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CONTENTS

FIGURES

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ABSTRACT

On the basis of a preliminary survey of the Moine thrust zone in the Assynt region, several areas were selected for a detailed study of the small folds and lineations, and of their relationship to the major thrusts and faults. A study was also made of the microfabric of quartz-bearing rocks in the Moine thrust zone and of the Moine schists, and of deformed dolomite rocks below the Moine thrust at Loch Ailsh.

Two groups of mylonitic rocks are developed in the thrust zone. The *primary mylonitic rocks,* which show considerable evidence of recrystallization, form a thick zone along the boundary mapped as the Moine thrust. Locally, these mylonitic rocks and the Moine schists are crushed and phyllonitized, resulting in the *secondary mylonitic rocks.* This evidence indicates at least two distinct periods of deformation (I and II).

Structural evidence shows that the first deformation (I) affected the primary mylonitic rocks, the Moine schists, and the Cambrian rocks. Folds and lineations (*B*) resulting from this deformation plunge at low angles to the east-southeast; the deformation was contemporaneous with the regional metamorphism of the Moine schists, which must therefore be of post-Cambrian age. Structural and petrofabric data suggest that three phases may be recognized in this deformation. During the early phase (*Ia*) there was movement of the Moine nappe to the south-southwest along the Moine thrust zone, along with displacement of the underlying thrust sheets. This was followed by a phase (*Ib*) in which the Moine schists and the primary mylonitic rocks were flattened in a direction normal to the Moine thrust and elongated in a west-northwest direction, parallel to the fold axes; the preferred orientations of quartz originated during this phase of deformation. This may have been followed by a third phase (*Ic*) during which the Moine schists were shortened in a north-south direction, perhaps with some transport of the Moines to the north. During the second deformation (II), folds with northerly trend were developed in the Moine thrust zone and the underlying thrust sheets. The Ben More thrust and associated reverse faults date from this deformation. The Moine thrust and the Glencoul (Assynt) thrust are displaced by the Ben More thrust (the former by approximately 500 feet), and the most extensive development of secondary mylonitic rocks is in the Moine thrust zone immediately above the Ben More thrust. The Moine schists were transported to the west during this deformation (II), but the amount of displacement may have been small.

Two large thrust sheets, the upper and lower Assynt nappes, are recognized between the Moine thrust and the sole, and their mode of emplacement is discussed.

INTRODUCTION

THE MOINE THRUST is now known to geologists throughout the world as one of the classic examples of a large-scale thrust zone. The zone extends from the Point of Sleat in Skye, in the south, to Whiten Head on the north coast of Sutherland, in the north—a distance of approximately 120 miles. It is well developed at both extremities and must extend farther in both directions. The thrusts are very well defined in the Assynt region, between the Cromalt Hills, in Wester Ross, and Loch Glendhu, in Sutherlandshire. In this region there is a wide embayment in the outcrop of the Moine thrust, generally known as the "Assynt bulge" or the "Assynt Culmination" (Bailey, 1935). Within this bulge several slices of rock carried on thrusts underlying the Moine thrust crop out. The region has become famous chiefly through the work of B. N. Peach and John Horne and their associates in the Geological Survey of Great Britain (Peach *et al.*, 1907).

In recent years the age and the origin of the Moine thrust, and its significance in the tectonic and metamorphic history of the Scottish Highlands, have become subjects of renewed interest. The present study was undertaken in the hope that the application of the techniques of structural petrology and structural analysis might provide answers to some of the problems that were not finally resolved during the systematic mapping and investigations of the Survey geologists. The Assynt region was selected for study because of the excellent development and exposure of the thrust planes.

An index map showing the location and the main geological features of the area is shown in figure 1 (in pocket), but reading of the paper will be greatly facilitated by reference to the geological map of the Assynt region (1923) or the maps in the memoir on the northwest Highlands (Peach *et al.*, 1907).

Historical Review

Geological work in the Assynt area began with the studies of MacCulloch (1814, 1824), and a considerable number of papers were published before the systematic mapping of the area was undertaken by members of the Geological Survey in the period following 1885. The development of thought on the stratigraphy and the structure of the area during this period has been reviewed by Horne (Peach *et al.*, 1907, chap. 2) and McIntyre (1954). The most notable contributions were those of Nicol (1844, 1857, 1861) and Callaway (1881, 1883), who noted many of the structural features later mapped and named by the Survey geologists.

Nicol (1861) was the first to recognize that the Moine schists were everywhere in fault contact with the Lewisian gneiss and the Torridonian and Cambrian rocks to the west,* and that the Cambrian succession in the Assynt area was disturbed and repeated by faulting. Although this discovery of Nicol's contained the clue to the complex structure of the northwest Highlands, his work was discredited at the time as a result of the efforts of Murchison and Archibald Geikie (Murchison, 1856, 1859, 1860; Murchison and Geikie, 1861), who considered that an undisturbed stratigraphic succession existed from the Lewisian gneiss, upward through the unmetamorphosed Torridonian and Cambrian formations, into the schists of the Moine series. Nicol's views were eventually vindicated by the work of Callaway (1881, 1883) in Assynt and of Lapworth (1883, 1884, 1885) in the Eireboll region to the north. These studies, which were supported by the later work of the Survey geologists (Peach and Horne, 1884; Peach *et al.*, 1888), led to the acceptance of the idea that the Moine schists had been carried over the unmetamorphosed sedimentary rocks of Torridonian and Cambrian age to the west on a series of great thrust planes.

The systematic mapping of the thrust zone by Survey parties, begun in Eireboll in 1883, reached the northern part of Assynt in 1885, but the area was not completely mapped until 1896, when Peach and Horne mapped the area east of Ben More. The 1-inch sheets 101 (Ullapool) and 107 (Lochinver and Assynt) were published in 1892, and the geology of the thrust zone in Assynt is described in the

* The modern stratigraphic terminology is adopted here to avoid confusion.

memoir, *The Geological Structure of the North-West Highlands of Scotland* (Peach *et al.*, 1907). The survey of the central parts of Sutherland and Ross-shire was initiated while the main Survey party was working on the thrust zone and the areas to the west. Sheets 102 (Strath Oykell and lower Loch Shin) and 108 (central Sutherland) both contain parts of the zone of dislocation, and these were not published until 1925 and 1931, respectively, but a composite geological map of the Assynt region, 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 *et al.*, 1926) and *The Geology of Central Sutherland* (Read, 1931).

The structure of the Assynt area is described in detail in the memoir on the northwest Highlands (Peach *et al.*, 1907) and summarized in the guide to the geological model of the district (Peach and Horne, 1914). The structure of the area and the sequence of movements, as described by Peach *et al.* (1907), are outlined below.

The region is traversed by four great thrust planes, each with a general dip toward the east-southeast. From east to west, these are (1) the Moine thrust, (2) the Ben More thrust, (3) the Glencoul thrust, and (4) the sole, or the lowest thrust plane. The Moine thrust is the most important of these structures. The trend of the outcrop of the thrust, which is remarkably constant to the north and south of Assynt, varies considerably in the area, giving rise to an embayment 15 miles long from north to south and approximately 7 miles wide. In the north the thrust dips at low angles to the northeast, whereas in the south it has a gentle southerly dip. It carries the crystalline schists of the Moine series, which underlie most of the northern Highlands, over the Lewisian gneiss, the Torridonian sandstone, and the Cambrian sedimentary rocks to the west.

The Ben More thrust carries a slice (the Ben More nappe) of Lewisian, Torridonian, and Cambrian rocks, showing their normal unconformable relations. The thrust has been folded and a number of klippen of the nappe lie to the west of the present outcrop of the thrust, on Beinn na Cnaimseag, on Beinn an Fhuarain, and between Ledbeg and Loch Urigill.

The Glencoul thrust to the west carries a slice (the Glencoul nappe) of Lewisian gneiss, capped by Cambrian sedimentary rocks. No Torridonian sandstones are exposed in the Glencoul nappe. The zone of thrusts is bounded on the west by the lowest thrust plane, or the sole.

Imbricate structure, or *Schuppen Struktur,* is commonly associated with the thrusts; in imbricate systems the Cambrian rocks are repeated by steep reverse faults which generally dip toward the east-southeast 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 at several localities.

Each of the thrusts appears to be overlapped in turn by the overlying one; the Ben More thrust overlaps the Glencoul thrust south of Ben More, and appears to be truncated by the Moine thrust near the Stack of Glencoul and at a number of localities to 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 succession 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 ceased. Peach *et al.* (1907, pp. 271–272) considered that the Moine thrust was probably the first of the great thrust planes to be produced.

The thrust masses were believed to have moved to the west-northwest over the foreland, perpendicular to the general strike of the thrusts and parallel to the prominent lineations in the mylonitic rocks and the Moine schists. The age of the movements was determined within certain limits. The plutonic igneous rocks of the Loch Ailsh and Loch Borolan masses and the numerous minor intrusions, all of post-Cambrian age, are cut by thrust planes, crushed and locally foliated by the movements. In central and north Sutherland the Moine schists are overlain unconformably by Middle Old Red Sandstone sediments. The movements must therefore be of post-Cambrian and pre–Middle Old Red (Devonian) age.

The Moine schists in the area are represented by mylonitic rocks, low-grade schists, and "granulitic siliceous flagstones." The following statement regarding the orientation of fold axes in the schists appears in Peach *et al.* (1907, 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 [trend], the inclination of the axial planes being ESE. . . . This plication may be regarded as an obvious accompaniment of the movement of the thrust masses in a WNW direction. The other system strikes [trends] generally WNW and ESE, as if produced by forces acting at right angles to this trend." No definite information is given as to the relative ages of the two groups of folds.

There has been considerable disagreement as to the relative ages of the Moine metamorphism and the thrust movements. "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" (Teall, in Peach *et al.*, 1907, p. 600). The conflicting hypotheses implicit in this statement have been more fully stated in later publications (Peach and Horne, 1930; Read, 1934). Peach considered that the Moine schists were metamorphosed Torridonian, and that the regional metamorphism of the Moine schists and the thrusting were contemporaneous and took place in post-Cambrian times (Peach and Horne, 1930, p. 200). Horne, on the other hand, regarded the Moine series as metasedimentary rocks of pre-Torridonian age, which were only modified and mylonitized along the thrusts during the post-Cambrian movements (Peach and Horne, 1930, p. 201). Phemister (in Read *et al.*, 1926) and Read (1931) also believed that the general Moine metamorphism was distinct from, and earlier than, the thrust movements. Read subsequently (1934) reviewed the evidence bearing on this problem. He concluded (1) that the low grade of the Moine schists near the thrust zone was due to retrogressive ("dislocation") metamorphism; (2) that the similarity in texture and composition between these schists and sheared Torridonian rocks below the Moine thrust (perhaps the best evidence for their correlation) was due to "metamorphic convergence," as metamorphism of different rocks of the same

bulk composition, whatever their texture, will tend to give similar products; and (3) that the Moine series and its metamorphism were of pre-Torridonian, and probably Lewisian, age.

Since the classic work of the Survey geologists in the Moine thrust zone, Bailey (1935) and Sabine (1953) have suggested modifications in the interpretation of the structures below the thrust in the Assynt "bulge." There has also been a considerable amount of research on the microfabric and the small structures in the Moine schists and the mylonitic rocks in the Assynt area and elsewhere near the Moine thrust. For convenience, the work of Bailey and Sabine is reviewed first. The fabric studies, which are of considerable relevance to the present work, are treated subsequently in some detail.

Bailey (1935) proposed a number of changes in the interpretation of some of the major thrusts. He considered that Peach and Horne had ascribed too much importance to the Glencoul and Ben More thrusts, and suggested that the Glencoul and Ben More nappes are in fact parts of a single tectonic unit. He also showed that the Sgonnan Beag thrust, which was thought to underlie the Loch Ailsh syenite mass, was the original intrusive contact, modified slightly by shearing. In conclusion, Bailey drew an analogy between the Assynt "bulge" and the Aulloch massif in Provence, implying that the Assynt bulge is an axial culmination which developed concurrently with the thrust movements.

Sabine (1953) discusses the structural implications of the distribution of various types of hypabyssal intrusive rocks in the different structural units. The widespread occurrence of grorudites in the Glencoul and Ben More nappes and in klippen of the Ben More nappe, and the absence of this rock type in the mass between the sole and the Glencoul and Ben More thrusts, were interpreted as indicating that the Glencoul and Ben More nappes were parts of a single tectonic unit, as Bailey (1935) had suggested. Sabine proposed that the term "Ben More thrust" be restricted to the portion north of its intersection with the Glencoul thrust (on Braebag Tarsuinn), and that the portions of the thrust south of this and underlying the klippen to the west be renamed the "Assynt thrust-plane." For the tectonic unit as a whole he used the term "Glencoul-Assynt thrust-masses," and referred to the klippen as "klippen of the Assynt thrust-plane."

The distinctive "Canisp porphyry" outcrops only in the Torridonian and Cambrian rocks of the foreland. In view of the extensive development of other intrusive rocks in the zone of the thrust masses, Sabine considered this to be evidence of considerable displacement on the sole. A ledmorite dike outcrops at intervals in a straight line extending across the foreland from Rhu More Coigach to Elphin; this line, if prolonged eastward into the thrust zone, passes through the Loch Borolan mass, in which the type rock occurs (at Ledmore). Sabine cited this as evidence of little displacement along the sole in a north-south direction, but the argument is weakened by the existence of other intrusions of this rock in the foreland to the north (at Achmelvich).

F. C. Phillips was the first, and for many years the only, geologist to use the techniques of petrofabric analysis in Britain. Phillips (1937) has described the orientation of quartz, muscovite, and biotite in the Moine schists, and in rocks from the zone of the thrusts and the foreland. The optic axes of quartz in the schists are consistently oriented in a more or less well-defined girdle; that is, they are *B*-tectonites in the terminology of Sander (1930). The micas also show a strong preferred orientation; the poles of (001) cleavages generally lie in a strong point maximum, normal to the foliation, but there is a gradation to a girdle, which generally coincides with the girdle of quartz *c*-axes. The axes of these girdles (*b*-axes) plunge to the southeast over the whole area of outcrop of the schists, and Phillips emphasizes that they are everywhere parallel to the megascopic linear structures, including fold axes, lineation, and rodding and mullion structures.

Some of the quartz diagrams show a preferred orientation of the *c*-axes in two intersecting (*Okl*) girdles, instead of a single (*ac*) girdle. Phillips considers that such orientations are due either (*a*) to a "crossed strain" causing rotation in a plane normal to the first girdle, or (*b*) to the influence of later movements on simple girdle patterns. He concludes that "*b*-axes . . . 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." In Phillips' view, the fabric evidence indicates that this deformation, which was concurrent with the regional metamorphism, was "prior to the dislocation phase [thrusting] of the Caledonian movements."

Phillips examined the effect of the "dislocation metamorphism" on the Moine schists and concluded that the later movements had had little, if any, effect on the schist fabrics. The larger relict grains in partially mylonitized rocks show the typical girdle fabrics and *b*-axes parallel to those in the schists. Cambrian and Torridonian rocks from the foreland and the zone of thrusts show little evidence of preferred orientation of quartz; but in a few such rocks from the thrust zone Phillips found an incipient girdle of quartz *c*-axes, with a northwest-southeast strike, "with its *b*-axis perpendicular to the direction of movement in the post-Cambrian dislocations." He concludes that these data lend support to Read's view that the "Moine series and its metamorphism are of pre-Torridonian date, whilst a Lewisian age is not excluded."

Phillips (1945) has strikingly demonstrated the homogeneity of the fabric over the total area of outcrop of the Moines. He infers, from the contrast in fabrics between the Moine schists and the rocks in the thrust zone, that schist fabrics were not imprinted during the thrust movements. He now ascribes the "crossed-girdle" patterns of quartz to "overprinting" on simple *B*-tectonite patterns (single girdles) by the thrust movements; the slight divergences of orientation between quartz and mica girdles in some specimens are also attributed to this overprinting. Later (1947, 1949, 1951) Phillips drew attention to certain similarities between Moine and Lewisian fabrics. While hesitating to press the identity of these fabrics, he emphasizes that the similarity favors the hypothesis that the general Moine metamorphism was of Lewisian age (1951, pp. 234–235).

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 has led many investigators to assume that the thrusting and the tilting and folding of the schists was caused by the same large-scale movements. The down-dip (east-southeast and southeast) lineations were considered to be a type of slickensides produced by the movement of the Moines to the northwest. Thus

Phillips' interpretation of the schist fabrics stimulated a brisk controversy on the relationship among fabric "girdles," lineations, and deforming movements. Structural workers in Norway (Strand, 1945; Kvale, 1945, 1947) and elsewhere (Martin, 1935; Cloos, 1946) have expressed the view that girdles may be produced by shearing in a direction either parallel or perpendicular to the girdle plane. Anderson (1948) went further, suggesting that the axes of girdles (*b*-axes of Phillips) and lineations are invariably parallel to the direction of shear movement. This view is consistent with Cloos's interpretation of the lineations in the Moines in the south of the Assynt area (Cloos, 1946).

