /

parallel to the fold-axes (B) and are therefore B-lineations according to the standard terminology (Figs. 6, 12, 17).

These lineations constitute one of the most important pieces of evidence for the direction of movement on the Thrust (Bailey, 1935, pp. 158-9). In view of the failure of this evidence, the currently accepted theory, involving transport of the Moine Schists to the west-north-west, must be reconsidered.

Although the Moine Schists were undergoing deformation and metamorphism during the main movement on the Moine Thrust, the degree of deformation of the schists for over a mile east of the Thrust is very low; the foliation is recognisably bedding over much of the area and the slabby nature and lack of folding of the schists indicate that there has been little differential movement. In the primary mylonitic rocks, on the other hand, the fine grain, closely spaced g-surfaces, colour-layering and folding all suggest intense differential movement of the type known as planar slip. The zone of primary mylonitic rocks (including some of the mylonitized quartzites) represents a zone of distributed movement between two relatively stable blocks. The term "thrust", which is a contraction of "thrust fault" (Reid et al., 1913, p. 179), implies a surface of rupture, along which movement is discontinuous and confined to a relatively thin zone. The horizon known as the Moine Thrust /

Thrust does not show the characteristic features of a fault, except at isolated localities such as Knockan Crag. The movement has been distributed continuously throughout a zone between 200 and 300 feet in thickness. Instead of the cataclastic textures developed along a fault, the primary mylonitic rocks show a considerable degree of neo-mineralization and even some of the Cambrian quartzites are recrystallized. The 'Thrust' is a lithological boundary in a movement-zone of the type which has been called a "movement horizon" by Knopf (1938, pp. 34-5). This author has discussed the principles governing movement in such zones (Ibid., pp. 33-5). She states that if movement is sufficiently penetrative, that is, if the component particles participating in the deformation are sufficiently small, the differential movement between individual particles may be slow enough to be accomplished by recrystallization, and "crystalloblastesis may predominate over cataclasis even in zones of intensive differential movement".

The 'direction of movement' in folded rocks is at present a subject of considerable controversy, but it is an indisputable fact that all the evidence preserved in the megascopic fabric of the primary mylonitic rocks indicates differential movement normal to the fold-axis (B). The majority of the folds are cylindroidal and therefore have monoclinic symmetry; /

symmetry; some are non-cylindroidal and axes of neighbouring folds on the same exposure may be mutually inclined at angles up to 35° , giving rise to triclinic symmetry on the scale of the exposure. The majority of the folds are recumbent and it is estimated that at least 70% are overturned to the south-south-west. If the megascopic fabric of the primary mylonitic rocks is considered on the scale of the whole area, the minor irregularities disappear and the symmetry is statistically monoclinic. According to the principle of symmetry, this fabric is interpreted in terms of slip movement in a direction normal to the regional fold-axis (B).

The geometry of small-scale folds must be used with caution in determining the sense of large-scale tectonic transport in a body of rocks, since minor drag-folds on different limbs of a large-scale fold may be overturned in different directions (Wilson, 1953, p. 149). No large-scale folding is visible in the primary mylonitic rocks, however, and the present writer considers that the sense of tectonic transport along the movement horizon may be deduced from the direction of overturning of the small folds. In a recumbent fold of the intrafolial type (e.g. Plate IIa; Figs. 8c, 14d, e), the sense of movement between the overlying and underlying layers may be definitely /

definitely determined from the form of the fold, as shown in Figure 20c. All the intrafolial folds observed in the zone of movement are overturned to the south-south-west and the movement-picture obtained by integrating the slip movement in all these folds is one of overall transport of the Moine Nappe towards the south-south-west. It is probable that many of the folds which are not evidently intrafolial on the scale of the exposures examined, are in fact parts of larger structures of this type. As has already been noted, the majority of these folds are overturned towards the south-south-west, a fact which confirms the conclusion that there has been transport of the Moine Nappe towards the south-south-west along the movement-horizon.

The style of the intrafolial folds is similar to that described by Kienow (1953), and called by him Gleitfaltung (glide-folding). He believes that these folds were formed in the following way. During movement on glide-surfaces, the surfaces may become unstable and bend into flexural-slip folds; the folds become overturned in a direction related to the sense of gliding. A new schistosity develops by shearing of the upper limbs of the smallest-scale folds (Fig. 20a). The new schistosity (b---b, Fig. 20b) is more stable than the original (a---a) /

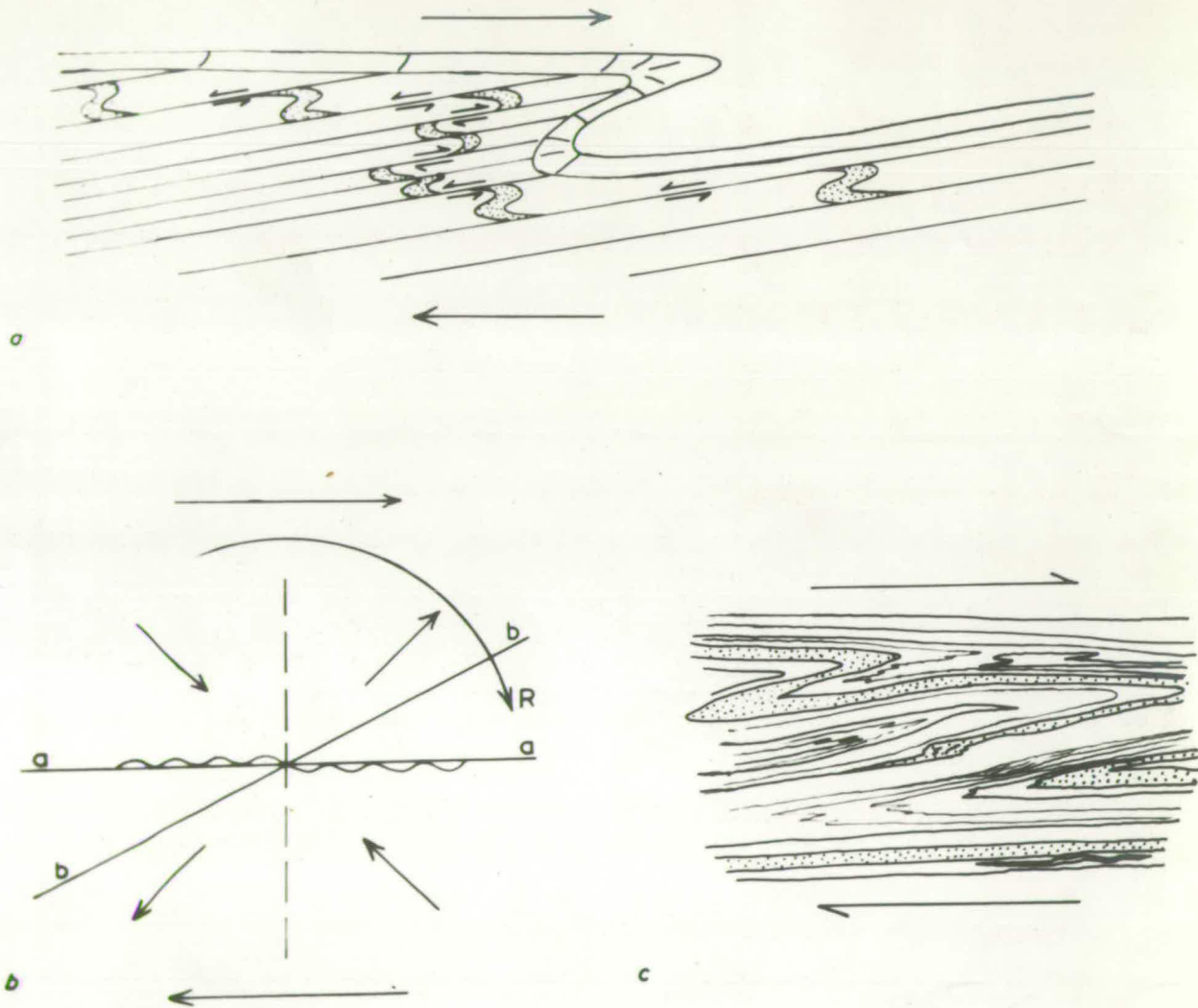


Figure 20. a. Diagram illustrating the development of Gleitfaltungsschieferung (after Kienow, 1953).

b. Analysis of movement in Gleitfaltung (after Kienow). Long arrows denote the sense of movement. Short arrows denote axes of compression and tension. The stable Gleitfaltungsschieferung (b---b) is rotated in the sense shown by the arrow (R) towards the unstable position a---a.

c. The sense of movement indicated by intra-folial folds.

(a---a) but is rapidly rotated towards the plane of the latter. For a schistosity developed in this way Kienow uses the term Gleitfaltschieferung (glide-fold schistosity). The present writer believes that this kinematic analysis holds for the intrafolial folds in the primary mylonitic rocks. An inclined schistosity, equivalent to b---b (Fig. 20b), and disintegration of small-scale folds are discernable, however, in only a few folds near the Stack of Glencoul (e.g. Plate IIb); elsewhere the deformation has been so penetrative that the inclined schistosity is not represented by megascopically visible surfaces, but by the general alignment of the chlorite flakes in the incompetent layers in an inclined plane. This mechanism, in the present writer's opinion, has played an important role in the production of the rapidly-alternating colour-layering in the primary mylonitic rocks.

It is evident that a number of the folds in the primary mylonitic rocks do not fit into the movement-picture deduced above. Polyclinal folds indicate squeezing parallel to the foliation in a direction normal to the fold-axis and the folds which are overturned towards the north-north-east suggest a sense of movement which is opposite to that postulated for the area as a whole. These folds may have been produced by slight /

slight local inhomogeneities in the movement during the main phase of deformation or they may have resulted from slight movements with the opposite sense at a later date. The style of the small-scale kink-zones and slip-surfaces, dipping to the south, in the Loch Ailsh and Cnoc a' Chaoruinn areas, suggests to the writer that the latter alternative is probable, but some of the folds may have formed both during and after the main movement. At Knockan Crag the folds in the primary mylonitic rocks are commonly associated with shear-surfaces and slight cataclastic deformation (Figs. 19a, b, c) indicating that they were produced after the main movements on the movement horizon. The shear-surfaces dip at variable angles to both north and south and the sense of movement is invariably such that the 'hanging wall' has moved up-dip. There is little displacement along the shear-surfaces and the general impression conveyed by the folding is of slight shortening in a north-south direction.

The possibility that there has been extensive elongation parallel to the fold-axes, as claimed by Read (1925, p. 121) and Anderson (1948), will be discussed after the grain orientation in the rocks has been described. It should be noted that such an elongation would in no way invalidate the conclusions /

conclusions drawn above. In terms of symmetry, this would mean that a movement with axial or orthorhombic symmetry was superposed on the monoclinic movement described, the axis of maximum elongation coinciding with B. This superposition would not lessen the overall symmetry of movement and the resulting symmetry of fabric would still be monoclinic. The strain would, however, be triaxial instead of biaxial. Axial elongation or "axial flow" (Weiss, 1954, p. 76) does not constitute tectonic transport, in the strict sense, for there is ideally no differential movement of parts parallel to B. The significance of the terms 'movement' and 'tectonic transport' has been discussed at length by Weiss (1954, pp. 76-7).

The movement during the secondary phase of deformation was discontinuous, in contrast to the main movement on the movement horizon. The deformation is localized in zones which cut across both the primary mylonitic rocks and the Moine Schists; the horizon mapped as the Moine Thrust was not generally active as a surface of movement during the secondary deformation, though there is evidence of movement on or near the horizon at several localities, notably at Knockan Crag. The slickensides in the phyllonitic rocks indicate that the direction of movement was westerly and the sense of movement, given by the folds in the deformed Moines east of Knockan Crag, is /

is from east to west. The form of the \underline{B}_n and \underline{B}_s folds in the phyllonites above the Ben More Thrust reflects primarily the movements on the underlying thrusts and reverse faults, as has already been shown (pp. 89-98), but this may have been combined with some degree of translation from east to west on surfaces of movement parallel to the Moine Thrust.

2. THE ZONE OF DISLOCATION

a. Introduction

In addition to the major thrusts which outcrop in the zone of dislocation - the Sole, the Glencoul Thrust, the Ben More Thrust and the Assynt Thrust - there are a large number of minor thrusts and faults of variable orientation. A prominent system of steep reverse faults with east-south-easterly strike cuts the syenites of the Loch Ailsh mass. The faults are well exposed on the eastern slopes of the Black Rock and Sail an Ruathair, where they are seen to dip between 50° and 70° towards the north. Portions of the faults are shown on the 1" Assynt map (1923), but no mention is made of the nature and orientation of the faults in the Memoir (1907). There is a considerable degree of cataclasis along the fault-surfaces and associated with the most northerly of the faults, which is exposed on Sail an Ruathair, there is a well-defined shatter-zone approximately four feet thick.

The most important group of minor faults in the area is the parallel system of steep reverse faults with northerly strike, which transects the whole zone of dislocation; the faults are in some cases almost vertical but more commonly they dip towards the east at steep angles. Some of the faults are shown /

shown on the 1" map (1923), chiefly in the Lewisian gneiss, and a greater number appear in Peach's sections across the area. The faults are well seen in the steepest parts of the mountains, where the rocks are well exposed, as on the south face of Ben Uidhe and in the sides of Coire a' Mhadaidh, north of Ben More. On the flat tops of the mountains and in the lower parts of the valleys and corries, however, the structures are frequently obscured by the deep covering of scree and peat; it is probable, in the writer's opinion, that these eastward dipping faults are more persistent than their distribution on the maps would suggest.

b. Nomenclature of Thrusts and Nappes

The classical (Survey) interpretation of the structures between the Moine Thrust and the Sole and subsequent modifications of this interpretation by Bailey and Sabine have already been outlined on pages 19 - 31 . It will be necessary to discuss the relative significance of the thrusts and the nature of the structural units in the zone of dislocation before the folds and other structures in the zone can be described.

The Glencoul Thrust is exposed only at the classic locality on the south shore of Loch Glencoul (Plate VII). It is /

is here represented by a sharply-defined, planar surface dipping eastwards at approximately 30° and separating the Cambrian dolomites from the overlying Lewisian gneiss. The gneiss is so heavily deformed that it is converted to a type of phyllonite for a distance of almost 20 feet above the Thrust. The Thrust is not exposed to the south but the outcrop may be followed in the topography as far as the Bealach Conival, where it is truncated by the Ben More Thrust. Although the rocks in the vicinity of the Allt Poll on Droighinn are not sufficiently well exposed to show the exact position of the Thrust, the present writer is unable to accept Bailey's suggestion (1935, p. 157) that the Thrust dies out at this locality.

The present writer has traced southwards the important dislocation which displaces the Moine Thrust at the Stack of Glencoul; there is no doubt that it is in fact the northward continuation of the Ben More Thrust, as shown by Peach and Horne (Assynt Sheet, 1923). Thus the contention of Clough and Bailey (1935, p. 160) that the line of outcrop of the Ben More Thrust lies to the west of that shown on the map and ends one mile south-west of the Stack of Glencoul (see p. 29, Fig. 1) is without basis.

The outcrop of the Ben More Thrust is clearly visible
on /

on the hillside west of Gorm Loch Mor (Plate VIa), where the Thrust dips at more than 40° towards the east and the overlying quartzites are contorted about a north-trending axis (Fig. 22, XIII). The course of the Thrust is again visible further to the south in Coire a' Mhadaidh (Plate VIb), where it dips at approximately 50° to the east. The gradient of the Thrust is steeper than that of ground surface at this locality, giving rise to the V-shaped outcrop seen on the map. On the south side of Conival the Ben More Thrust is well exposed above the level where it transects the Glencoul Thrust, and the Thrust is again seen to dip at more than 50° towards the east. At both of the last-mentioned localities the rocks to the east of the Thrust are also folded about north-trending axes (Fig. 22, XIV, XXII). South of Conival the Thrust is nowhere well exposed but the writer's revision of the mapping between Loch Ailsh and Cnoc a' Chaoruinn (Fig. 11) shows that the Thrust does not follow the course previously assigned to it, but crosses the ground west of Strathsheaskich to Cnoc a' Chaoruinn, where it again displaces the Moine Thrust. The thrust previously referred to as the Ben More Thrust, the Assynt Thrust, is also displaced by the Ben More Thrust. Sabine, following the mapping of Peach and Horne, considered that the Assynt Thrust /

Thrust was an extension of the Ben More Thrust, but regarded it as "continuing southward the effect of the Glencoul Thrust" (1953, pp. 151-2). Whereas previous writers have postulated only one major thrust south of Conival, the evidence suggests to the present writer that two thrusts - the Assynt Thrust and the Ben More Thrust - are in fact present. Detailed re-mapping of the area between Conival and Sgonnan Beag is required to ascertain the exact outcrops of the two thrusts, but the present writer considers that the line shown on the Assynt Sheet as the Ben More Thrust is actually the Assynt Thrust and that the Ben More Thrust outcrops slightly to the west (Fig. 21). It is conceivable, however, that the outcrops of the two thrusts are almost coincident along this section.

In the literature on the North-west Highlands, the term 'thrust' generally denotes a reverse fault with low inclination; that is, it is equivalent to the term 'overthrust' in the system recommended by the Committee on the Nomenclature of Faults (Reid et al., 1913). The term 'thrust' has been used to denote any reverse fault, without regard to its inclination (Ibid., p. 179), but the present writer prefers to restrict the use of the term 'thrust' to reverse faults with low inclination /

inclination (cf. 'thrust-plane', J. Geikie, 1905, p. 168) and to refer to compressional dislocations dipping at angles greater than 45° as reverse faults. The dip of the Ben More Thrust is generally greater than 45° and according to this distinction would be called a reverse fault. It may be regarded as the most important and most persistent of the widely-developed group of easterly-dipping reverse faults in the zone of dislocation.

The Ben More Thrust displaces the Moine Thrust in the two areas described in the previous chapter and it also transects both the Glencoul and Assynt Thrusts. Thus it is evident that it did not develop contemporaneously with the other major thrusts, but is a late-stage dislocation cutting across the pre-existing nappes. Moreover, the degree of deformation along the Ben More Thrust where it is exposed is low, suggesting that movement on the Thrust has been slight. The displacement of the Moine Thrust at the Stack of Glencoul and Cnoc a' Chaoruinn probably represents the total displacement on the Thrust; this is slightly more than 500 feet in the north and less than 500 feet in the south.

This conclusion provides additional support for the hypothesis, first suggested by Bailey (1935) and later developed by /

by Sabine (1953), that the Ben More and Glencoul Nappes (Survey usage) are parts of a single tectonic unit, for which Sabine proposed the term "Glencoul-Assynt thrust-masses" (1953, pp. 151-2). If the displacement on the Ben More Thrust is of the order of 500 feet, as the writer believes, then the Glencoul and Assynt Thrusts are indeed parts of the same great dislocation, as Sabine implied. It is inconvenient to use two separate names for different parts of the same thrust and the present writer will refer to the whole dislocation as the Assynt Thrust. Where that part of the Thrust north of Conival is specifically discussed, the term Assynt (Glencoul) Thrust will be used.

Peach and Horne (1907) regarded the whole mass of rocks below the Glencoul and the southerly part of the Ben More Thrust (Survey usage) and above the Sole as an immense zone of imbrication produced by the movements on these thrusts. However, this mass contains the massive syenites of the Loch Borolan complex and a considerable volume of Lewisian and Cambrian rocks which do not show the degree of reverse faulting characteristic of a zone of imbrication. The mass may be regarded as a second great nappe of similar significance to that above the Assynt Thrust.

The /

The present writer can add nothing to the evidence adduced by Bailey and Sabine relating to the existence of the Sgonnan Beag Thrust, which Peach and Horne considered as outcropping round the Loch Ailsh syenite mass. The geometry of the outcrop of the boundary known as the Sgonnan Beag Thrust shows that it is definitely not a planar or gently-curved surface; it resembles more the marginal surface of an intrusion, as Bailey has pointed out. The additional evidence afforded by the presence of intrusions of grorudite within the syenite mass itself and in the Lewisian gneiss surrounding the mass (Sabine, 1953, p. 152) strengthens the case against the existence of an important thrust. Thus the Loch Ailsh syenite appears to be neither a klippe carried on the Sgonnan Beag Thrust, as represented by Peach and Horne, nor a window exposed through the Thrust, as suggested by Lugeon (see p. 29), but a part of the Ben More Nappe of Peach and Horne.

From this evidence, then, it is apparent that the rocks between the Moine Thrust and the Sole belong to two great thrust slices or nappes (= German "Decken"), as shown in Figure 21. The lower nappe rests on the Sole and is overlain by the Assynt Thrust, which supports the upper nappe. To avoid the introduction of additional place-names into the nomenclature /

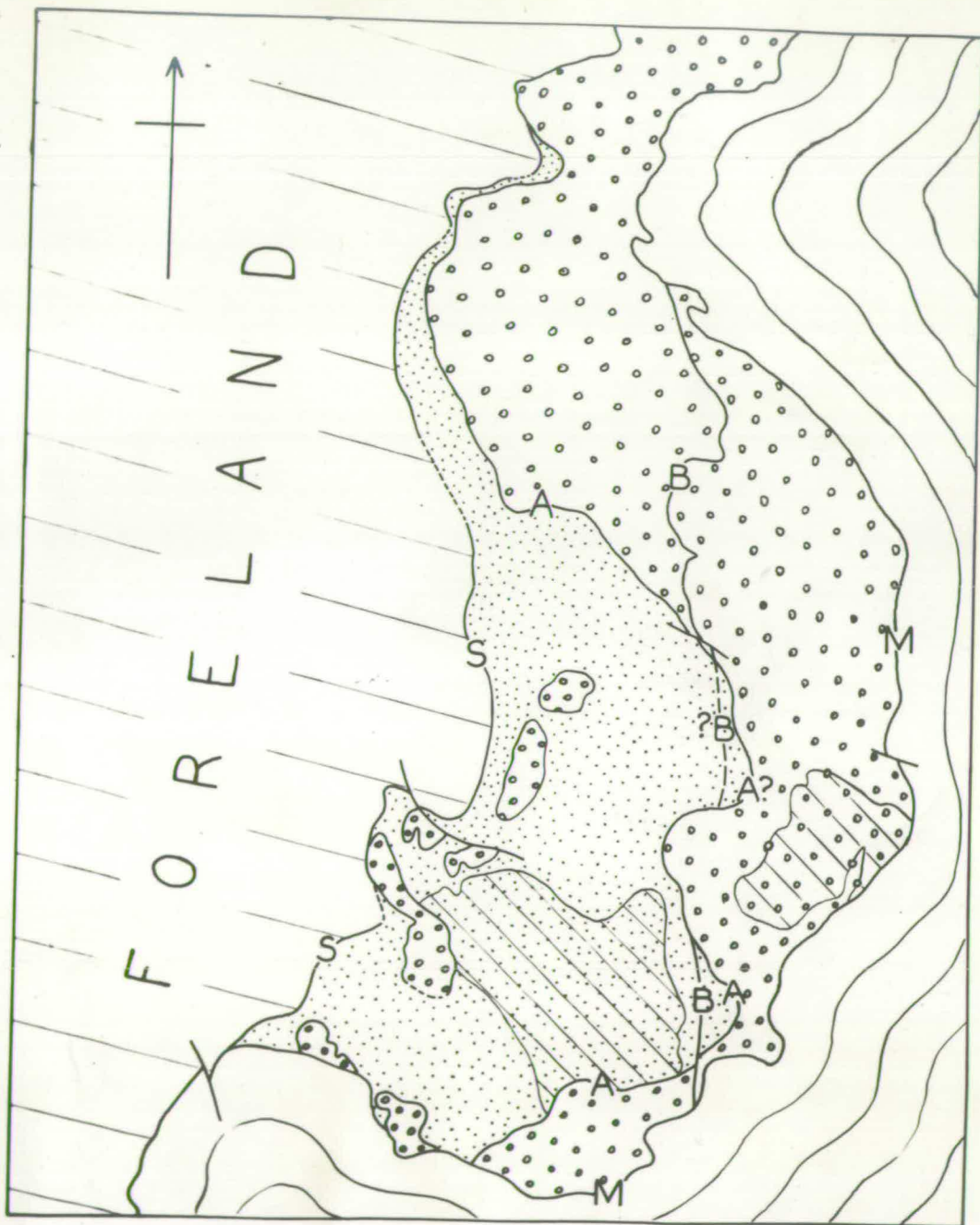


Figure 21. Diagrammatic map showing the major thrusts and nappes in the zone of dislocation in Assynt.
M - the Moine Thrust; A - the Assynt Thrust;
S - the Sole; B - the Ben More Thrust.
The Upper Assynt Nappe is shown by coarse ornament and the Lower Assynt Nappe by fine ornament. Shaded areas are the plutonic complexes of Loch Ailsh and Cnoc na Sroine.

nomenclature the present writer will call the slices the Upper Assynt Nappe ("Glencoul-Assynt thrust-masses" of Sabine) and the Lower Assynt Nappe. The rocks exposed in the Upper Nappe include Lewisian gneisses, Torridonian and Cambrian sediments and the syenitic rocks of the Loch Ailsh mass. The Lower Nappe consists of Lewisian and Cambrian rocks along with the great plutonic mass of Cnoc na Sroine; Torridonian rocks are not exposed in the small area where the base of the Cambrian is exposed, but may be present elsewhere underneath the Cambrian rocks. Whereas the Lower Nappe contains a considerable thickness of Cambrian and a comparatively small amount of Lewisian, the Upper Nappe consists largely of Lewisian with only a thin veneer of Cambrian sediments. Thus it is evident that the Upper Nappe must have been derived from a lower stratigraphic level than the Lower Nappe.

c. Folding

Small-scale folds are uncommon in the zone of dislocation; the only examples observed by the writer are in the phyllonitic rocks along the Assynt (Glencoul) Thrust, south of Loch Glencoul (Plate VII). Six folds have been recognised within two feet of the thrust-plane. The trend of the folds varies between /

between N 10° W and N 15° E. The folds are asymmetrical and overturned towards the west and the style is less 'plastic' than in the primary mylonitic rocks along the Moine Thrust.

Medium-scale folds are locally developed in the limestones and dolomites; the folding of the Loch Ailsh dolomites has already been described and similar folds are developed in the calcareous rocks near the Sole in the southern part of Assynt (Plate VIIIb). The orientation of these folds at two localities, south of Knockan village and at Knockan Crag, is shown in Figure 22. The fold-axes plunge at low angles to the south-east and the folds are overturned to the south-west.

There is considerable large-scale folding of the Cambrian and Torridonian sediments in both the Upper and Lower Nappes and at several localities the rocks are sufficiently well exposed to show the form of the folds. The orientation of the bedding surfaces over several of these folds was measured and β -diagrams constructed to determine accurately the orientation of the fold-axis (Fig. 22: areas II, IV, V, XII, XIV, XVI, XIX, XXII, XXIII, XXVI). Certain other areas of Cambrian and Torridonian rocks, in which the form of the folds is not evident, were examined and β -diagrams were also constructed /

constructed for these areas. The majority of the areas were found to be homogeneous with respect to the fold-axis(β), but a few are heterogeneous.

A full discussion of the principles involved in the analysis of folding by means of β -diagrams is outside the scope of the present work. Briefly, heterogeneous areas are broken down until they are resolved into a number of smaller homogeneous areas so that the variation of the fold-axis (β) within the heterogeneous area may be visualized. The homogeneity of the smaller areas may be tested, if necessary, by means of partial diagrams. Two of the heterogeneous areas studied (XI, XXV) were found to be divisible into two homogeneous areas; in each case the trend of the β -axis in one of the sub-areas is easterly and in the other northerly. Several of the other areas shown in Figure 22 are not completely homogeneous but a thorough analysis of the folding in these areas is not possible as sub-areas were also found to be inhomogeneous and the diversity of orientation of the bedding-planes on individual exposures is not sufficiently great to give β -axes for each exposure.

However, in all the areas shown in Figure 22 there is a single strong maximum in the β -diagram, which, even in areas with /

with slight inhomogeneity, approximates to the fold-axis. The orientation of the β -axes in the areas examined is shown in the synoptic diagram (Fig. 22; also Fig. 32 b). The axes fall into three groups, one with northerly trend (β_n) and two plunging to the east (β_e) and south-east (β_{se}).

d. Distribution and Style of the Large-scale Folds

Folding about south-east trending axes, generally on a large scale, is found in both the Lower and Upper Assynt Nappes. In the Lower Nappe the limestones near the Sole are folded at the south-east end of Loch Assynt (Fig. 22, XII), on the Stronechrubie plateau (XIX) and in the neighbourhood of Knockan. The large-scale folds at Loch Assynt and Stronechrubie are open and asymmetrical with the steeper limbs dipping to the south-west (Plate VIIa); the medium-scale folds near Knockan are recumbent and more tightly compressed but are also overturned to the south-west. The Cambrian quartzites east of Glenbain (Fig. 22, XVI, XVII) are folded into an immense asymmetrical anticline with the steeper limb again dipping to the south-west, similar to the large anticlines in the limestones; the exposure of basal quartzites in the core of the anticline gives rise to the elongate outcrop which is well seen on the map.