Wilson (1952) describes a spectacular example of quartz-filled tension gashes in the Moine schists near Melness. His kinematic analysis of the structures reveals a "south-south-~~east~~westward 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 microfabrics of neighboring rocks. Later, Wilson (1953) demonstrated the widespread occurrence of fold axes and other *B*-structures (lineations, mullions, rodding) with east-west or northwest-southeast trend in the Moine schists. He considers that they "owe their forms primarily to tectonic movements which acted in directions perpendicular to the elongation of the structures."

Wilson draws attention to the contrast in tectonic style between the recumbent folds in the Moine schists and the dislocations in the thrust zone, and stresses the independent origin of the two sets of phenomena. He concludes, with Read (1934) and Phillips (1951), that the evidence is in favor of a pre-Torridonian age for the Moine schists; the Moine orogenic phase, for which he suggests the term Sutherlandian, was probably the same as the Laxfordian phase of metamorphism in the Lewisian rocks of the foreland (Sutton and Watson, 1951).

McIntyre (1954) reviewed the history of research on the Moine thrust and reexamined the evidence for dating the movements. He concludes, with Read, Phillips, and Wilson, that there is no genetic significance to be attached to the parallelism of the linear structures in the mylonites and 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." With regard to the ages of the 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 . . . 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, it was shown that the thrusting was definitely older than a monchiquite-fourchite dike, probably of Permian age, which cuts the mylonites of A'Mhoine (McIntyre, 1954).

I began a study of the tectonics of the thrust zone in Assynt in 1953 and noted that many of the linear structures in the rocks of the mylonite zone, previously taken to be slickensides parallel to the direction of thrusting, are in fact *B*-lineations similar to those described in the Moine schists. After this discovery, McIntyre, Weiss, and I made a reconnaissance study of exposures of the thrusts between Skye and Eireboll. The results of this study have been summarized in an appendix to McIntyre's paper (1954, pp. 219–220). A number of our conclusions are at variance with the hypothesis favored by Read, Phillips, and Wilson on the connection between the folding of the Moines and the 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. [Christie *et al.*, 1954, pp. 219–220].

The presence of folds with axes plunging to the east and the southeast in the mylonitic rocks in the thrust zone has been noted by Wilkinson (1956) in Eireboll and by Johnson (1956) in the Lochcarron and Coulin Forest areas. The structural relations in the Coulin and Lochcarron areas have been described by Johnson in later publications (1957, 1960).

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 Northwest Highland and Central Sutherland memoirs (Clough, in Peach *et al.*, 1907, pp. 506–507; Read, 1931, p. 10) make specific reference to folds in the mylonitic rocks. Subsequent investigators (e.g., Phillips, 1937, 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 mlyonites.

The authors of the Northwest Highland memoir claim 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, considers (Read *et al.*, 1926, p. 121) that they were formed during two distinct phases of deformation: the east-southeast trending folds were produced during an early phase and the north-northeast trending folds originated with the thrust movements during a later phase. Read (1934) has developed this interpretation, and concludes that the east-southeast trending folds were contemporaneous with the general Moine metamorphism and are of pre-Torridonian age. This view has been supported by Phillips (1937, 1949, 1951), Wilson (1953), and McIntyre (discussion of Wilson, 1953; 1954). The evidence presented by Bailey, Kennedy, and MacGregor (see MacGregor, 1952), however, suggests that the Moine metamorphism and folding were entirely "Caledonian" (post-Cambrian), a conclusion that is in harmony with the views expressed in the northwest Highlands 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?

Scope and Procedure

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 the 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-southeast 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.

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 3 miles eastward from the Moine thrust.

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 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 I wish to emphasize that the synthesis and the 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. Orientation data throughout the paper are recorded on the lower hemisphere of an equal-area projection.

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PRINCIPLES AND TERMINOLOGY

Fabric Axes

Several systems of notation have been suggested for fabric axes (Cloos, 1946, pp. 5–6), but the one proposed by Sander is now almost universally adopted by structural petrologists. Because at least some of the controversy in structural problems stems from a lack of uniformity in the use of symbols denoting the fabric axes (a, b, B, c), their meaning is here discussed.

Sander (1930) defined the fabric axes a, b, and c for fabrics with monoclinic symmetry as follows: ab is the principal fabric plane; ac is the plane of symmetry in the fabric; and c is normal to ab. Around any flexual 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. Weiss (1955, pp. 229–230) has discussed the significance of these terms and has distinguished *fabric axes*, which are descriptive and are defined in terms of the geometric 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.

This definition of fabric axes, it must be noted, holds only for fabrics with monoclinic symmetry and cannot be transferred arbitrarily to fabrics with another order of symmetry. Sander extends the use of the term "B-axis" to fabrics with triclinic and orthorhombic symmetry. He relates the orientation of all the fabric elements in tectonics to "*s*-planes" (a descriptive term signifying any type of planar structure in a rock). 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^a_1 and s^a_2, s^b_1 and $s_b = (h0l)$—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 *s*-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

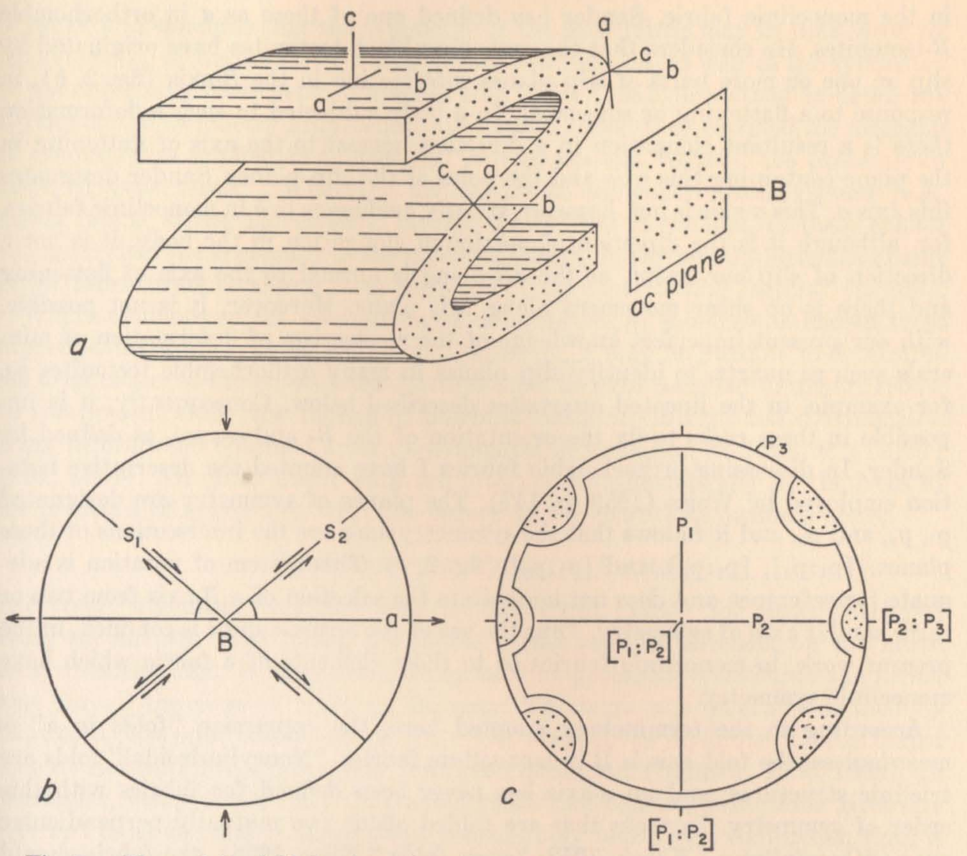

Fig. 2. *a*. Flexural slip fold showing orientation of fabric axes. *b*. Diagram illustrating fabric axes in orthorhombic fabrics, after Sander (1930). S_1 and S_2 are equivalent slip planes; arrows indicate axes of flattening and extension. *c*. Reference coördinates used in the present study for orthorhombic fabrics; p_1, p_2, and p_3 are planes of symmetry in a projection showing the statistical orientation of a hypothetical fabric element.

II), the over-all symmetry of the fabric is orthorhombic, or very rarely tetragonal or isometric. Where B has the properties of a 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 $B \perp B'$ tectonites, and considers B and B' to be syngenetic in such rocks. There is a further group of triclinic tectonics in which two mutually oblique B-axes are recognizable (the $B \wedge B'$ tectonites). 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, but have been produced by the superposition of two unrelated deformations.

In fabrics with orthorhombic symmetry there are at least two, and usually three, mutually perpendicular planes of symmetry and, consequently, two or three symmetry axes which have the same "symmetrological" significance as B

in the 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*-axis (fig. 2, *b*), in response to a flattening or squeezing. 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, as the *aB*-plane is normal to the axis of flattening and there is no shear movement along this plane. 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 below. 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 I have adopted the descriptive notation employed by Weiss (1959, p. 147). 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 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. "Noncylindroidal" folds are triclinic structures, and an *a*-axis has never been defined for fabrics with this order of symmetry. In rocks that are folded about two mutually perpendicular axes (*"Querfaltung,"* Koark, 1952; "cross folds," King, 1956), the fabric should be described with reference to two *B*-axes ($B \perp B'$ tectonites).

Interpretation of the Fabrics of Deformed Rocks

The fabric of a rock comprises the geometry of all the structural elements (foliation, lineations, textural relations, and orientation of mineral grains) in the rock. The type of movement which the rock has undergone may, to some extent, be inferred from its fabric. Sander (1911) first suggested that the orientation of the fabric elements records in some way the movements that have given rise to the fabric. Later (1930) he developed this idea and postulated that the symmetry of the fabric of a tectonite has the same symmetry as the movements that produced the fabric. Three types of symmetry—orthorhombic, monoclinic, and triclinic—are common in the fabrics of tectonites, and Sander has interpreted such fabrics in terms of a "movement picture" with the same order of symmetry.

Though numerous writers on petrofabric analysis have neglected symmetry, the principle has been used frequently in the interpretation of fabric data. The validity of the principle has been questioned (Kvale, 1947, 1953; Anderson, 1948), but all recent experimental work on deformation of rocks and other materials tends to support the theory, with certain qualifications (Turner, 1957). Both Weiss (1955) and Turner (1957) have considered the effect of original anisotropy

in rocks, and conclude that the symmetry of the final fabric may be influenced by the symmetry of the fabric of a rock before deformation, as well as the symmetry of the deforming movements. Paterson and Weiss (1961) examined in detail the application of symmetry arguments to deformed rocks; they clarified the meaning of symmetry as applied to fabrics and movements and restated the principle in more rigorous terms: "Whatever the nature of the contributing factors [e.g., initial fabric, stress, movement], the symmetry that is common to them cannot be higher than the symmetry of the observed fabric, and symmetry elements absent in the fabric must be absent in at least one of the contributing factors" (p. 880).

Where evidence of the mechanism of deformation of minerals is known from experimental studies, as for calcite and dolomite, it may be possible to determine the orientation of the stress from features such as twin lamellae (Turner, 1953). In the present study the fabrics of dolomite rocks are interpreted dynamically, using information obtained from experimental deformation of dolomite (Turner *et al.*, 1954). All other fabric data are interpreted kinematically on the basis of the principle of symmetry, with due regard to the conditions outlined above.

Terminology of Mylonitic Rocks

The term "mylonite" was first used by Lapworth (1885) for rocks developed along the thrusts constituting the Moine thrust zone in Eireboll, on the north coast of Sutherland. It was subsequently used by geologists working in the thrust zone for all the crushed rocks in the zone. The term was carefully defined by Lapworth, however, and many of the rocks mapped as mylonites in the thrust zone do not conform to his rather restricted definition (Christie, 1956, 1960). In particular, many of the finely laminated rocks that constitute the zone generally referred to as the Moine thrust show considerably more recrystallization than is consistent with the use of the term "mylonite." These are really augen schists (Lapworth, 1885) and blastomylonites (Sander, 1912), and many might be described as quartz schists and chlorite schists. These rocks are texturally similar to the overlying Moine schists, and there is a gradation from the true mylonites, which occur in the lower part of the zone of finely laminated rocks, into the schists; the gradation is characterized by an upward increase in grain size, a decrease in the degree of lamination, and an increase in the degree of neomineralization and recrystallization. Laminated mylonites, augen schists, and blastomylonites are referred to collectively as *primary mylonitic rocks* (Christie, 1960).

In a number of localized areas in the thrust zone, other types of crushed or mylonitized rocks occur. At several localities, notably at Knockan Crag and near the Stack of Glencoul, both the primary mylonitic rocks and the Moine schists have been redeformed and crushed to form breccias consisting of disoriented fragments in a very fine-grained matrix of crushed material. These are termed "kakirites" (Quensel, 1916). Where this deformation is most intense the product is an extremely fine-grained rock, which lacks well-developed planar structure and shows no neomineralization or recrystallization. The term "cataclasite" (Grubenmann and Niggli, 1924) is used for these rocks. Many of the rocks of pelitic composition in the zone have the textural features of phyllonites (Sander, 1911; Knopf, 1931), indicating that they have originated by deformation of rocks that were originally of coarser grain size. These outcrop extensively in the vicinity of the Stack of Glencoul in the northern part of the area, and near Cnoc a' Chaoruinn in the south, but most of the pelitic rocks in the mylonite zone show phyllonitic textures. Kakirites, cataclasites, and phyllonites are referred to below as *secondary mylonitic rocks,* as there is good evidence that many of them were produced from primary mylonitic rocks (Christie, 1960).

The textures in the primary mylonitic rocks are predominantly crystalloblastic, and the gradation into normal low-grade Moine schists suggests that they may have been produced at the same time as the schists. The textures of the secondary mylonitic rocks, on the other hand, are almost purely cataclastic; as they are formed from primary mylonitic rocks, they indicate at least one later phase of deformation affecting the rocks in the thrust zone. The relationship between these separate phases of deformation and the metamorphism and deformation of the Moine schists is discussed after the structural evidence is described.

MEGASCOPIC STRUCTURES

The Moine Thrust

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 toward the south at low angles; along the eastern margin of the bulge the strike of the thrust is north-northeast and the dip is toward the east-southeast; to the north, from the headwaters of the river Cassley to the Stack of Glencoul, the strike becomes northwest with dip toward the northeast. Mylonitic rocks of various types are developed both above and below the surface mapped as the Moine thrust. The commonest of these are the finely laminated, color-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-northeast, 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 northwest and west, the scarp feature is not so distinct and the rocks are poorly exposed. 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 the Moine schists is parallel to the Moine thrust. East of Knockan Crag the strike of the foliation is east, and the dip is toward the south. The strike swings round the southeast corner of the bulge and becomes north-northeast, parallel to the regional strike of the Moine schists. In the northern part of the area the strike of the foliation is generally northwest, and the dip is toward the northeast. 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 and the 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 3. There is a marked preferred orientation

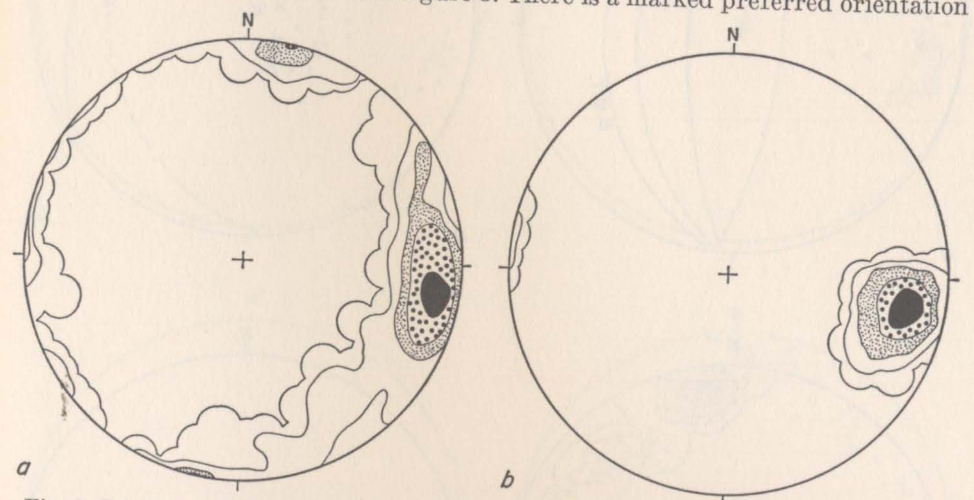

Fig. 3. Orientation of linear structures measured in the preliminary survey of mylonitic rocks along the Moine thrust. *a.* Axes of 166 small folds. Contours: .6, 2, 4, 6, 12 per cent per 1 per cent area. *b.* 112 penetrative lineations. Contours: 1, 5, 10, 20, 30 per cent per 1 per cent area.

of fold axes (fig. 3, *a*) with a strong maximum plunging at a low angle to approximately N. 100° E., and a submaximum with north-south trend. The penetrative lineations (fig. 3, *b*) 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-southeast–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 trend 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 southeast, on Cnoc a' Chaoruinn (Cnoc Chaornaidh on the 1-inch 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, in Peach *et al.,* 1907, pp. 502–507; Phemister, in Read *et al.,* 1926, p. 21).

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 has been 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.