In the Upper Nappe the most extensive folding about south-east trending axes occurs in the Ben Uidhe area. The crest of the mountain is formed from a shallow syncline of quartzite which is continuous with a large anticline on the south-west flank of the mountain. The north-east limb of the anticline dips gently to the north-east and the south-west limb becomes almost vertical. Folding of the quartzites on a somewhat smaller scale is visible in the corrie north of Mullach an Leathaid Riabhaich (Plate IXa) and in Choire Dheirg on Glasven (Fig. 22, IV, II). To the north of Gorm Loch Mor the Cambrian Quartzites, Fucoid Beds, Serpulite Grit and limestones are folded on a large scale (see Fig. 5). The β -axis in the area plunges to the south-east (Fig. 22, VI, VII). If the boundaries between the formations are stratigraphic horizons, as shown by Peach and Horne, the form of the fold (determined by projecting the outcrops along the β -axis on to a plane normal to this axis) is a recumbent syncline with closely appressed limbs. The rocks in this area are poorly exposed, however, and it is not improbable that they have been affected by the reverse faulting which is so common in the area, in which case the profile obtained by projection of the lithological boundaries along the β -axis would not be a true representation of the form of the fold. In the areas in which east-plunging β -axes were determined large-scale folding is not visible.

Visible folding about north-trending axes is of widespread occurrence in the zone of dislocation, but the most spectacular folds are found in the central part of the zone, at no great distance from the outcrop of the Ben More Thrust. Folding of the quartzites east of the Thrust at Gorm Loch Mor and Na Tuadhan has already been noted. South of the latter locality, on the north slopes of Ben More, similar folding is discernible, and on the south side of Conival, immediately east of the Ben More Thrust, the Torridonian rocks are also folded into a syncline with north-trending axis (Fig. 22, XXII). Still further to the south, in Coirean Ban, west of the River Oyke, another large anticlinal fold is exposed near the supposed outcrop of the Thrust. The most intense folding about north-trending axes is found a short distance to the west of the Thrust, on the ridge formed by Braebag, Creag Liath and Meall Diamhain. Much of this ridge is scree-covered, so that the exact form and extent of the folds is difficult to determine, but the approximate distribution of the folds is shown in Figure 22.

The folds in this group are of variable style, but they are generally open and commonly asymmetrical, the steeper limbs dipping towards the west. They are associated with shear- /

shear-surfaces and reverse faults, which dip to the east, sub-parallel to the Ben More Thrust (see Plate VIb). It may be inferred from the limited distribution of the folds and their close relationship with shear-surfaces parallel to the Ben More Thrust that the folding and faulting were produced by the same movements as the Thrust.

The relationship between the south-east- and north-trending folds is evident in the Ben Uidhe area. The south-easterly folds between Glasven and the Mullach an Leathaid Riabhaich are transected by a considerable number of easterly-dipping reverse faults; in the vicinity of these faults the near-horizontal beds are bent and locally folded about north-trending axes. Thus the north-trending folds and the eastward-dipping reverse faults (including the Ben More Thrust) must obviously have been produced during a later phase of deformation than the south-east-trending folds.

e. Lineations

Penetrative lineations are not developed in the zone of dislocation, except in the vicinity of the Moine Thrust, where the rocks have been affected by the penetrative 'Moinian' deformation. Slickensides on bedding-planes and shear-surfaces are /

are, however, comparatively common. The most intense lineations of this type were observed on shear-surfaces in the Cambrian quartzites on Ben Uidhe and near the summit of Ben More (Plate IXb). At both these localities the shear-surfaces dip at variable angles towards the north and the slickensides on the surfaces plunge to slightly west of north.

f. Discussion of the Movements

The rocks in the zone of dislocation generally show little trace of deformation. Only along the thrusts and faults is there appreciable cataclastic breakdown of the gneisses and sediments, and mylonitic rocks comparable with those along the Moine Thrust are developed only above the As-synt (Glencoul) Thrust. It is probable that movement in the sedimentary rocks took place chiefly by slip on the bedding-surfaces, while the minor thrusts and faults originated in the massive gneisses and igneous rocks, and in those sediments in which the bedding-planes were not suitably oriented with respect to the stress-system for bedding-slip to take place.

The large-scale folding in the nappes is generally open and simple in style, as is commonly found in competent sediments such as the Cambrian quartzites and Torridonian sandstones. /

sandstones. The folds are non-cylindroidal and though many are asymmetrical, they are seldom overturned or recumbent. In kinematic terms, the folding denotes shortening within the nappes in a direction normal to the fold-axes, probably while the nappes were being transported along the major thrusts.

Folding about south-east-plunging axes is not common in the Lower Nappe and the majority of the folds with this orientation are situated within a short vertical distance of the Sole (at Loch Assynt, Stronechrubie and Knockan). The proximity of these structures to the Sole suggests that they were produced by drag on the Thrust. The axial planes of all the folds are inclined to the north-east, indicating a consistent sense of rotation between Loch Assynt and Knockan Crag, and if the folds were produced by movement on the Thrust, as appears to be likely, they indicate that the sense of movement of the Lower Nappe along the Sole was from the north-east to the south-west.

The widespread folding about south-east-trending axes in the Upper Nappe, particularly in the vicinity of Ben Uidhe, is evidence of ^aconsiderable degree of shortening of the Nappe in a north-easterly direction. This may have been produced by transport of the nappe along the Assynt Thrust in the same /

same direction. But at the only locality where the Thrust is exposed (at Loch Glencoul) the small-scale folds in the mylonitic rocks trend north-south and are overturned towards the west, indicating transport to the west along the Thrust. However, folding about north-trending axes elsewhere in the zone of dislocation was contemporaneous with movement on the Ben More Thrust, which displaces, and therefore post-dates, the Assynt Thrust. Thus it is probable that the north-trending folds above the Assynt Thrust at Loch Glencoul were produced by late-stage movement and do not reflect the main movements on the Thrust.

The north-trending folds in the zone of dislocation were produced during a later phase of deformation than the south-easterly folds, discussed above. They indicate shortening of the thrust-masses in an easterly direction and the asymmetry of the folds and displacement on the Ben More Thrust and related reverse faults denote slight transport of the overlying rocks towards the west. The orientation of the small-scale folds in the mylonitic rocks along the Assynt (Glencoul) Thrust show that it was also active during this phase of deformation, although it was already in existence before the movement began. It is not necessary to postulate a large downfold /

downfold of the Assynt Thrust to the west of the main outcrop to account for the existence of the klippen at a lower structural level in the region of Beinn an Fhuarain, Ledbeg and Cromalt. The great thickness of gneiss and quartzites on the ridge of Braebag and Creag Liath was produced by reverse faulting and folding during the later phase of deformation, that is, after the Upper Nappe was emplaced. The cumulative effect of the small displacements on the Ben More Thrust and the plexus of eastward-dipping reverse faults is to raise the level of the Assynt Thrust from west to east.

Thus in the zone of dislocation, as in the Moine Thrust-zone, there is evidence of at least two separate phases of deformation. During the earlier phase there was shortening of the nappes in a south-westerly direction, probably associated with transport of the nappes in this sense on the major thrusts. This was followed by movement in a westerly direction, during which the nappes were broken by a series of eastward-dipping reverse faults, the most important of which is the Ben More Thrust.

IV. MICROSCOPIC STRUCTURAL DATA

1. GRAIN ORIENTATION IN THE DOLOMITE ROCKS

a. Introduction The widespread occurrence of marble and crystalline dolomite in the Assynt region has long been recognised. The first detailed description of the marbles was given by Heddle (1882 & 1884), who observed that they outcrop "round, and nowhere at much greater distance than a mile from the quartz porphyry of Cnoc-na-Strome [Cnoc na Sroine], - or from the spurs of this hill." (1884, p. 274). He traced the marble northwards to Ben an Fhurain, noting a gradual decrease in the crystallinity until it graded into unaltered dolomite, and concluded that the marble was formed by metamorphism of the dolomite. The obvious conclusion that the igneous rock was the agent which caused the metamorphism, though evidently implied, was not specifically stated. Teall (1907, Memoir, pp. 453-462) described the petrography of the rocks and gave a detailed account of the constituent minerals, which include calcite, dolomite, forsterite, serpentine, brucite and mica, indicating that the thermal metamorphism has produced considerable chemical rearrangement in the rocks. Teall considered that the silicate minerals originated by combination of magnesia from the dissociated dolomite with quartz, chert and argillaceous materials originally present as impurities in the rocks. Phemister (1926) /

(1926) made a similar study of the petrography of the carbonate rocks in the vicinity of the Loch Ailsh syenite mass, which showed that silicate minerals are present in greater variety and amount than in the aureole of the Loch Borolan mass. There is considerable evidence of introduction of material from the igneous rock into the surrounding sediments and Phemister considers that many of the silicate minerals in the marbles are of metasomatic origin. He observed that the deformation of the carbonate minerals has produced a "flow-structure", defined by elongate, almost acicular grains of carbonate minerals and tremolite fibres. Both Teall and Phemister found that the original rock from which the marbles were formed was dolomite, with variable amounts of calcite and quartz as impurities (Phemister, 1926, p. 95).

The marbles are polymetamorphic in character, having suffered successively (1) thermal metamorphism during the emplacement of the plutonic masses of Loch Ailsh and Loch Borolan and (2) dynamic metamorphism during the post-Cambrian movements. Read and Phemister (1926, p. 8) consider that these two phases of metamorphism were separated by an appreciable, though indeterminate, period of time. Bailey (1935), however, is of the opinion that the periods of intrusion and deformation overlapped to some extent (see above, p. 28).

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The specimens described in the present study come, with one exception, from a small area to the north of Loch Ailsh, shown on the map (Fig. 16). This is the only locality in the Assynt area where crystalline carbonate rocks are in contact with the mylonitic rocks along the Moine Thrust and it is here that the fabric of the carbonate rocks might be expected to bear the most pronounced imprint of the thrust movements. It was for this reason that the area was selected for an intensive study of the fabric of the carbonate rocks.

b. Intragranular deformation in dolomite True plastic deformation of a crystal involves gliding or differential slipping of layers of ions along certain planes and parallel to certain directions in the crystal lattice. Plastic deformation in crystals is effected chiefly by two types of gliding, which are generally distinguished by the terms "twin-gliding" and "translation-gliding" (Buerger, 1928; Knopf, 1938, p. 88 et seq.). In twin-gliding, one part of a crystal is displaced with reference to another part by homogeneous slipping which is continuous (spatially) throughout the deformed part of the crystal. The amount of displacement between separate layers of lattice is less than the distance between ions in the lattice. The ions become "locked" in a new position so that the twinned /

twinned lattice is different from, but symmetrically related to, the lattice in the undeformed part of the crystal. Twin lamellae may be recognised under the microscope as layers showing a different optical orientation from the parent crystal. In calcite and dolomite, thin lamellae which are not optically recognisable as twin lamellae, are commonly developed parallel to twin planes. These probably represent the initial stages of twinning, in which the zones of twinned lattice are too narrow to be distinguished by optical means. In the following pages these are referred to as "non-twinned lamellae", whereas lamellae with an optical orientation different from that of the parent crystal are called "twinned lamellae" (cf. Borg and Turner, 1953, p. 1345).

While the amount of deformation achieved by twinning is limited by the "locking" of the lattice layers in the twinned position, the degree of deformation which may be achieved by translation-gliding is theoretically unlimited. The amount of slip between adjacent layers of the crystal lattice in translation-gliding is a whole number of inter-ionic distances. Thus the orientation of the lattice in a deformed portion of a grain is the same as the orientation in an undeformed portion of the same grain and the optic orientation in the two portions, consequently, is also the same. Since translation-gliding /

translation-gliding does not involve reorientation of the lattice, identification of the process by optical means is difficult. Lamellae parallel to translation planes may be recognised in some materials (notably in metals), but in minerals such as calcite and dolomite lamellae are not generally developed. The process may be recorded, however, by the offsetting of crystal boundaries and by internal rotation of pre-existing lamellar structures through the crystal lattice : this is discussed in greater detail below.

The first published analyses of dolomite orientation were given by Sander in "Gefugekunde der Gesteine" (1930), but no attempt was made to interpret the orientation data. Fairbairn and Hawkes (1941) made the first detailed study of dolomite fabrics, using a number of specimens from Montana, Vermont and Ontario. They found that $\{02\bar{2}1\}$ twin lamellae were extensively developed in all the specimens and inferred from the orientation of the lamellae that the sense of gliding on $\{02\bar{2}1\}$ in dolomite was opposite to that on $\{01\bar{1}2\}$ in calcite. The authors discussed the possibility that translation-gliding on /

The distinction between internal rotation and external rotation, originally made by Sander, is emphasised by Turner (1954, Turner, Briggs and Heard: pp. 227-9), who describes the relationship between the two phenomena in deformed crystals. The geometry of internal rotation is clearly illustrated by Weiss (1955, pp. 227-9).

on $\{0001\}$, produced experimentally by Johnsen (1902), might be an important orienting mechanism, concluding that it might be of some importance, though this would be difficult to prove in view of the difficulty of identifying the process.

In a comprehensive study of Alpine dolomite-tectonites, Ladurner (1953) has recorded the orientation of $[0001]$ -axes in more than 40 rocks. On the basis of the preferred orientation of dolomite he classified the rocks into S-tectonites and three types of E-tectonite, according to the number of s-planes and symmetry planes which he recognised in the fabrics. The similarity between synoptic diagrams showing maxima of $[0001]$ -axes in dolomite-tectonites and analogous diagrams for calcite-tectonites led Ladurner to assume that the same mechanism was responsible for producing the preferred orientation in dolomite as was assumed for calcite: namely, gliding on $\{01\bar{1}2\}$, combined with rotation of the $\{01\bar{1}2\}$ planes about the E-axis of the fabric. Experimental deformation of calcite (e.g. Turner, Griggs and Heard, 1954) has shown, however, that several kinds of gliding operate during the deformation of calcite and that the mechanism by which calcite acquires a preferred orientation in marbles is considerably more complex than Ladurner suggested. Moreover, similar work on dolomite carried out up to the present gives no indication that gliding on $\{01\bar{1}2\}$ occurs in dolomite (see below, p. 147).

Despite /

Despite repeated attempts, both Tschermak (1882) and Johnsen (1902) failed to produce twin-gliding on either $\{02\bar{2}1\}$ or $\{01\bar{1}2\}$ planes in dolomite experimentally. Johnsen succeeded, however, in deforming dolomite crystals by translation-gliding on $\{0001\}$, with one of the a crystal axes as the glide line.

More recently, a detailed fabric study of Dover Plains dolomite (Turner, Griggs, Heard & Weiss, 1954) deformed at high temperature and confining stress, has shown that two mechanisms of deformation are demonstrable under such conditions. A cylinder of the rock was compressed 9.4% at 380°C. and 3000 atmospheres confining pressure. A comparison of the microscopic fabric before and after deformation showed that two mechanisms of plastic deformation operated during the deformation:

(1) "twin-gliding on $\{02\bar{2}1\}$, the sense of shear being such that the upper layers of the crystal lattice are displaced downwards from the upper end of the c axis", that is, with a negative sense of shear (Turner, Griggs & Heard, 1954, p. 897);

(2) "translation-gliding on $\{0001\}$, with the a-axes as probable glide directions."

Numerous grains in the deformed Dover Plains rock contained lamellae occupying anomalous positions in the crystal lattice; these were chiefly of two types, designated f' and L9. f' lamellae were shown to be pre-existing $\{02\bar{2}1\}$ -lamellae (= f) rotated /

rotated internally by twin-gliding on another set of $\{02\bar{2}1\}$ lamellae in the same grain. The L9 lamellae were also shown to be pre-existing $\{02\bar{2}1\}$ -lamellae, internally rotated by gliding on another plane. The authors concluded that the observed data could be satisfactorily explained only by gliding on $\{0001\}$, with one of the crystallographic a-axes as glide line.

It is now possible, as a result of experimental deformation of certain rocks and single crystals, to make a dynamic interpretation of the intra-crystalline deformation structures (twin lamellae &c.) in the fabrics of some naturally deformed rocks. From detailed investigations of experimentally deformed Yule Marble (Turner & Chi'h, 1951; Griggs, Turner, Borg and Sosoka, 1951; 1953; Borg and Turner, 1953) and single crystals of calcite (Turner, Griggs and Heard, 1954), much is now known of the mechanism of deformation of calcite under different physical conditions. Several papers have been published applying the results of these investigations to the interpretation of fabrics of naturally deformed marbles (e.g. Turner, 1953; McIntyre & Turner, 1953). The Dover Plains dolomite study has yielded similar information on the mechanism of deformation of dolomite and the fabric data from the Assynt dolomites are interpreted in the light of this information. The method is analogous to that employed in the interpretation of marble fabrics (Turner, 1953, pp. 281-3).

Figure /

Figure 23a shows the orientation of the $\{02\bar{2}1\}$ twin plane in relation to the cleavage rhomb ($r = \{10\bar{1}1\}$) in dolomite and the arrow indicates the direction and sense of gliding on the plane. The angle between $[0001]$ (C_V) and the pole of the lamellae, $[02\bar{2}1]$, is $62\frac{1}{2}^\circ$ (Fig.23b), so that $[0001]$ in the twin lamellae (C'_V) also lies $62\frac{1}{2}^\circ$ from $[02\bar{2}1]$ in the zone containing C_V and $[02\bar{2}1]$. The applied stresses which would be most effective in causing twin-gliding on $\{02\bar{2}1\}$ are shown in figure 23b. A compression applied parallel to the axis C and a tension parallel to the axis T would give maximum resolved shear stress on $\{02\bar{2}1\}$ parallel to the glide line, suitable for gliding with the appropriate sense.

A similar dynamic interpretation of L9 lamellae in a grain may be made. For the purpose of interpreting the L9 lamellae recorded in the present study it is assumed that they have been rotated by translation on $\{0001\}$ parallel to one of the a crystallographic axes. In the experimentally deformed Dover Plains rock only one set of L9 lamellae were found in any grain, but the present writer has recorded two sets of L9 lamellae in several grains in one of the Loch Ailsh dolomites. Figures 23c and d illustrate diagrammatically the phenomenon of translation-gliding on $\{0001\}$. The lattice orientation (C_V, a_1, a_2, a_3) is unchanged by gliding. Pre-existing $\{02\bar{2}1\}$ lamellae /

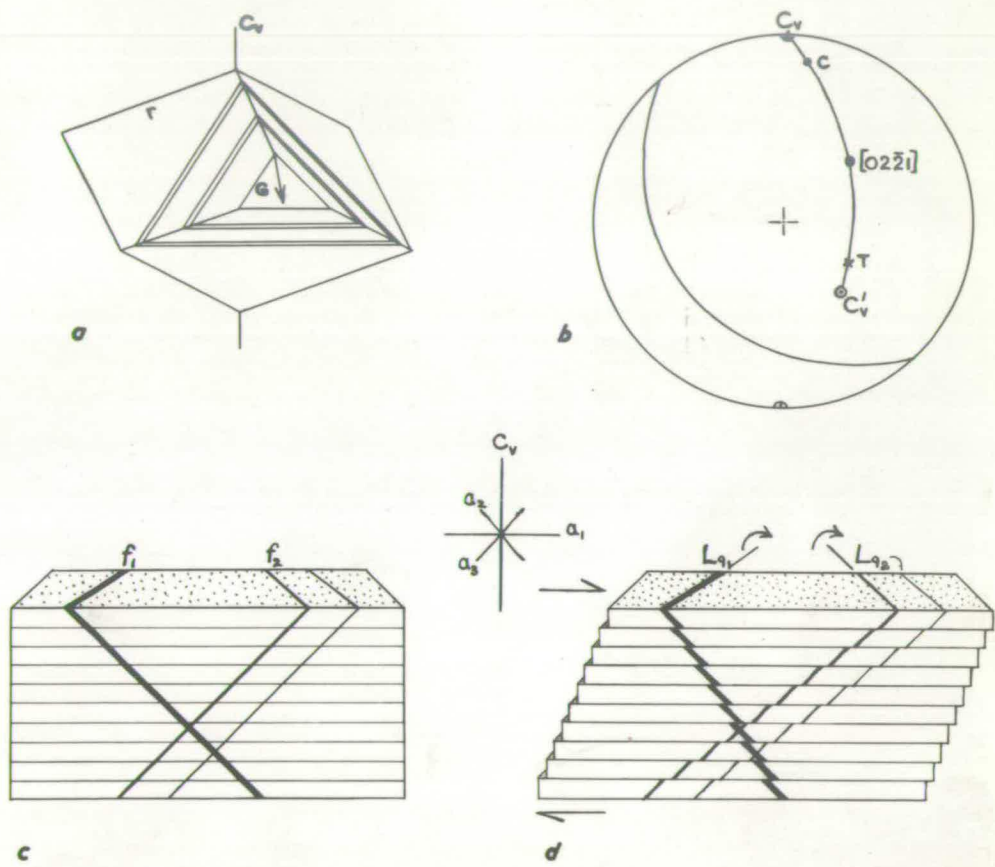


Figure 23. a. $\{10\bar{1}1\}$ cleavage rhomb of dolomite, showing the orientation of the $\{02\bar{2}1\}$ twin-plane. The sense of shear on $\{02\bar{2}1\}$ is shown by the arrow (G). After Fairbairn and Hawkes, 1941.

b. Projection showing the orientation of $[0001]$ in the host lattice (C_V) and the twinned lattice (C'_V) in a partially twinned crystal of dolomite. C and T are respectively the axes of compression and tension which give maximum resolved shear stress on $\{02\bar{2}1\}$ favourable for gliding with the sense indicated.

c, d. Diagrams illustrating the internal rotation of $\{02\bar{2}1\}$ lamellae f_1 and f_2 to L_{9_1} and L_{9_2} by translation-gliding on $\{0001\}$ parallel to a_1 . C_V, a_1, a_2 and a_3 are the crystal axes.

lamellae, f_1 and f_2 , are internally rotated about axes which are the intersections of the lamellae with the glide plane; these intersections, $[02\bar{2}1:0001]$, are the \underline{a} crystal axes. The sense of rotation about the axes of internal rotation is the same as the sense of movement on the glide plane. The lamellae f_1 and f_2 are rotated about \underline{a}_3 and \underline{a}_2 respectively by gliding parallel to \underline{a}_1 and become $L9_1$ and $L9_2$. If three sets of $\{02\bar{2}1\}$ lamellae are present in a grain before the inception of translation-gliding on $\{0001\}$, the potential axes of internal rotation are parallel to the three \underline{a} -axes of the lattice. Thus it is evident that only two sets of lamellae can undergo rotation by gliding, since the potential axis of rotation for the third set is parallel to the glide line.

The orientation of two sets of L9 lamellae in the dolomite lattice is shown in figure 25d. Dynamic interpretation of the L9 lamellae is made in the following way: since \underline{a}_2 and \underline{a}_3 are the axes of internal rotation of $L9_1$ and $L9_2$, the only possible glide line is the remaining \underline{a} -axis - \underline{a}_1 . The sense of slip on the glide plane is given by the sense of rotation of the L9 lamellae. The axes of compression and tension which give maximum resolved shear stress on $\{0001\}$ parallel to \underline{a}_1 suitable for gliding with the sense indicated are C_1 and T_1 . Axes of compression and tension favourably oriented to produce /

produce translation-gliding may be determined in this way for all grains in which two sets of L9 lamellae are recorded. For grains in which only one set of L9 lamellae is present or accessible it is impossible to determine the orientation of the glide line without ambiguity. For example, if only $L9_1$ lamellae are present in the grain (Fig.25 d), the axis of internal rotation of $L9_1$ is a_2 and the active glide line may be either a_1 or a_3 . The stress axes most favourably oriented to produce gliding parallel to a_3 with the requisite sense are C_2 (compression axis) and T_2 (tension axis). Thus the axes of compression and tension most suitably oriented to produce the lamellae $L9_1$ may be either C_1 and T_1 or C_2 and T_2 .

c. Fabric Data

The Loch Ailsh dolomites are more or less coarsely crystalline rocks with saccharoidal texture (Plates X, XI). The proportion of impurities is very small, calcite being virtually absent, except in the lenticles of marble referred to above; quartz is present in some specimens in the form of small, isolated grains and, associated with feldspar, as extremely thin veins. The isolated quartz grains are rounded, resembling the detrital grains in the unmetamorphosed dolomites and /

ROYAL CHARLES

and it is probable that they are elastic grains which have survived the metamorphic changes in the rocks. While thermal metamorphism of dolomite is generally accompanied by the mineralogical changes known as dedolomitisation, these rocks contain none of the characteristic minerals produced by this process; consequently it is not certain whether the crystalline texture of the rocks was produced by thermal metamorphism during the emplacement of the Loch Ailsh syenite mass or is due to some other cause. The present writer has examined sedimentary dolomites with coarse holocrystalline texture collected a short distance below the Moine Thrust at Loch an Nid (Sheet 92), where no igneous rock outcrops within a considerable distance of the beds. It is possible that the Loch Ailsh rocks have been recrystallised, as these rocks appear to have been, by some agency other than thermal metamorphism. The dolomites elsewhere in Assynt, however, are not crystalline and considering the proximity of the plutonic mass and the presence of thin veins of syenitic composition in the Loch Ailsh dolomites, the writer favours the view that the rocks were recrystallised by low-grade thermal metamorphism.

A gradation can be traced (Plates X, XI) from rocks in which the grains are clear, with interlocking boundaries /

boundaries and few deformation lamellae (Plate X a), through rocks showing increasing marginal granulation of grains and greater development of deformation lamellae (Plates Xb, XIa), to rocks consisting entirely of minute granules (Plate XIb). In the intermediate stages the degree of marginal granulation is in general proportional to the frequency of the lamellae present. These phenomena are produced by intergranular and intragranular movement and it is evident that the series shows increasing grades of dynamic metamorphism.

More than 60 specimens, collected in traverses across the dolomite, were examined under the microscope to determine whether the comparatively fine grain of the rock is a property of the initial crystalline fabric or a product of post-crystalline granulation. In most of the rocks the degree of granulation is not great, suggesting that the crystalline dolomite was initially fine-grained. The degree of granulation, though locally variable, increases, in general, towards the Moine Thrust. Of 14 specimens showing complete granulation, 11 were collected within 100 feet of the Thrust and complete disruption of the grains appears to be general in this zone.

The results of a detailed fabric analysis of six specimens are given below. Specimen M1, from Loyne, north of Cnoc /

Cnoc na Sroine, was selected for analysis as it was the only available specimen showing no marginal granulation of grains and negligible development of deformation lamellae. The remaining five specimens, from the Loch Ailsh area (Localities M13, 14, 15, 17 and 18 in figure 16), were selected on account of their comparatively coarse grain, the majority of the rocks in the area being too fine-grained for fabric analysis. In all the specimens $[0001]$ -axes were measured in at least 300 grains and a detailed analysis of the lamellar ~~z~~ structures was carried out in specimens M14, M15, M17 and M18. Lamellae which are inclined at low angles (less than 35°) to a section are not accessible for measurement with the universal stage, on account of the limited rotation obtainable about the horizontal axes of the stage. Since the three $\{02\bar{2}1\}$ planes in dolomite are inclined to each other at 80° , one set of lamellae is commonly inaccessible for measurement. This limitation was overcome by measuring lamellar structures in three mutually perpendicular sections from each specimen. It should be noted that L9 lamellae can be recorded satisfactorily only if the intersection $[L9: 02\bar{2}1]$ can be rotated into parallelism with the microscope axis. Consequently, in any section L9 lamellae can be measured only in grains with a limited range of orientation. The range of orientation of grains in which two sets of L9 lamellae can be /

be measured is obviously further restricted. Thus, in order to obtain a reliable statistical picture of the orientation of L9 lamellae in a rock it is necessary to examine a number of sections with different orientation.

Specimen M1 differs from the Loch Ailsh specimens in containing forsterite and small amounts of calcite. The two minerals are concentrated in layers which almost certainly represent the original bedding-planes in the rock. The pure dolomitic layers in the rock are equigranular and the grains show interlocking boundaries and almost complete absence of post-crystalline deformation (Plate X a). The preferred orientation of $[0001]$ -axes, measured in 300 grains, is shown in figure 24 a. The pattern of preferred orientation is a diffuse girdle about an almost vertical axis. The plane of the girdle coincides with the orientation of the foliation which is defined by the forsterite-rich layers.

The specimens from Loch Ailsh are massive, with no trace of foliation or lineation. They show varying degrees of post-crystalline deformation. In all the specimens there is considerable development of $\{02\bar{2}1\}$ -lamellae and in specimens M14 /

This rock shows a higher grade of thermal metamorphism than the Loch Ailsh specimens. The textures in the forsterite-rich layers suggest that the mineral was formed by combination of silica in clastic quartz grains with magnesia from the surrounding dolomite, leaving the accessory calcite (Teall, 1907; Pheister, 1926).

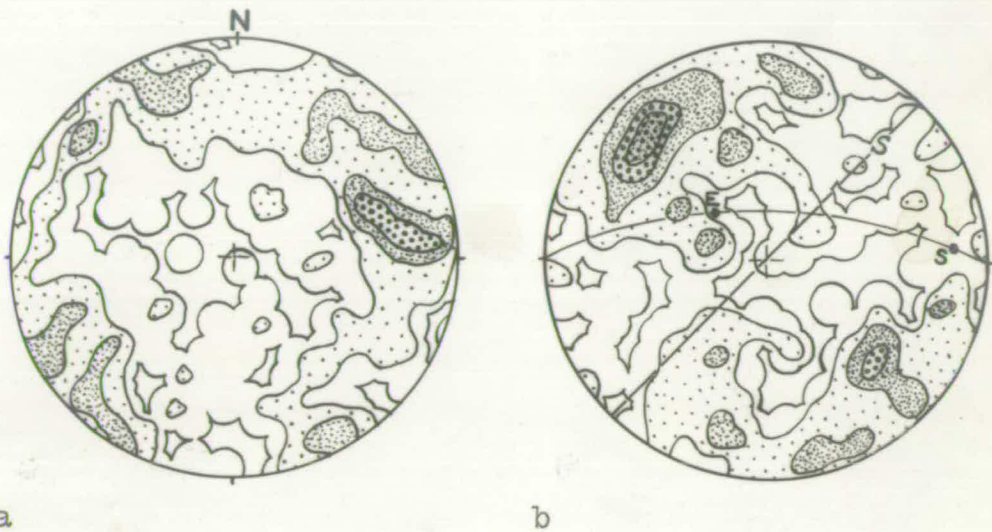


Figure 24.

a. 300 $[0001]$ axes of dolomite in specimen M1.
 Contours: $\frac{1}{3}$, 1, 2, 3% per 1% area.

b. 300 $[0001]$ axes of dolomite in specimen M13.
 Contours: $\frac{1}{3}$, 1, 2, 3, 4% per 1% area.

M14, M15, M17 and M18 twinning on $\{02\bar{2}1\}$ is optically recognisable in a number of grains. Tables I and II contain an analysis of the lamellae present in each specimen: "twinned" and "non-twinned" lamellae are not distinguished in Table I; Table II shows the proportion of grains with "twinned" lamellae in each specimen. Although optically recognisable twinning is present in a limited proportion of the grains in each specimen, the majority of the grains in all the specimens contain two or three sets of $\{02\bar{2}1\}$ lamellae. The percentage of granulated material in each specimen, measured by means of a point counter in three specimens, is shown in Table III.

The preferred orientation of $[0001]$ -axes in 300 grains in specimen M13 is shown in figure 24b. There is a high degree of preferred orientation, with a single area of high concentration containing two distinct maxima. Optically recognisable twin-lamellae are sparsely developed in this specimen and are not recorded.

Figure 25a shows the orientation of $[0001]$ -axes in specimen M14. The diagram is based on 300 measurements made in three mutually perpendicular sections, 100 in each section. A strong similarity in the partial diagrams from individual sections indicates a high degree of homogeneity on the scale of the specimen. As in specimen M13, the pattern is a single area /

TABLE I

Analysis of $\{02\bar{2}1\}$ lamellae in the Loch Ailsh dolomite specimens

Specimen No.	M14	M15	M17	M18
Grains containing three sets of $\{02\bar{2}1\}$ lamellae	71%	36%	48%	60%
Grains containing two sets of $\{02\bar{2}1\}$ lamellae	25%	52%	30%	32%
Grains containing one set of $\{02\bar{2}1\}$ lamellae	4%	5%	18%	8%
Grains containing no $\{02\bar{2}1\}$ lamellae	0	7%	4%	0

TABLE II

Analysis of twinned $\{02\bar{2}1\}$ lamellae in the Loch Ailsh dolomite specimens

Grains containing three sets of twinned $\{02\bar{2}1\}$ lamellae	0	0	0	0
Grains containing two sets of twinned $\{02\bar{2}1\}$ lamellae	1%	25%	7%	5%
Grains containing one set of twinned $\{02\bar{2}1\}$ lamellae	19%	33%	30%	31%
Grains containing no twinned $\{02\bar{2}1\}$ lamellae	80%	32%	63%	64%

N.B. The data in the tables are based on grains in which all three $\{02\bar{2}1\}$ planes were accessible for measurement.

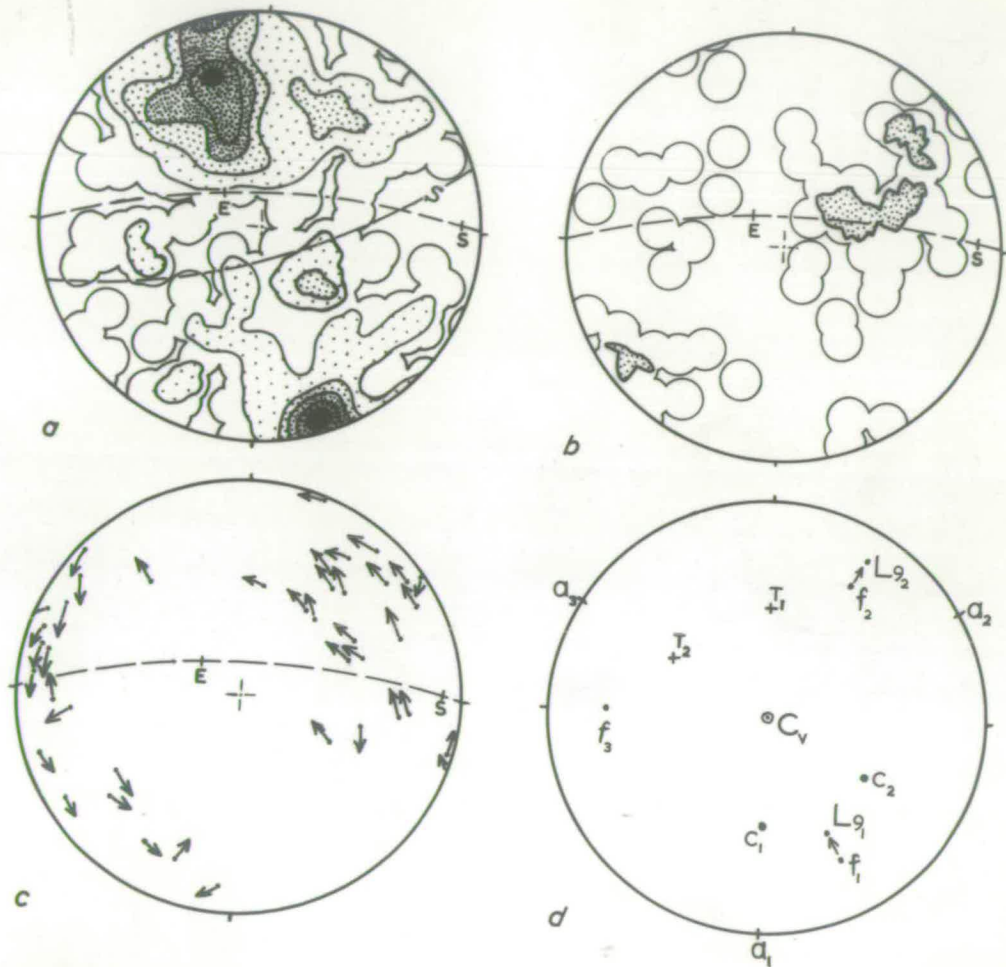


Figure 25.

a. Specimen M14. 310 $[0001]$ axes of dolomite.
Contours: $\frac{1}{3}, 1, 2, 3, 4, 5\%$ per 1% area.

b. Specimen M14. Poles of 60 twinned $\{02\bar{2}1\}$ lamellae.
Contours: $1\frac{1}{2}, 5\%$ per 1% area.

c. Specimen M14. Poles of $\{02\bar{2}1\}$ lamellae (points) and associated L9 lamellae (arrow-heads) observed in 37 grains.

d. Diagram showing the position of $\{02\bar{2}1\}$ lamellae (f) and L9 lamellae in the dolomite lattice. For fuller explanation see text.

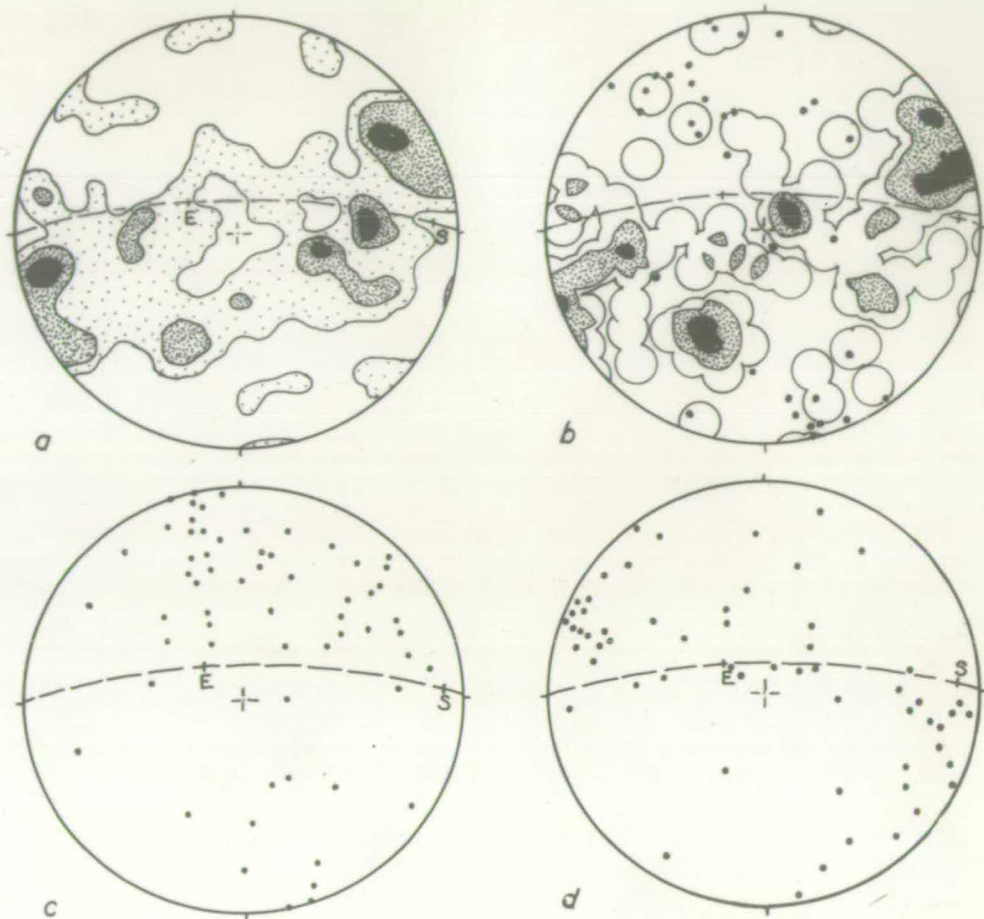


Figure 26.

a. 300 \underline{a} crystallographic axes from 100 unselected grains in specimen M14. Contours: 1, 2, 3% per 1% area.

b. The orientation of the lattices in 34 grains containing L9 lamellae in specimen M14. Points represent [0001] axes. Contours show the distribution of the \underline{a} crystallographic axes in the same grains: 1, 3, 5% per 1% area.

c. [0001] axes of the host lattices in 59 twinned grains in specimen M14.

d. [0001] axes of the twinned lattices in the same 59 grains in specimen M14.

area of concentration containing two maxima, approximately 30° apart; the maxima in M14 are of equal strength, unlike those in specimen M13. The orientation of the a crystallographic axes is restricted by the strong preferred orientation of the $[0001]$ -axes. The a-axes are disposed in a broad zone normal to the maxima of $[0001]$ -axes (Fig. 26a), with a high concentration near the periphery of the diagram.

There is a strong development of $\{02\bar{2}1\}$ lamellae in the grains, as the photomicrograph (Plate XI a) shows. The orientation of recognisably twinned lamellae, measured in three sections, is shown in figure 25b. The poles of the lamellae are concentrated in a single maximum. L9 lamellae were recorded in 35 grains in the three sections examined. These lamellae (Plate XII) differ from $\{02\bar{2}1\}$ lamellae in being less sharply defined; they have a discontinuous, granular appearance and accurate measurement of their orientation is consequently more difficult than measurement of twin lamellae and cleavages. L9 lamellae may frequently be recognised by this characteristic granular appearance, but this is not invariably possible and to avoid errors of identification they were recorded only in those grains containing lamellae parallel to the corresponding $\{02\bar{2}1\}$ plane, as illustrated in the photomicrographs /

photomicrographs. In the experimentally deformed Dover Plains dolomite only one set of L9 lamellae were recorded in any grain, but two sets of L9 lamellae are present in four of the grains analysed in specimen M14. Figure 25 c shows the orientation of the L9 and associated $\{02\bar{2}1\}$ lamellae in the specimen: all but two of these sets of L9 lamellae were measured in the section with the same orientation as the diagram. The angle between L9 and $[02\bar{2}1]$ varies between 5° and 12° , with a mean value of $8\frac{1}{2}^\circ$, a figure which is comparable with that obtained in the deformed Dover Plains dolomite. The sense of rotation of $[02\bar{2}1]$ to L9 is statistically constant in the diagram.

The pattern of $[0001]$ -axes in the rock is that of an S-tectonite (Ladurner, 1953); there is a statistically defined s-plane (S) normal to the maximum of $[0001]$ -axes. The elongation of the inequidimensional grains in the sections, described above, is approximately parallel to the trace of this s-plane in each section. This dimensional orientation is, however, very weak.

The orientation of $[0001]$ -axes in 300 grains in specimen M15 is shown in figure 27 a. The pattern is that of a B-tectonite, belonging to Type III of Ladurner's classification. The maxima in the broad girdle do not lie in the ac plane /

Figure 27.

a. Specimen M15. 300 [0001] axes of dolomite.
Contours: $\frac{1}{3}$, 1, 2, 3, 4% per 1% area.

b. Specimen M15. Poles of 106 twinned {02 $\bar{2}$ 1}
lamellae. Contours: 1, 3, 6% per 1% area.

c. Specimen M17. 300 [0001] axes of dolomite.
Contours: $\frac{1}{3}$, 1, 2, 3% per 1% area.

d. Specimen M17. Poles of 66 twinned {02 $\bar{2}$ 1}
lamellae. Contours: $1\frac{1}{2}$, $4\frac{1}{2}$ % per 1% area.

e. Specimen M18. 300 [0001] axes of dolomite.
Contours: $\frac{1}{3}$, 1, 2, 3, 4, 5% per 1% area.

f. Specimen M18. Poles of 62 twinned {02 $\bar{2}$ 1}
lamellae. Contours: $1\frac{1}{2}$, $4\frac{1}{2}$ % per 1% area.

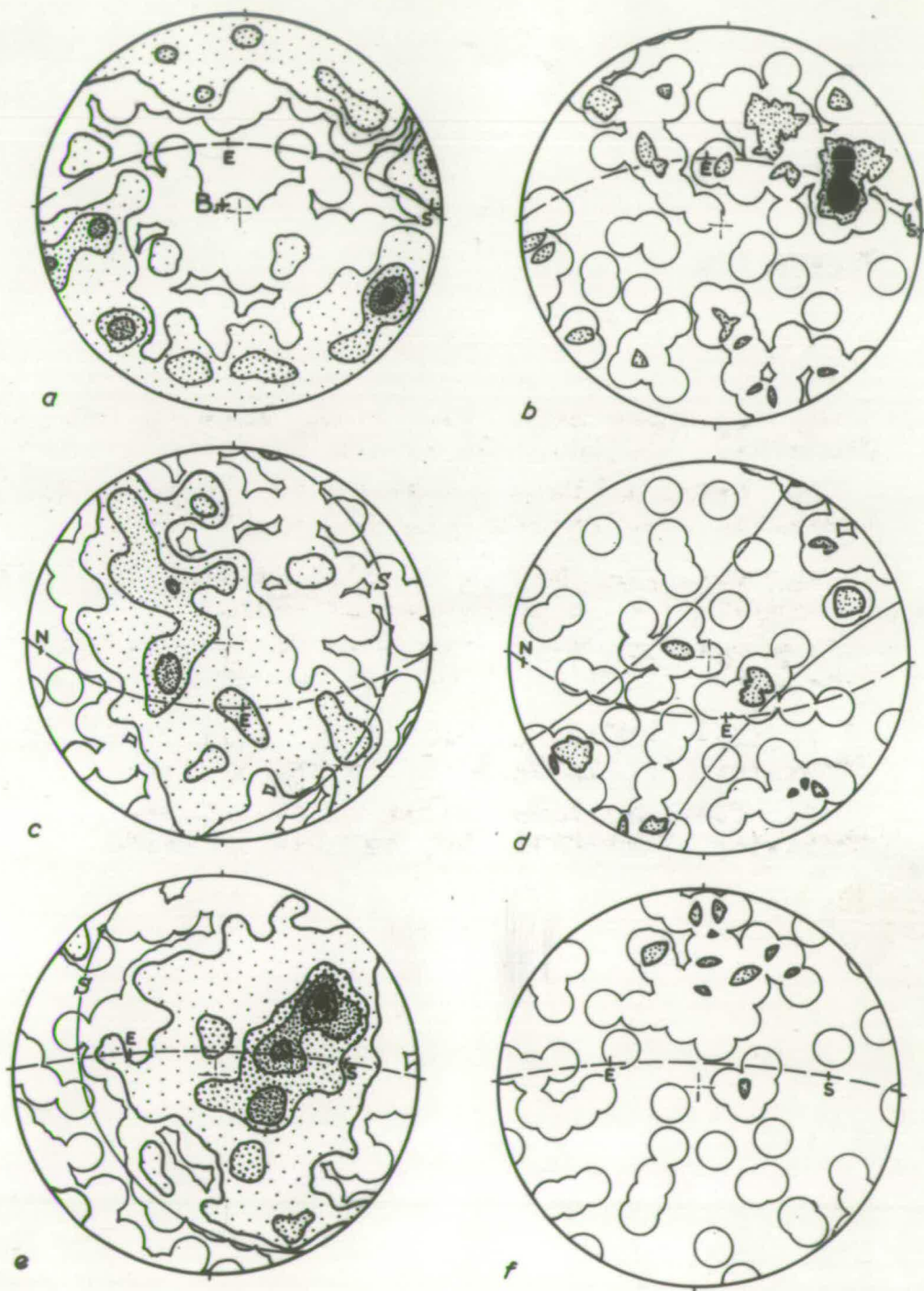


Figure 27.

plane of the fabric, but are inclined at approximately 20° to it.

$\{02\bar{2}1\}$ lamellae are present in most of the grains in this specimen, but the distance between individual lamellae in the majority of grains is much greater than in specimen M14; despite this paucity of lamellae, however, optically recognisable twinning is present in a greater proportion of the grains. Figure 27b shows the orientation of $\{02\bar{2}1\}$ lamellae in the rock, measured in three sections. There is a moderately strong preferred orientation, the poles of the lamellae defining a single maximum, similar in character and orientation to that in the equivalent pattern for specimen M14. L9 lamellae are present in too small a proportion of grains in specimens M15, M17 and M18 for a statistical analysis to be made.

The preferred orientation of $[0001]$ -axes in specimen M17 is shown in figure 27c. The pattern of preferred orientation is similar to that in specimens M13 and M14, in that it shows two closely spaced maxima. The axes in specimen M17, however, show a tendency to spread into a girdle about a northward plunging axis. The orientation of twinned lamellae measured in three sections from the specimen is shown in figure 27d. The poles of the lamellae are disposed in a broad girdle, but the preferred orientation is weak.

Figure 27e shows the preferred orientation of $[0001]$ -axes /

[0001]-axes in specimen M18. The pattern of preferred orientation is of the S-tectonite type, with a single area of concentration containing two maxima, again approximately 30° degrees apart. In two of the three sections examined, as has already been noted, there is a parallelism of elongate grain-sections. The direction of elongation in each section is again approximately parallel to the trace of the g-plane which is defined by the orientation of [0001]-axes. The orientation of twinned {02 $\bar{2}$ 1} lamellae measured in three mutually perpendicular sections is shown in figure 27 f. The degree of preferred orientation is weak, but the poles of the lamellae tend to lie in a single maximum, as in specimens M14 and M15.

d. Interpretation and conclusions Since there is no evidence of post-crystalline deformation in specimen M1, the rock has obviously been recrystallised in the late stages of its metamorphic development. The preferred orientation may reflect an anisotropy in the precrystalline fabric, reproduced mimetically by recrystallization, or it may have been produced in the course of recrystallization (i.e. the fabric may be a growth fabric). There are certain facts which suggest that the girdle of [0001]-axes is not a B-tectonite girdle: whereas all the B-axes measured in the Assynt area are almost horizontal, the /

the axis of the girdle is almost vertical. The plane of the girdle is, moreover, parallel to the bedding-foliation in the specimen. In view of this parallelism the writer considers that the girdle is genetically related to the foliation.

There are two possible ways of accounting for this relationship:

- (1) the preferred orientation of $[0001]$ -axes may reflect a similar preferred orientation in the depositional fabric of the dolomite, which has been reproduced by recrystallization;
- (2) the preferred orientation may be due to the influence of the bedding during recrystallization of the rock: the metamorphic changes involved in the production of forsterite from quartz in the impure layers may have exerted a control over the direction of growth of the dolomite crystals.

Compression and tension axes most favourably oriented to produce twin-gliding in grains with recognisably twinned lamellae and translation-gliding in grains with L9 lamellae are shown in figures 28 and 29 .

The axes of compression and tension which would be most effective in causing the twinning in specimen M14 are shown in figure 28a. There is a strong concentration of both compression and tension axes and it is clear that a strong compression parallel to the axis C and a tension parallel to the axis T could account for the observed twinning. Figure 28 b shows the glide lines (a) and axes of compression (C) and tension (T) deduced for four grains in which two sets of L9 lamellae were recorded. /

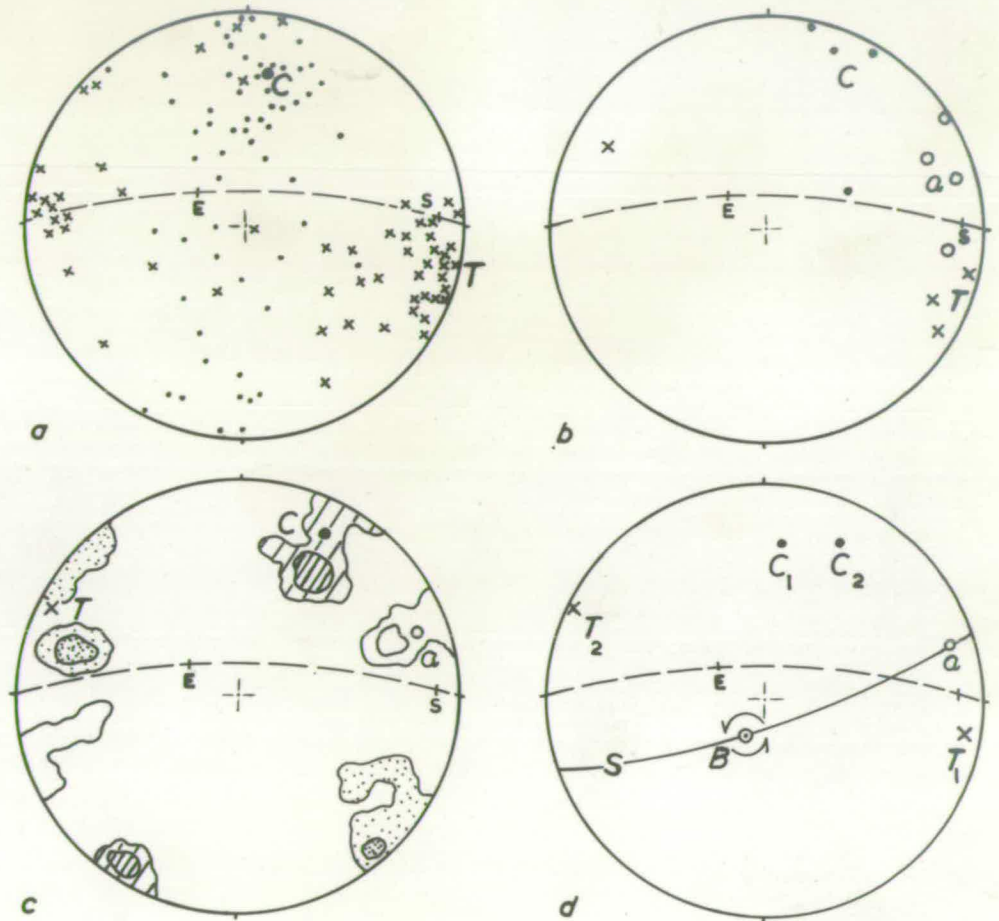


Figure 28.

a. Axes of compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on twinned $\{02\bar{2}1\}$ lamellae observed in specimen M14.

b. Active glide lines (circles) and axes of compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for translation-gliding on $\{000\}1$ in grains containing two sets of L9 lamellae in specimen M14.

c. Synoptic diagram showing maxima of possible glide-lines (\underline{a}), tension axes (\underline{T}) and compression axes (\underline{C}) inferred for 31 grains in specimen M14 containing one set of L9 lamellae. Contours: 10%, 5% per 1% area.

d. Kinematic and dynamic interpretation of the data for specimen M14. \underline{S} is a slip-plane defined statistically by $\{000\}1$; \underline{a} and \underline{B} are kinematic axes inferred from the orientation of the L9 lamellae. \underline{C}_1 , \underline{T}_1 and \underline{C}_2 , \underline{T}_2 are stress axes inferred from twinning and translation-gliding respectively.

Figure 29.

a. Axes of compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on twinned $\{02\bar{2}1\}$ lamellae observed in specimen M15.

b. Axes of compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on twinned $\{02\bar{2}1\}$ lamellae observed in specimen M17.

c. Axes of compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on twinned $\{02\bar{2}1\}$ lamellae observed in specimen M18.

d. Synoptic diagram showing geometric and kinematic data for the analysed dolomite specimens. S_{13} , S_{17} and S_{18} are s-planes statistically defined by the preferred orientation of $\{0001\}$; B_{15} is a fabric axis, similarly defined. B_{14} is a kinematic E-axis inferred from the data for specimen M14.

e. Synoptic diagram showing axes of compression (C) and tension (T) inferred from the data for specimens M14, M15, M17 and M18.

f. Synoptic diagram showing maxima of $[0001]$ axes of dolomite in specimens M13, M14, M15, M17 and M18. Contours: 5, 4, 3% per 1% area. Cross-hatched maxima are from specimen M17 (3% per 1% area).

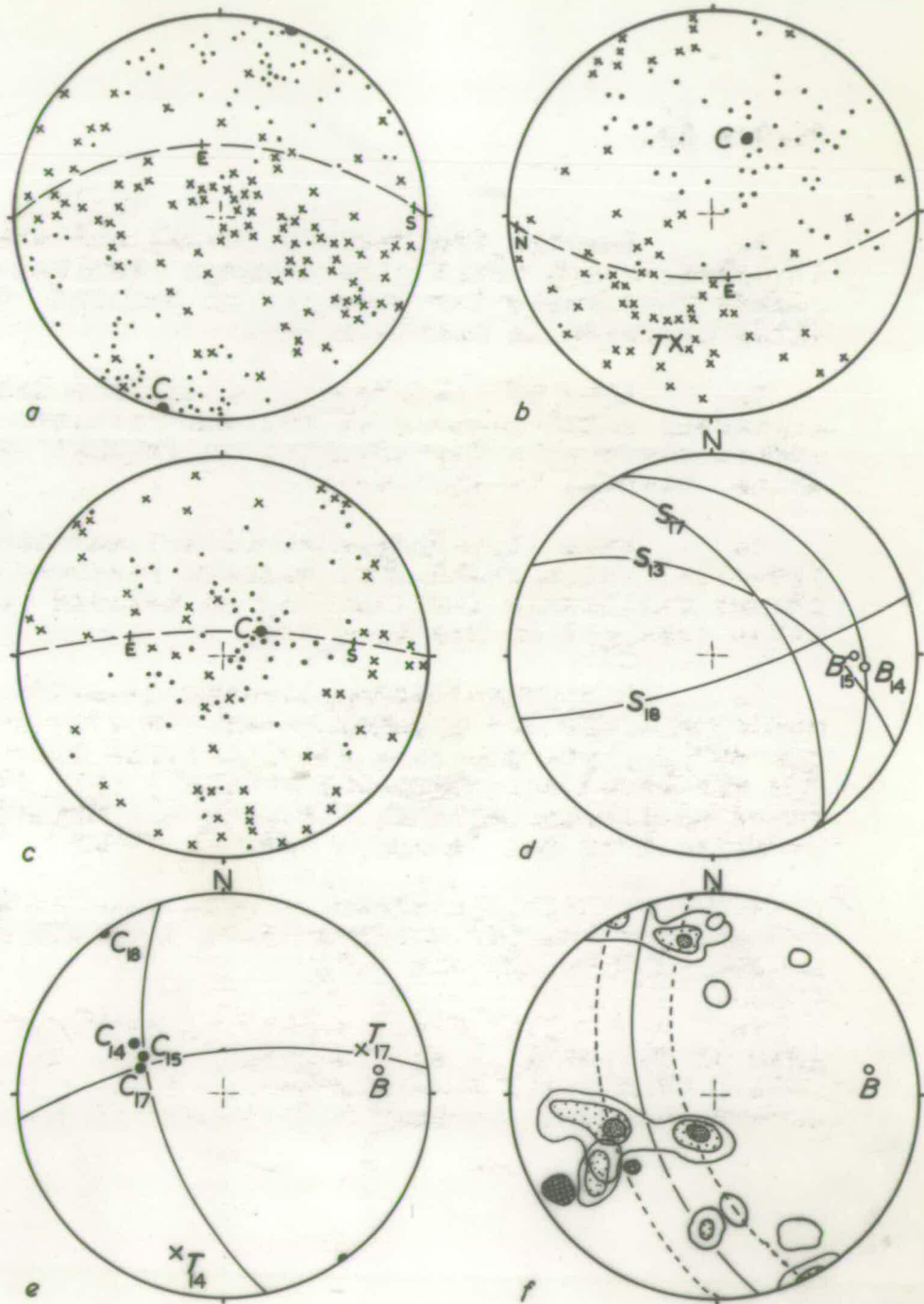


Figure 29.

recorded. For the 31 grains with one set of visible L9 lamellae the 62 possible glide lines are shown contoured in figure 28c. (unshaded contours). It is probable that the active glide lines in the grains lie near the centre of the single maximum (a in the figure). The possible axes of compression (shaded contours) and tension (stippled contours) deduced for the 31 grains are also shown in figure 28c. The maxima of possible glide lines (a) and axes of compression (C) and tension (T) in figure 28c have an orientation similar to the glide lines and axes of compression and tension inferred for grains with two sets of L9 lamellae (Fig. 28 b). The axes of compression and tension most favourably oriented to produce the twinning in the rock (respectively C_1 and T_1 , Fig. 28d) are subparallel to the axes of compression and tension most favourably oriented to produce the translation-gliding (respectively C_2 and T_2).