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

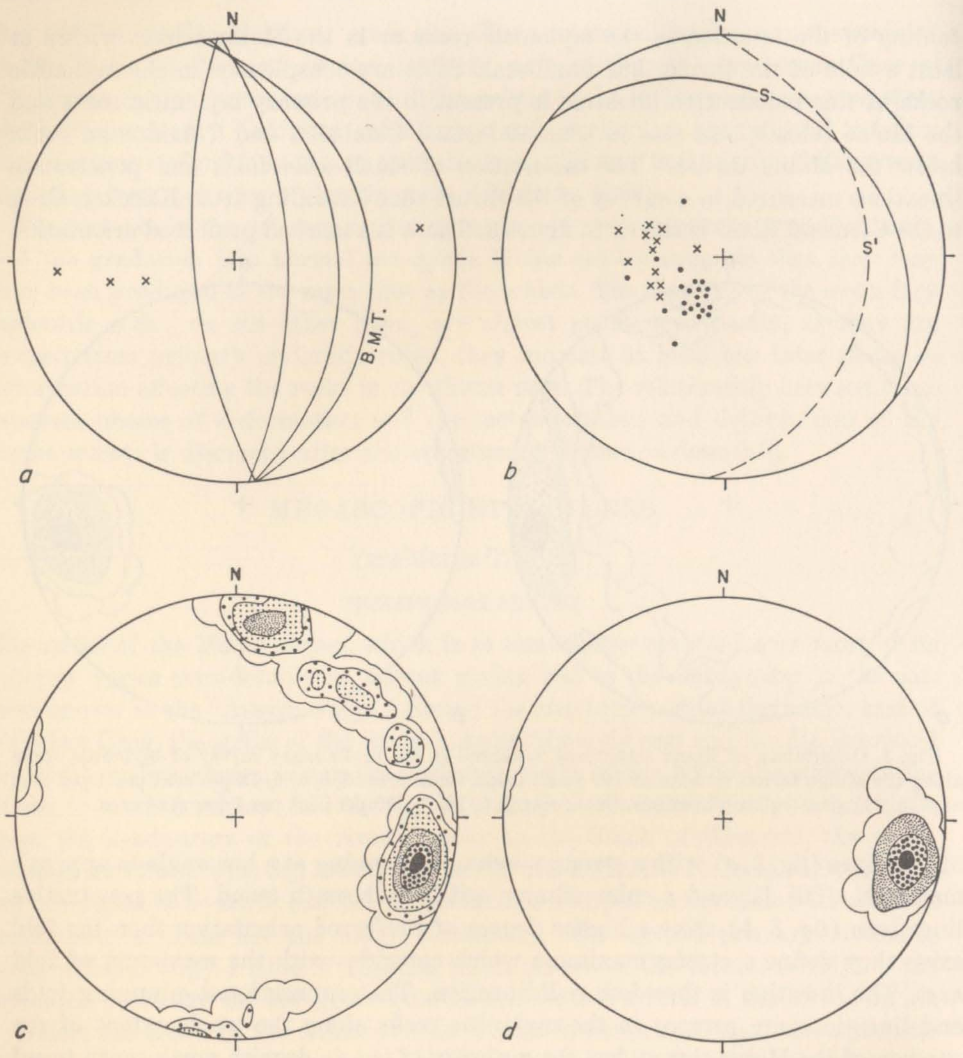

Fig. 5. Structural data from the Stack of Glencoul area. *a.* The orientation of the Ben More thrust and three reverse faults associated with it. Crosses represent the poles of the planes. *b.* Poles of foliation planes in primary mylonitic rocks (dots) and phyllonites (crosses). *S* and *S'* represent the mean orientations of foliation in primary mylonitic rocks and phyllonites, respectively. *c.* Axes of 97 small folds in the area. Contours: 1, 3, 5, 10, 15, 20 per cent per 1 per cent area. *d.* 70 penetrative lineations. Contours: 1.5, 10, 30, 50 per cent per 1 per cent area.

THE STACK OF GLENCOUL AREA

General description of area.—Figure 4 (in pocket) is a structural map of the Moine thrust zone between Beinn Aird da Loch and the Fionn Allt. The contacts 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 I made in the area. The data are recorded more fully in the fabric diagrams (figs. 5, 6).

The outcrop of the Moine thrust in the area is sinuous, but the general trend

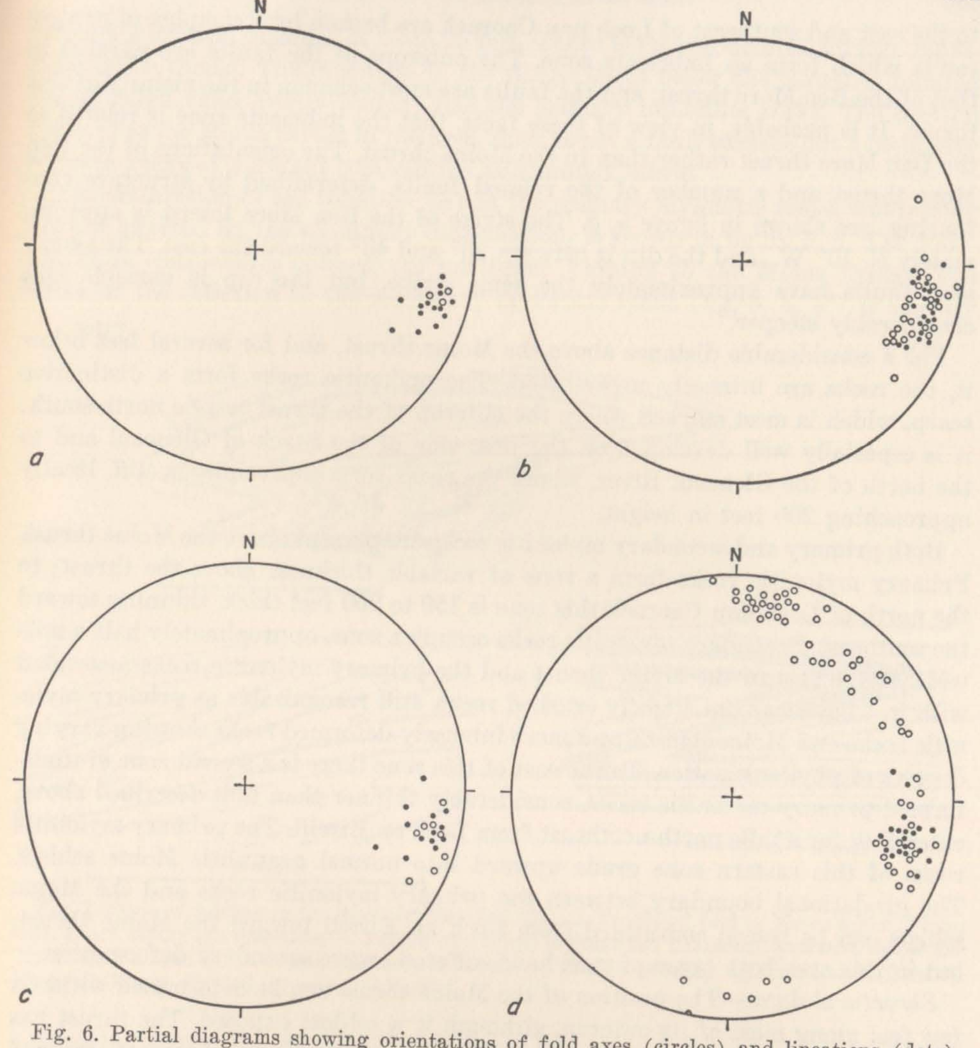

Fig. 6. Partial diagrams showing orientations of fold axes (circles) and lineations (dots). *a.* Cambrian and Torridonian rocks below the Moine thrust. *b.* Primary mylonitic rocks. *c.* Moine schists. *d.* Zone of secondary mylonitic rocks (B_n).

of the outcrop is northwest. To the west of the thrust, Lewisian and Cambrian rocks forming parts of the Glencoul and Ben More nappes are exposed. In the western part of the area shown in figure 4 (in pocket), the Lewisian gneiss and the Cambrian quartzites belong to the upper part of the Glencoul nappe. The Ben More thrust outcrops to the southeast of Loch nan Caorach, and the rocks to the east of this 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 thrusts; 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 southeastward beyond the limits of the map. The Cambrian rocks to the east and southeast of Loch nan Caorach are broken by a complex of reverse faults which form an imbricate zone. The outcrops of the faults are parallel to that of the Ben More thrust, and the faults are most common in the vicinity of this thrust. It is probable, in view of these facts, that the imbricate zone is related to the Ben More thrust rather than to the Moine thrust. The orientations of the Ben More thrust and a number of the related faults, determined by structure contouring, are shown in figure 5, *a*. The strike of the Ben More thrust is approximately N. 10° W., and the dip is between 30° and 40° toward the east. The associated 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 mylonitized. 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 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 zone is 150 to 200 feet thick, thinning toward the southeast. 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 recognizable 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-northeast from Loch an Eircill. The primary mylonitic rocks of this eastern zone grade upward into normal granulitic Moine schists. The gradational boundary between the primary mylonitic rocks and the Moine schists can be traced southward from Loch an Eircill toward 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 northwesterly strike and dips at approximately 20° to the northeast. East of Loch nan Caorach the thrust is warped into a gentle antiform (pl. 1, *a;* fig. 9, *b*), so that on the ridge southeast 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 (Peach *et al.,* 1907, p. 505, fig. 30; p. 506). Peach considered, moreover, that the eastern zone of primary mylonitic rock (μ, fig. 4, in pocket) was caused by a fold affecting the Moine thrust, so that the mylonitic rocks were warped upward along this zone (illustrated in a 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 that 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 color-layered primary mylonitic rocks

through a vertical distance of 10 to 20 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 5, *b*. The foliation dips consistently toward the northeast, parallel to the Moine thrust. The strike of the foliation in the secondary mylonitic rocks (fig. 5, *b*, S') is slightly

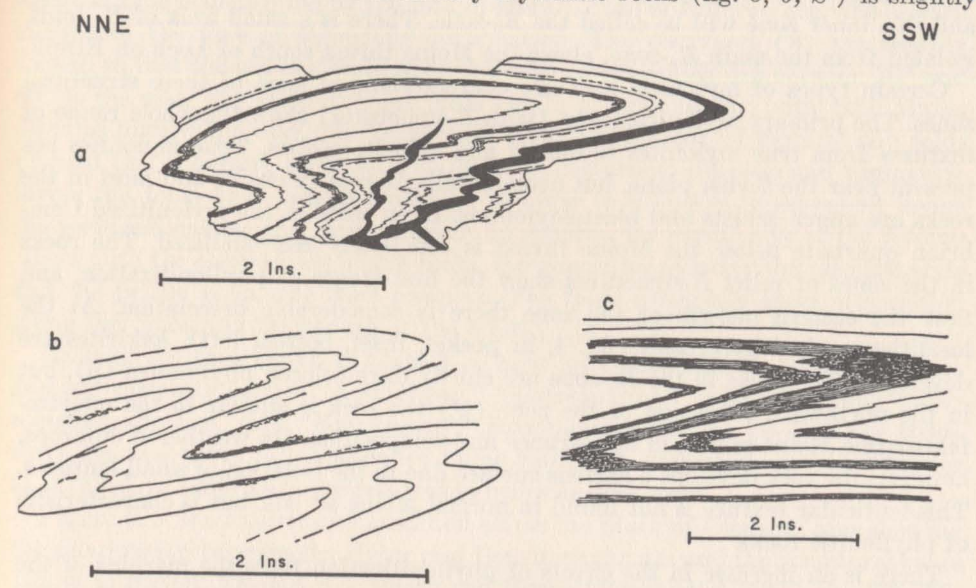

Fig. 7. Style of folding in the Stack of Glencoul area. *a*. Profile of fold in Moine schist, Fionn Allt. Black layers are quartzite. *b*. Profile of fold in mylonitized Cambrian quartzite below the Moine thrust, east of Loch nan Caorach. *c*. Profile of fold in primary mylonitic rock, Cnoc an Fhuarain Bhain. Shaded layers are chloritic.

east of north and the dip is approximately 35° toward the east. Figure 5, *c–d*, shows the orientation of all the small-scale folds and penetrative lineations, respectively, measured in the mylonitic rocks and the Moine schists in the area. There is a strong maximum of fold axes plunging toward the east-southeast (B), and a submaximum with north-south trend (B_n); there is a slight spread of the axes in a great circle parallel to the regional foliation (S). The lineations are consistently parallel to the maximum of fold axes (B), and show a very high degree of preferred orientation.

The partial diagrams in figure 6 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 toward the east-southeast, whereas the B_n-folds are confined to the zone of secondary mylonitic rocks. Folding is comparatively rare in the Moine schists, but is very common in the rocks in the vicinity of the thrust. The style of the folding in the Cambrian rocks (fig. 7, *b*), the primary mylonitic rocks (pls. 1, *b;* 2; fig 7, *c*), and the Moine schists (fig. 7, *a*) 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 toward the south-southwest. Thus there appears to be a common B-axis in the Cambrian rocks, the primary mylonitic rocks, and the Moine schists.

Along the margins of the zone of secondary deformation, fold structures plunge to the east-southeast and toward the north. The east-southeast–plunging folds are similar in style to those in the primary mylonitic rocks, and are obviously relict B-structures which have survived the secondary deformation. In the central parts of the zone, however, only B_n-folds are present (fig. 4, in pocket, inset, top right), and this inner zone will be called the B_n-zone. There is a small area of B_n-folds, isolated from the main B_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 B-structures) show the whole range of textures from true mylonites to quartz and chlorite schists. True 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 Cambrian quartzite below the Moine thrust is completely recrystallized. The rocks in the zones of relict B-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. 4, in pocket, inset, bottom left), kakirites are developed. The rocks in the B_n-zone are chiefly dark-colored phyllonites (p), but in the 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 toward the center. 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 S' (fig. 5, b), defined by the orientation of chlorite flakes, is produced; this is steeply inclined to the old s-surfaces (S). Near the center of the zone the s-surfaces (S) are intensely folded, but in the most extremely phyllonitized rocks the old foliation (S) has been completely transposed. These rocks bear a superficial resemblance to phyllites, but close examination reveals that the s-surfaces are uneven or wavy, as in the "frilled schists" and the "oyster-shell rock" of the Survey geologists (Peach *et al.*, 1907, pp. 481, 598). Lineations are not common in the phyllonites, but in some there is a faint streaking on the s-surfaces, resembling slickensides. This lineation is approximately normal to the axes of B_n-folds; that is, it is an a-lineation. In some of the quartzite layers the old penetrative lineation (B) is preserved and is locally folded about north-trending axes (B_n).

Although many of the rocks that show phyllonitic textures are of pelitic composition, some are highly siliceous. The factor controlling the development of these textures seems to be the presence of a well-defined lamination in the rocks before deformation. Although 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 recognized by Clough, who named them "Stack-schists" (in Peach *et al.*, 1907, pp. 502, 505). He described them as "crumpled schists" and "puckered schist with thin siliceous streaks." With customary attention in detail, Clough recorded evidence of late-stage deformation: "The shear-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*" (*ibid.*, p. 502; italics added).

The style of the B_n-folds is shown by the profiles in figure 8 and plate 3. The simplest type is illustrated by the fold in plate 3, *a*, on an outcrop near the eastern margin of the zone of secondary deformation. The s-surfaces (S) are sharply folded, so that the steeper limbs define regular layers which dip between 30° and 60° to the east. The more complex folds (pl. 3, b) are angular, with axial planes dipping toward the east. The folds show all the properties of flexural slip folds (Knopf and Ingerson, 1938, pp. 160–162); 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 style and the pelitic rocks, the most complex. The folds commonly show attenuation along the limbs and thickening at the crests.