A comparison of the diagrams showing the preferred orientation of the lattice in unselected grains in specimen M14 (Figs. 25a and 26a) with ^{the} _^ diagram showing the orientation of the lattice in grains with L9 lamellae (Fig. 26b) reveals that statistically the orientation of grains with L9 lamellae is the same as that of unselected grains. This would suggest that all or many of the grains in the rock may have undergone some degree of translation-gliding on {0001}. The absence of L9 /

L9 lamellae does not indicate that translation has not taken place, since L9 lamellae are only produced if suitably oriented $\{02\bar{2}1\}$ lamellae are present in a grain before the inception of gliding on $\{0001\}$. Thus the g-plane, defined statistically by the orientation of $\{0001\}$, also represents a statistical slip-plane (Fig. 28 d). The kinematic a-axis in this slip-plane is given by the preferred orientation of the active glide-lines (a) and the kinematic B-axis is normal to a in the slip-plane. The orientation of $[0001]$ in this specimen is similar to that in the Claire River dolomite, described by Fairbairn and Hawkes (1941). The kinematic axes in specimen M14, determined from the orientation data, have the same orientation with reference to the pattern of $[0001]$ -axes as the fabric axes in the Claire River rock, which are determined from megascopic fabric features.

The axes of compression and tension most favourably oriented to produce the observed twinning in specimen M15 are shown in figure 29a. There is a strong concentration of compression axes about C, while the tension axes are distributed in a girdle normal to C; there is no concentration of tension axes in the girdle. The twinning in the rock must have been produced by a strong compression applied parallel to C. This inference is confirmed by a consideration of the effect of compressive /

compressive and tensile stresses on the dolomite lattice. The geometry of the dolomite lattice is such that a compression applied subparallel to $[0001]$ will tend to produce twin-gliding simultaneously on two or three of the $\{02\bar{2}1\}$ planes. But if a tensile force is applied normal to $[0001]$ in such a way as to give high resolved shear stress on one $\{02\bar{2}1\}$ plane the resolved shear stress on the other two $\{02\bar{2}1\}$ planes will be low and twin-gliding will take place on only one set of $\{02\bar{2}1\}$ lamellae. Thus we might expect to find two or three sets of twin lamellae in each grain in rocks which have been deformed by compression, whereas tension should give a fabric in which most grains have only one set of twin lamellae. The presence of two or three sets of L9 lamellae in the majority of grains in specimens M14, M15, M17 and M18 indicates that the rocks have been deformed by compression. Although $02\bar{2}1$ lamellae are common in the rocks, a relatively small proportion of grains show optically recognisable twinning on more than one set of lamellae. It is well known that twin-gliding on $\{01\bar{1}2\}$ in calcite may be produced with the aid of a penknife, but all attempts to produce twinning on $\{02\bar{2}1\}$ in dolomite at room temperature have failed. Moreover, the experimental deformation of Dover Plains dolomite at 380°C . and 3000 atmospheres confining stress showed that dolomite is less ductile and three times /

times as strong as Yule marble deformed under comparable conditions. Under these conditions the plasticity of dolomite is closer to that of basalt or granite than that of marble. The scarcity of optically recognisable twinning in the grains may be attributed to the fact that a high resolved shear stress on $\{02\bar{2}1\}$ is necessary for twinning to proceed.

The axes of compression and tension most favourably oriented to produce the observed twinning in specimen M17 are shown in figure 29b. There is a strong preferred orientation of both compression and tension axes with maxima at C and T respectively. It is noticeable that there is a stronger concentration of compression axes than of tension axes, as in specimen M15.

The compression and tension axes suitably oriented to produce the twinning in specimen M18 are shown in figure 29c. The compression axes are concentrated about C and the tension axes are scattered in a diffuse girdle normal to C.

Figure 30 illustrates diagrammatically the changes of lattice orientation and shape in a dolomite grain undergoing plastic deformation by twin-gliding on $\{02\bar{2}1\}$ (Figs. b and c) and translation-gliding on $\{0001\}$ (Figs. d, e and f). Figure 30b represents a grain with circular cross-section in which one /

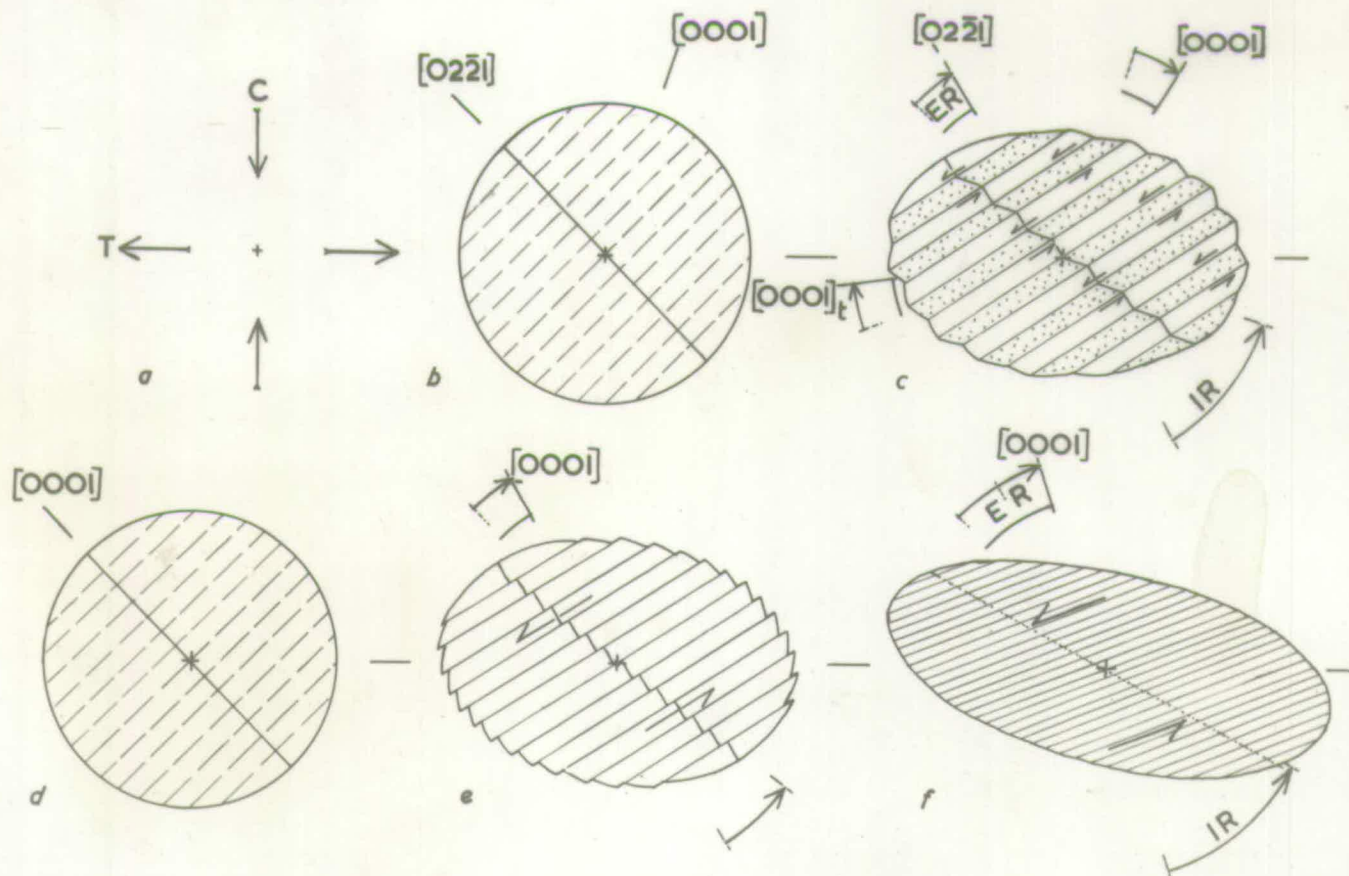


Figure 30. Diagrammatic representation of the mechanism of deformation of dolomite by translation-gliding on $\{0001\}$ and twin-gliding on $\{0221\}$. For explanation see text.

one set of $\{02\bar{2}1\}$ lamellae are favourably oriented with reference to the stress system (Fig. 30a) for twin-gliding to take place. The partially twinned grain is shown in the next diagram (30c). The sense of internal rotation in the twinned layers, shown by the distortion of the line $[02\bar{2}1]$, is anti-clockwise. In response to the gliding there is also external rotation of the grain in a clockwise sense (Turner, Griggs and Heard, 1954, p. 898). The whole lattice is rotated in this sense and it is evident from the diagram that the $[0001]$ -axes in both the host lattice and the twinned lattice are rotated away from the axis of compression. The grain tends to become elongated parallel to the axis of tension. Figure 30d shows a grain suitably oriented for translation-gliding on $\{0001\}$. The internal rotation of passive structures in response to deformation is again anti-clockwise and the external rotation of the lattice is clockwise. Since there is no internal reorientation of the lattice in translation-gliding the $[0001]$ -axis tends to rotate towards the axis of compression. The change of shape is similar to that produced by twin-gliding. Consequently, in an aggregate of dolomite crystals with random orientation subjected to compression, translation-gliding on $\{0001\}$ would tend to give a concentration of $[0001]$ close to the axis of compression, while twin-gliding would tend to give the opposite /

opposite effect, a migration of $[0001]$ from the axis of compression. If these are the only two mechanisms of deformation in dolomite, the final pattern of preferred orientation would depend solely on which of the two types of gliding was produced with the greatest ease.

Since specimen M14 has yielded considerable evidence of both twin-gliding and translation-gliding, the fabric of the specimen deserves further consideration. Attention has already been directed to the similarity of the lattice orientation of grains with L9 lamellae to that of unselected grains, suggesting that many of the grains in the specimen may have deformed to some extent by translation on $\{0001\}$. On the other hand, the orientation of $[0001]$ in grains containing recognisably twinned $\{02\bar{2}1\}$ lamellae is restricted (Fig. 30 c) and differs from the orientation in unselected grains (Fig. 25a). The very restricted orientation of the twinned lamellae shows that the resolved shear stress on $\{02\bar{2}1\}$ must be high before twin-gliding can proceed. Obviously twinned lamellae are present, moreover, in only 20% of the grains. The evidence of the fabric, then, would suggest that translation-gliding on $\{0001\}$ was more important than twin-gliding on $\{02\bar{2}1\}$ during the final stages of deformation of the rock.

In /

In view of the extreme post-crystalline deformation in specimen M14 and the high degree of consistency in the dynamic inferences based on both twinned $\{02\bar{2}1\}$ and rotated L9 lamellae, the writer believes that the preferred orientation of the grain lattices in the fabric was produced, or at least modified, by the movements which caused the visible twinning and rotation of lamellae. Some degree of translation-gliding on $\{0001\}$ in most of the grains would not seriously affect the existing pattern of preferred orientation of the lattices. The observed twinning, however, is tending to disrupt the existing orientation, as the diagrams (figures 26c and d) indicate. It is almost certain that the orienting mechanism in the rock was a complex interaction of the two types of gliding, combined with external rotation of the grains: the grains probably translated on $\{0001\}$ and rotated externally until the resolved shear stress on a $\{02\bar{2}1\}$ plane was sufficiently high for twin-gliding to take place. Such grains would then rotate externally in response to twin-gliding until they were again more favourably oriented for translation on $\{0001\}$. The preferred orientation of the grains in the rock in all probability does not represent a stable condition, but a state of equilibrium in which the effects of translation-gliding on $\{0001\}$ counteract those of twin-gliding on $\{02\bar{2}1\}$.

The /

The geometrical and dynamic data from the analysed specimens are summarised in the synoptic diagrams 29 d, e and f. Figure 29 d shows the orientation of the \underline{s} -planes defined by the preferred orientation of $[0001]$ -axes in specimens M13, M14, M17 and M18 and the \underline{E} -axis similarly defined in specimen M15. The kinematic \underline{E} -axis deduced from the data in specimen M14 is also shown for comparison. With the exception of \underline{S}_{17} , the \underline{s} -planes intersect close to \underline{E}_{14} and \underline{E}_{15} , which are parallel to maximum of the β -diagram, lineations and the axes of most of the megascopic folds in the rocks (Fig.17). Thus the fabric on a microscopic scale is consistent with that on the larger scales observable in the field, and may be assumed to reflect the same movements.

Figure 29 e shows the axes of compression and tension deduced from the orientation data in specimens M14, M15, M17 and M18. The axes of compression and tension for specimens M14, M15 and M18 lie close to the great circle normal to \underline{E} , indicating that the twinning and translation-gliding in these rocks was produced by a deformation similar to that which caused the visible megascopic folding and the grain orientation. The axes of compression for three of the specimens (M14, M15 and M17) are almost coincident, plunging steeply towards the west, that is, normal to the foliation over most of the area. It /

It has already been demonstrated that the twinning in the rocks was caused by compression and the parallelism of the compression axes in three of the four specimens suggests that the whole region was subjected to a powerful compression along this axis.

The fabric of specimen M17 has so far been omitted from this discussion as the symmetrological and dynamic evidence from this specimen is not consistent with that from the other specimens. The pattern of preferred orientation of $[0001]$ in the rock is similar in most respects to that in the other \underline{S} -tectonites, but the \underline{g} -plane is not cozoal with the \underline{g} -planes in the other specimens (Fig. 29 d) and there is a slight spread of the $[0001]$ -axes into a girdle about a north-plunging axis. The twinning in the rock, moreover, reflects a deformation in which the axes of maximum and minimum principal stress lay in a plane with east-west strike. The \underline{B} kinematic axis associated with this deformation-plane would have a north-south trend. It is possible that the \underline{g} -plane in specimen M17 was originally cozoal with those in the other specimens and was subsequently rotated by movement about this axis.

Table III shows the degree of preferred orientation of $[0001]$ -axes in the fabric of each specimen and the proportion of granulated material present. The degree of preferred orientation is given in terms of the size of the 'pole-free area' (Ladurner /

TABLE III

Table showing grain-size, degree of granulation and degree of preferred orientation of the dolomite lattice in the Loch Ailsh dolomite specimens.

Specimen No.	M13	M14	M15	M17	M18
Mean diameter of grain sections (in mms.) ...	0.45	0.54	0.42	0.37	0.40
Degree of granulation ...	10%	27.5	25%	35%	29%
Areal analysis of preferred orientation of [0001] (in sq. cms. on net of 10 cms. radius) ...					
Pole-free area ...	51.5	60.5	41.5	46.3	46.1
Areas (5% per 1% area ...)	0	1.4	0	0	0.4
of (4% per 1% area ...)	5.6	7.8	0	0	3
Maxima: (3% per 1% area ...)	9.2	21.7	5	2	12

(Ladurner, 1953, p. 284) and the maxima, measured on the original contoured diagrams (net of 10 cms. radius) with a planimeter. The importance of the pole-free area in comparing the degree of preferred orientation in different specimens of carbonate rocks has been pointed out by Ladurner. The pole-free areas, together with areas of high concentration, afford a reliable basis for comparing the degree of preferred orientation of a fabric element in a number of rocks, provided that (a) the orientation patterns are similar and (b) the same number of recordings is considered for each rock. The degree of preferred orientation of [0001] in specimens M13, M14, M17 and M18 may be compared in this way, since the diagrams fulfil both these conditions. It is evident that there is no correlation between the strength of the preferred orientation and the degree of granulation in the specimens; the degree of granulation in specimen M17 is considerably greater than in the other three rocks whereas the preferred orientation is weaker. This lack of correlation must be due to one of two causes: either the physical conditions varied over the mass during the main phase of deformation and specimen M17 was at a lower temperature or confining pressure than the other specimens, or the specimen was affected by a late phase of post-crystalline deformation unrelated /

unrelated to the main deformation. In view of the evidence of a north-trending B-axis in the specimen, in contrast to the easterly-plunging B-axis in the other rocks, the writer favours the alternative that the granulation dates, at least in part, from a later phase of deformation, which only locally affected the dolomite.

The evidence from ^{the} _λ microfabric of the Loch Ailsh dolomites appears to warrant the following conclusions. The rocks have suffered intensely penetrative deformation with movement about a B-axis plunging to the east; the characteristic grain orientation produced during this phase of deformation is of the S-tectonite type. During or towards the end of this phase of deformation the rocks were strongly compressed along an axis which is normal to the foliation planes over much of the area. This was probably followed by movement about a north-trending B-axis, the effects of which were local in the dolomite. The final conclusion, which is based on the evidence of a single specimen, is advanced tentatively and will be considered in the light of other evidence at a later stage in the discussion (see p. 174).

2. GRAIN ORIENTATION IN THE QUARTZ-BEARING ROCKS

a. Introduction

The rocks on which fabric analysis was carried out vary from pure Cambrian quartzites to micaceous and chloritic quartzo-feldspathic schists, but they all contain more than 50% of quartz. The specimens were collected at the localities shown on the map (Fig. 31). The petrographic characters of the rocks will be described briefly and certain conclusions drawn concerning the sequence of movement and crystallization before the lattice orientations of quartz and mica are described.

b. Petrography

The Cambrian quartzites along the eastern margin of the zone of dislocation show progressive mylonitization towards the Moine Thrust. Plate XIIIa shows a slightly deformed quartzite, without foliation or lineation, in which the clastic grains of quartz are considerably flattened; the grains show undulose extinction and development of deformation lamellae and there is granulation along grain boundaries and in zones cutting the rock. In the more intensely deformed, foliated and lineated quartzites (Plate XIVa & b) the granulation is more advanced and the dimensional orientation of the relict grains is much stronger: the ratio of the grain dimensions is of the order of 1 : 10 : 100, the /

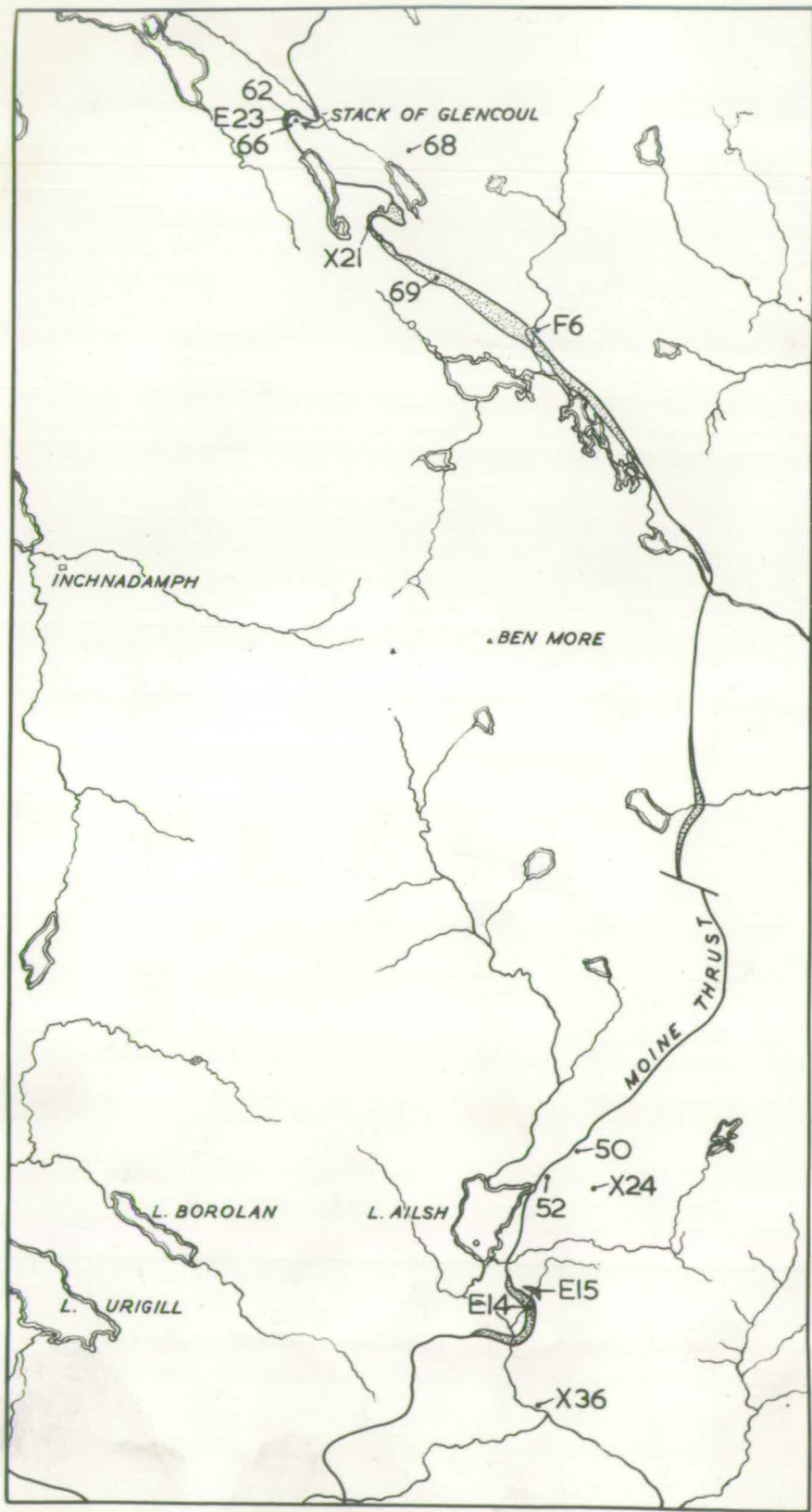


Figure 31.

Map showing localities of the analysed specimens of quartz-bearing rocks.

the shortest axis being normal to the foliation and the longest parallel to the lineation. The grains show intense undulose extinction in bands sub-parallel to {0001}, but deformation lamellae are absent. Close to the Moine Thrust the mylonitic textures are obliterated by recrystallization: the rocks consist of an equigranular (granoblastic) aggregate of quartz grains, which, though small, show no trace of ruptural strain (Plate XIIIb). The dimensional orientation in these rocks is weak compared with that in the quartzites described above but the grains are slightly flattened in the foliation and elongate parallel to the lineation. These two types of quartzites, one showing intense ruptural breakdown and granulation of grains and the other showing post-kinematic crystallization, will be referred to as "Quartzites of Type I and Type II" respectively.

The primary mylonitic rocks consist essentially of quartz and feldspars in variable proportions, with chlorite and sericite defining the foliation; some varieties contain epidote, sphene and pyrite as accessory minerals. In the majority of the rocks crystalloblastic textures predominate over cataclastic, as has already been noted. Even in the mylonite figured in Plate XV there is some recrystallized quartz and feldspar in the crushed matrix of the rock. In the augen schists (Plate XVIa, b), granulated materials are closely associated /

associated with layers in which granoblastic textures predominate. The blastomylonites (Plate XVIc, d) and quartzschists, though fine-grained, are completely granoblastic and the grains show no trace of post-crystalline strain. Only the fine grain and the evidence of crushing in the relict augen of feldspar in these rocks (Plate XVIa, b) give an indication of their mode of origin. The dimensional orientation is generally weak and frequently absent; in the more quartzose varieties the grains are flattened normal to the foliation and elongated parallel to the lineation.

The Moine Schists in the area under consideration are quartzo-feldspathic rocks with small amounts of biotite and colourless mica, and traces of accessory minerals. The texture is granoblastic ("granulitic"). The small mica flakes are generally disposed along the intergranular boundaries of the quartz and feldspar grains, but are sometimes partially or wholly enclosed in them; mica flakes are mostly parallel to the foliation but are not concentrated to any great extent in layers and do not impart a fissility to the rocks. The quartz and feldspar show no trace of undulose extinction or granulation. The rocks are texturally similar to the holocrystalline members of the primary mylonitic rocks and differ from them only in being of coarser grain.

Plates XVII and XVIII show the characteristic textures of the secondary mylonitic rocks. The phyllonites of pelitic composition are characterized by lenticular texture (Plate XVIIa, b) and optical parallelism of the chlorite flakes within individual lenticles. In the more quartzose phyllonites and in layers of quartzite in the zones of phyllonite (Plate XVIIc, d) the quartz is completely granulated and shows no trace of recrystallization; feldspars show similar, though less extreme cataclastic breakdown and pulverization. The kakirites and cataclasites (Plate XVIII) also are characterized by granulation of all the minerals; Plate XVIIIa, b shows a kakirite produced by deformation of a primary mylonitic rock, while the final product of this type of deformation is represented by the cataclasite in Plate XVIIIc, d.

It is evident from the foregoing survey of the textures in the mylonitic rocks and schists that, whereas the deformation of the primary mylonitic rocks (including the quartzites of Type II) and schists was pre- or para-crystalline, the deformation of the secondary mylonitic rocks was entirely post-crystalline. The variable amount of granulation in the primary mylonitic rocks is probably due to local variations in the physical conditions during deformation: where the rate of movement was great compared with the rate of recrystallization the /

the rocks would yield by granulation of the minerals and differential movement of the granules (direct componental movement), whereas if the rate of movement was slow, the rocks would deform by movement on the ionic scale, i.e. by recrystallization (indirect componental movement; Weiss, McIntyre, Kürsten, 1955, p. 33). However, in addition to these local variations in physical conditions, there was a large-scale difference in conditions between the Moine Nappe and the foreland. The fabric of the quartzites of Type I (see below) is similar to that of the primary mylonitic rocks, suggesting that they were deformed during the primary deformation; the post-crystalline strain in these quartzites reflects a transition from the physical conditions of the "zone of flowage" (Holmes, 1944, pp. 67-70) in the Moine Nappe to those of the "zone of fracture" below the Moine Thrust.^x

The porphyroclastic fragments which survive as "augen" in the primary mylonitic rocks, notably the mylonites and augen schists, invariably consist of feldspar (Plates XV & XVI), as Teall has noted (1918, pp. 2-3). Thus, under the conditions in /

^xNormally fracture phenomena are found at higher levels in the earth's crust than flowage phenomena. However, the "inversion" along the Moine Thrust appears to be reflected also in an upward increase of metamorphic grade in the Moine Schists to the east.

in which these rocks were produced, quartz yielded readily to deformation by granulation and recrystallization, but the larger feldspar grains retained their coherence until deformation became more intense. Under the conditions of the secondary deformation, on the other hand, quartz and feldspar alike deformed by cataclastic breakdown.

c. Fabric Data

The preferred orientation of [0001] axes of quartz, measured in 13 specimens, including Cambrian quartzites, primary mylonitic rocks, Moine Schists, and a quartz vein, and the preferred orientation of [001] axes of mica, measured in the schist specimens, is shown in diagrams D1-D21. In general, the primary mylonitic rocks are too fine-grained to allow satisfactory measurement of the orientation of the quartz grains with the U-stage, even with the highest power lenses available (UM 3 objective), and the analyzed specimens are of slightly coarser grain than average. In the secondary mylonitic rocks the quartz is reduced to a mass of minute granules (Plates XVII and XVIII) and for this reason it is impossible to measure the preferred orientation of quartz in the fabric by optical means. Except in the quartzites of Type I, the quartz grains are free from post-crystalline strain. In the quartzites of Type /

Type I, however, all the grains show a high degree of undulose extinction and the orientation of $[0001]$ varies, in many cases quite considerably, over a single grain. For those grains in which the variation in orientation was slight, the mean orientation of $[0001]$ in the grain was recorded, but where the variation was great, two or three measurements were made.

In the majority of the specimens $[0001]$ axes of quartz were measured in a single section cut normal to the foliation and the lineation. $[0001]$ may be measured in grains with any orientation in a section, but errors may arise through unconscious omission or underselection of grains in which $[0001]$ is normal to the plane of the section and which, consequently, remain in extinction during rotation about the vertical axis of the U-stage. In three of the specimens $[0001]$ axes were measured in two sections cut with different orientation from the specimen and the patterns obtained from each section were found to be essentially similar for all three specimens. Measurement of planar structures with the U-stage, on the other hand, leaves a "blind spot", since planes inclined at low angles to the section cannot be rotated into parallelism with the microscope axis. For this reason, $\{001\}$ cleavages of mica were measured in two mutually perpendicular sections from each of the schist specimens and the diagrams from the two sections were /

were rotated into the same plane and combined; for each of the specimens, however, it was found that the preferred orientation was such that the partial diagrams from different sections did not differ to any great extent.

The specimens may be divided into five groups, four of which correspond to the petrographic types described above. Distinctive characters of the specimens in each group are listed below.

Quartzites of Type I: Specimens 69, 62, E23 and E14 (diagrams D1, D2, D3, D8 respectively).

The rocks are all characterized by a well-developed planar foliation (S) and strong penetrative lineation (L). In specimen 62, the least deformed of the group, the lineation is defined by "pipes" (annelid tubes in the "pipe-rock") which lie with perfect parallel alignment in the plane of the foliation. The "pipes" have a flattened or elliptical cross-section. The porphyroclastic quartz grains in the rocks of this group have a tabular or ribbon-like habit: the average mean grain dimension in the sections normal to the lineation ranges up to 1 mm., while in the most deformed specimen (69) the grains are up to 2 cm. long in the section parallel to the lineation.

Quartzites /

Quartzites of Type II: Specimens X21 and E15 (diagrams D4 and D9 respectively).

Both specimens have a well-developed foliation (S) and lineation (L) and specimen X21 is closely folded about B. The dimensional orientation of the grains is weak; they are slightly flattened in the foliation and elongate parallel to the lineation as in the previous group.

Primary Mylonitic Rocks: Specimens F6 (diagram D6), 50 (diagram D7) and 52 (diagrams D10, D11).

The rocks in this group have a strong platy foliation (S) and rather weak lineation (L). The grains are just within the limits of measurement with the U-stage (average mean grain dimension is less than .01 mm.) but the grains are generally without undulose extinction. Dimensional orientation of the quartz grains is very weak, but similar to that in the quartzites of Type II.