Folds of the type shown in plate 3, *a*, have been described by German writers and are variously termed *"Knitterung," "Knickbander," "Zerknitterung," "Verschiebungsflachen,"* and *"Knickzonen"* (Hoeppener, 1955, pp. 34–35). The structures are analogous to the so-called "kink-bands" in deformed crystals (Turner *et al.*, 1954, p. 896). They are referred to below as *kink zones.*

Figure 9, *b*, 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. 4, in pocket, *RB* and B_n). Peach and Horne (Peach *et al.*, 1907, pp. 471–472; Peach and Horne, 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 reverse displacement of 500 to 1,000 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 the Moine schists have suffered the most intense secondary deformation. Thus the evidence clearly indicates 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 within the zone of relict B-structures (fig. 9, a), the movement picture is exactly the same as that in the rocks below the Moine thrust: the s-surfaces (S_1) are "kinked" along layers (S_2), which I believe are genetically related to the Ben More thrust and associated reverse faults. Combined with the slip movement parallel to S_2, there is slip on the foliation S_1. The parallelism of the axial planes of more complex folds with 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 S_1. The presence of the competent layers

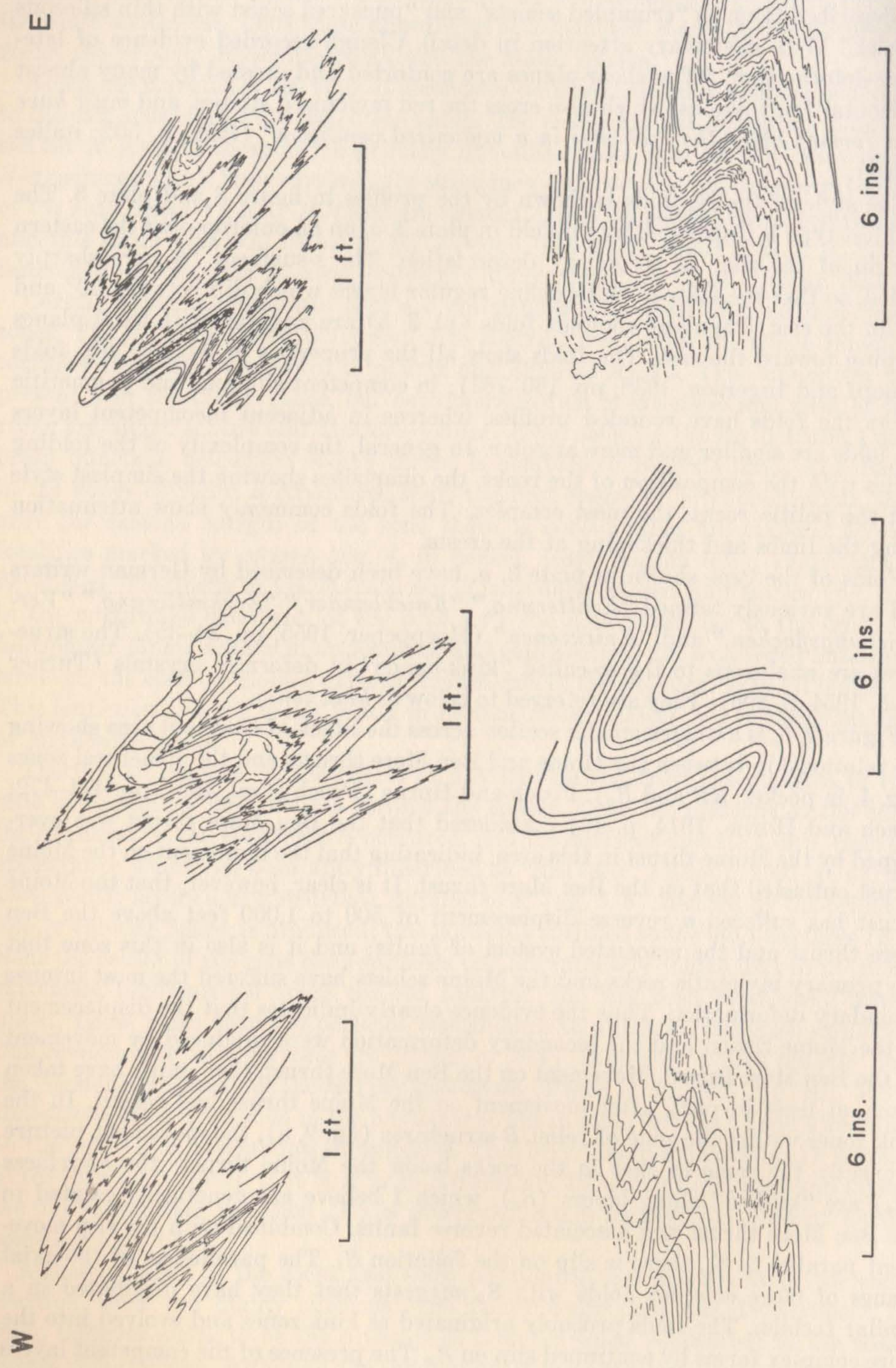

Fig. 8. Profiles of folds in zone of north-trending folds (B_n), Stack of Glencoul area.

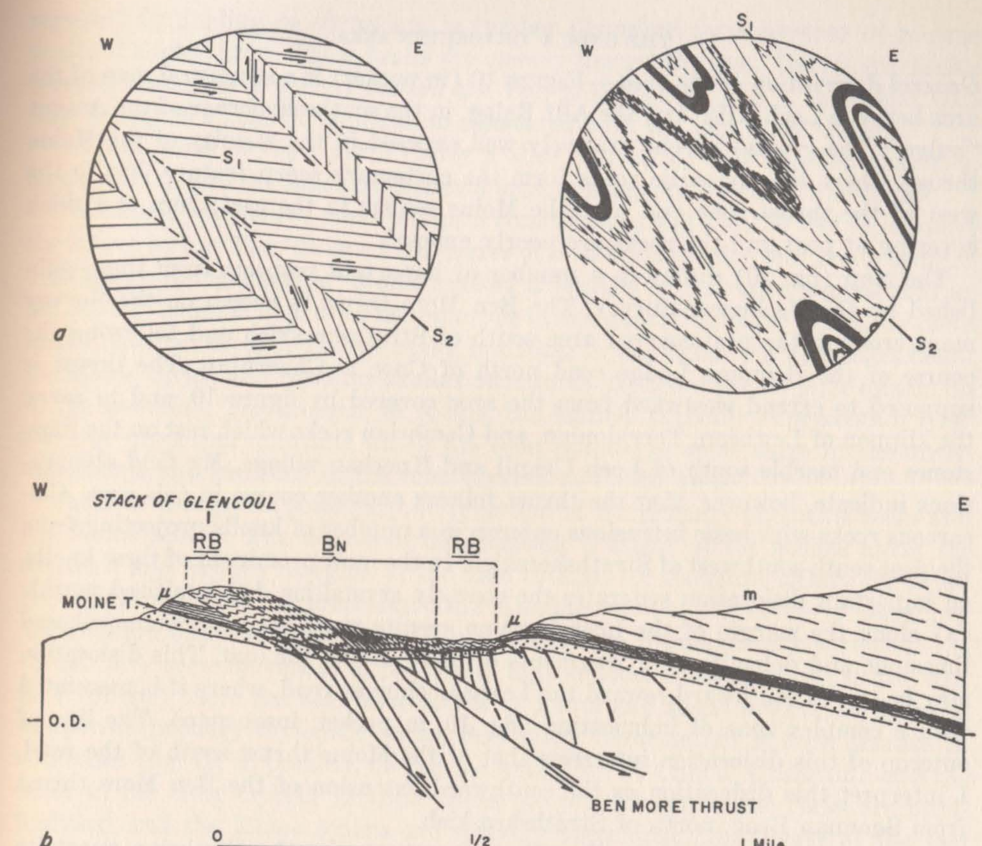

Fig. 9. *a*. Diagrams illustrating development of B_n-folds in zone of secondary deformation, Stack of Glencoul area. S_1 is foliation in primary mylonitic rocks; S_2 is the new *s*-plane produced during secondary deformation. *b*. Diagrammatic section across Stack of Glencoul area, showing relationship of the structural zones (*RB* and B_n) to the Ben More thrust.

of quartzite and pegmatitic rocks (in black) has probably had some influence on the formation of the folds, as there seems to be complete transposition of S_1 to S_2 where no competent layers are present.

At certain localities the primary mylonitic rocks and the Moine schists near the Moine thrust are traversed by parallel systems of planar quartz veins. The veins, which are usually between 1 and 5 mm 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 toward the east. The veins must have originated by the infilling of extension fissures at some period before the phase of secondary deformation. I consider that they were internally rotated 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.

THE CNOC A' CHAORUINN AREA

General description of the area.—Figure 10 (in pocket) is a structural map of the area between Loch Ailsh and the Allt Ealag, in the southeast 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. 10) 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 10, 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. My field observations indicate, however, that the thrust follows another course in this area. Calcareous rocks with basic intrusions outcrop in a number of knolls projecting from the peat south-southwest of Strathsheaskich. In the most prominent of these knolls, an important dislocation separates the coarsely crystalline dedolomitized 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 southward toward the Lairg-Lochinver road, where it is associated with a complex zone of imbrication (fig. 10, in pocket, inset map). The line of outcrop of this dislocation intersects that of the Moine thrust south of the road. I interpret this dislocation as the southward extension of the Ben More thrust from Sgonnan Beag, north of Strathsheaskich.

Another thrust, east of the Ben More thrust, carries the Cambrian quartzite that overlies the limestones at Strathsheaskich and the quartzite, Fucoid 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 (fig. 25). Sabine (1953, pp. 151–152) has proposed the term "Assynt thrust-plane" for this thrust, which he believes to be, in effect, an extension of the Glencoul thrust. I am in agreement with this interpretation, and retain the term "Assynt thrust" for this dislocation. The relationship of the thrusts is 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 recognizable 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, whereas on the north slope of Cnoc a' Chaoruinn the beds dip consistently toward 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 toward the east. The reverse faults become more closely spaced toward the Ben More thrust, and it is evident that they belong to a zone of imbrication associated with the Ben More 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 neomineralization and grade upward 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. As 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 color-layered mylonitic rocks.

There is widespread secondary deformation of the primary mylonitic rocks and the 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 effects of secondary deformation increase toward 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 movements of joints and slight brecciation in more competent primary mylonitic rocks. Secondary deformation is most intense in two zones (fig. 10, in pocket), one on the west slope of Cnoc a' Chaoruinn and the other in the river Oykell. 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 Oykell, cuts across the Moine thrust and the boundary between the primary mylonitic rocks and the 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 the Moine schists throughout the area dips consistently toward the southeast (fig. 11, *a*). In the secondary mylonitic rocks (fig. 11, *b*) the strike of the foliation is generally north-northwest, and the dip, though variable, is generally toward the east-northeast at approximately 45°. The fold axis (β, fig. 11, *b*) plunges at 15° to the south-southeast. 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 11, *c*, shows the orientation of small-scale folds measured throughout the area. The majority of the folds plunge to the east-southeast (B), but there is a submaximum in the diagram, representing folds that plunge toward the south-southeast (B_s). A persistent lineation, plunging to the east-southeast, is common to the quartzites below the Moine thrust, the primary mylonitic rocks, and the Moine schists (fig. 11, *d*). The partial diagrams in figure 12 show the orientation of folds and lineations in

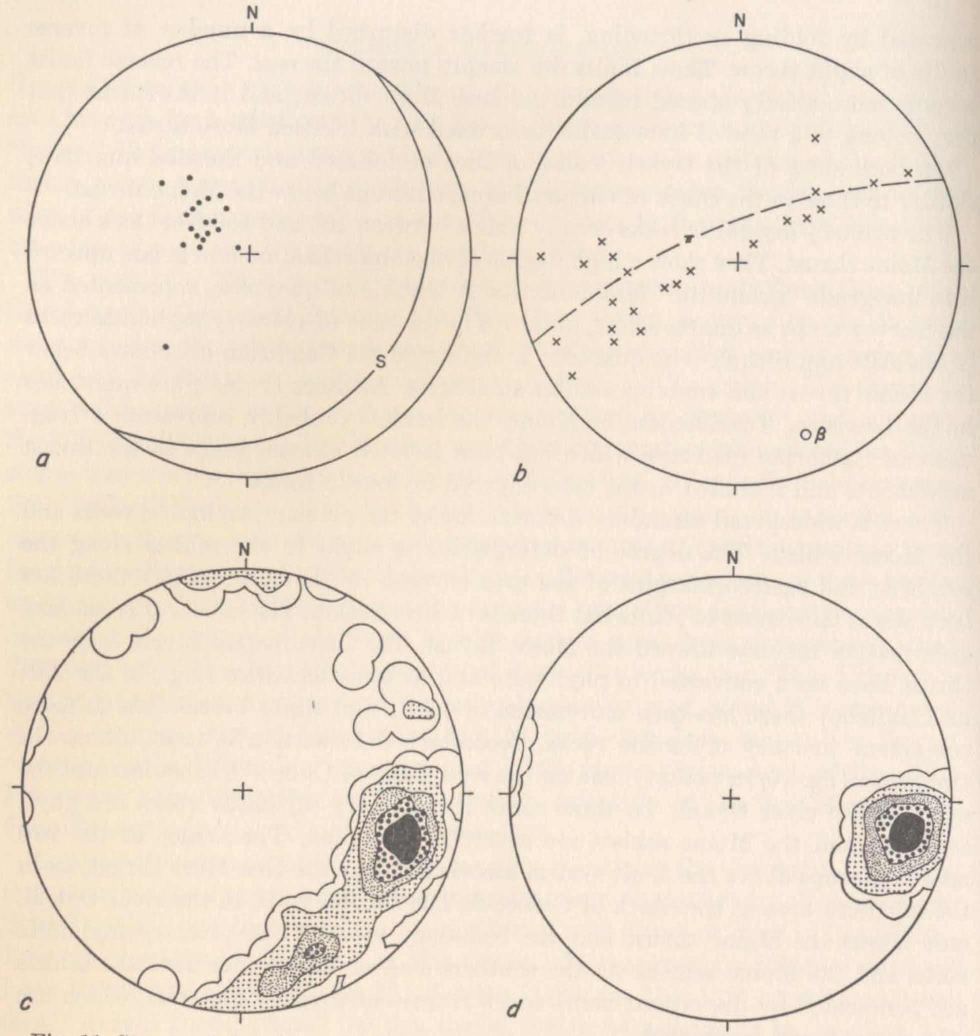

Fig. 11. Structural data from the Cnoc a' Chaoruinn area. *a.* Poles of foliation planes in primary mylonitic rocks and Moine schists; *S* represents the mean attitude of the foliation. *b.* Poles of foliation planes in phyllonites on Cnoc a' Chaoruinn, showing the great circle (π) and the fold axis (β). *c.* Axes of 143 small folds. Contours: $\frac{2}{3}$, 2, 6, 10, 14 per cent per 1 per cent area. *d.* 80 penetrative lineations. Contours: 1.25, 5, 10, 20, 30 per cent per 1 per cent area.

the quartzites, the primary mylonitic rocks, the Moine schists, and the secondary mylonitic rocks. The folds and lineations in the quartzites, the primary mylonitic rocks, and the schists plunge, with few exceptions, to the east-southeast, whereas the B_s-folds are confined to the phyllonites in the two zones shown on the map. These zones are analogous to the B_n-zones in the Glencoul area and will be referred to as the B_s- and B'_s-zones, the latter of which is smaller.

In certain layers in the B_s-zone, deformation is slight and the rocks in these layers retain the *B*-folds and -lineations (fig. 11, *d*). 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-southeast (B_s)

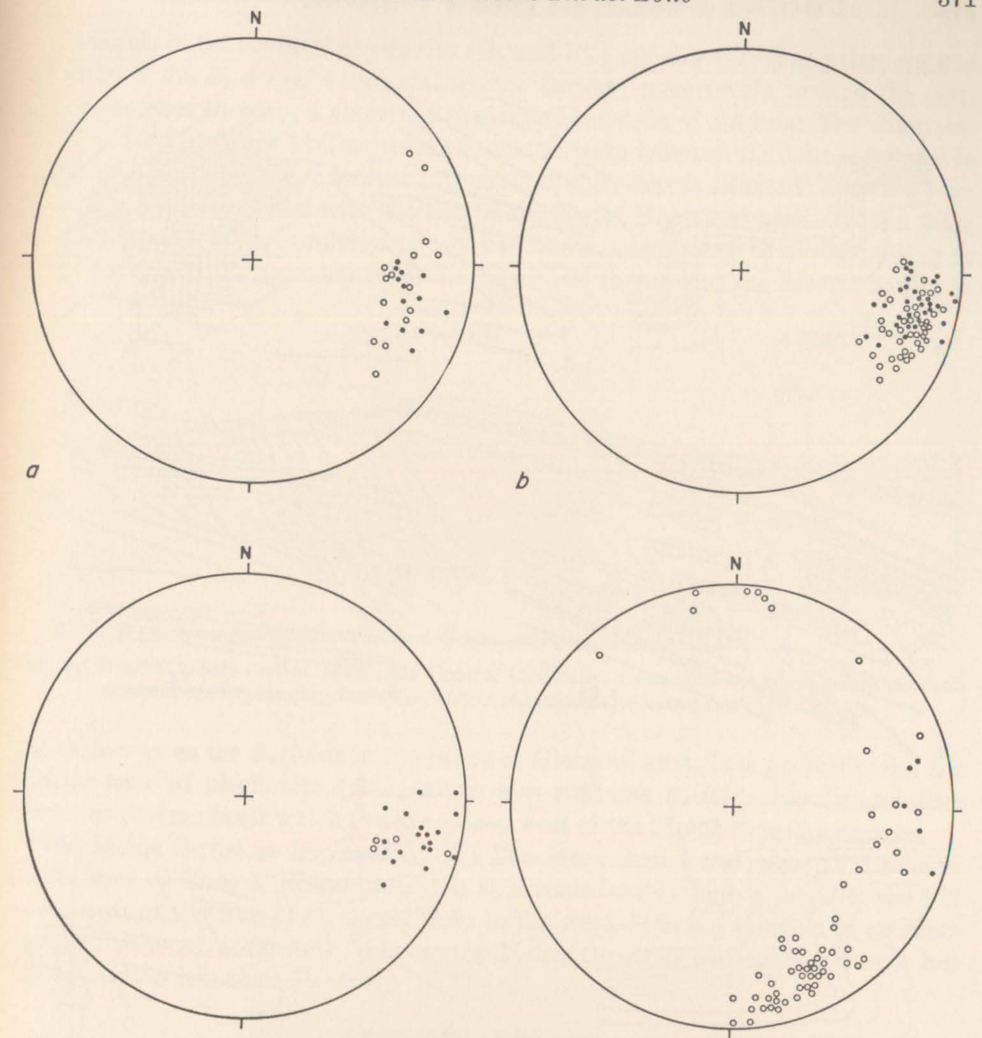

Fig. 12. Partial diagrams showing orientations of fold axes (circles) and lineations (dots). *a.* Cambrian quartzite below the Moine thrust. *b.* Primary mylonitic rocks. *c.* Moine schists. *d.* Phyllonitized rocks in zone of secondary mylonitic rocks (B_s).

axes. As in the northern area, the only new lineation in the phyllonites is a faint, inconstant streaking, approximately normal to the fold axes.

Figure 13 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 13, *b*, are present. Intrafolial folds (fig. 13, *d–e*) are common in the primary mylonitic rocks, though the style of the folds is variable. At some localities in this zone closely spaced kink zones (fig. 13, *c*) 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.

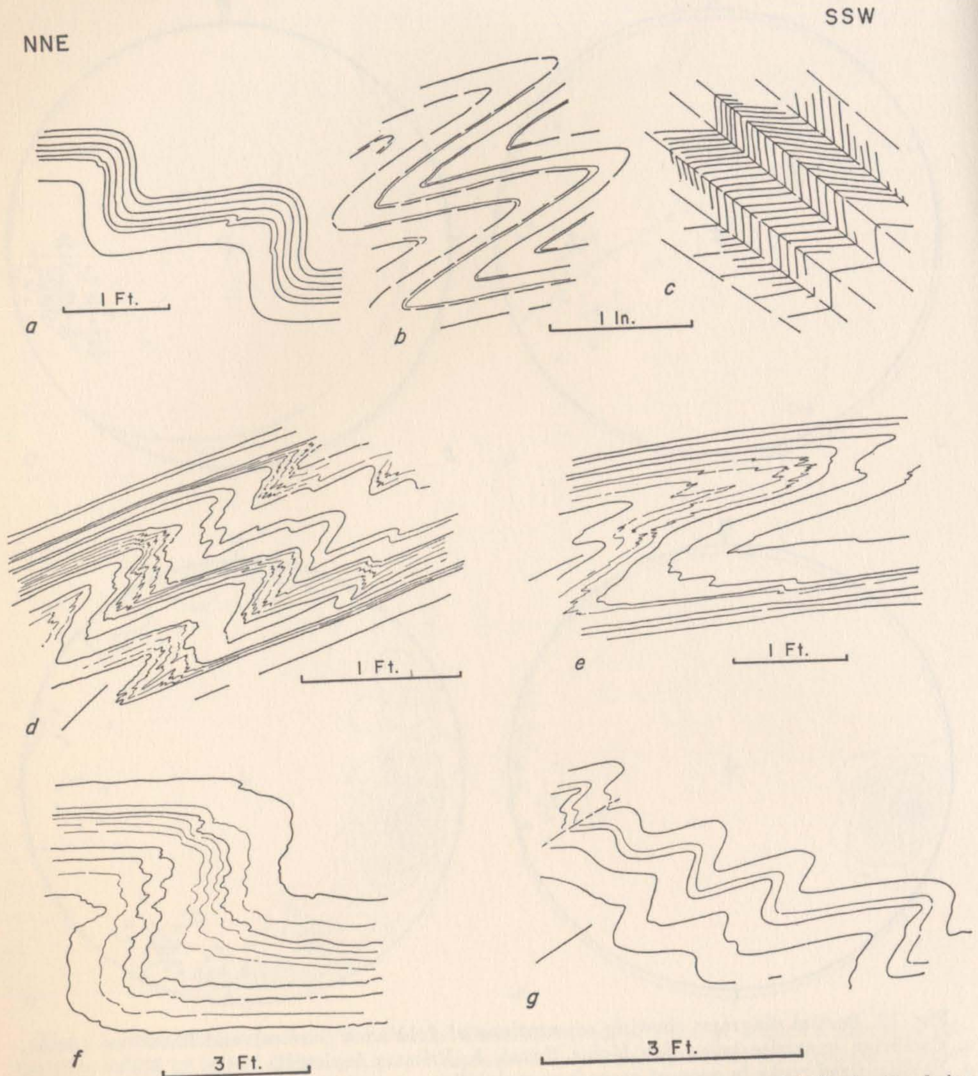

Fig. 13. Style of folding in the Cnoc a' Chaoruinn area. *a–b.* Profiles of folds in Cambrian quartzite below the Moine thrust, near the river Oykell. *c–e.* Profiles of folds in primary mylonitic rocks, Cnoc a' Chaoruinn. *f–g.* Profiles of folds in Moine schists, in the river Oykell approximately 2 miles below Loch Ailsh.

The only two folds observed in the Moine schists are shown in figure 13 (*f–g*). They are medium-scale, open folds, overturned toward the south-southwest.

The style of the folding in the quartzites, the primary mylonitic rocks, and the schists is so similar that they must reflect similar conditions of deformation. From the parallelism of the fold axes and the similarity in style, I infer that most of 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 per cent are overturned toward the south-southwest and the remainder toward the north-northeast.

The folds in the zones of phyllonite (B_s and B'_s) are closed and angular, similar to those in the B_n-zones, with axial planes dipping consistently toward the east. The structures in plate 4 show the characteristic style of folding. The diagrammatic section in figure 14 illustrates the relationship between the zones of B_s-folds and the major thrusts and faults in the area. The B_s-zone is situated above the zone of imbrication associated with the Ben More thrust. The axial planes of the folds are subparallel to the underlying reverse faults, suggesting that the folding is probably related to movements on the Ben More thrust and the reverse faults in

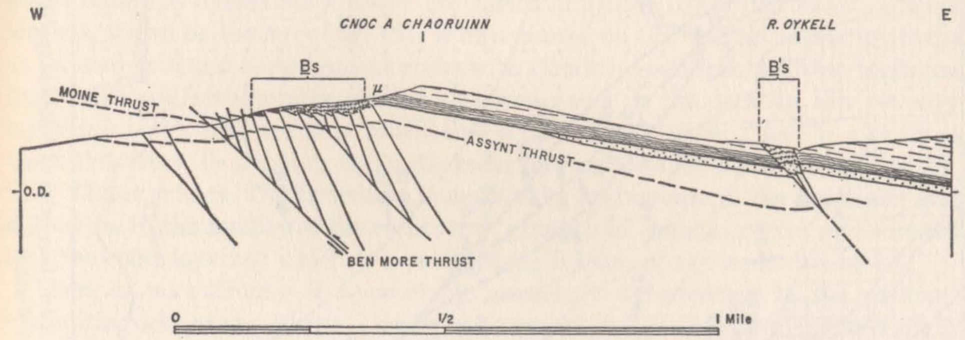

Fig. 14. Diagrammatic section across the Cnoc a' Chaoruinn area, showing relationship between zones of south-plunging folds (B_s) and the major thrusts and faults in the area.

the same way as the B_n-folds in the Stack of Glencoul area. It is 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 west of the Moine thrust.

The Moine thrust is displaced by the Ben More thrust and associated reverse faults west of Cnoc a' Chaoruinn; it 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.

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. 15). The outcrop of the Moine thrust extends from the northeast extremity of the loch with a northeasterly trend. The thrust gives rise to a marked topographic feature, the resistant mylonitic rocks and schists to the east forming a scarp of considerable height, and the 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 for the position of the thrust to be determined within a few feet along most of the outcrop. Exposures are common 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 center 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

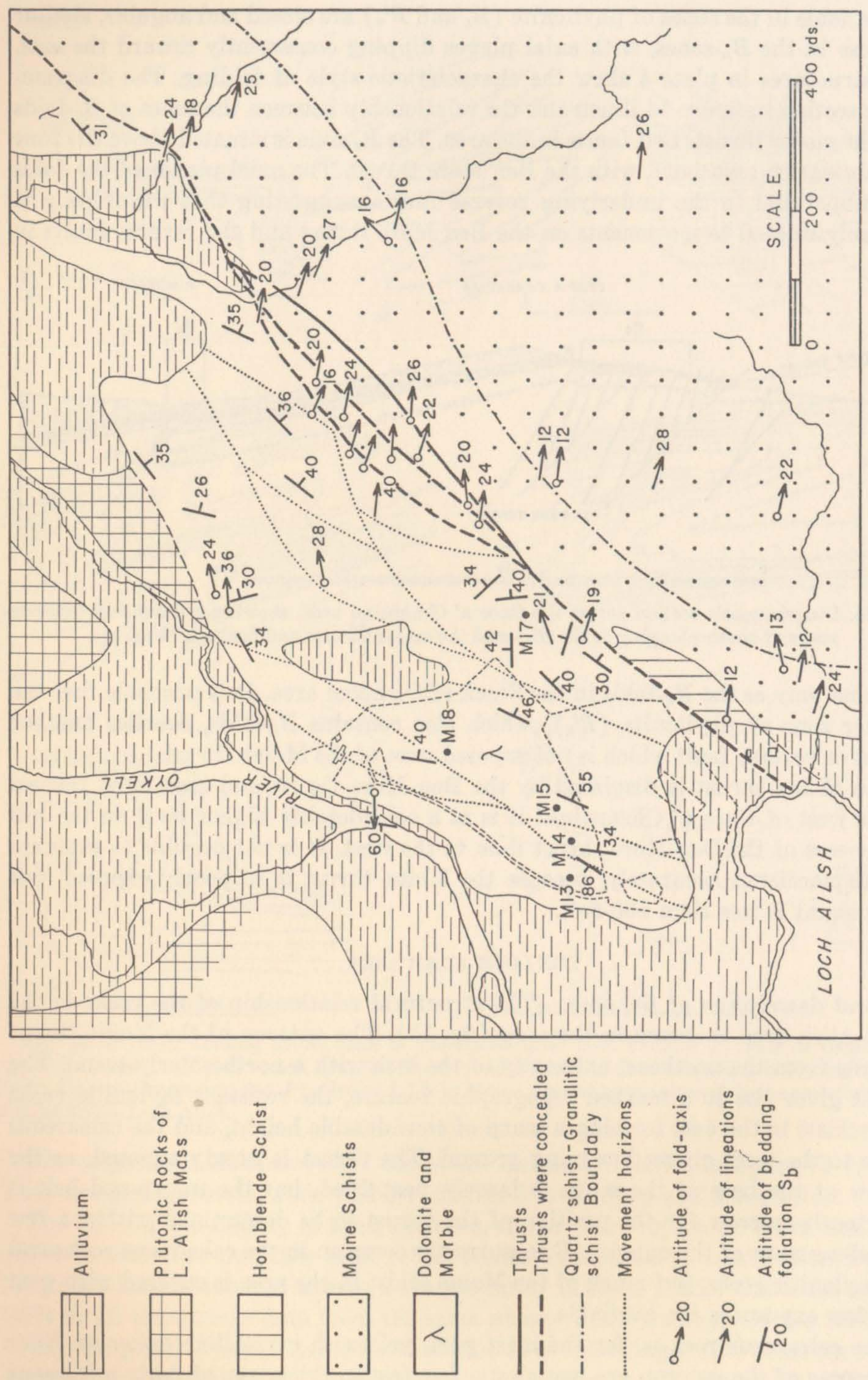

Fig. 15. Structural map of area around Benmore Lodge, northeast of Loch Ailsh. Localities of dolomite specimens are shown by spots and specimen numbers (e.g., M13). North is upward.

a number of ridges which are subparallel to the outcrop of the Moine thrust. These features seem 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. Farther to the northeast, a thick lenticle, shown on the map (fig. 15), is represented on the Geological Survey 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 the primary mylonitic rocks, and are here considered a part of this zone. There is a gradual transition from the primary mylonitic rocks upward 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 color 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 recognizable 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. These layers may be closely spaced, several occurring in a thickness of 1 inch, but commonly the rock is massive, with no trace of this foliation. Figure 16, *a*, shows the attitude of S_b measured at twenty-two localities. The dip of the beds, though generally at low angles to the east and the southeast, 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 submaxima. 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 toward 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 dolomite are shown in figure 16, *b*. 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 that plunge steeply to the west. The folds are all closed and overturned to the north (fig. 17, *a–b*). The westward-plunging folds are of similar style to those at the other localities.

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° to 30° toward the east-southeast, parallel to the Moine thrust. It is a very fine lamination

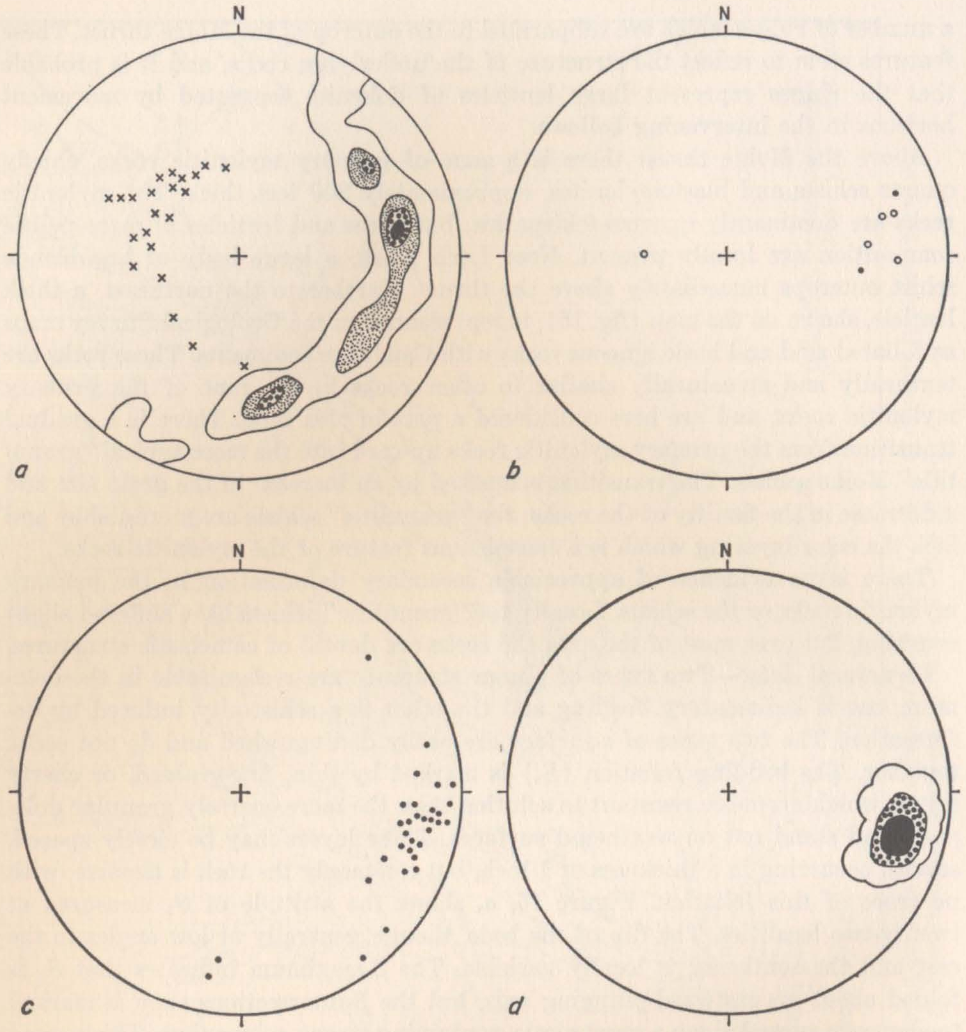

Fig. 16. Structural data from the Loch Ailsh area. *a.* Orientation of bedding foliation (S_b) in dolomite. Crosses are poles of S_b. Contours of β-intersections: 2, 5, 8, 10 per cent per 1 per cent area. *b.* Fold axes (circles) and lineations (dots) in dolomite. *c.* Fold axes (32) in primary mylonitic rocks. *d.* Lineations in primary mylonitic rocks and Moine schists. Contours: 2.5, 20, 40 per cent per 1 per cent area.

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 dips at low angles to the east-southeast. Folding of the foliation is very common throughout the zone of primary mylonitic rocks but decreases upward and is absent in the slabby schists. The axes of a representative number of folds are shown in figure 16, *c*. The majority of the folds plunge toward the east and east-southeast (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 that flows into Loch Ailsh,

quartz rodding (fig. 17, *g*) is developed. The axes of the quartz rods are parallel to the axes of folds in the primary mylonitic rocks. There is a single faint lineation on the *s*-surfaces in the primary mylonitic rocks and the Moine schists. The lineations show a very high degree of preferred orientation (fig. 16, *d*), and define a single strong maximum plunging slightly south of east, parallel to the maximum of fold axes (B).