Moine Schists: Specimens 68 (diagrams D13, 14), X24 (diagrams D16, 17, 18) and X36 (diagrams D19, 20, 21).

There is a well-defined foliation in specimen 68, but in specimens X24 and X36 the foliation is weakly developed. Lineation is faint in all three specimens. In specimen X36, in addition to the fine lineation (L₁ = L) generally found in the /

the rocks, there is a crude lineation (L_2), defined by the outcrop of mica flakes on the foliation. The rocks are fine-grained (average mean grain dimension is approximately .05 mm.), and the dimensional orientation of quartz and feldspar is very weak: some of the grains are flattened in the foliation.

Quartz Vein cutting Mylonite: Specimen 66 (diagram D5).

The vein (S_v) belongs to one of the systems of veins which cut the primary mylonitic rocks and schists and is approximately normal to the foliation (S) and lineation (L) in the specimen. The quartz grains in the vein are of variable size (average mean grain dimension .2 mm.) and considerably larger than the grains in the mylonite of the specimen. Some of the grains show undulose extinction and there is a strong dimensional orientation, the short axes of the grains being normal to the foliation in the surrounding mylonite.

The characteristic features of the patterns of preferred orientation of quartz and mica in each of the groups are summarized below. Reference is made in the summary to Sander's synoptic diagram showing the orientation of common maxima of $[0001]$ axes of quartz in S-tectonites (1930, Diagram D61), the essential features of which are reproduced in diagram D22. /

D22. In this diagram Sander plotted the maxima for 19 tectonites, oriented so that the foliation (ab) and the lineation (b) were parallel.^x

Quartzites of Type I

The pattern of preferred orientation of quartz [0001] axes in specimen 69 (D1), the least deformed of the rocks in this group, consists of a girdle normal to the lineation, with high concentrations of axes near the position of maximum II of Sander's diagram. The girdle tends to divide near the pole of the foliation. Diagrams D2 and D3 show a stronger preferred orientation than D1, with very strong maxima corresponding to maximum II of Sander's diagram: the maxima spread into a partial girdle which is divided near the pole of the foliation (S). The orientation diagram for the remaining specimen of the group (D8) shows two almost complete crossed girdles which are equally inclined to the foliation and intersect in an axis normal to the lineation. The strongest maximum is situated near /

^xIt is standard procedure to describe patterns of preferred orientation of quartz and other minerals with reference to fabric axes derived from a study of the megascopic fabric of the specimen. But there is considerable evidence that the quartz orientation in the rocks discussed here was not produced at the same time as the foliation and folding and the present writer, for this reason, has not followed this procedure.

near the intersection of the girdles (maximum I of Sander's diagram) and numerous sub-maxima occur within the girdles. The symmetry of diagrams D2 and D3 is perfectly orthorhombic and that of diagrams D1 and D8 is almost orthorhombic.

Quartzites of Type II

The diagrams (D4, D9) for specimens in this group consist essentially of two crossed girdles, intersecting in an axis normal to the lineation. In diagram D4 the strongest maxima are close to the orientation of maximum IV of Sander's diagram, but additional maxima are situated elsewhere in the girdles; one of the girdles is markedly stronger than the other and the symmetry of the pattern is triclinic (though tending towards orthorhombic). Diagram D9 is characterized by a large maximum near the intersection of the girdles and smaller maxima with varied orientation within the girdles. The symmetry is again almost orthorhombic.

Primary Mylonitic Rocks

The diagrams (D6, D7, D10, D11) showing the preferred orientation of quartz in the specimens of this group all show crossed girdles intersecting in an axis normal to the lineation. The strongest maxima are generally situated at or near the intersection of the girdles (D6, D10, D11) but in diagram D7 they lie /

lie within the girdles with an orientation close to maximum IV of Sander's diagram. The symmetry of all four diagrams again approximates to orthorhombic.

Diagrams D10 and D11 are based on measurements made in separate limbs of the fold shown in diagram D12. The diagrams are similar with regard to the orientation of the girdles, maxima and symmetry planes so that the quartz orientation may be regarded as homogeneous throughout the fold.

Moine Schists

The diagrams (D13, D16, D19) showing the preferred orientation of quartz for the three schist specimens are not unlike those for the quartzites and primary mylonitic rocks, but the preferred orientation is noticeably weaker. The orientation diagrams consist of two partial girdles, intersecting in an axis normal to the prominent lineation, with the strongest maxima situated near the axis of intersection of the girdles. The symmetry is orthorhombic.

The diagrams showing the preferred orientation of poles of {001} cleavages of mica in the schist specimens (D14, D17, D20) consist of a strong maximum normal to the foliation (S) spreading into a girdle normal to the only lineation (L) in specimens 68 and X24, and the weaker lineation (L₂) in specimen /

specimen X36. The girdles in diagrams D17 (specimen X24) and D20 (specimen X36) each contain two sub-maxima, defining statistical \underline{S} -planes \underline{S}_1 and \underline{S}_2 in the fabric. These \underline{S} -planes are not equally inclined to \underline{S} . The symmetry of diagram D14 is orthorhombic and that of diagrams D17 and D20 monoclinic.

In each of the schist specimens the symmetry of the quartz diagrams does not agree with the symmetry of the mica diagrams and the overall symmetry of the microfabric is monoclinic in specimen 68 and triclinic in specimens X24 and X36 (see the synoptic diagrams D18 and D21).

The preferred orientation of quartz in the vein in specimen 66 is weaker than that in the primary mylonitic rocks, but the pattern (diagram D5) is similar in its essential features to that in some of the quartzites (e.g. diagram D4) and mylonitic rocks (e.g. diagram D7). The diagram shows maxima near the positions I and IV of Sander's diagram and symmetry is almost orthorhombic.

d. Interpretation

The symmetry of the quartz fabric in all the analysed specimens is characteristically nearly orthorhombic, while a few of the rocks, notably the quartzites of Type I (diagrams D2 /

D2 and D3) show perfect orthorhombic symmetry. Moreover, there is a strong resemblance between individual diagrams from each of the four main groups, as a comparison of, for example, diagrams D8 (quartzite of Type I), D9 (quartzite of Type II), D6 (primary mylonitic rock) and D13 (Moine Schist) will readily show. In view of these similarities there can be no doubt that the quartz orientation in the quartzites, the primary mylonitic rocks and the Moine Schists was induced during the same phase of deformation.

Diagram D15 is an idealized "crossed girdle" pattern showing the planes of symmetry. For the purposes of the discussion the symmetry-planes are named p_1 , p_2 , and p_3 and the unique orientation of p_1 , p_2 , and p_3 in relation to the girdles is shown in the diagram. With this arbitrary definition of the symmetry planes, the symmetry axes p_1 ; p_2 ; p_2 : p_3 and p_3 : p_1 also have a unique orientation in relation to the girdles. The symmetry axes of the quartz fabric in all the analysed specimens are shown in the synoptic diagram D24. The geographical orientation of the axes is remarkably constant for all the specimens, indicating a high degree of homogeneity in the quartz fabric throughout the area. The maxima of quartz [0001] axes from all the diagrams are shown in the synoptic diagram D23 /

D23, oriented with reference to geographical co-ordinates. The orthorhombic symmetry of this diagram is a further illustration of the homogeneity of the quartz fabric throughout the area.

The preferred orientation of quartz and mica in the analysed specimens is similar to that in many of the Moine Schists described by Phillips (1937). Many of Phillips' quartz diagrams show the "crossed-girdle" type of pattern with orthorhombic symmetry. His investigations indicate that the commonest type of mica diagram in the schists consists of a single maximum of cleavage poles normal to the foliation, similar to D14, but he also obtained diagrams (1937, D24) with paired maxima inclined to the foliation, as in the present writer's diagrams D17 and D20. In 1937 Phillips stated that the degree of preferred orientation in the Cambrian and Torridonian rocks below the Moine Thrust was not high (pp. 601-603) and the only constructive effect which he observed in these rocks was the formation of a weak girdle of quartz axes about an axis trending parallel to the outcrop of the Thrust. Later studies of the Tarskavaig Moine Series (Phillips, 1939) appeared to confirm these observations. He concluded (1937, p. 603) that "in many of the rocks in immediate association with /

with the thrust planes the visible lineation is no longer parallel to the b-axis, but is a true direction of stretching, or slickensides (Rillen)". The present writer's investigations show, however, that the Cambrian quartzites in the vicinity of the Moine Thrust in Assynt are characterized by a stronger preferred orientation than the Moine Schists to the east of the Thrust, and that the pattern of preferred orientation of quartz bears the same relationship to the lineation in these rocks as in the Moine Schists. Although some of the Cambrian quartzites show mylonitic textures (cf. Phillips, 1937, p. 602), some are characterized by complete recrystallization of the granulated material and the quartz fabric of these rocks is so similar to that of the primary mylonitic rocks and schists that there can be no doubt that they date from the same phase of deformation. The variability of the angle between the girdles in the common "crossed-girdle" type of patterns in the Moine Schists has been discussed by Phillips (1945, pp. 217-8): he considered that the girdles were produced by "overprinting on a previously existing simple B-tectonite fabric [ac-girdle] during the Caledonian overthrusting" (1945, p. 218). Variation in the angle between the girdles is also apparent in the present writer's diagrams, but the angle between the girdles is /

is greatest in some of the Moine Schist diagrams (D16, D19) and least in the primary mylonitic rocks and quartzites, which should obviously show the maximum effects of the "overthrusting" movements. It is clear, then, that some other explanation must be sought for the formation of the "crossed-girdle" patterns.

Petrofabric studies carried out in many parts of the world have shown that quartz fabrics with orthorhombic symmetry, notably of the "crossed-girdle" type, are of common occurrence. Numerous examples have been described from the granulites of Saxony (Sander, 1915, 1930), the Finnish granulites (Sahama, 1936) and the Finnish quartzites (Hietanan, 1938); patterns of the "crossed-girdle" type have also been recorded in Dalradian quartzites (Weiss, McIntyre & Kürsten, 1955), in quartz-tectonites in the Appalachians (Balk, 1952) and in the basement gneisses of Kenya (Weiss, in press). Such patterns are so commonly developed that the present writer considers that they represent a special type of quartz fabric, as most investigators have maintained (Sander, 1930; Turner, 1948; Fairbairn, 1949).

In contrast to the dominant orthorhombic symmetry of the quartz fabric, the symmetry of the megascopic fabric is generally monoclinic and locally triclinic (see pp. 115-6). This may be seen in the folded specimens, X21 and 52. The axis /

axis of the fold in specimen X21 is parallel to the regional maximum of fold-axes (B). The quartz orientation is similar in both limbs of the fold and the symmetry axis $p_1: p_2$ of the quartz fabric does not coincide exactly with the axis of the fold (B). The fold in specimen 52 was selected for analysis as the fold-axis is inclined at a large angle to the regional maximum, though the style of the fold is similar to that of the majority of the folds in the area. The quartz orientation is similar in both limbs of the fold (diagrams D10, D11). Thus the quartz orientation is homogeneous in both the folds examined. Such a relationship of the internal fabric in different parts of a fold is generally taken to indicate that the fold is a slip-fold (shear-fold) produced by slip on a single set of s-surfaces transecting the fold (Sander, 1930; Knopf, 1938, p. 159). However, the symmetry axes of the quartz fabric are unrelated to the B-axes or the axial planes of the folds and it is more likely, in the writer's opinion, that the quartz was reoriented throughout the rock after the folding took place. As Sander has stated: "It is quite possible to find a homogeneous imprint and preferred orientation imposed on folds of any origin" (1934, p. 44). A lack of agreement between the quartz fabric and the megascopic fabric is also evident /

evident in a number of the other diagrams (D6, D8, D13, D16, D19); in these diagrams the foliation does not coincide with any of the planes of symmetry of the quartz fabric. The evidence of the fabric of these specimens suggests that the foliation was passive or 'dead' when the quartz orientation was induced.

Detailed studies in the granulite terrains of Saxony by Sander (1915, 1930) and others, and of Finland by Sahama (1936) are of particular relevance to the present case, for although the so-called "granulites" of the Moine Series are, in general, neither mineralogically nor texturally similar to the true granulites, there appears to be a close similarity between the fabrics of the two groups of rocks. Sander found that the Saxon granulites show orthorhombic symmetry with quartz in many cases oriented in crossed (Ok1) girdles. He interpreted the fabric in terms of a flattening achieved by slip on two equivalent h01 slip-planes, combined with yielding on Ok1 planes. Whereas the orthorhombic symmetry of the fabric indicates that there was little tectonic transport while this fabric was being produced, Sander considered that the quartz fabric reflected only the final imprint (Aufprägung) of deformation, which may have been preceded by translative movements of considerable magnitude. /

magnitude. Sahama's extensive study (1936) of the Finnish granulites shows that they possess a similar type of quartz fabric: the fabric is predominantly orthorhombic and the commonest type of orientation pattern consists of crossed girdles. However, the symmetry of the fabric becomes triclinic when the megascopic fabric elements are considered. The quartz orientation is remarkably uniform over the whole area of the granulites, and Sahama attributed the triclinic symmetry of the fabric to a superposition of two deformations: he considered that the quartz had been re-oriented by a late overprint, obliquely superposed on the pre-existing megascopic fabric during a separate and unrelated deformation. He inferred that the type of movement during this late deformation was a flattening combined with a small amount of translation.

The relationship between the quartz fabric and the megascopic fabric in the Moine Schists and mylonitic rocks of Assynt is analogous to that described by Sahama in the Finnish granulites, although the divergence between the megascopic fabric axes and those of the quartz fabric is more marked in the Finnish rocks. The homogeneity of the quartz fabric over the whole Assynt area and in individual folds indicates that it was imprinted during a late phase of deformation with orthorhombic symmetry. /

symmetry. However, the symmetry axis $p_1 : p_2$ of the quartz fabric is statistically parallel to the B-axis of the folds in the area (diagram D24), a fact which suggests strongly that the two phases of deformation were genetically related. The present writer considers that the quartz orientation was induced by the final (orthorhombic) imprint of the same deformation which produced the folding in the rocks, as Sander suggested for the Saxony and the Finnish granulites (1934, p. 41).

In view of the diversity of opinions on the mechanism by which quartz acquires a preferred orientation (Fairbairn, 1949, pp. 117-133) no attempt will be made to account for the quartz orientation. The orthorhombic symmetry of the patterns, however, and the homogeneity of the fabric over the area denote that the final imprint of the deformation was fairly intense and homogeneous, and involved little or no tectonic transport. A strain of this type may be defined in terms of shortening or elongation parallel to three mutually perpendicular axes, A, B and C, and there are three transformations which a body may undergo as a result of such a strain; these are tabulated as follows:

Types /

Types of Homogeneous Strain without Transport

Changes of dimension parallel to three mutually perpendicular axes:-

Type of Strain:-

A	B	C	
1. Shortened	Unchanged	Elongated	Biaxial
2. Shortened	Elongated	Elongated	Triaxial
3. Shortened	Shortened	Elongated	Triaxial

According to the principle of symmetry, the symmetry axes of the quartz fabric $P_1 : P_2$, $P_2 : P_3$ and $P_3 : P_1$ represent strain axes of this type. It is impossible to determine the exact nature of the deformation from the symmetrological evidence, but the dimensional orientation in some of the rocks is instructive in this connection. In the quartzites of Type I, the quartz grains have almost certainly developed from the original grains of the sediment.^x The grains in the undeformed quartzites /

^xExperimental investigations of the behaviour of quartz on deformation (Griggs & Bell, 1938) indicate that even under high pressures the mineral tends to deform by rupture into minute fragments or granules, rather than plastic gliding along planes or lines in the lattice. Thus the large flattened grains in the quartzites of Type I cannot have been produced purely by plastic deformation of the original grains of the sediment. However, these quartzites represent a stage in the transition from undeformed quartzites to rocks consisting entirely of granulated or "crush" quartz; moreover the large size of the grains /

quartzites are approximately equidimensional whereas those in the deformed rocks are extremely flattened in the foliation and elongated parallel to the lineation. The rocks appear, on this evidence, to have been intensely flattened or shortened parallel to $p_2 : p_3$ and elongated parallel to $p_1 : p_2$. The deformation may have been biaxial with no change of dimension parallel to $p_3 : p_1$, or it may have been triaxial with slight shortening or elongation parallel to this axis. This interpretation accords well with the common interpretation of quartz fabrics of the "crossed-girdle" type (Sander, 1930; Sahama, 1936; Turner, 1948) in terms of "flattening" (Plattung). The degree of flattening and elongation parallel to the lineation and folds during this final imprint may have been quite extensive. It must be noted that although this elongation does represent a type of movement, it is not tectonic transport; the passage of the elongating mass over the rigid basement or foreland, however, would give rise to differential movement (transport), relative to the foreland in this direction.

It /

grains in comparison with the recrystallized grains in the quartzites of Type II suggests that they have been produced from the original grains of the sedimentary quartzites without complete disintegration. The grains were probably derived directly from the original grains of the sediment by a process involving recrystallization and perhaps some degree of plastic flow.

It is probable that there was a gradual transition during the deformation from the translative (monoclinic) movement about \underline{B} to the final (orthorhombic) imprint involving flattening and elongation. If a body of rocks is shortened by folding or thickening of the strata the vertical dimension becomes increasingly greater. Eventually a stage will be reached when the lower rocks are flattened under the influence of the weight of superincumbent rocks. The mass is constricted in the direction of shortening and the elongation produced by the flattening will be parallel to the horizontal axis which is normal to the direction of shortening, i.e. the fold-axis. The present writer considers that such an evolutionary sequence of deformation occurred in the Moine Schists and mylonitic rocks in the Assynt area, and that the quartz was reoriented during the final stages of the sequence, after the translative movement normal to the fold-axes had ceased. It is not unlikely that during the intermediate stages of the deformation folding about \underline{B} and elongation parallel to \underline{B} ($= p_1 : p_2$) occurred simultaneously.

It has been pointed out that the quartz and mica diagrams for the Moine Schists are heterotactic. The strongest maxima in each of the ^{mica} Δ diagrams defines the foliation, which was passive during the final orthorhombic stages of the deformation. Thus /

Thus, these maxima are relics from the early (monoclinic) phase of movement. However, the s-planes S_1 and S_2 , defined by sub-maxima in the mica diagrams, were probably produced during the final stages of the deformation. Similarly, slight departures from orthorhombic symmetry in the quartz orientation in some of the specimens may reflect the influence of an earlier preferred orientation dating from the monoclinic phase of deformation. On the other hand, they may have been caused by slight irregularities in the movement during the final imprint of the deformation.

The north-east trending quartz veins in the primary mylonitic rocks and Moine Schists are extensively deformed and granulated where the rocks have suffered secondary deformation, indicating that the veins were emplaced before the inception of the secondary phase of deformation. The preferred orientation of the quartz lattice in the vein in specimen 66 (diagram D5) is similar to that in the primary mylonitic rocks and schists: the symmetry of the pattern is almost orthorhombic and there is a tendency towards the formation of crossed girdles containing maxima with the same orientation as those in the other diagrams. The grains in the vein also show some degree of flattening normal to the foliation in the surrounding rock. This evidence suggests that the veins have been affected to some extent by the /

the final orthorhombic phase of the primary deformation and must therefore have been emplaced before the close of the deformation. It was inferred above that there was some degree of elongation parallel to $p_1 : p_2 (= \underline{E})$ during this phase of deformation and it is probable that the veins were formed by infilling of tension gashes normal to the direction of elongation.

The quartz fabric of the primary mylonitic rocks and Moine Schists is of special importance as it reveals evidence of a phase of deformation which is not reflected in the megascopic fabric of the rocks. During the final stages of the primary deformation when the quartz was reoriented the foliation and folds were passive. The movement during this phase of deformation was extremely penetrative and homogeneous and was probably achieved by direct and indirect componental movement between individual grains of quartz and feldspar. The relationship between the symmetry axes of the early monoclinic movements and the late orthorhombic imprint is such that there could be little change in the orientation of early-formed linear structures during the later stages of deformation. However, flattening of the rock mass would have the effect of changing the form of the folds so that the limbs of recumbent folds were compressed and the profiles generally "flattened". The closely appressed /

appressed nature of many of the folds in the primary mylonitic rocks may be due to flattening during the final orthorhombic stages of the primary deformation.

EXPLANATION of PETROFABRIC DIAGRAMS (D1-D24)

Geographical orientation of diagrams is shown by the the broken line (horizontal) and principal compass directions (E, S).

Determined from megascopic fabric:

S, S', S'' represent foliation.
 $\underline{L}, \underline{L}_1, \underline{L}_2$ represent lineations on foliation.
 \underline{E} represents fold-axis.

Determined from microscopic fabric data:

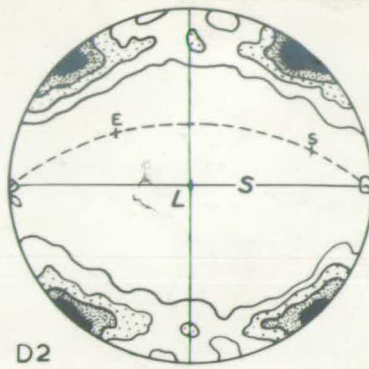
S_1, S_2 represent s-planes defined by mica orientation.
Dotted lines are planes of girdles of quartz [0001] axes.

Full lines are symmetry planes in quartz fabric.

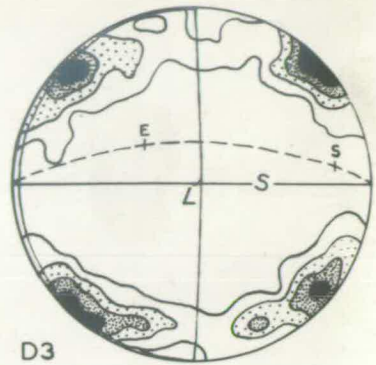
- D1. [0001] axes of 300 quartz grains in specimen 69. Quartzite of Type I. Contours: 1, 2, 3% per 1% area.
- D2. [0001] axes of 300 quartz grains in specimen 62. Quartzite of Type I. Contours: 1, 3, 5, 8% per 1% area.
- D3. [0001] axes of 211 quartz grains in specimen E23. Quartzite of Type I. Contours: 1, 3, 5, 7% per 1% area.
- D4. [0001] axes of 206 quartz grains in specimen X21. Quartzite of Type II (folded). Contours: 1, 2, 4, 6% per 1% area.
- D5. [0001] axes of 200 quartz grains in quartz vein (S_v) cutting mylonite, specimen 66. S and L represent foliation and lineation in the mylonite. Contours: 1, 2, 4% per 1% area.
- D6. [0001] axes of 205 quartz grains in specimen F6. Primary mylonitic rock (quartz schist). Contours: 1, 3, 5, 7% per 1% area.
- D7. [0001] axes of 200 quartz grains in specimen 50. Primary mylonitic rock (quartz schist). Contours: 1, 2, 4, 6% per 1% area.
- D8. [0001] axes of 200 quartz grains in specimen E14. Quartzite of Type I. Contours: 1, 2, 3, 4% per 1% area.
- D9. [0001] axes of 200 quartz grains in specimen E15. Quartzite of Type II. Contours: 1, 2, 3, 4% per 1% area.
- D10. [0001] axes of 200 quartz grains in quartzose layer, specimen 52. Upper limb of fold (S'). Contours: 1, 2, 4% per 1% area.



D1



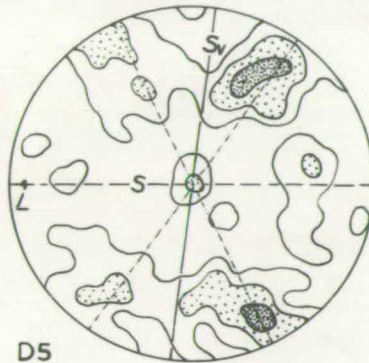
D2



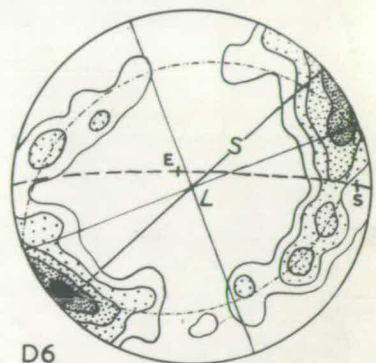
D3



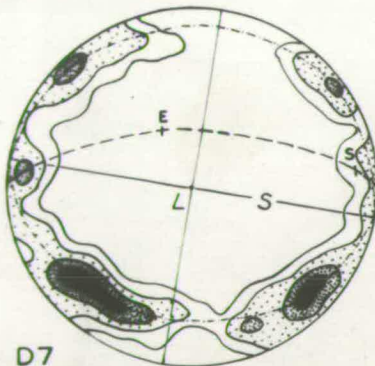
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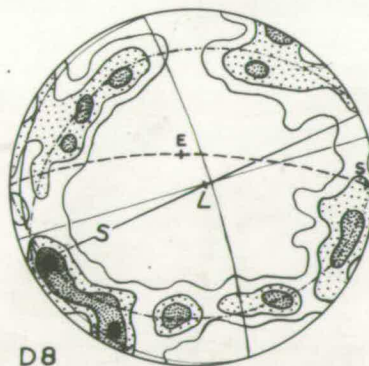
D5



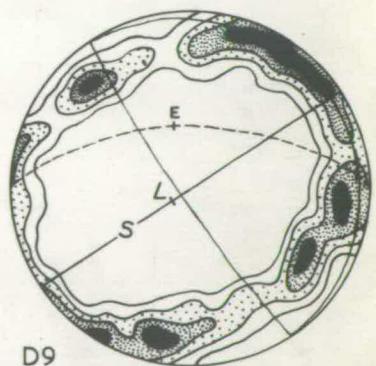
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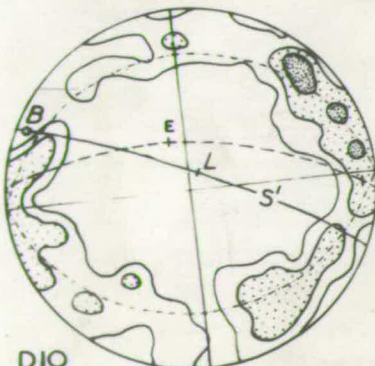
D7



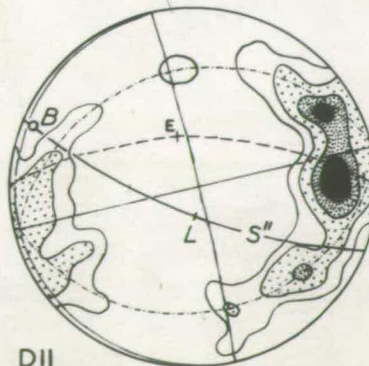
D8



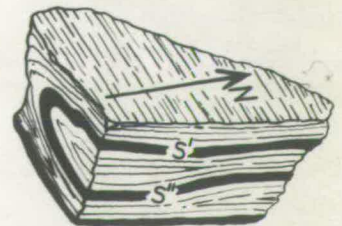
D9



D10



D11

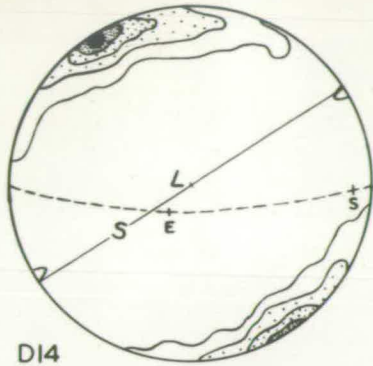


D12

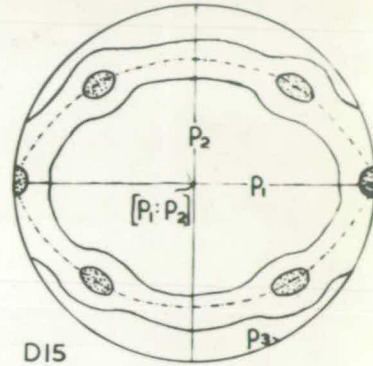
- D11. [0001] axes of 200 quartz grains in same quartzose layer, specimen 52. Lower limb of fold (\underline{S}). Contours: 1, 2, 4, 6% per 1% area.
- D12. Specimen 52 showing fold; quartzose layer in black. One-third true size.
- D13. [0001] axes of 202 quartz grains in specimen 68. Moine Schist. Contours: 1, 2, 4, 6% per 1% area.
- D14. [001] axes of 209 mica grains in specimen 68. Contours: 1, 5, 10, 15, 20% per 1% area.
- D15. Diagram showing relationship of planes of symmetry p_1 , p_2 and p_3 to girdles of quartz [0001] axes.
- D16. [0001] axes of 300 quartz grains in specimen X24. Moine Schist. Contours: 1, 2, 3% per 1% area. Same geographic orientation as diagram D17.
- D17. [001] axes of 200 mica grains in specimen X24. Contours: 2, 6, 10, 14% per 1% area.
- D18. Synoptic diagram for specimen X24, showing s -planes defined by mica and planes of symmetry in the quartz fabric.
- D19. [0001] axes of 400 quartz grains in specimen X36. Moine Schist. Contours 1, 2, 3% per 1% area.
- D20. [001] axes of 300 mica grains in specimen X36. Contours: 1, 3, 6, 8, 10% per 1% area.
- D21. Synoptic diagram for specimen X36, showing s -planes defined by mica and planes of symmetry in the quartz fabric.
- D22. Orientation of common maxima in \underline{S} -tectonites, after Sander, 1930, diagram D61.
- D23. Synoptic diagram showing the orientation of the maxima of quartz axes in diagrams D1-D4, D6-D11, D13, D16, D19, in relation to geographical coordinates.
 Large circles represent maxima of over 6%
 Small circles represent maxima of 4 - 6%
 And points represent maxima of 2 - 4%.
- D24. Synoptic diagram showing the orientation of planes of symmetry in the quartz fabric of the analysed specimens;
 points - $p_1:p_2$; circles - $p_2:p_3$; crosses - $p_3:p_1$.