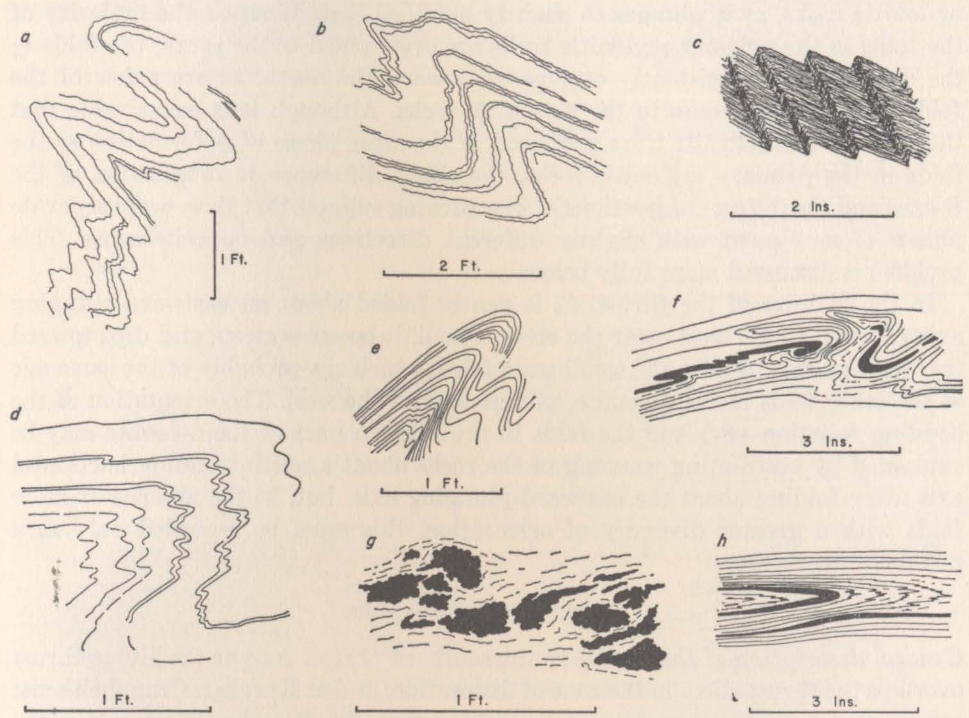

Fig. 17. Style of folding in the Loch Ailsh area. *a–b.* Profiles of folds in dolomite, viewed toward the east. *c–f.* Profiles of folds in primary mylonitic rocks, viewed toward the east-southeast. *g.* Profile of quartz rods in Moine schists, viewed toward the east-southeast. *h.* Profile of south-plunging fold in primary mylonitic rocks, viewed down plunge.

The style of the folding in the primary mylonitic rocks is illustrated by the profiles in figure 17, *c–f*, *h*. The commonest type is a simple recumbent fold (fig. 17, *d*) with or without minor drag folds on the limbs, but more complex types (fig. 17, *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. 190–191) and referred to by him as "polyclinal." Many of the smallest-scale folds are intrafolial and seem to have suffered a considerable degree of flattening normal to the foliation (fig. 17, *f*, *h*). On a few exposures small-scale kink zones are visible (fig. 17, *c*), 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 during the deformation; 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 per cent were overturned toward the south, 20 per cent were overturned toward the north, and the remainder were polyclinal.

The folds in the primary mylonitic rocks are similar with regard to orientation and style to those in the other two areas described above. The dominant fold axis in the dolomitic rocks, however, differs slightly from the *B*-axis in the primary mylonitic rocks, as it plunges to slightly north of east. Whereas the majority of the folds in the primary mylonitic rocks are overturned to the south, the folds in the dolomite are consistently overturned toward the north, as are a few of the folds and the kink zones in the mylonitic rocks. Although it is conceivable that the folds in the dolomite were produced in the same phase of deformation as the folds in the primary mylonitic rocks, the slight difference in orientation of the *B*-axes and the different directions of overturning suggest that there were separate phases of movement with slightly different directions and opposite sense. This problem is discussed more fully below.

In the vicinity of the thrust, S_b is gently folded about an eastward-plunging axis (β), but to the west, near the river Oykell, it becomes steep, and dips toward the west. At this locality the small-scale folds, which are probably of the same age as the other folds in the dolomite, plunge toward the west. The orientation of the bedding foliation (S_b) and the folds in the western part of the dolomite may be explained by postulating warping of the rocks about a north-trending horizontal axis after folding about the eastward-plunging axis, but, in the absence of more folds with a greater diversity of orientation, this must be regarded only as a possible hypothesis.

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 the schists directly onto 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, toward 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, 2 or 3 feet thick, of cataclasite and kakirite, containing fragments of primary mylonitic rock. The degree of cataclastic deformation decreases rapidly upward 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. The schists are comparatively 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.

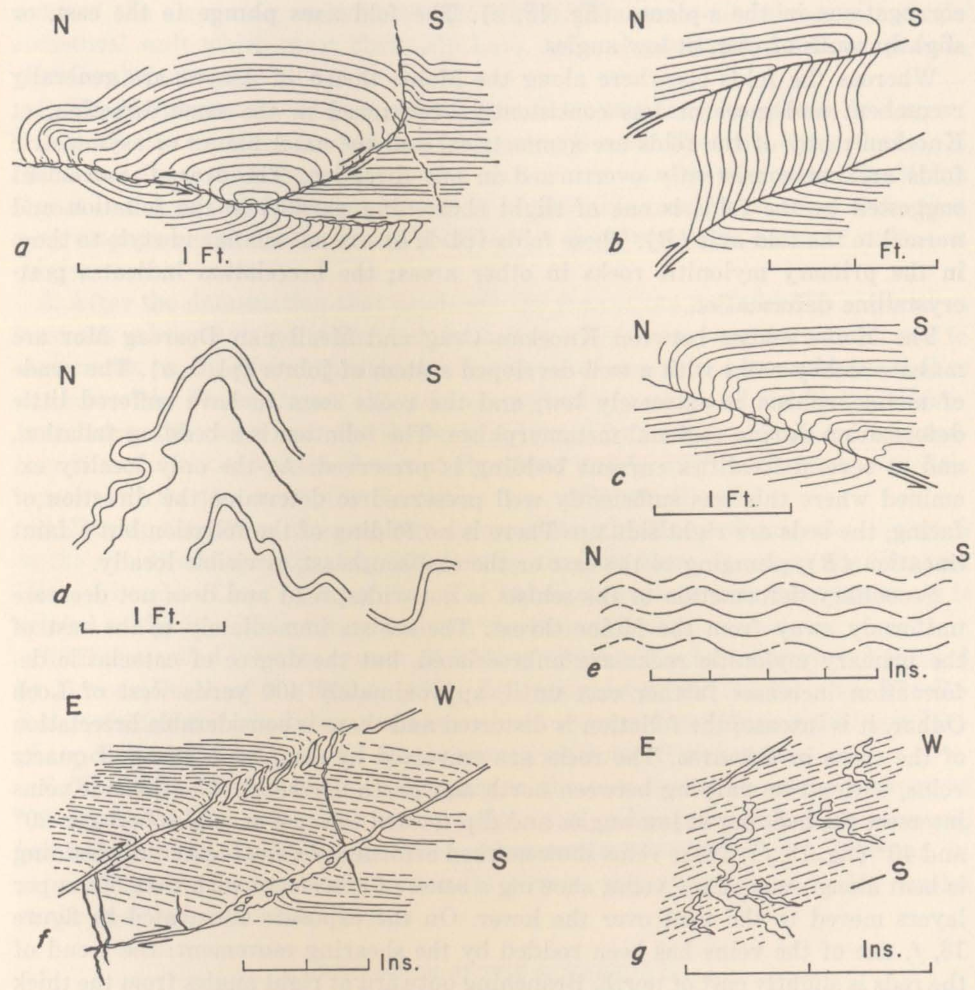

Fig. 18. Style of folding in the Knockan Crag area. *a–e*. Profiles of folds in primary mylonitic rocks at Knockan Crag. *f*. Rodded quartz vein in deformed Moine schist southeast of Knockan Crag. Note bending of foliation (*S*). *g*. Folded quartz veins in deformed Moine schist near Loch Odhar. *S* is foliation in the schist.

Structural data.—The foliation in the primary mylonitic rocks east of Knockan Crag has an easterly strike and dips at angles up to 10° toward the south. The strike swings at the crag and becomes north-northeast, and the dip is at low angles toward the east-southeast. Folding of the mylonitic rocks, though not so common as in the other areas described, is by no means absent. Some of the folds are symmetrical (fig. 18, *a, d–e*) and others (fig. 18, *b–c*) are asymmetrical but not overturned. The folding is commonly associated with shear surfaces and some degree of brecciation; 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 18 (*a–c*). The intensity of the folding decreases upward toward the summit of Cnoc an t'Sasunnaich, and the highest folds are small symmetrical corrugations in the *s*-planes (fig. 18, *e*). The fold axes plunge to the east, or slightly south of east, at low angles.

Whereas the folds elsewhere along the Moine thrust in Assynt are generally recumbent and more or less consistently overturned in the same direction, at Knockan many of the folds are symmetrical and the axial planes of asymmetric folds are not consistently overturned in one direction. The over-all movement suggested by the folds is one of slight shortening parallel to the foliation and normal to the fold axis (*B*). These folds (pl. 5, *b*) are not similar in style to those in the primary mylonitic rocks in other areas; the brecciation indicates post-crystalline deformation.

The Moine schists between Knockan Crag and Meall nan Dearcag Mor are massive slabby rocks with a well-developed system of joints (pl. 5, *a*). The grade of metamorphism is extremely low, and the rocks seem 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 facing, the beds are right side up. There is no folding of the foliation but a faint lineation (*B*), plunging to the east or the east-southeast, 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 farther 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-northeast. The thickest veins intersect the bedding at low angles and dip toward the east at angles between 20° and 40° (fig. 18, *f*). These veins show marked evidence of shearing and the 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 18, *f*, one of the veins has been rodded by the shearing movement; the trend of the rods is slightly east of north. Branching outward at right angles from the thick veins are thinner veinlets, which are relatively undeformed. The origin of the veins is problematical, but it is clear that they define a *B*-axis with northerly trend, and their present disposition seems to be due to slip movement in which the upper layers moved toward the west. In some instances the main movement has been along the veins, but elsewhere (fig. 18, *g*) the foliation seems 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 slip on *S*, a process analogous to that postulated to account for the eastward-dipping quartz veins near the Stack of Glencoul.

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 that are recognizable as Cambrian or Torridonian from mylonitic rocks of unknown origin.

3. After the deformation that produced the *B*-axis, the rocks locally suffered at least one subsequent (secondary) deformation which was not generally related to movements on the Moine thrust; the deformation was most intense in zones that 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 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 (Peach *et al.*, 1907, p. 468), does not exist in the Assynt area. The B_n- and B_s-folds form two distinct maxima which were produced during the secondary phase of deformation, and not synchronously with the *B*-structures.

6. The widespread lineation, plunging to the east-southeast, in the competent rocks near the Moine thrust is not an *a*-lineation, as has previously been assumed, but a *B*-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 the east-southeast.

DISCUSSION OF THE MOVEMENTS

The first fact cited above in the summary is of great importance, as it clarifies the controversial issue of the age of the general Moine metamorphism and deformation. The deformation that produced the east-southeast–trending *B*-structures in the Cambrian rocks, the primary mylonitic rocks, and the Moine schists must obviously be of post-Cambrian age. It is clear on petrographic grounds that these east-southeast–trending folds (*B*) were formed before or, more probably, during the regional metamorphism of the rocks (Phillips, 1937). The hypothesis favoring a pre-Torridonian age for the general Moine metamorphism (Read, 1934; Phillips, 1937; Wilson, 1953) is therefore untenable; the Moine metamorphism and deformation took place in post-Cambrian times, as claimed originally by Peach (Peach and Horne, 1930), and more recently by Bailey (1950) and others.

The east-southeast–plunging lineations in the vicinity of the Moine thrust have generally been assumed to be *a*-lineations marking the direction of movement on the thrust, and have frequently been referred to as "slickensides" (Read, 1931; Bailey, 1935). They are penetrative, however, and cannot be confused with the true slickensides that are present in some of the phyllonitized rocks. The penetrative lineations are statistically parallel to the fold axes (B) and are therefore B-lineations, according to the standard terminology (figs. 5, 11, 16). These lineations constitute one of the most important pieces of evidence for the direction of movement on the thrust (Bailey, 1935, pp. 158–159). In view of the failure of this evidence, the currently accepted theory, involving transport of the Moine schists to the west-northwest, 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 more than a mile east of the primary mylonitic rocks is very low. The foliation is recognizably bedding over much of the area, and the slabby nature and the lack of folding of the rocks indicate that there has been little shear movement. In the primary mylonitic rocks, on the other hand, the fine grain, the well-developed lamination, the color layering, and the folding all suggest large amounts of slip on the lamination planes. The zone of primary mylonitic rocks (including the mylonitized quartzites) represents a zone of distributed movement between two relatively undeformed blocks. The term "thrust," which is a contraction of "thrust-fault" (Reid *et al.*, 1913, p. 179), implies a surface of rupture, along which the deformation is restricted to a relatively thin zone. The Moine thrust does not show the characteristic features of a fault, except at isolated localities such as Knockan Crag. The movement has been distributed through a zone approximately 300 feet thick. Instead of the cataclastic textures developed along a fault, the primary mylonitic rocks show a considerable degree of recrystallization, and even some of the Cambrian quartzites are recrystallized. The "thrust" is a lithological boundary in a movement zone of the type that has been called a "movement-horizon" by Knopf (Knopf and Ingerson, 1938, pp. 33–35), and this term would be more fitting for the zone of primary mylonitic rocks.

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 have monoclinic symmetry; some are noncylindroidal, and axes of neighboring folds on some exposures may be inclined to each other at angles up to 35°, giving rise to triclinic symmetry for the foliation over the field of the exposure. The majority of the folds are recumbent, and it is estimated that approximately 75 per cent are overturned to the south-southwest. 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 symmetry principle, this should indicate a monoclinic movement picture; the simplest movement of this type is slip along the planes of lamination in a direction perpendicular 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 rocks, as minor drag folds on different limbs of a large fold may be overturned in opposite directions (Wilson, 1953). No large-scale folding is visible in the primary mylonitic rocks, however, and I consider that the sense of movement of the Moine nappe over the movement zone may be deduced from the sense of overturning of the small folds. In a recumbent fold of the intrafolial type (pl. 1, *b;* fig. 13, *d–e*), the sense of movement between

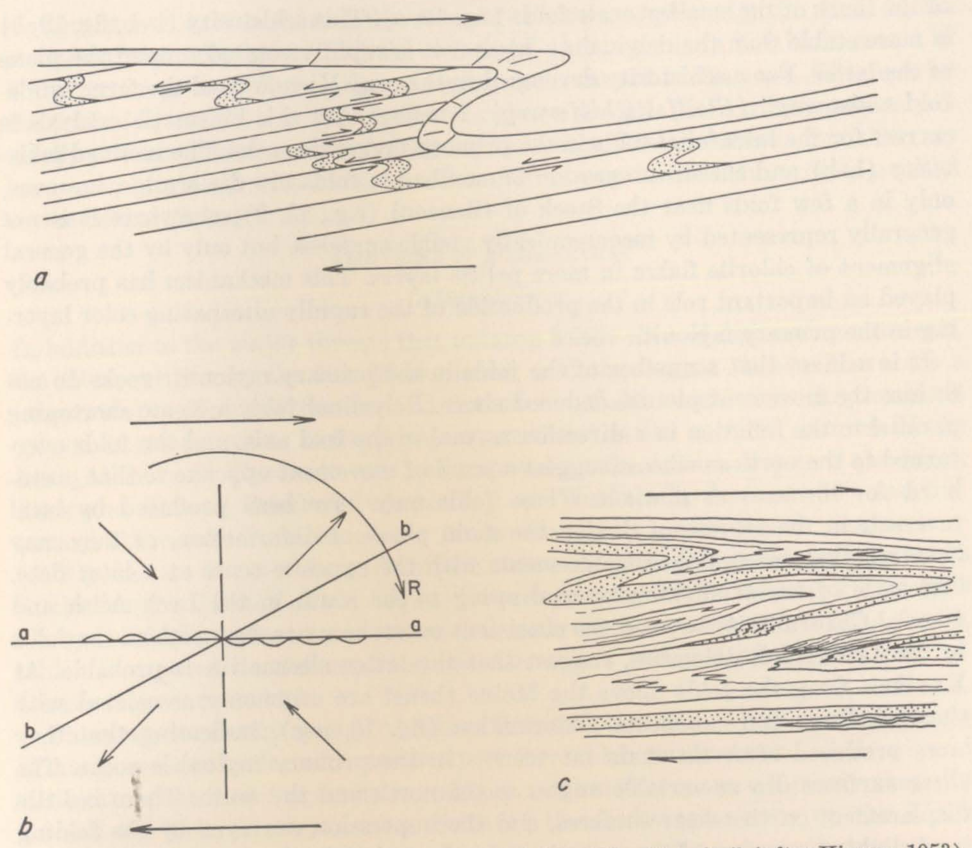

Fig. 19. *a.* Diagram illustrating development of "glide-fold schistosity" (after Kienow, 1953). *b.* Analysis of movement in "glide folding" (after Kienow, 1953). Long arrows indicate the sense of shear; short arrows denote axes of "compression" and "tension." The stable glide-fold schistosity (b–b) is rotated in the sense shown by the arrow (R) to the unstable orientation (a–a). *c.* The sense of slip indicated by intrafolial folds.

the overlying and the underlying layers may be definitely determined from the form of the fold, as shown in figure 19, *c.* All the intrafolial folds observed in the movement zone are overturned to the south-southwest, and the movement picture obtained by integrating the slip movement in all these folds is one of over-all transport of the Moine nappe toward the south-southwest. It is probable that many of the folds that are not obviously intrafolial on the scale of the outcrops in which they occur, are in fact parts of larger structures of this type. The majority of these folds are also overturned to the south-southwest, which confirms the conclusion that there was movement of the Moines in that direction along the movement horizon.