D13



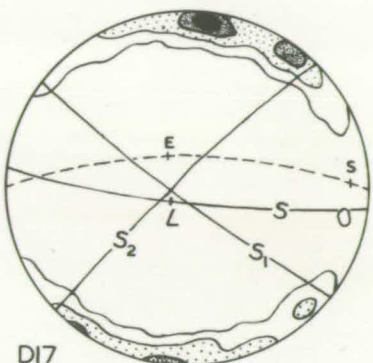
D14



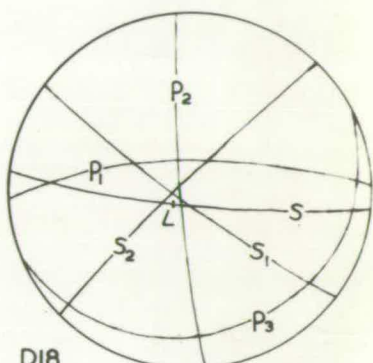
D15



D16



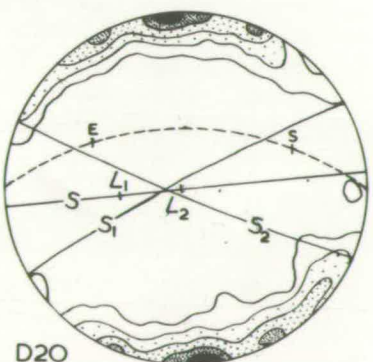
D17



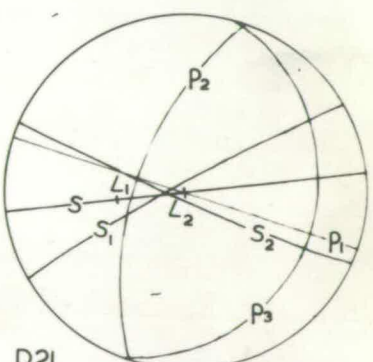
D18



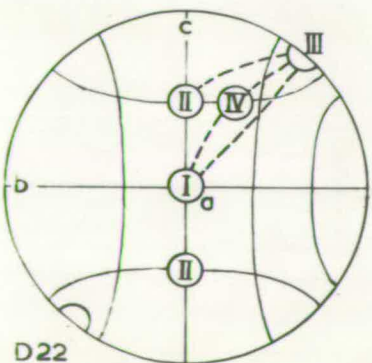
D19



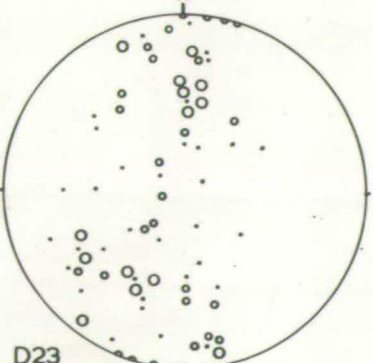
D20



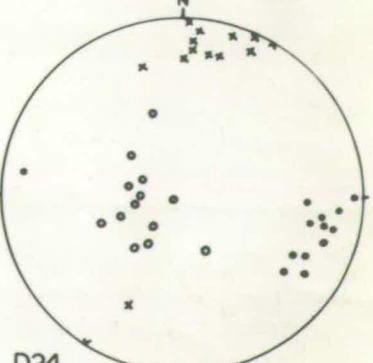
D21



D22



D23



D24

V. TECTONIC SYNTHESIS

1. INTRODUCTION

From the evidence described in the foregoing chapters a consistent kinematic picture emerges for the whole area. Several phases of deformation have been inferred from the fabric data in the mylonitic rocks along the Moine Thrust and in the rocks in the zone of dislocation. In the following paragraphs separate phases of deformation in the Moine Schists and the mylonitic rocks and the rocks in the zone of dislocation are correlated, and a kinematic synthesis is made on the basis of the megascopic and microscopic fabric of all the rocks in the area. Finally, the evidence on the age of the movements is briefly reviewed.

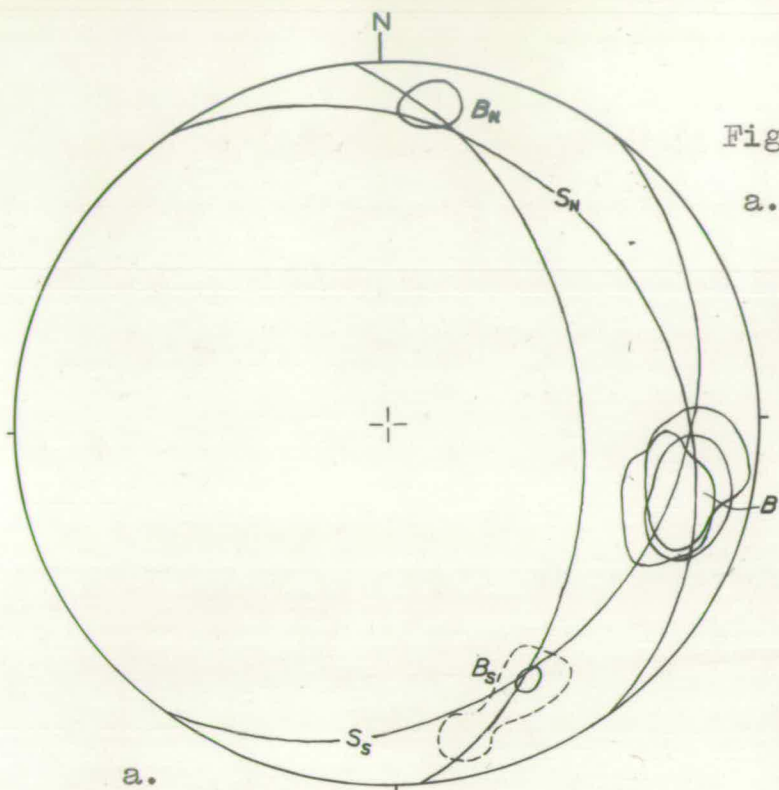
2. STRUCTURAL CORRELATIONS

Figure 32a is a synoptic diagram showing the maxima of fold-axes in the mylonitic rocks along the Moine Thrust at the Stack of Glencoul, Loch Ailsh and Cnoc a' Chaoruinn. The diagram shows clearly the close relationship between the folds in secondary mylonitic rocks (\underline{E}_n , \underline{E}_s) and the Ben More Thrust. The planes \underline{S}_n and \underline{S}_s show the mean orientation of the foliation in the primary mylonitic rocks in the northern and southern areas /

areas respectively, and the plane representing the Ben More Thrust is based on the orientation of the thrust at the localities where it is exposed in the zone of dislocation. The axes of folds in the secondary mylonitic rocks at the Stack of Glencoul (\underline{E}_n) and Cnoc a' Chaoruinn (\underline{E}_s) are parallel to the intersection of the Thrust and the foliation in the primary mylonitic rocks in both areas. This fact confirms the view, advanced above, that the folding was contemporaneous with movement on the Ben More Thrust and that the folds were formed by kinking of the \underline{g} -surfaces in the primary mylonitic rocks (\underline{S}) along surfaces which are parallel to the Thrust and associated reverse faults.

The diagram also illustrates the significance of the embayment in the outcrop of the Moine Thrust in the Assynt region. The foliation planes in the mylonitic rocks in the northern and southern parts of the Assynt 'bulge' are parallel to the Thrust and intersect in an axis plunging towards the east, parallel to \underline{E} ; thus the change in orientation of the Thrust and the foliation is not related to folding about axes parallel to the general strike of the Thrust, but to the east-south-east-plunging axis \underline{E} . The foliation surfaces in the primary mylonitic rocks and schists in the northern and southern parts of the 'bulge' are analogous to the limbs of a large fold with small amplitude /

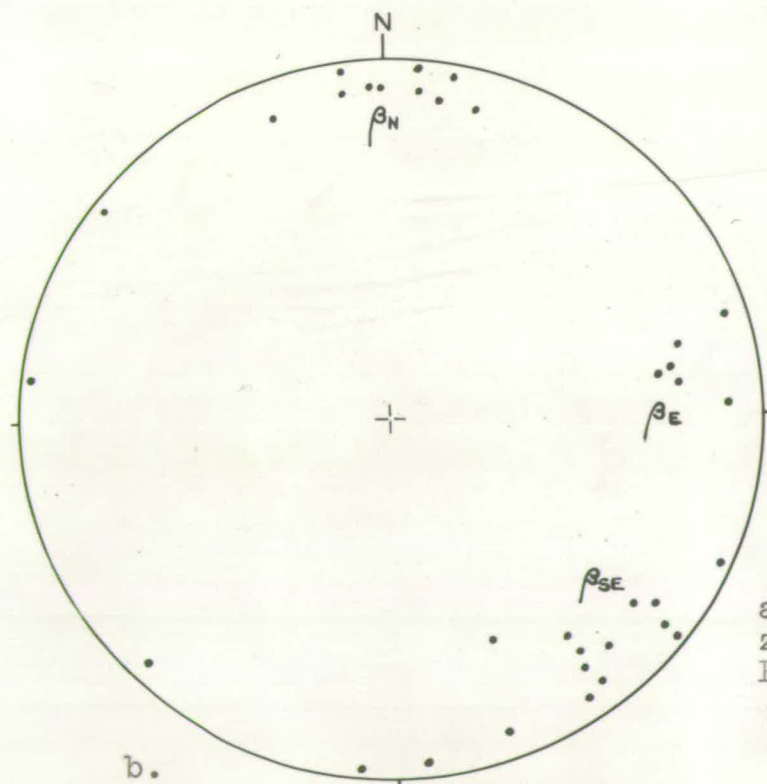
Figure 32.



a. Synoptic diagram showing maxima of fold-axes in the Stack of Glen-coul area (B_n , B_s), the Loch Ailsh area (B) and the Cnoc a' Chaoruinn area (B , B_s). S_n and S_s represent the mean orientation of the foliation in the primary mylonitic rocks in the north and south areas respectively.

B.M.T. represents the mean orientation of the Ben More Thrust in Assynt.

Full lines are 10% contours and the broken line is a 6% contour.



b. Synoptic diagram showing the orientation of β -axes measured in selected areas of Cambrian and Torridonian rocks in the zone of dislocation (See Fig. 22).

amplitude about the axis \underline{B} . Thus the embayment of the Thrust is not due to an axial culmination, as claimed by Bailey (1935), but to a slight anticlinal fold of the Thrust about the regional fold-axis \underline{B} . The width of the embayment reflects the low angle of plunge of the fold-axis. The fold originated during the primary movements, when there was penetrative movement along the 'Movement horizon'. The only modification of the structure by the secondary movements was the slight displacement of the horizon at the Stack of Glencoul and Cnoc a' Chaoruinn: these displacements are scarcely reflected in the outcrop of the Moine Thrust.

The \underline{B}_n and \underline{B}_s folds in the secondary mylonitic rocks are genetically related to the Ben More Thrust and the reverse faults associated with this dislocation, and there is also close connection between these reverse faults and the north-trending folds (β_n) in the zone of dislocation. Thus it is evident that folding about north-trending axes in the zone of dislocation was contemporaneous with the secondary deformation of the rocks in the vicinity of the Moine Thrust. The movement pictures inferred from the structures in the secondary mylonitic rocks above the Moine Thrust and the north-trending folds in the zone of dislocation are similar: the Moine Schists and thrust /

thrust masses were transported towards the west during the secondary deformation, and the movement was concentrated along the major thrusts in the zone of dislocation and in the pelitic layers near the Moine Thrust.

The south-east- and east-plunging fold-structures in the zone of dislocation (Fig. 32b, β_e, β_{se}) and the widespread east-south-east-plunging folds in the primary mylonitic rocks and Moine Schists (Fig. 32a, B) are earlier than the westward movements and were probably formed contemporaneously. The divergence of orientation between the B-folds above the Moine Thrust and the β_{se} and β_e folds in the zone of dislocation may be due to either or both of the following causes:

1. The folds in the zone of dislocation may have formed with their present orientation as a result of inhomogeneities in the movement.
2. The axes of the folds in the zone of dislocation may originally have been parallel to B and have been subsequently rotated during the later westward movement.

The deformation in the zone of dislocation was extremely discontinuous and there is a wide variation in the physical properties of the rocks; under these conditions irregularities in the movement-patterns are to be expected. The variation in the orientation of the folds probably stems mainly from this cause but it is not unlikely that the folds in the zone of dislocation were modified by the later movements.

The structural picture obtained from the analysis of the microscopic fabric of the Loch Ailsh dolomites (pp. 151-174) agrees very closely with that obtained from the megascopic fabric (pp. 101-106). The E-axis determined from the grain orientation plunges towards the east, parallel to the axes of most of the folds in the area. This E-axis was probably produced during the same movements as the E-structures in the primary mylonitic rocks and schists. But the sense of rotation about the eastward-plunging axis in the dolomites is opposite to that indicated by the folding in the overlying primary mylonitic rocks. It has already been stated, however, that there may have been slight movement ^{towards the north-north-east} along the Moine 'Movement horizon' near the end of the primary deformation (pp. 118-119). It was tentatively inferred from the microscopic and megascopic data that the dolomites were later affected by slight deformation about a north-trending E-axis. In view of the extensive development of folds with this trend elsewhere in the Moine Thrust-zone and in the zone of dislocation there can be little doubt that the inhomogeneity of the fabric of the dolomites has indeed resulted from slight deformation about a north-trending axis after the main movement which produced the east-plunging E-axis.

3. DISCUSSION OF THE MOVEMENTS

The current controversy regarding the relative age of the Moine Metamorphism and movement on the Moine Thrust has arisen because it has been generally assumed that there was only one phase of movement on the Thrust and that all the mylonitic rocks along the Thrust were produced during this phase of movement. The evidence adduced in the foregoing chapters proves that at least two separate phases of dislocation and movement are recognisable in the rocks of the thrust-zone; these have been referred to as the primary and secondary phases of deformation. The contrast between the "brittle" style of deformation in the mylonitic rocks near the Moine Thrust and the "plastic" style of the folding in the Moine Schists does exist, but the cataclastic ("brittle") structures were produced during the secondary phase of deformation and this cataclastic breakdown affects the earlier-formed primary mylonitic rocks as well as the Moine Schists. It has not hitherto been recognised that the primary mylonitic rocks, which include the true mylonites of Lapworth and the Survey geologists (Peach, Horne et al., 1907), exhibit a style of deformation which is just as "plastic" as that in the Moine Schists. The horizon mapped as the Moine Thrust originated during the primary phase of deformation, when there was extensive penetrative movement throughout the zone of /

of primary mylonitic rocks. The Thrust was not an active movement-surface during the secondary phase of deformation, when the "brittle" surfaces were produced.

The primary deformation (I) may be divided into two phases, one following closely on the other. The two phases of deformation were closely related and it is probable that the later movement with orthorhombic symmetry evolved from the earlier movement, which had monoclinic symmetry. The secondary deformation (II), on the other hand, breaks down the structures which were formed by the primary deformation and the two deformations are not apparently related. The structures formed during each phase of deformation and the characteristics of each deformation are summarized in the following table:

	Moine Schists and Primary Mylonitic Rocks	Zone of Dislocation
Ia	<ol style="list-style-type: none"> 1. Movement with monoclinic symmetry 2. E-folds produced 3. Deformation precrystalline and continuous 	<ol style="list-style-type: none"> 1. Movement with monoclinic symmetry 2. β_{se} and β_e folds produced 3. Deformation post-crystalline and discontinuous
Ib	<ol style="list-style-type: none"> 1. Movement with orthorhombic symmetry (flattening) 2. Quartz and mica (in part) reoriented 3. Deformation paracrystalline and extremely penetrative 	No evidence
II	<ol style="list-style-type: none"> 1. Movement with monoclinic symmetry 2. E_n, E_s folds produced 3. Deformation post-crystalline and discontinuous 	<ol style="list-style-type: none"> 1. Movement with monoclinic symmetry 2. β_n folds produced 3. Deformation post-crystalline and discontinuous

During the early monoclinic phase of the primary deformation (Ia) there was intensely penetrative movement throughout the zone of primary mylonitic rocks, and the Moine Schists were transported towards the south-south-west along this 'Movement horizon'. The presence of folds with east and south-east trend in the zone of dislocation and the close relationship between these folds and the major thrusts suggests that the Assynt Nappes were transported during this phase of deformation. It was inferred on page 138 that there was movement of the Lower Assynt Nappe along the Sole towards the south-west and it is probable that there was also transport along the Assynt Thrust in the same direction (pp. 138-9). These inferences are very significant as they indicate that the Assynt Nappes were derived from the north-east and not from the east-south-east, as claimed by Clough (1907) and Bailey (1935). Thus if Clough's correlation of the Lewisian gneiss in the Upper Nappe at Loch Glencoul with that of the foreland in the Laxford-Stack area is valid (and the present writer considers that it is), the Nappe was transported a distance of six or eight miles. Bailey has stated (1935, p. 159) that: "It is important also to bear in mind that the displacement of the Laxford-Stack line indicates a minimum movement of thrusting of six miles. It would require more courage to choose six miles approximately at /

at right angles to the abundant flow structure of the district, rather than thirteen miles as closely as possible along the line of flow". However, the "line of flow" to which Bailey referred has not the significance which he attributed to it; the lineation is parallel to B and not to a and the evidence of the fabric indicates that tectonic transport was indeed approximately at right angles to this direction.

Phemister (1926, p. 21) has drawn attention to the possibility that the plutonic masses of Loch Borolan and Loch Ailsh have exerted some influence in the formation of the Assynt 'bulge'. The Loch Ailsh mass appears to be a part of the Upper Nappe and the Loch Borolan mass belongs to the Lower Nappe, but the present writer considers that the latter has played an important part in the formation of the 'bulge', as Phemister suggested. It is clear from Figure 21 that by far the thickest and most extensive part of the Upper Nappe lies to the north of the Loch Borolan complex. The following hypothesis, though based largely on circumstantial evidence, accounts for the presence of two major nappes in the zone of dislocation and for the formation of the Assynt 'bulge'. The Upper Nappe was probably detached from the basement, while the Moine Schists were being transported to the south-south-west along the movement horizon, and dragged along under the moving Moine rocks, until /

until its progress was impeded by the upper portions of the Loch Borolan mass; the syenite is more massive and resistant to deformation than the bedded sediments elsewhere in the zone of dislocation and would tend to form an obstruction of this type. The Sole probably originated at this stage of the deformation, when the stress on the upper part of the syenite mass became sufficiently great to rupture the mass. The upper part of the mass then sheared off along the Sole and was transported to the south-west along with a slice of the sediments in which it is emplaced. The 'bulge' is due to a gentle anticlinal fold of the movement horizon over this accumulation of thrust materials. The fact that the axis of the fold in the movement horizon is parallel to the kinematic B-axis in the primary mylonitic rocks is significant as it indicates that the formation of the fold was contemporaneous with the primary movements on the movement horizon.

In the transitional stages of the primary deformation between the monoclinic movement and the orthorhombic imprint, there was probably slight differential movement normal to B combined with flattening normal to the foliation and extension parallel to B. But during the closing stages of this deformation, the foliation was no longer an active slip surface, and the flattening and elongation parallel to B were not accompanied by tectonic transport normal to B.

Whereas /

Whereas the movement in the Moine Schists and mylonitic rocks throughout the primary deformation was pre- and para-crystalline, the movements during the later secondary deformation were post-crystalline. The sense of movement during this phase of deformation was towards the west and the Ben More Thrust and other eastward-dipping reverse faults were formed. The only zones of imbrication found by the present writer also date from this phase of deformation.

Although the north-trending fold-structures in the Moine Thrust-zone and the zone of dislocation are definitely later than the \underline{B} -structures, the rectangular relationship between \underline{B} and \underline{B}_n , \underline{B}_s , and β_n suggests that there may be a close connection between the two phases of deformation. It is probable, in the writer's opinion, that the north-trending folds in the thrust-zone were produced, after the rocks in the zone had become "brittle", as a result of elongation parallel to \underline{B} in the Moine Schists further to the east. That is, the fabric may have $\underline{B} \perp \underline{B}'$ triclinic symmetry on a regional scale. Large-scale axial elongation in the Moine Schists, though not constituting tectonic transport in the rocks themselves, would naturally give rise to differential movement and rotation about an axis normal to \underline{B} in a zone between the Schists and the rigid basement; the north-trending folds (\underline{B}_n , \underline{B}_s , β_n) in the thrust-zone# may have originated in this fashion.

Balk (1937, 1953) has described the fabric of the rocks associated with thrust-zones in the eastern United States: the megascopic fabric of these rocks is almost identical with that in the mylonitic rocks along the Moine Thrust in Assynt: the rocks are intensely foliated and lineated and the lineations and the majority of the folds plunge parallel to the dip of the thrust-planes: there is frequently a sub-maximum of fold-axes with trend parallel to the strike of the thrusts (1953). Balk regarded the lineation as a type of slickensides, parallel to the direction of movement on the thrust. He considered that the fabric was produced entirely by flattening normal to the foliation with intense elongation parallel to the lineation, and that the folds originated by slight movement of blocks of rocks in a direction normal to the main direction of movement:

"The origin of the lineation and lamination is believed to be identical with that of corresponding structures in rolled steel and glass.

"However, the formation of folds with axes parallel to the direction of thrust requires an additional shear stress acting perpendicularly to the direction of thrusting. The inhomogeneous composition, strength and mobility of the flooring rocks are pointed out, and it is suggested that unequal rates of yielding of local rock masses below the thrust blocks generated these supplementary stresses, producing slight movements of small masses sideways" (1953, p. 102).

E. Cloos (1946) holds similar views on the origin of what he describes as "folds in a". He cited the Assynt area and /

and certain areas in Scandinavia and Lapland as affording examples of folds of this type (Ibid, pp. 26-9). He stated that "the principle involved is the same as that used in the machinal folding of maps, the making of corrugated iron, rain gutters, and other folds accompanied by lateral shortening normal to the principal movement" (Ibid., p. 28). Cloos considered that the main movement and transport in the Moine Schists of the Assynt area was towards the north-west, parallel to the lineation; the orientation of the lineation varies slightly in different parts of the area and the author attributed this to variations in the direction of movement, produced by local restriction of transport in certain parts of the area. Cloos also concluded that there may have been subordinate movement perpendicular to the general direction of advance.

The movement postulated by Balk and Cloos is similar to that inferred by the present writer for the later (orthorhombic) phase of the primary deformation, but the present writer's analysis of the fabric of the Moine Schists and primary mylonitic rocks of the Assynt area indicates that the folding was not produced during this phase of deformation, as Cloos has claimed. Some of the folds, such as those in the primary mylonitic rocks of the Knockan Crag area, indicate shortening normal to the fold-axis without much tectonic transport, but the symmetry and style of the folding in the other areas examined indicates that there /

there was considerable translative movement normal to the fold-axes.

4. THE AGE OF THE MOVEMENTS

The present writer's conclusion on the relative age of the different groups of fold-structures in the Moine Schists and mylonitic rocks are essentially the same as those advanced by Read (1931), but the evidence set out in the foregoing chapters proves that the absolute ages of the two phases of deformation are not as Read has inferred. It has been shown above (pp. 111, 113) that the east-south-east plunging folds and lineations (B) were produced during the regional metamorphism of the Moine Schists, but that this deformation and metamorphism date from post-Cambrian times. The regional metamorphism of the Moine Schists, then, was not pre-Torridonian, as claimed by Read (1934), Phillips (1937, 1949, 1951) and Wilson (1953), but entirely "Caledonian" (that is, post-Cambrian, and pre-Middle Old Red Sandstone). Moreover, there was movement along the Moine Thrust during the Moine metamorphism and deformation; the primary mylonitic rocks formed a movement horizon along which the deforming and crystallizing Moines were transported over the rigid basement. The "dislocation" effects described by Read (1931) and the "brittle" structures referred to by Wilson /

Wilson (1953) and McIntyre (Discussion of Wilson, 1953, 1954) were produced during a later phase of deformation, when the north-trending folds in the thrust-zone were formed. It is not possible to determine an upper age-limit for these later movements and they may, as McIntyre suggested, be of Hercynian or even Tertiary age, for the Permian dyke in the mylonitic rocks of A'Mhoine (McIntyre, 1954, pp. 216-7) cuts primary mylonitic rocks. However, if there is a genetic ($\underline{B} \perp \underline{B}'$) relationship between the \underline{B} -structures and the north-trending folds in the thrust-zone, as the present writer has reason to believe (p. 213), then the westward movement on the thrusts must have followed closely on the primary movements. Thus it is probable that the secondary deformation of the Moine Schists and mylonites and the westward movements on the thrusts also date from the Caledonian orogeny.

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PLATES

PLATE I.

a. The Stack of Glencoul, viewed from the west, showing the approximate position of the Moine Thrust.

b. The Stack of Glencoul area, viewed from the south, with the Stack and Loch nan Caorach in the middle distance. Note the gentle anticlinal fold in the Moine Thrust, the outcrop of which is shown by the line. One of the steep reverse faults west of the Ben More Thrust is visible in the right foreground.



PLATE II

a. Specimen of primary mylonitic rock from the Stack of Glencoul, showing the characteristic style of folding (intrafolial). Slightly less than half natural size. (Specimen lent by kind permission of the Director of the Royal Scottish Museum).

b. Folding in primary mylonitic rocks at the Stack of Glencoul; viewed in profile, towards east-south-east.



PLATE III

a. Exposure near the eastern margin of the zone of secondary deformation, half a mile north-east of the Stack of Glencoul, showing several kink-zones dipping towards the east.

b. Exposure of phyllonite in the valley of the Glencoul River, showing the characteristic style of folding. The folds are closed and angular, with axial planes dipping towards the east (along direction of hammer shaft).



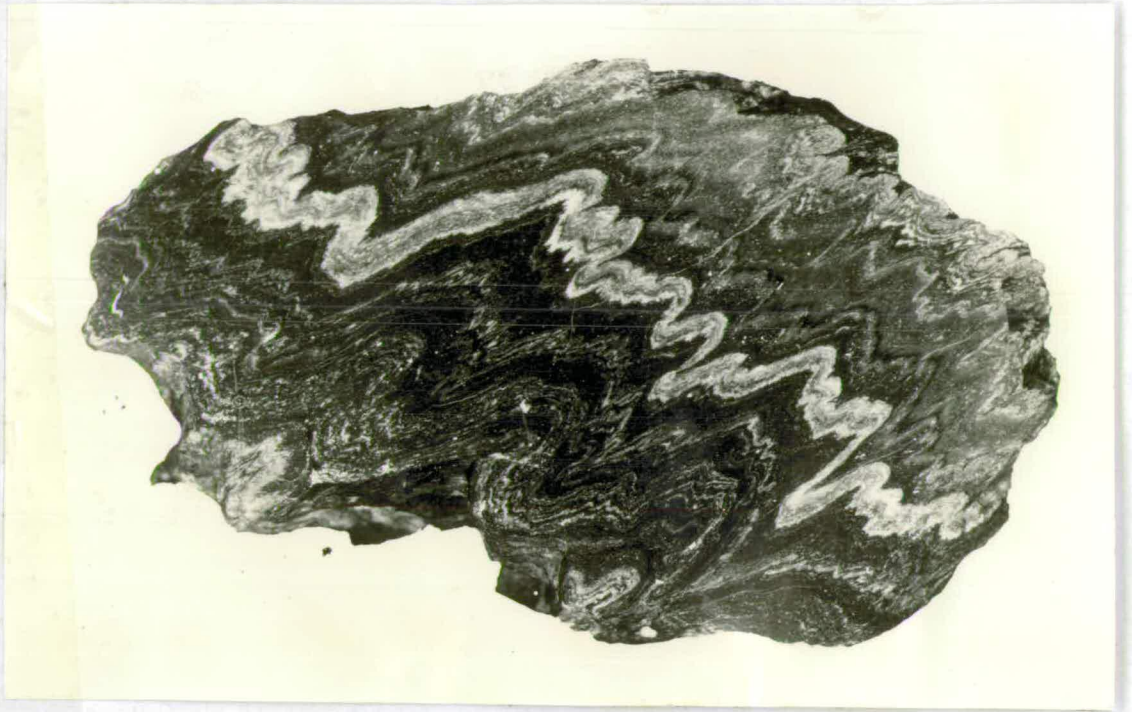
PLATE IV

a. Specimen of folded phyllonite from the disused quarry on the Lairg - Lochinver road, half a mile south-east of the Ben More road. The folding is more complex in the dark, pelitic layers than in the light-coloured quartzo-feldspathic layer. Actual size.

b. Block of folded phyllonite in the quarry where the above specimen was collected, showing the characteristic style of folding.

IV

A



B



PLATE V

a. Fold in primary mylonitic rock at Knockan Crag. Folding of this type is associated with shear-surfaces dipping to the north and to the south.

b. Low-grade Moine Schist, east of Knockan Crag. The exposure shows the slabby nature of the schists in this area and the well-developed joint-system; the most prominent group of joints strike parallel to the lineation. The foliation is evidently bedding.

c. Deformed Moine Schists near Loch Odhar, cut by a complex system of quartz-veins with north-north-easterly strike. Bending of the foliation along the thicker veins near the centre of the photograph gives the sense of shear along the veins.

A



B



C



PLATE VI

a. Gorm Loch Mor and Ben More Assynt from the north, showing the outcrop of the Ben More Thrust west of Gorm Loch Mor. The Cambrian quartzites above the Thrust at this locality are folded about a north-trending axis.

b. Coire a' Mhadaidh and Na Tuadhan from the south. The large-scale fold in the quartzites on Na Tuadhan is associated with steep eastward dipping faults which are sub-parallel to the Ben More Thrust, the outcrop of which is marked.

A



B



PLATE VII

a. The Assynt (Glencoul) Thrust at the classic locality south of Loch Glencoul. The Thrust separates phyllonitized Lewisian Gneiss from Cambrian dolomite (below). Note the contortion of the bedding in the dolomite.

b. The Assynt (Glencoul) Thrust, 50 yards west of the above locality. The Thrust again separates phyllonitized gneiss from dolomite.

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VII

A



B



PLATE VIII

a. Large-scale fold in Cambrian limestones above the Sole, east of Chalda House, Loch Assynt; viewed in profile towards the south-east.

b. Medium-scale fold in Cambrian limestone, approximately 300 yards south of Burnside Cottage, Knockan; viewed in profile towards the south-east.

VIII

A



B



PLATE X

a. Photomicrograph of dolomite specimen M1. Shows absence of post-crystalline deformation; the grains have interlocking boundaries and contain few lamellar structures. (The opacity of the grains in this plate, compared with those in plate b., is due to the low illumination employed to emphasize grain boundaries; the grains are, in fact, quite clear.) Ordinary light. X 50.

b. Photomicrograph of dolomite specimen M13. Grains in this field show no marginal granulation and moderate development of untwinned $\{02\bar{2}1\}$ lamellae. Ordinary light. X 50.

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(X)

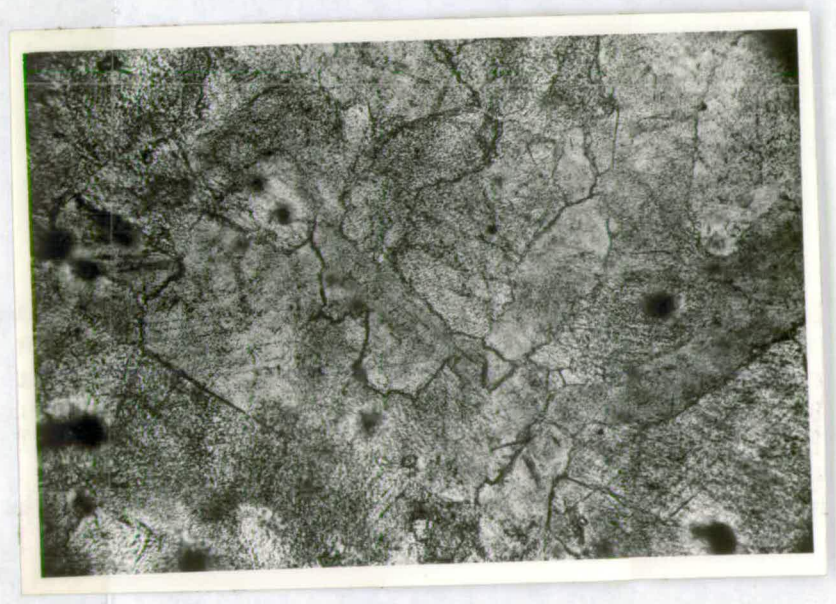
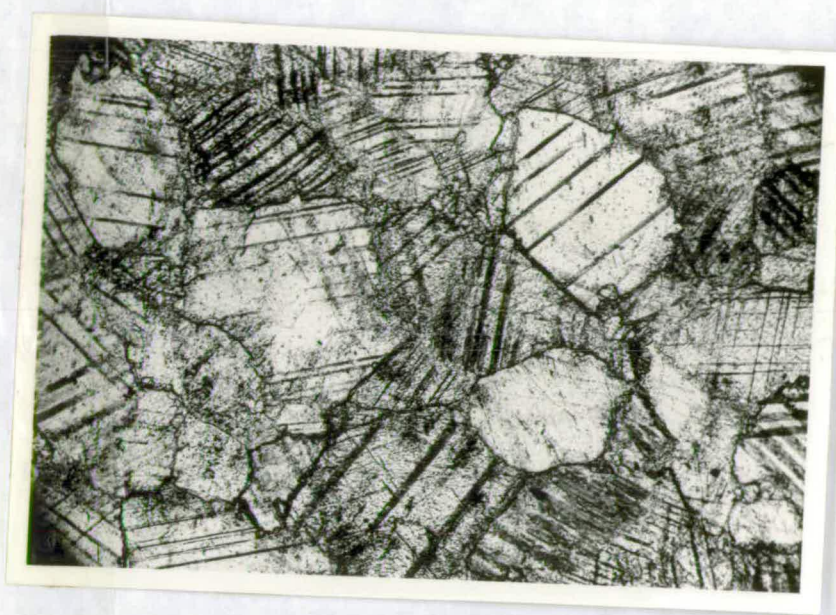


PLATE IX

a. Large-scale fold with south-east trend in Cambrian quartzites, in the corrie due north of Mullach an Leathaid Rhiabhaich.

b. Slickensides on curved shear-surfaces in Cambrian quartzite, near the summit of Ben More Assynt, viewed towards the south-west. The bedding in the quartzite dips to the south and the shear-surfaces to the north; the slickensides plunge to slightly west of north.

A



B



PLATE XI

a. Photomicrograph of dolomite specimen M14. There is considerable granulation along intergranular boundaries and grains are almost opaque with closely-spaced, twinned and untwinned $\{02\bar{2}1\}$ lamellae. Ordinary light. X 50.

b. Photomicrograph of dolomite specimen, showing the final stages of post-crystalline deformation. The rock consists almost entirely of minute granules. Ordinary light. X 50.

(X)

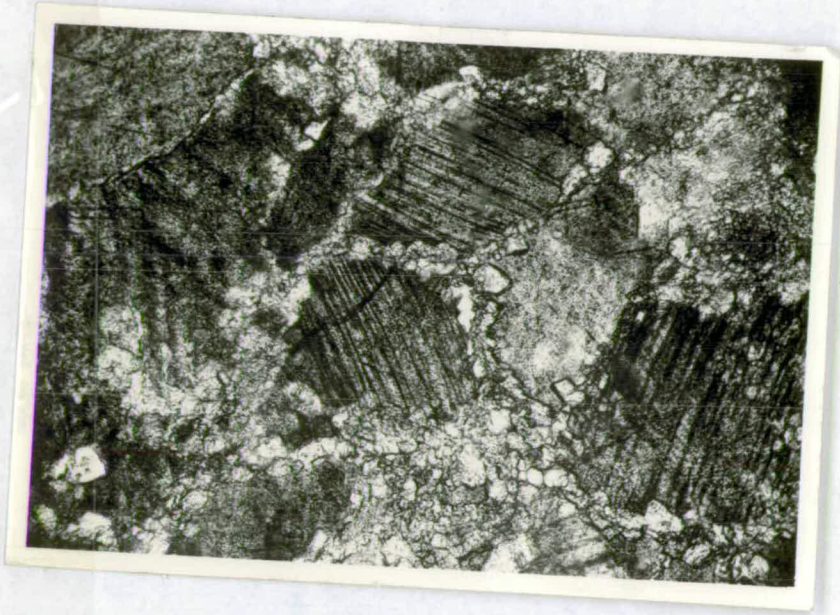


PLATE XII

a, b. Photomicrographs of dolomite grains showing L9 lamellae intersected by later {0221} lamellae. The intersection of L9 and {0221} is vertical in both cases.



ROYAL CHARLES

A



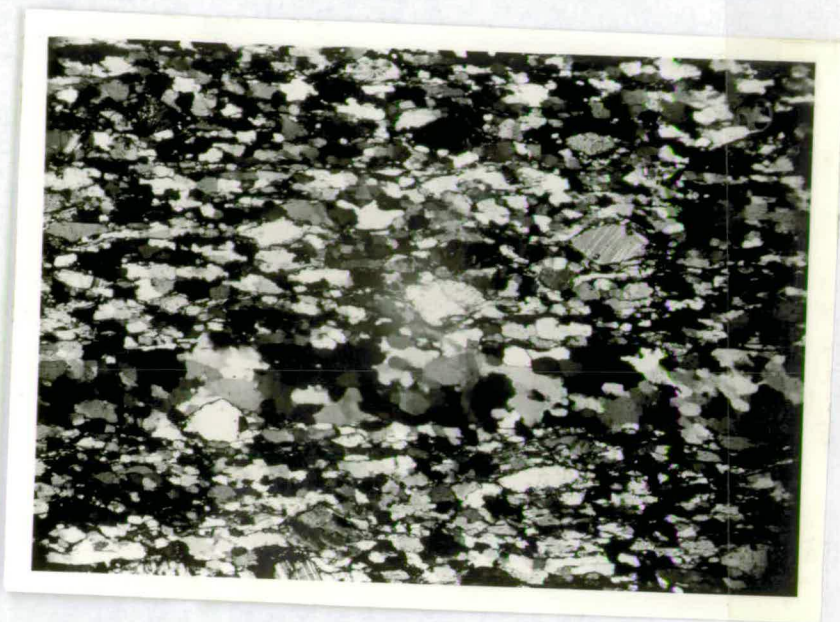
B



PLATE XIII

a. Photomicrograph of slightly deformed Cambrian quartzite. Grains are flattened and show slight granulation; deformation lamellae and planes of minute inclusions are present in some grains. Crossed Nicols. X 40.

b. Photomicrograph of recrystallized Cambrian quartzite (quartzite of Type II). Grains are small, but devoid of any traces of post-crystalline strain. Crossed Nicols. X 40.



三十一

PLATE XIV

a. Photomicrograph of intensely deformed Cambrian quartzite (Quartzite of Type II, specimen 62. Section normal to the foliation and the lineation. The rock is heavily granulated and the grains show extreme undulose extinction. Crossed Nicols. X 40.

b. Same. Section normal to the foliation and parallel to the lineation.

XIV

A



B

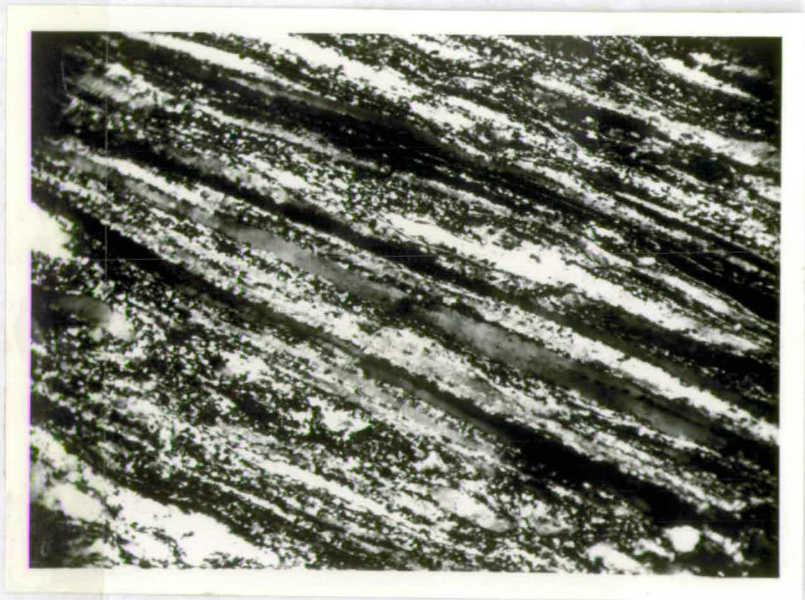


PLATE XV

PRIMARY MYLONITIC ROCKS

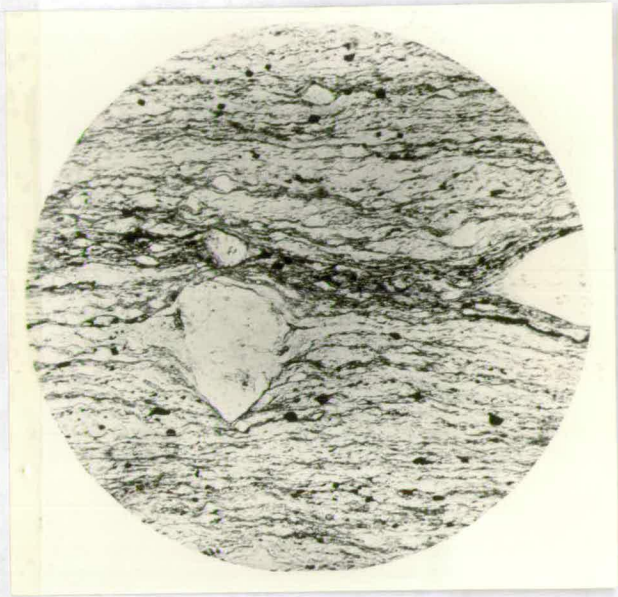
a. Mylonite with porphyroclastic fragments
(augen) of feldspars. Ordinary light. X 50.

b. Same field. Crossed Nicols. Note
the granulation of most of the constituents.

ROYAL CHARLES

XV

A



B

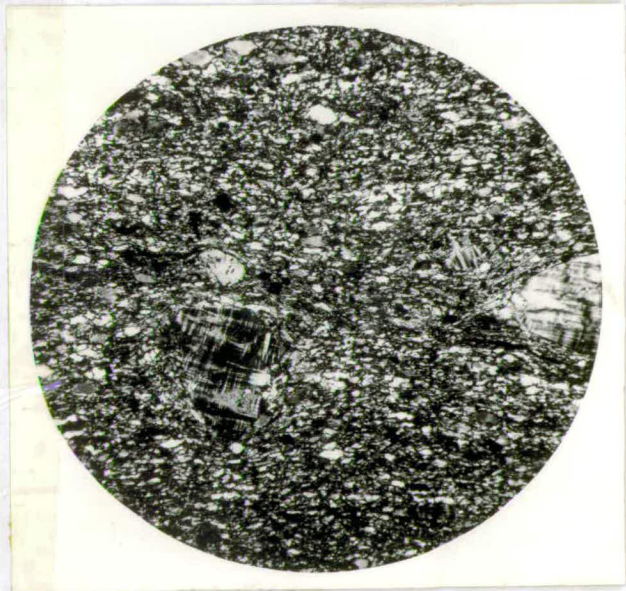


PLATE XVI

PRIMARY MYLONITIC ROCKS

a. Augen schist. Large augen of feldspar are set in a finely laminated matrix. Ordinary light. X 50.

b. Same field. Crossed Nicols. Note the cataclastic textures in the feldspar augen and the recrystallized quartz and feldspar grains in the matrix.

c. Blastomylonite. Laminated rock of more uniform and coarser grain than the varieties shown above. Ordinary light. X 50.

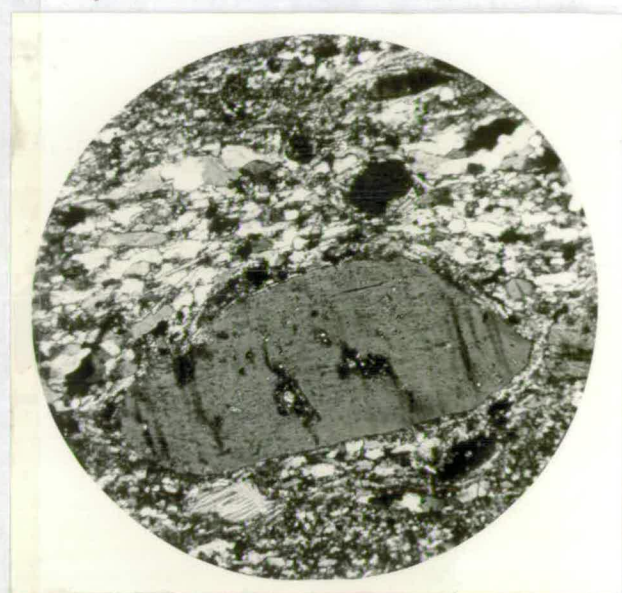
d. Same field. Crossed Nicols. The minerals are almost completely recrystallized and the grains are free from post-crystalline strain.

XVI

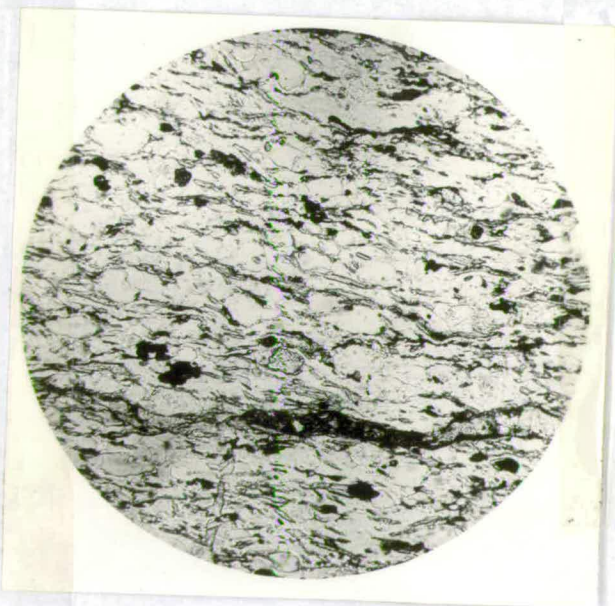
A



B



C



D

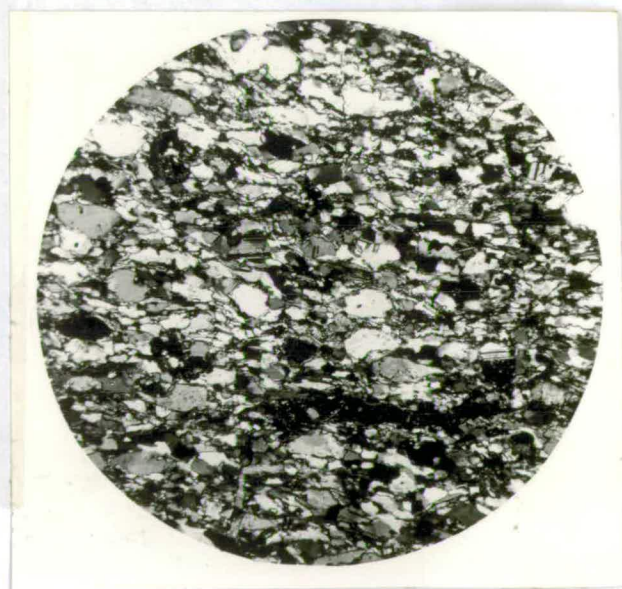


PLATE XVII

SECONDARY MYLONITIC ROCKS

a. Phyllonite, showing the characteristic lenticular structure. Ordinary light. X 50.

b. Same field. Crossed Nicols. Note the extensive granulation of the minerals in the quartzo-feldspathic layers and lenticles.

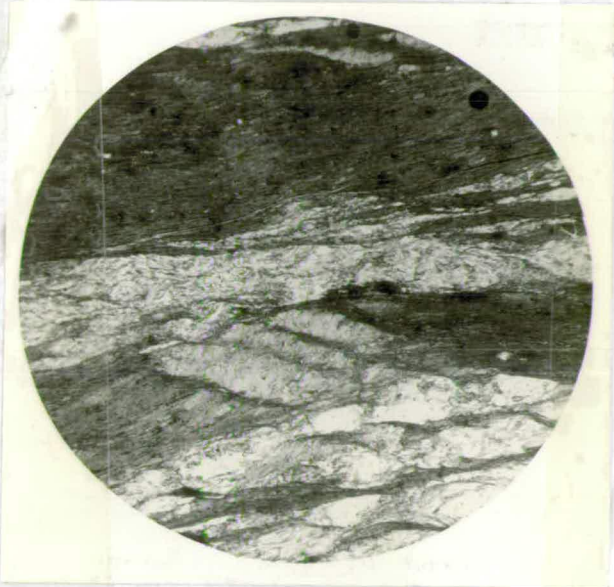
c. Folded layer of quartzite from the zone of secondary deformation, Stack of Glencoul. Ordinary light. X 20.

d. Same field. Crossed Nicols. Note the complete granulation of the quartz.

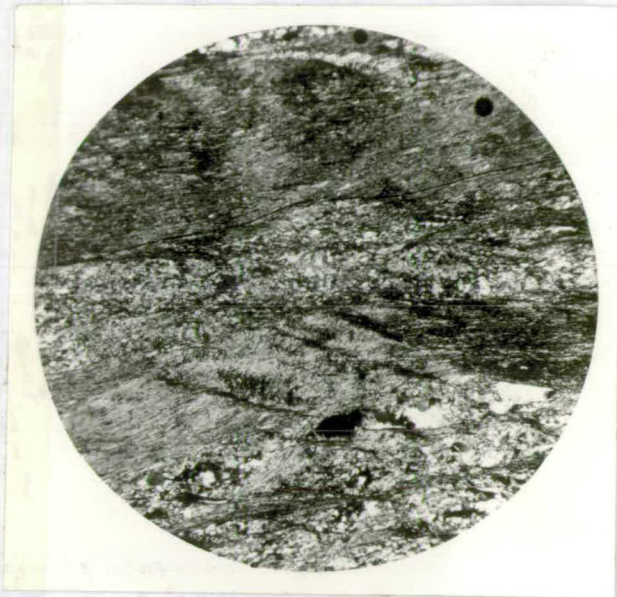
ROYAL CHARLES

XVII

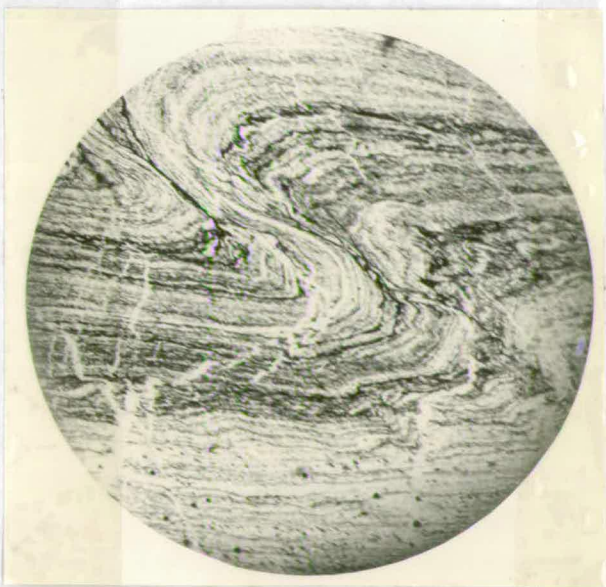
A



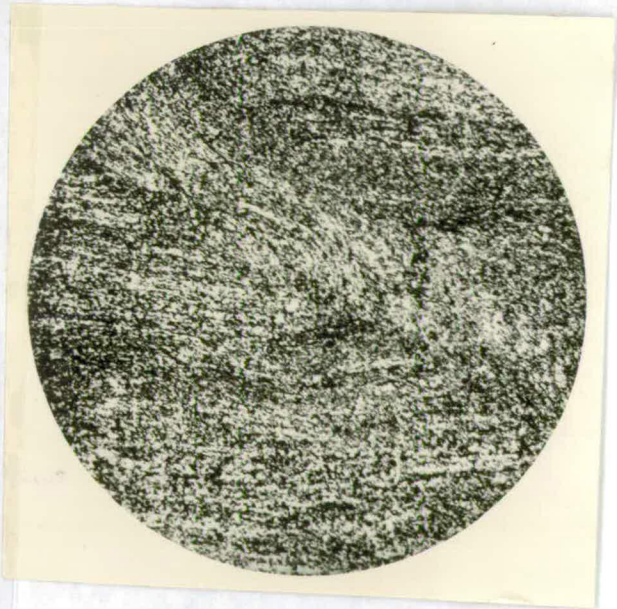
B



C



D



ROYAL CHARLES

PLATE XVIII

SECONDARY MYLONITIC ROCKS

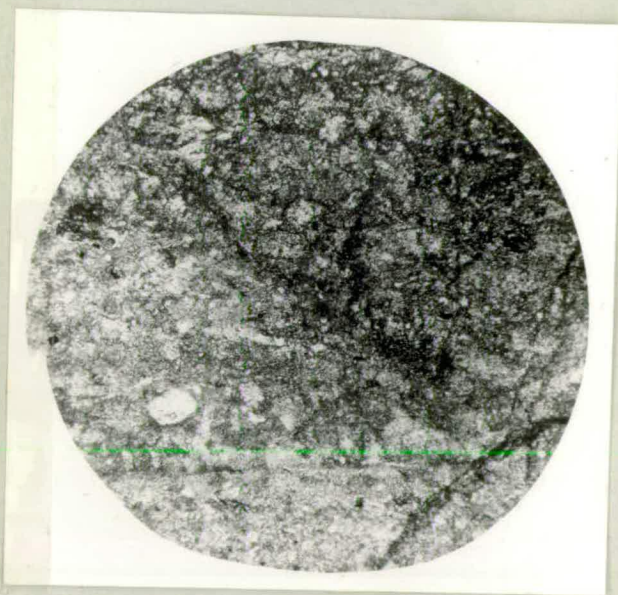
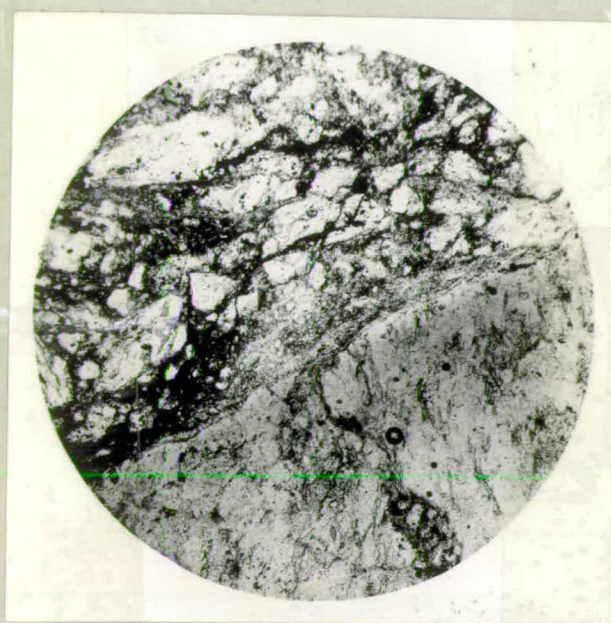
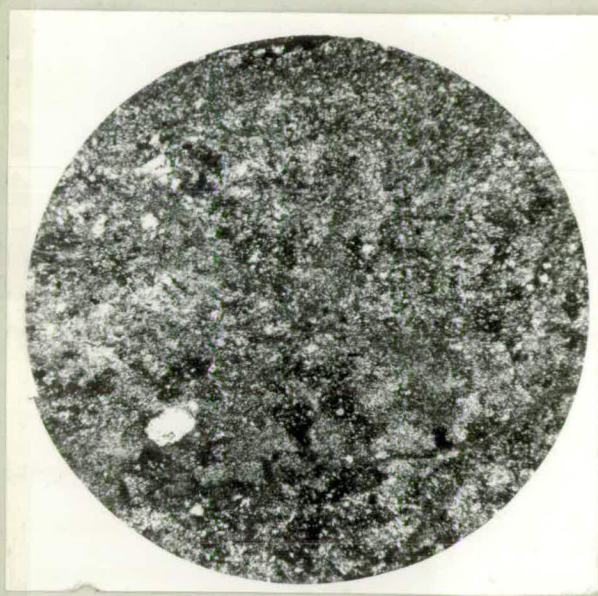
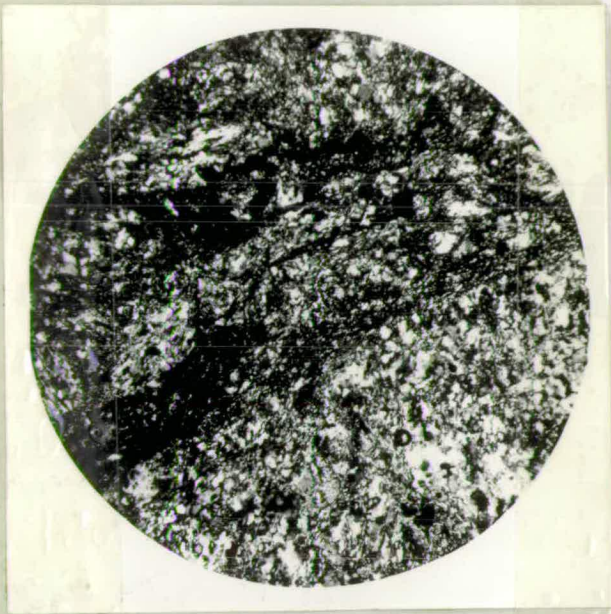
a. Kakirite, formed by brecciation of a primary mylonitic rock. The rock consists of disoriented, angular fragments of the original rock in a completely pulverized matrix. Ordinary light. X 50.