The style of the intrafolial folds is similar to that described by Kienow (1953) and called by him "glide folding" (*Gleitfaltung*). He outlined the development of these folds. During slip on the slip surfaces (a–a, fig. 19, *b*), the surfaces become unstable and bend into flexural slip folds (*Biegefalten*), which become overturned in a direction related to the sense of shear. A new schistosity develops by shearing of the limbs of the smallest-scale folds (fig. 19, *a*). This schistosity (b–b, fig. 19, *b*) is more stable than the original (a–a), but it is rapidly rotated toward the plane of the latter. For a schistosity developed in this way Kienow used the term "glide-fold schistosity" (*Gleitfaltschieferung*). I believe that this kinematic analysis is correct for the intrafolial folds in the primary mylonitic rocks. The inclined schistosity (b–b) and the disintegration of small-scale folds are discernible, however, only in a few folds near the Stack of Glencoul (e.g., pl. 2); elsewhere it is not generally represented by megascopically visible surfaces, but only by the general alignment of chlorite flakes in more pelitic layers. This mechanism has probably played an important role in the production of the rapidly alternating color 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 shortening parallel to the foliation in a direction normal to the fold axis, and the folds overturned to the north-northeast suggest a sense of movement opposite to that postulated for the area as a whole. These folds may have been produced by local reversals in the movement during the main phase of deformation, or they may have resulted from slight displacements with the opposite sense at a later date. The style of the small kink zones dipping to the south in the Loch Ailsh and Cnoc a' Chaoruinn areas, and the consistent overturning to the north of the folds in the Loch Ailsh dolomites, suggest that the latter alternative is probable. At Knockan Crag the folds above the Moine thrust are commonly associated with shear surfaces and cataclastic deformation (fig. 18, *a–c*), indicating that they were produced after the main movements in the primary mylonitic rocks. The shear surfaces dip at variable angles to the north and the south. There is little displacement on the shear surfaces, and the impression conveyed by the folding is of slight shortening of the rocks in a north-south direction.

The possibility that there was extensive elongation parallel to the fold axes, as claimed by Read (Read *et al.*, 1926) and Anderson (1948), is discussed after the grain orientation in the rocks is described. But it should be noted that such an elongation would not invalidate the conclusions drawn above regarding the direction and the sense of shear displacement or "transport." In terms of symmetry this would mean that a movement with axial or orthorhombic symmetry was superimposed on the monoclinic movement described, the axis of greatest elongation coinciding with *B*. This would not lessen the over-all symmetry of movement, and the resulting symmetry of fabric should still be monoclinic. The strain would, however, be triaxial instead of biaxial. Axial elongation or "axial flow" (Weiss, in Turner *et al.*, 1954, p. 76) does not constitute tectonic transport, in the strict sense, as there is ideally no shear movement parallel to *B*.

The movement during the secondary phase of deformation was discontinuous, in contrast to the main movements in the primary mylonitic rocks. The deformation is localized in zones that cut across both the primary mylonitic rocks and the Moine schists. The horizon mapped as the Moine thrust was not generally active as a shear surface 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 east-west, and the sense of movement, given by the folds in the secondary mylonitic rocks and the deformed quartz veins in the Moines east of Knockan Crag, is such that the overlying rocks moved to the west. The form of the folds (B_n and B_s) in the phyllonites above the Ben More thrust reflects primarily the movements on the underlying thrusts and reverse faults, but this may have been combined with some translation from east to west on surfaces parallel to the Moine thrust.

The Zone of Dislocation*

INTRODUCTION

In addition to the major thrusts that 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-southeast 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° toward the north. Portions of the faults are shown on the 1-inch Assynt map (1923), but no mention is made of the nature and the orientation of the faults in the memoir (Peach *et al.*, 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 4 feet thick.

The most important group of minor faults in the area is the parallel system of steep reverse faults with northerly strike, which transacts the whole zone of dislocation; some of the faults are almost vertical, but more commonly they dip toward the east at steep angles. Some of the faults are shown on the 1-inch Assynt map (1923), chiefly in the Lewisian gneiss, and a larger 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 the corries, however, the structures are frequently obscured by the deep covering of scree and peat; it is probable, in my opinion, that these eastward-dipping faults are more persistent than their distribution on the maps would suggest.

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 been outlined in my historical review. It is necessary now 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 well exposed at the classic locality on the south shore of Loch Glencoul (pl. 6, *a*). It is here represented by a sharply defined, planar

* The term "zone of dislocation" refers to the zone between the Moine thrust and the lowest thrust, the sole (cf. Peach *et al.*, 1907), and must not be confused with the "zone of dislocation metamorphism" of Read (1934).

surface dipping eastward at approximately 30°, and separating the Cambrian dolomites from the overlying Lewisian gneiss. The gneiss is so heavily deformed that it is converted to 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 outcrop of the thrust, I am unable to accept Bailey's suggestion (1935, p. 157) that the thrust dies out at this locality.

I have traced southward the important dislocation that 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 (in Peach *et al*, 1907) 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 a mile southwest of the Stack of Glencoul is without basis.

The outcrop of the Ben More thrust is clearly visible on the hillside west of Gorm Loch Mor (pl. 6, *b*), where the thrust dips at more than 40° toward the east, and the overlying quartzites are contorted about a north-trending axis (fig. 20 in pocket, XIII). The course of the thrust is again visible farther to the south, in Coire a' Mhadaidh (pl. 7, *a*), where it dips at approximately 50° to the east. The gradient of the thrust is steeper than that of the ground surface at this locality, giving rise to the V-shaped outcrop seen on the map (fig. 1, in pocket). 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° toward 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. 20, in pocket, XIV, XXII). South of Conival the thrust is nowhere well exposed, but my revision of the mapping between Loch Ailsh and Cnoc a' Chaoruinn (fig. 10, in pocket) 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 (Peach *et al.*, 1907), the Assynt thrust of Sabine (1953), is also displaced by the Ben More thrust. Sabine considered that the Assynt thrust was an extension of the Ben More thrust, but regarded it as "continuing southward the effect of the Glencoul Thrust" (1953, pp. 151–152). Whereas previous writers have postulated only one major thrust south of Conival, the evidence suggests that two thrusts—the Assynt thrust (the southern extension of the Glencoul thrust) and the Ben More thrust—are in fact present. Remapping of the area between Conival and Sgonnan Beag is required to ascertain the exact outcrops of the two thrusts. The Ben More thrust may outcrop in the Oykell Valley, where the rocks are poorly exposed, or the outcrops (fig. 20, in pocket) of the two thrusts may be almost coincident along this section.

The Ben More thrust displaces the Moine thrust in the two areas described above (pp. 360–373), 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 preëxisting 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 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. 151–152). If the displacement (slip) on the Ben More thrust is of the order of 500 feet, the Glencoul and Assynt thrusts are indeed parts of the same great dislocation. It is inconvenient to use two separate names for different parts of the same thrust, and hereafter I refer to the whole dislocation as the "Assynt thrust." When that part of the thrust north of Conival is specifically discussed, the term "Assynt (Glencoul) thrust" is used.

Peach and Horne (Peach *et al.*, 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. This mass, however, 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 geometry of the outcrop of the boundary known as the Sgonnan Beag thrust shows that it is definitely not a planar or a gently curved surface; it resembles more the boundary surface of an intrusion, as Bailey (1935) 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 seems to be neither a klippe carried on the Sgonnan Beag thrust, as represented by Peach and Horne (Peach *et al.*, 1907), nor a window exposed through the thrust, as suggested by Lugeon (in Bailey, 1935), 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, as shown in figures 20 (in pocket) and 25. 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, I call the slices the *upper Assynt nappe* (the "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 syenitic rocks of the Loch Ailsh mass. The lower nappe consists of Lewisian and Cambrian rocks along with the great plutonic mass of Loch Borolan; 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 the upper nappe must have been derived from a lower stratigraphic level than the lower nappe.

FOLDING

Small-scale folds are uncommon in the zone of dislocation; the only examples I observed are in the phyllonitic rocks along the Assynt (Glencoul) thrust, south of Loch Glencoul (pl. 5, *a*). Six folds were recognized within 2 feet of the thrust plane. The trend of the folds varies between N. 10° W. and N. 15° E. The folds are asymmetrical and overturned toward 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 the dolomites; the folding of the Loch Ailsh dolomites has already been described, and folds of similar size and style are developed in the calcareous rocks near the sole in the southern part of Assynt. The orientations of these folds at two localities, south of Knockan village and at Knockan Crag, are shown in figure 20 (in pocket). The fold axes plunge at low angles to the southeast, and the folds are overturned to the southwest.

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 were constructed to determine accurately the orientation of the fold axis (fig. 20, 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 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. Heterogeneous areas may be broken down until they are resolved into a number of smaller homogeneous areas, so that the variation of the fold axis (β) within the larger area may be visualized. The homogeneity of the smaller areas may be tested, if necessary, by means of partial diagrams. Two of the areas studied (XI, XXV) were found to be divisible into two subareas, each with a single fold axis (β); in each instance the trend of the β-axis in one of the subareas is easterly and in the other northerly. Several of the other areas shown in figure 20 are not completely homogeneous, but a thorough analysis of the folding in these areas was not possible.

In all the areas shown in figure 20 there is a single strong maximum in the β-diagram, which, even in areas with slight inhomogeneity, approximates to the fold axis. The orientation of the β-axes in the areas examined is shown in the synoptic diagram (figs. 20, 24). The axes fall into three groups, one with northerly trend (β_n) and the others plunging to the east (β_e) and the southeast (β_{se}).

DISTRIBUTION AND STYLE OF LARGE-SCALE FOLDS

Folding about southeast-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 southeast end of Loch Assynt (fig. 20, in pocket, XII), on the Stronechrubie plateau (XIX), and in the neighborhood of Knockan. The large-scale folds at Loch Assynt and Stronechrubie are open and asymmetrical, with the steeper limbs dipping to the southwest (pl. 7, *b*); the medium-scale folds near Knockan are recumbent and more tightly compressed but are also overturned to the southwest. The Cambrian quartzites east of Glenbain (fig. 20, XVI, XVII) are folded into an immense asymmetrical anticline with the steeper limb again dipping to the southwest, 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 clearly seen on the Assynt sheet.

Visible folding about north-trending axes is widespread in the zone of dislocation, but the most spectacular folds are found in the central part of the zone, at short distances 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 (pls. 6, *b*; 7, *a*). South of the latter locality, on the north slopes of Ben More (fig. 20, XXI), folding of a similar type is present, 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. 20, XXII). Still farther to the south, in Coirean Ban, west of the river Oykell, 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 (fig. 20, XXIII, XXVI). 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 20.

The folds in this group are of variable style, but they are generally open and commonly asymmetrical, the steeper limbs dipping toward the west. They are associated with shear surfaces and reverse faults, which dip to the east, subparallel to the Ben More thrust (pl. 7, *a*). 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 the faulting were produced by the same movements as the thrust.

The relationship between the southeast- and north-trending folds is evident in the Ben Uidhe area. The southeasterly folds between Glasven and the Mullach an Leithaid Riabhaich are transected by a considerable number of eastward-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 southeast-trending folds.

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, 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. At both these localities the shear surfaces dip at variable angles toward the north, and the slickensides on the surfaces plunge to slightly west of north.

DISCUSSION OF THE MOVEMENTS

The rocks in the zone of dislocation generally show comparatively little evidence of deformation. Only along the thrusts and the faults is there appreciable cataclastic breakdown of gneisses and sediments, and mylonitic rocks comparable with those along the Moine thrust are developed only above the Assynt (Glencoul) thrust. It is probable that movement in the sedimentary rocks took place chiefly by slip on the bedding surfaces, whereas 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 the Torridonian sandstones. The folds are noncylindroidal 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 southeast-plunging axes (β_{se}) 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 northeast, indicating a consistent sense of rotation between Loch Assynt and Knockan Crag, and if the folds were produced by movement on the thrust, as seems likely, they indicate that the sense of movement of the lower nappe along the sole was from northeast to southwest.

The widespread folding about southeast-trending axes in the upper nappe, particularly in the vicinity of Ben Uidhe, is evidence of a considerable degree of shortening of the nappe in a northeasterly direction. This may have been produced by transport of the nappe along the Assynt thrust in the same direction. But at the only locality (Loch Glencoul) where the thrust is well exposed, the small-scale folds in the mylonitic rock trend north-south and are overturned toward the west, indicating transport to the west along the thrust. Folding about north-trending axes elsewhere in the zone of dislocation, however, was contemporaneous with movement on the Ben More thrust, which displaces, and therefore postdates, the Assynt thrust. Thus it is probable that the north-trending folds above the Assynt (Glencoul) thrust at Loch Glencoul were produced by late-stage movement and do not reflect the main movements on the thrust.

The north-trending folds (β_n) in the zone of dislocation were produced during a later phase of deformation than the southeasterly folds, discussed above. They indicate shortening of the thrust masses in an east-west direction, and the asymmetry of the folds and the displacement on the Ben More thrust and related reverse faults denote slight transport of the overlying rocks toward 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 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 progressively 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 southwesterly 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. The third set of fold axes (β_e), plunging to the east, may date from the earlier phase of deformation, or from a separate one whose age relationship to the other two is unknown.

MICROSCOPIC FABRICS

Grain Orientation in Dolomite Rocks

INTRODUCTION

Crystalline dolomite and marble are of widespread occurrence in the Assynt region, particularly in the vicinity of the plutonic masses of Loch Borolan and Cnoc na Sroine. The dolomitic limestones have locally undergone the progressive changes known as "dedolomitization"; the resulting marbles consist of calcite, brucite (probably after periclase), white mica, and forsterite or serpentine. These thermally metamorphosed marbles show considerable evidence of later deformation, which is generally considered to be a result of the thrust movements (Teall, in Peach *et al.*, 1907; Read *et al.*, 1926). Thus many of the Assynt marbles are polymetamorphic in character, having suffered successively (1) thermal metamorphism during the emplacement of the syenitic masses, and (2) dynamic metamorphism during the post-Cambrian movements.

The crystalline dolomites described below occupy a small area to the north of Loch Ailsh. The localities of the analyzed specimens (M13, M14, M15, M17, M18) are shown on the map in figure 15. This is the only area in the Assynt region where carbonate rocks are in contact with the quartzose 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.

As the rocks in the Loch Ailsh area are cut by a large number of minor thrusts and shear zones, it is impossible to determine the relationship between the crystalline dolomites and the plutonic igneous rocks that outcrop nearby. Hence it cannot be demonstrated from field evidence whether the dolomite was recrystallized by contact metamorphism during the emplacement of the Loch Ailsh syenite or by some other agency.

PETROGRAPHY

The Loch Ailsh dolomites are more or less coarsely crystalline rocks with saccharoidal texture. The proportion of impurities is very small, calcite being virtually absent. Quartz is locally present in the form of small, isolated grains, and, associated with feldspar, as extremely thin veins; the isolated quartz grains are small and rounded and probably represent detrital fragments.

A gradation may be traced from rocks in which the grains are clear, with interlocking boundaries and few deformation lamellae, through rocks showing increasing marginal granulation of grains and greater development of deformation lamellae, to rocks consisting entirely of minute granules. In the intermediate stages the degree of marginal granulation is, in general, proportional to the frequency of the lamellae present.

More than sixty specimens, collected in traverses across the dolomite, were examined in thin section under the microscope to determine whether the comparatively fine grain of much of the dolomite is a property of the initial crystalline fabric or a result of the later granulation. In most of the rocks the degree of granulation is not great, indicating that the crystalline dolomite was initially fine-grained. The degree of granulation along grain boundaries is very variable over the mass, but increases, in general, toward the Moine thrust. Of fourteen specimens showing complete granulation, eleven were collected within 100 feet of the thrust (on the ground surface), and complete disruption of the grains seems to be general in this zone. The analyzed specimens were selected because of their comparatively coarse grain, the majority of the rocks being too fine-grained for fabric analysis.

FABRIC DATA

In all five specimens [0001] axes were measured in at least 300 grains, and a complete analysis of the lamellar structures was made in specimens M14, M15, M17, and M18. In specimen M13, twinned grains with lamellae thick enough for the twinning to be demonstrated optically are very scarce, and orientations of lamellae were not recorded. It is of particular importance in studies of dolomite fabrics that measurements be made in several sections cut with different orientation from a specimen (Christie, 1958), and in all the specimens described below, approximately 100 grains were examined in each of three mutually perpendicular sections.

The analyzed specimens are massive, with no trace of foliation or lineation. They show varying degrees of postcrystalline deformation; in all the specimens there is considerable development of $\{02\bar{2}1\}$ lamellae, and optically recognizable twinning is present in an appreciable number of grains in all specimens except M13. Tables 1 and 2 contain an analysis of the $\{02\bar{2}1\}$ lamellae present in each specimen. "Twinned" and "nontwinned" lamellae (Borg and Turner, 1953) are not distinguished in table 1, but table 2 shows the proportion of grains with twinned lamellae in each specimen. Although optically recognizable twinning is present in only 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.