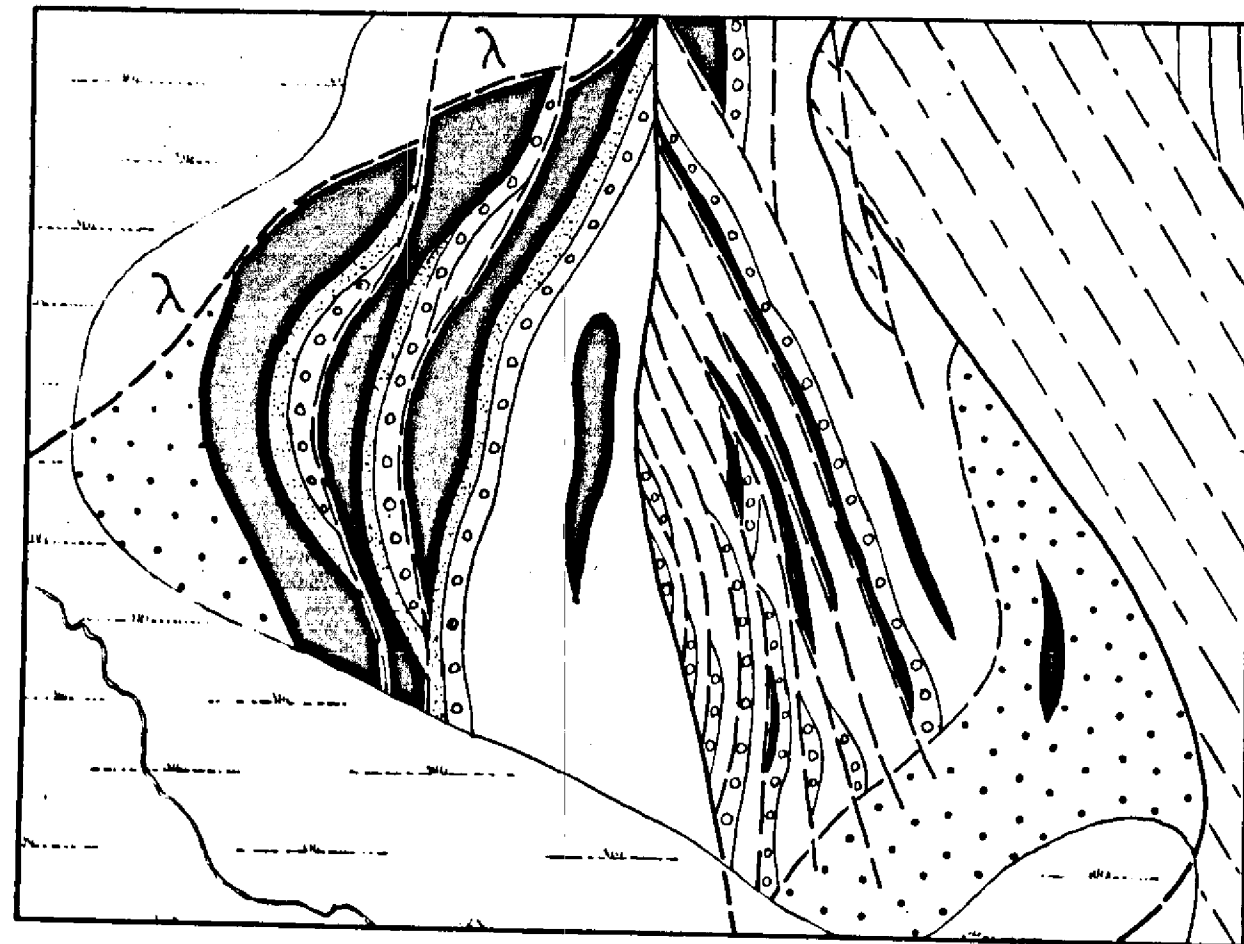
b. Same field, Crossed Nicols.

c. Cataclasite. The rock consists of finely-ground, unlaminated material containing a few fragments of the original rock. Ordinary light. X 50.

d. Same field. Crossed Nicols.

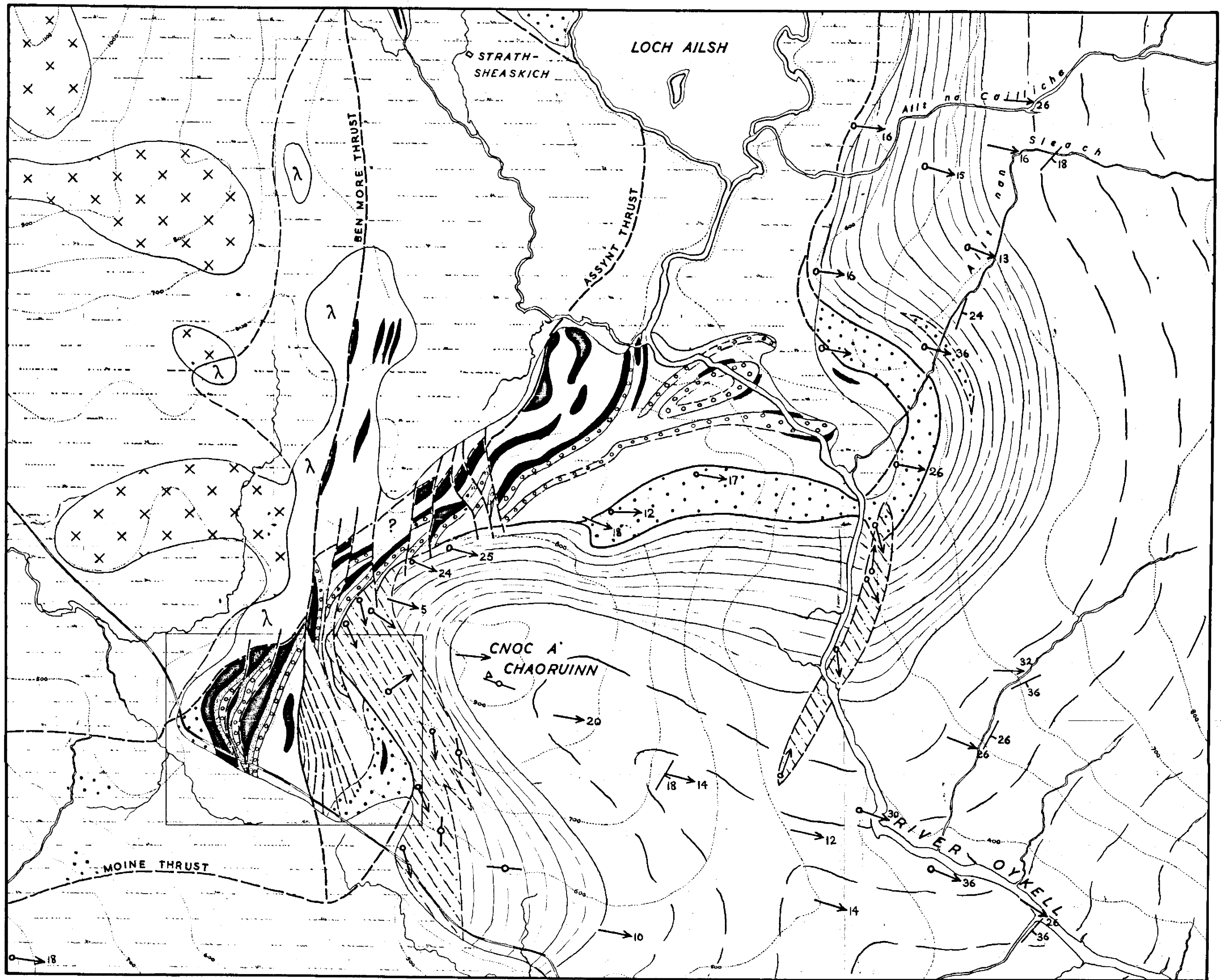
XVII





0 300 600 yds.

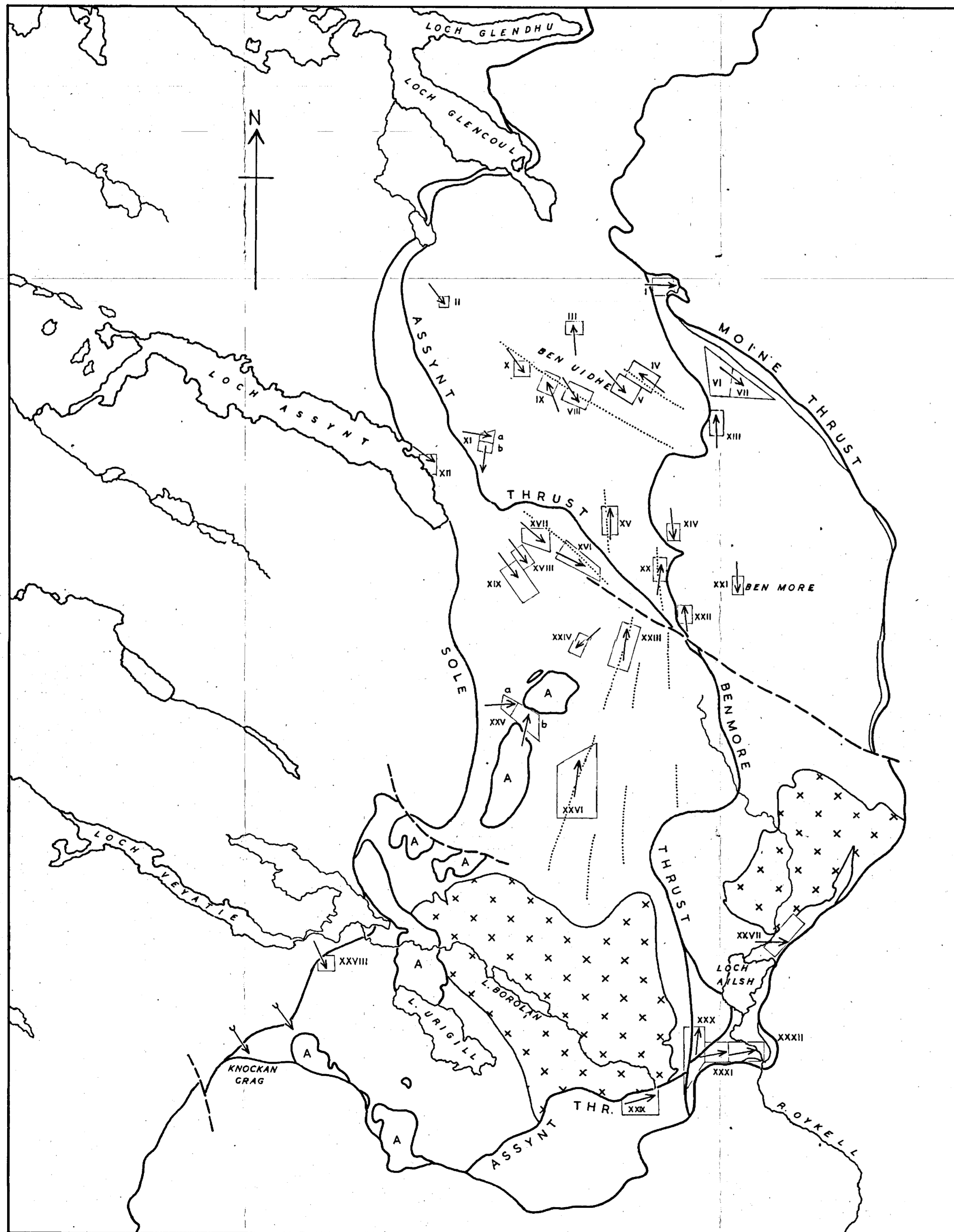
- | | | | | |
|--|--------------------------|-----------------|--|----------------------|
| | Peat | CAMBRIAN | | Marble |
| | Phyllonite & Cataclasite | | | Limestone |
| | Moine Schist | | | Serpulite Grit |
| | Primary Mylonitic Rocks | | | Fucoid Beds |
| | Minor Intrusions | | | Quartzite |
| | Syenite | | | Foliation |
| | Faults | | | Plunge of fold-axis |
| | Road | | | Plunge of lineation |
| | | | | Horizontal fold-axis |



0 1/4 1/2 3/4 1 MILE

MAP SHOWING FOLDING IN CAMBRIAN AND TORRIDONIAN SEDIMENTARY ROCKS IN THE ZONE OF DISLOCATION

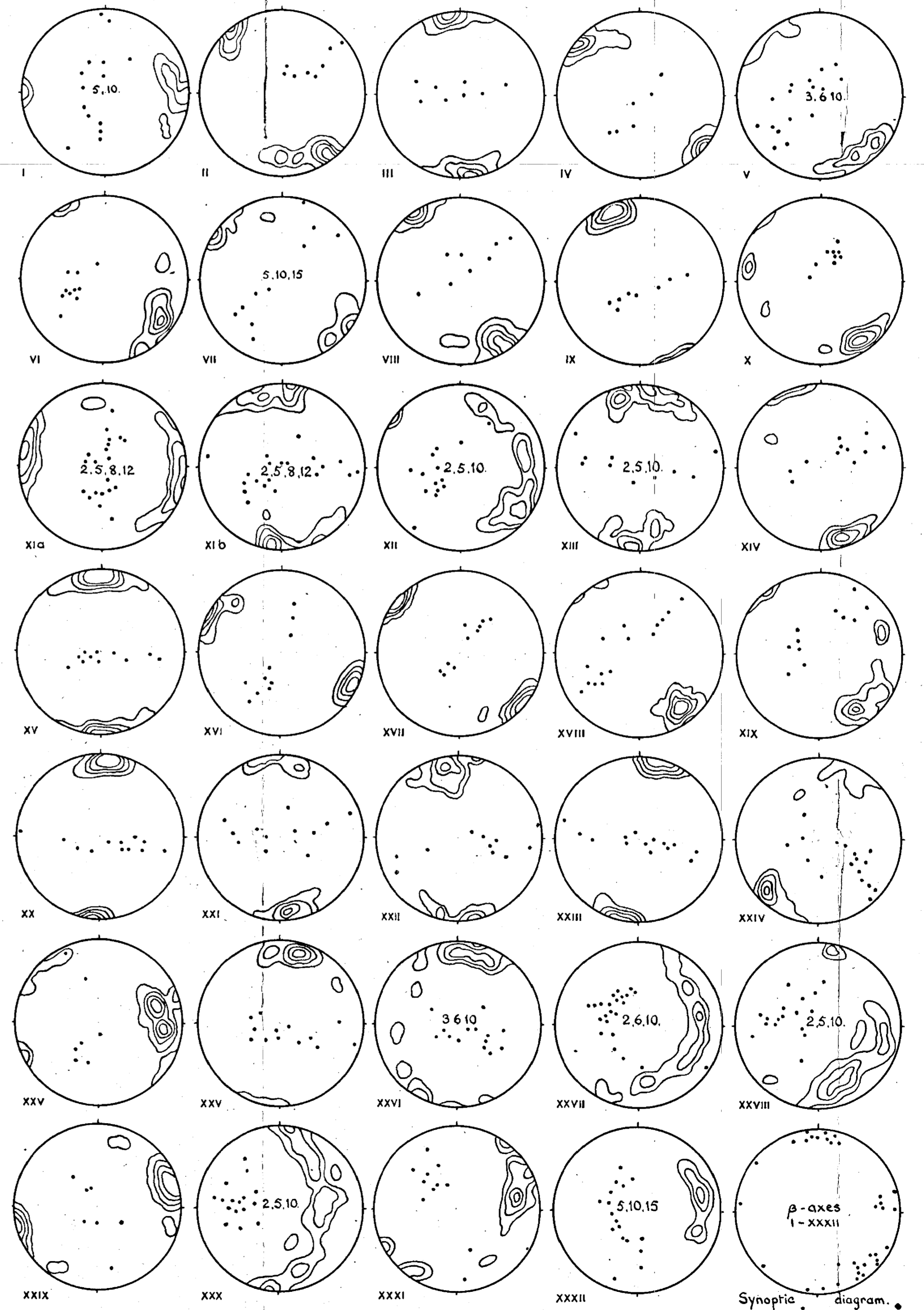
x Syenite of the L. Borolan and L. Ailsh Masses
 'A' Klippen of the Assynt Thrust-plane
 Approx. outcrop of axial planes of large-scale anticlinal folds
 — Major Thrust-planes

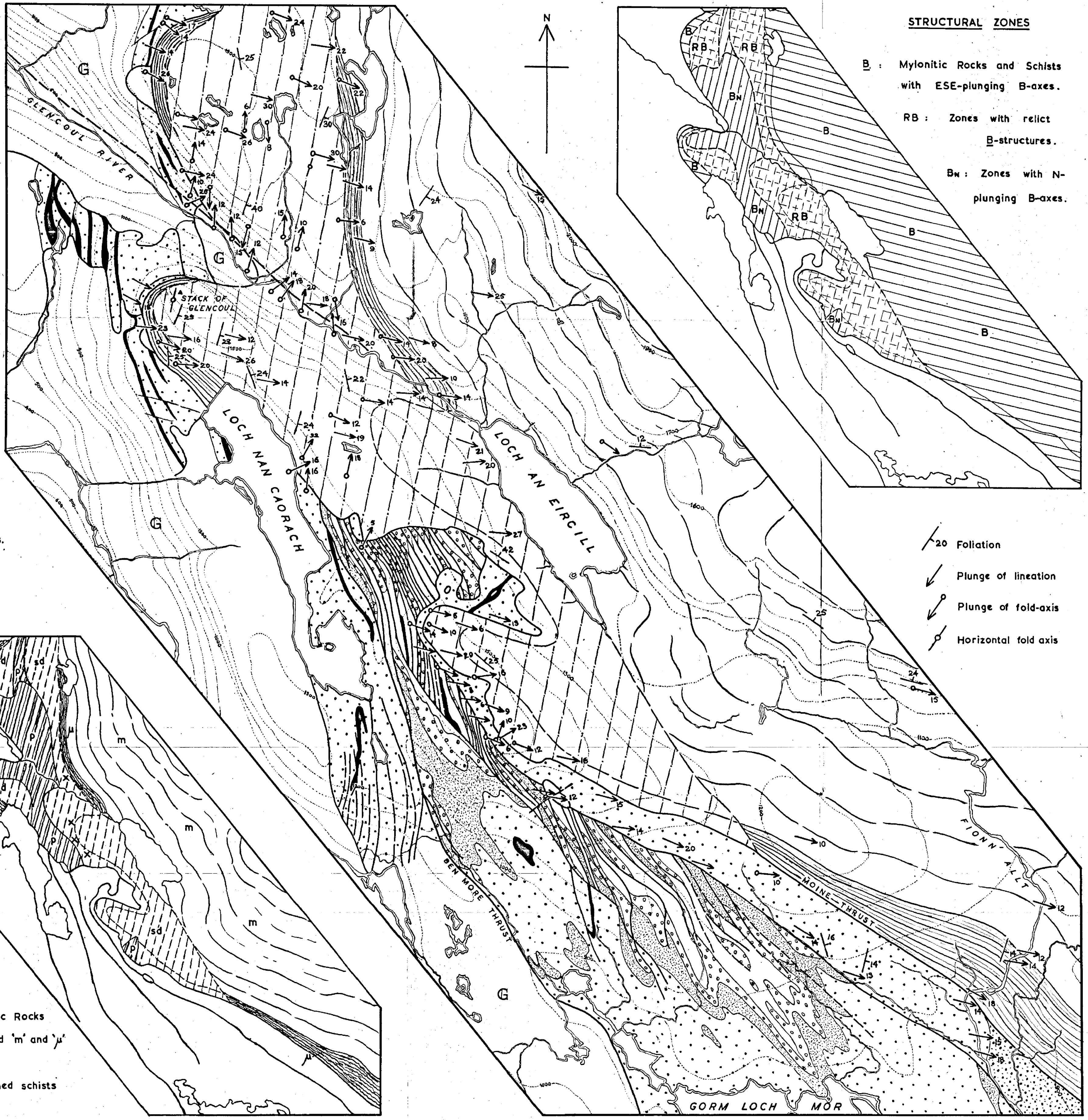
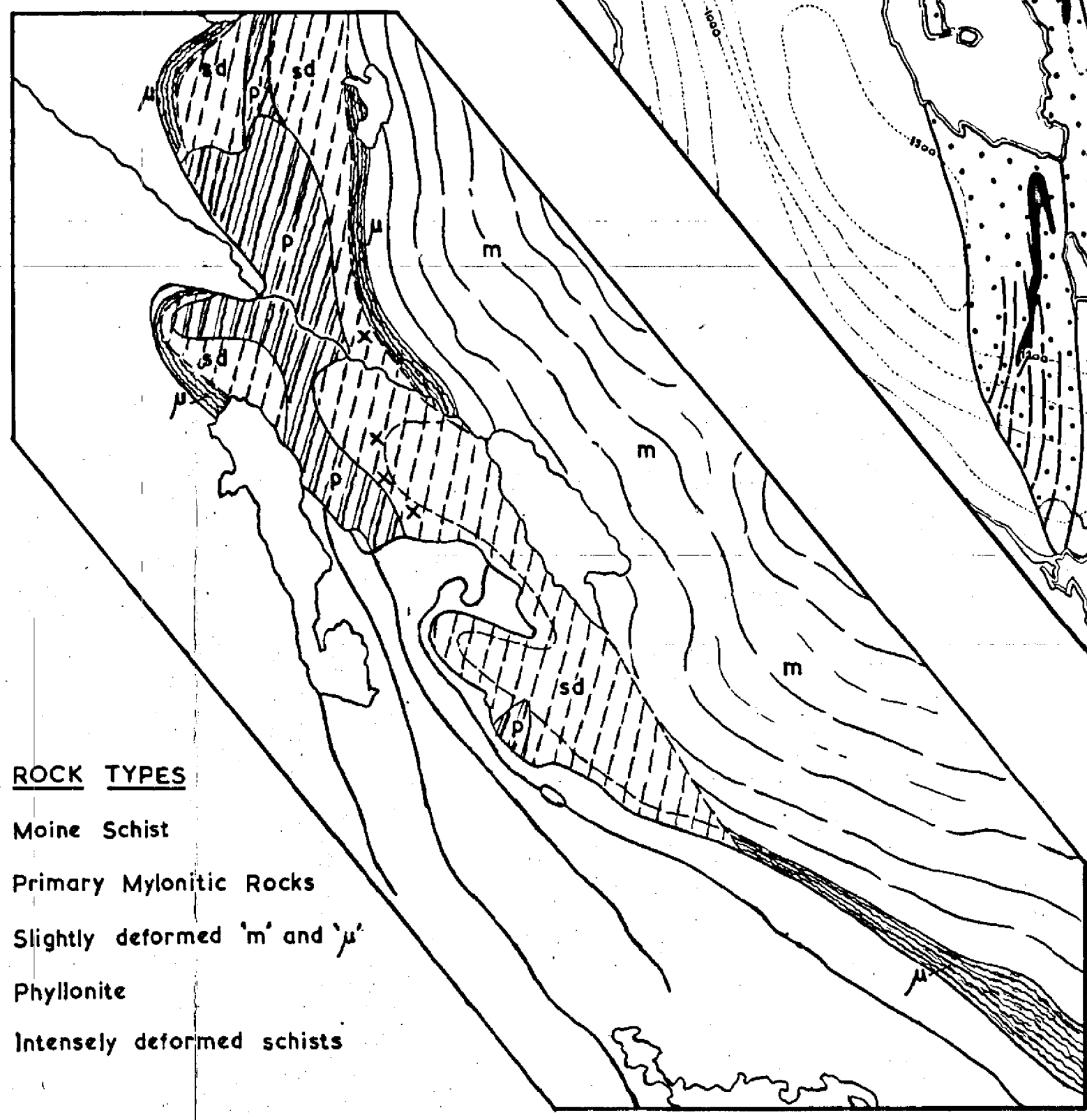
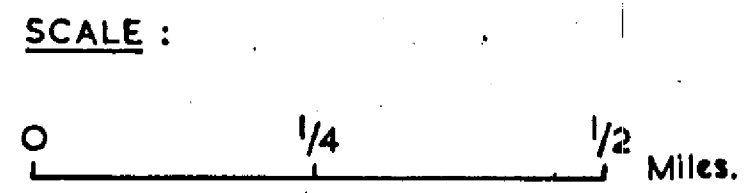
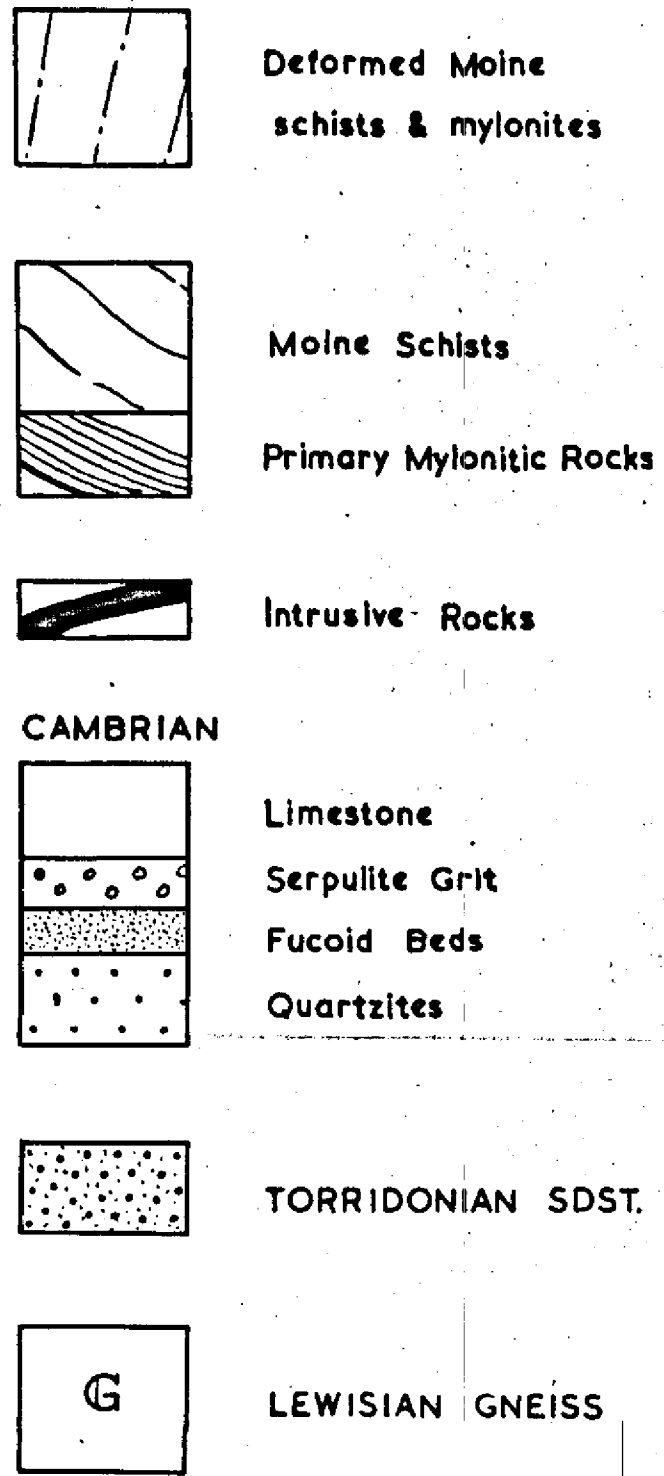


β -DIAGRAMS IN SELECTED AREAS SHOWN ON MAP.

Contour intervals: > 5, 10, 15, 20% per 1% area unless otherwise stated.

Points represent poles of bedding planes (π). Arrows on map show plunge of β -axes.





ABSTRACT OF THESIS

Name of Candidate John McDougall CHRISTIE
Degree Doctor of Philosophy Date July, 1956
Title of Thesis " A TECTONIC STUDY OF THE POST-CAMBRIAN THRUSTS OF
THE ASSYNT REGION"

The fabrics of the rocks in the vicinity of the post-Cambrian thrusts are described and analysed. The study embraces structures ranging from the largest-scale folds visible in the field to intra-crystalline structures observed under the microscope; the kinematic synthesis is based on a consideration of the structures on all scales.

Laminated rocks mapped as mylonite by the Survey geologists do not conform strictly to Lapworth's definition. Many show marked recrystallization and are more accurately described as augen schists and blastomylonites. These rocks, referred to here as Primary Mylonitic Rocks, occupy a zone along the horizon mapped as the Moine Thrust and grade upwards with increasing crystallinity into low-grade Moine Schists. There is structural continuity from the mylonitized Cambrian rocks below the Moine Thrust, through the primary mylonitic rocks, to the Moine Schists: they have a common B-axis (defined by megascopic fabric elements) which plunges to the east-south-east (B). The deformation of the primary mylonitic rocks and Moine Schists was dominantly pre-crystalline. It is inferred that the primary mylonitic rocks were formed along a "movement horizon", rather than a thrust, during the regional metamorphism of the Moine Schists. Cambrian rocks are affected by these movements, which must therefore be of post-Cambrian age. The form of the folds in the primary mylonitic rocks indicates that the Moine Schists were transported to the south-south-west along the "movement horizon".

Whereas the symmetry of the megascopic fabric of the primary mylonitic rocks (including some deformed Cambrian quartzites) and the Moine Schists is monoclinic, the symmetry of the quartz fabric is characteristically orthorhombic. The symmetry of the quartz fabric differs from that of the megascopic fabric on the scale of specimen, indicating that the quartz did not acquire its orientation while the foliation was an active slip-plane. The quartz orientation is homogeneous in individual folds and is comparatively homogeneous throughout the mylonitized Cambrian quartzites, the primary mylonitic rocks and the Moine Schists in the area. It is inferred that the quartz in all these rocks was reoriented after the folding about B. One of the symmetry axes of the quartz fabric is statistically parallel to B, however, a fact which suggests that the quartz was reoriented during the final imprint of the same deformation which produced the folding. The movement during this imprint is interpreted as a "flattening", with concomitant elongation parallel to B.

Locally the primary mylonitic rocks and Moine Schists have been affected by secondary deformation of a post-crystalline nature. Well-laminated rocks, chiefly of pelitic composition, were converted to phyllonite and more massive rocks to kakirite and cataclasite. These are designated Secondary Mylonitic Rocks. The greatest development of these rocks is in /



in two areas - at the Stack of Glencoul and Cnoc a'Chaoruim. The Ben More Thrust displaces the Moine Thrust in both areas and the zones of secondary deformation cross the primary mylonitic rocks and Moine Schists above the plane of the Ben More Thrust. Folds in the secondary mylonitic rocks trend approximately north-south and mostly originated as "kink-zones" related to the Ben More Thrust and other eastward-dipping reverse faults. The sense of movement was such that the upper layers moved to the west over the lower.

In the zone of dislocation two great thrust-nappes, termed the Upper and Lower Assynt Nappes, are recognised. Large-scale folds with south-easterly trend in the nappes are crossed by steep, eastward-dipping reverse faults. Folding about north-trending axes is associated with these faults, of which the Ben More Thrust is the most important. The nappes were transported from the north-east or north-north-east during the primary deformation and subsequently faulted and folded during the secondary deformation.