TABLE 1

ANALYSIS OF $\{02\bar{2}1\}$ LAMELLAE IN LOCH AILSH DOLOMITE SPECIMENS[a]
(In per cent)

Specimen number	Number of sets of $\{02\bar{2}1\}$ lamellae in grains			
	Three	Two	One	None
M14	71	25	4	0
M15	36	52	5	7
M17	48	30	18	4
M18	60	32	8	0

[a] Data are based on grains in which all three $\{02\bar{2}1\}$ planes were accessible for measurement.

TABLE 2

ANALYSIS OF TWINNED $\{02\bar{2}1\}$ LAMELLAE IN LOCH AILSH DOLOMITE SPECIMENS[a]
(In per cent)

Specimen number	Number of sets of twinned $\{02\bar{2}1\}$ lamellae in grains			
	Three	Two	One	None
M14	0	1	19	80
M15	0	25	33	32
M17	0	7	30	63
M18	0	5	31	64

[a] Data are based on grains in which all three $\{02\bar{2}1\}$ planes were accessible for measurement.

TABLE 3

GRAIN SIZE, DEGREE OF GRANULATION, AND DEGREE OF PREFERRED ORIENTATION OF DOLOMITE GRAINS IN LOCH AILSH DOLOMITE SPECIMENS

Specimen number	Mean diameter of grain section (in mm)	Degree of granulation (in per cent)	Areal analysis of preferred orientation of [0001] axes (in sq cm on net of 10-cm radius)			
			Pole-free area	Areas of maxima		
				5% per 1% area	4% per 1% area	3% per 1% area
M13	0.45	10	51.5	0	5.6	9.2
M14	0.54	27.5	60.5	1.4	7.8	21.7
M15	0.42	25	41.5	0	0	5
M17	0.37	35	46.3	0	0	2
M18	0.40	29	46.1	0.4	3	12

The postcrystalline strain is also evidenced by varying amounts of marginal granulation of the constituent grains of the rocks. The percentage of granulated material in each specimen, measured by means of a point counter in three sections, is shown in table 3. In addition to $\{02\bar{2}1\}$ lamellae, $\{10\bar{1}1\}$ cleavages are present in most of the grains, and a few grains in each specimen contain internally rotated $\{02\bar{2}1\}$ lamellae (L_9), which are not parallel to rational crystal planes (Turner *et al.*, 1954). Only in specimen M14 are lamellae of the latter type present in a significant proportion of the grains, and they are described and interpreted elsewhere (Christie, 1958).

The preferred orientations of [0001] axes in the analyzed specimens are shown in figure 21 (in pocket), diagrams D1–D5. There is a high degree of preferred orientation in all the specimens. In specimens M13, M14, M17, and M18 the patterns of preferred orientation are similar; the [0001] axes tend to form a single area of concentration, containing two distinct maxima, and there is some suggestion of a girdle in each instance. In specimen M15, however, the [0001] axes define a diffuse girdle which contains several maxima. These maxima do not lie in the periphery of the girdle but are inclined to it at small angles ("cleft-girdle" pattern). The degree of homogeneity of the [0001] axis orientation in the rocks (as indicated by the similarity of the component diagrams from the three sections) is variable but usually high.

The patterns of preferred orientation of [0001] resemble closely those of Alpine dolomites described by Ladurner (1953). Specimens M13, M14, M17, and M18 are similar, with regard to the orientation of [0001] axes, to the *S*-tectonites of Ladurner's classification (though they lack any texturally defined *s*-plane), and specimen M15 is similar to Ladurner's *B*-tectonites of Type III.

Diagram D6 in figure 21 (in pocket) is a synoptic diagram showing the main maxima (3, 4, and 5 per cent per 1 per cent area) in the patterns for each of the five specimens, geographically oriented. In general, the maxima lie in a girdle about the axis *B*, and the broken lines, which are drawn parallel to this girdle, pass through the main maxima for specimens M14 and M18. The axis *B* of the girdle is approximately parallel to the axes of medium-scale folds measured in the dolomite (fig. 16, *b*). Thus the fabric on a microscopic scale is consistent with that on the larger scales observable in the field, and this aspect of the fabric may be assumed to reflect the same movements.

The orientation of twinned $\{02\bar{2}1\}$ lamellae in specimens M14, M15, M17, and M18 is shown in diagrams D7, D8, D9, and D10, respectively. The poles of the lamellae are concentrated in a single maximum in specimens M14, M15, and M18, whereas in specimen M17 they tend to lie in a diffuse girdle which is diagonal in the diagram.

INTERPRETATION

The mechanisms of deformation of dolomite have been determined by experiments on dolomite rock (Turner *et al.*, 1954; Handin and Fairbairn, 1955) and single crystals (Higgs and Handin, 1959). These are (*a*) twin gliding on $\{02\bar{2}1\}$ planes, normal to the directions $[02\bar{2}1{:}0001]$, with negative sense, and (*b*) translation gliding or slip on the basal plane {0001} parallel to one of the *a*-axes. Twin lamellae are formed by the former mechanism and the latter is recorded by rotation through the crystals of preëxisting $\{02\bar{2}1\}$ lamellae to irrational orientations. The internally rotated lamellae have been designated L_9 (Turner *et al.*, 1954) and L_T^c (Higgs and Handin, 1959).

Turner (1953) plotted axes of compression (*C*) and tension (*T*), which would be ideally oriented to cause twinning on the prominent $\{10\bar{1}2\}$ twin lamellae in the calcite grains of several marbles. He found that these axes, *C* and *T*, show a

preferred orientation in the rocks, reflecting the stress that produced the twinning. By using the method devised by Turner, it is possible to determine the orientation of the stress that produced the twinning in a natural dolomite, assuming that the experimentally determined mechanism operated (Christie, 1958; Crampton, 1958). Similar deductions may be made from the orientations of internally rotated lamellae in grains (Christie, 1958). The experimental evidence indicates that slip on {0001} is a more important mechanism than twinning on $\{02\bar{2}1\}$ under most experimental conditions, but the deformation due to this mechanism can be recognized only if twin lamellae were present before slip began. Internally rotated (L_9) lamellae are present, but extremely rare, in specimens M15, M17, and M18; they are more common in specimen M14. It has been demonstrated that the stress deduced from rotation of lamellae due to basal slip in specimen M14 is the same as that deduced from the twinning (Christie, 1958). The axes *C* and *T* deduced from twinning $\{02\bar{2}1\}$ lamellae in specimens M14, M15, M17, and M18 are shown in figure 21 (in pocket), diagrams D11–D14.

From the orientation of the $\{02\bar{2}1\}$ planes in dolomite and the sense of twin gliding, it follows that the *C*-axes are inclined at a small angle (17.5°) to the [0001] axis, and the *T*-axes are similarly inclined to the base (0001). Thus in a dolomite rock so intensely deformed that twinning has taken place on all the $\{02\bar{2}1\}$ planes, the preferred orientation of the *C*- and *T*-axes deduced from the fabric would be controlled, not by the orientation of the applied stress, but by the preferred orientation of the lattices of the grains. For example, in a rock in which the [0001] axes define a single maximum, the *C*-axes inferred from the twin lamellae would form a maximum coincident with the concentration of [0001] axes, and the *T*-axes would be oriented in a diffuse girdle normal to the maximum of compression (*C*) axes; the preferred orientation of the inferred stress axes in such a rock will not necessarily give the orientation of the applied stress during deformation. In the specimens under consideration two features suggest that the stress axes inferred from the twinning do, in fact, represent the stress that produced the twinning: first, the orientation of the interpreted twin lamellae is rather highly restricted, and, second, the maxima of compression axes (*C*) do not coincide with the maxima of [0001] axes in any of the specimens.

If there is a strong point maximum of both *C*- and *T*-axes, the maxima probably indicate the orientation of the greatest and least principal stress axes, σ_1 and σ_3, respectively (compressive stress positive). In this instance the third principal stress was probably intermediate between σ_1 and σ_3, so that $\sigma_1 > \sigma_2 > \sigma_3$. If there is a point maximum of *C*-axes, and the *T*-axes are distributed in a great circle normal to it, two of the principal stresses (σ_2 and σ_3) were probably equal and less than the third (σ_1), which is parallel to the maximum of *C*-axes. The stress would then be axial ($\sigma_1 > \sigma_2 = \sigma_3$).* An axial stress would also be indicated by a point maximum of *T*-axes (σ_3) with a great circle of *C*-axes normal to it ($\sigma_1 = \sigma_2 > \sigma_3$). The least principal stress in the last instance might be either tensile or compressive, though it is unlikely that tensile stresses exist at depth in the earth's crust.

There are point concentrations of *C* and *T* in specimens M14 (D11) and M17

* The term "axial" is used to characterize the stress when two of the principal stresses are equal, because "uniaxial," as usually defined, implies that two of the principal stresses are zero.

(D13), suggesting that the principal stresses were unequal ($\sigma_1 > \sigma_2 > \sigma_3$), but the stress inferred from M15 (D12) and M18 (D14) seems to be axial ($\sigma_1 > \sigma_2 = \sigma_3$). The orientations of the axes of greatest and least principal stress, as indicated by the maxima of *C*- and *T*-axes in the specimens, are shown in the synoptic diagram D15 (fig. 21, in pocket). The axes *C* and *T* (σ_1 and σ_3) inferred from the twinning in M14, M15, and M18 lie close to a great circle normal to *B*, and the *C*-axes for M14, M15, and M17 are almost parallel, plunging steeply toward west-northwest. The parallelism of the axes of maximum principal stress in three of the four specimens indicates strong compression in this direction, which is more or less perpendicular to the plane of the Moine thrust.

The evidence derived from the fabric of specimen M17 is not consistent with that derived from the other specimens. The paired maxima in the pattern of [0001] axes (fig. 21, D4) are considerably weaker than in other specimens with similar patterns, and there is a rather diffuse girdle about a northward-plunging axis; it is also evident that the maxima do not lie in the girdle about the regional *B*-axis (fig. 21, D6). The twinning in the rock, moreover, reflects a deformation in which the axes of maximum and minimum principal stress lay in a steep plane with easterly strike (fig. 21, D15). This indicates that the last deformation of the rock was related to a north-trending *B*-axis, and it is possible that the preëxisting pattern of [0001] axes was partially rotated and disrupted during the deformation.

Although a considerable proportion of the grains in all the specimens contain two or three sets of $\{02\bar{2}1\}$ lamellae, optically recognizable twinning is scarce, and there is no evidence that any of the grains are more than half-twinned. The evidence of twin gliding on $\{02\bar{2}1\}$, even with considerable translation on {0001}, is inadequate to account for the strong preferred orientation of the dolomite lattice in the rocks (Christie, 1958). It is probable that the preferred orientation existed in the rocks before the visible lamellae were produced, and that the principal stress axes inferred from the lamellae relations in the rocks reflect only the final stage of the deformation (cf. Turner, 1953). The patterns of preferred orientation of [0001], however, are so similar to those of dolomite tectonites described by Fairbairn and Hawkes (1941) and Ladurner (1953) that there can be little doubt that they originated by deformation. There is a rather close approach to orthorhombic symmetry in patterns of preferred orientation of [0001], notably for specimens M13, M14, and M18, indicating that the deformation that oriented the grains had this symmetry.

Table 3 shows the degree of preferred orientation of [0001] axes in the fabric of each of the specimens 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, 1953), and the maxima, measured on the original contoured diagrams (net of 10-cm 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 (1) the orientation patterns are similar, and (2) 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, as the diagrams fulfill 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. This lack of correlation provides support for the view that the preferred orientation in the rocks was not attained during the movements that caused the visible granulation along grain boundaries and plastic deformation of the grains.

The evidence of the microfabric of the Loch Ailsh dolomites seems to warrant the following conclusions. The crystalline fabric of the dolomites is a tectonite fabric with almost orthorhombic symmetry; the recrystallization was therefore probably caused by regional metamorphism and not thermal metamorphism, as is true of many of the crystalline marbles of the Assynt region. In varying degrees the rocks suffered postcrystalline deformation as a result of strong compression along an axis plunging steeply to west-northwest, and this was accompanied or followed by rotation about a *B*-axis plunging 25° to slightly north of east. The fabric of specimen M17 suggests that there was also local rotational movement about a northward-plunging axis, but this conclusion, based on the evidence of a single specimen, is advanced tentatively and will be considered along with other evidence at a later stage of the discussion.

Grain Orientation in Quartzose Rocks

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 per cent quartz. The specimens were collected at the localities shown on the map (fig. 22). The petrographic character of the rocks is described briefly, and certain conclusions are drawn concerning the sequence of movement and crystallization, before the lattice orientations of quartz and mica are described.

PETROGRAPHY

The Cambrian quartzites along the eastern margin of the zone of dislocation show progressive mylonitization toward the Moine thrust. Plate 8, *a*, shows a slightly deformed quartzite, without foliation or lineation, in which the clastic grains of quartz are considerably flattened; the grains show undulatory 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 (pl. 9, *a*–*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 shortest axis being normal to the foliation and the longest parallel to the lineation. The grains show intense undulatory extinction in bands subparallel 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 (pl. 8, *b*). 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

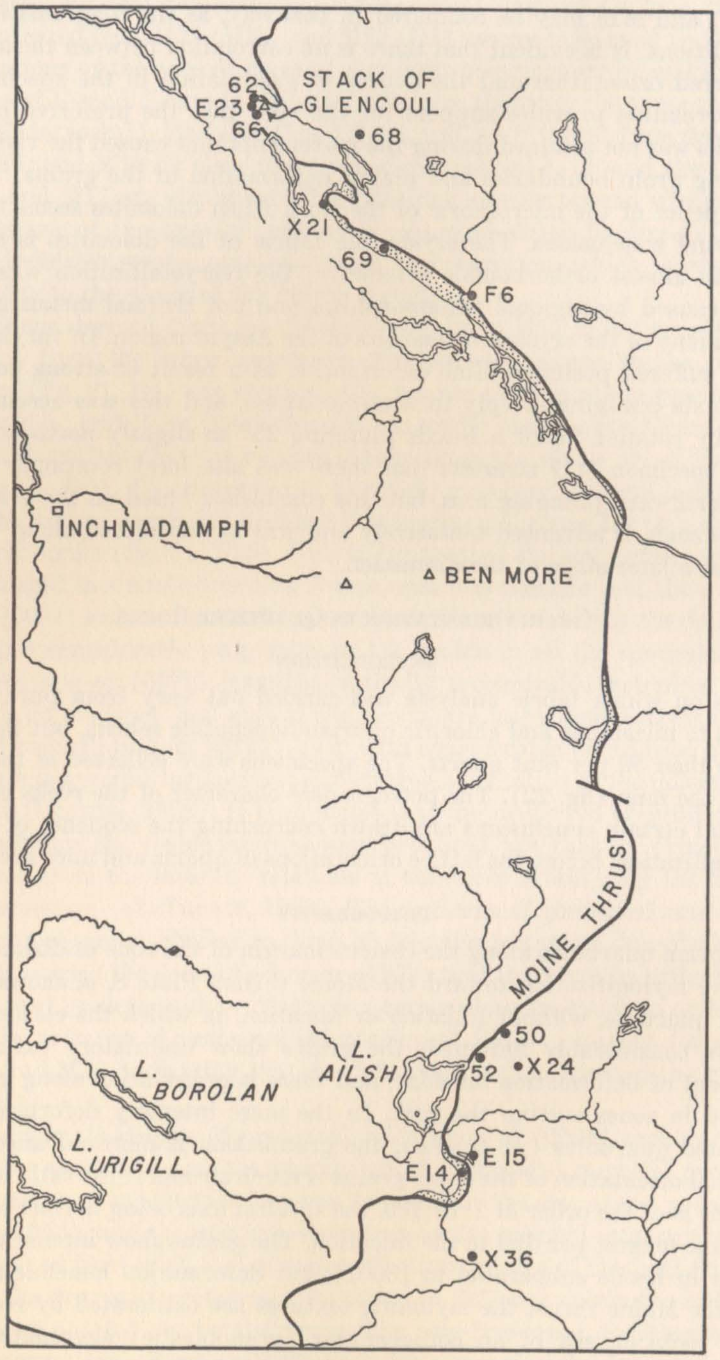

Fig. 22. Map showing localities of analyzed specimens of quartz-bearing rocks. Shaded areas are lineated Cambrian and Torridonian rocks immediately below the Moine thrust.

intense plastic deformation and granulation of grains and the other showing postkinematic crystallization, are referred to as quartzites of Type I and Type II, respectively.

The Moine schists in the area under consideration are quartzo-feldspathic rocks with small amounts of biotite and colorless 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 fissility to the rocks. The quartz and the feldspar show no trace of undulatory extinction or granulation. The rocks are texturally similar to the eucrystalline members of the primary mylonitic rocks, and differ from them only in being of coarser grain.

The petrographic character of primary and secondary mylonitic rocks is described in detail elsewhere (Christie, 1960).

FABRIC DATA

The preferred orientations of [0001] axes of quartz, measured in thirteen specimens, including Cambrian quartzites, primary mylonitic rocks, Moine schists, and a quartz vein, and the preferred orientations of {001} cleavages of mica, measured in the schist specimens, are shown in figure 23 (in pocket). 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, and the analyzed specimens are of slightly coarser grain size than average. In the secondary mylonitic rocks the quartz is reduced to a mass of minute granules (Christie, 1960, pl. VII), and for this reason it is impossible to measure the preferred orientation of quartz in the fabric by optical means. Except in quartzites of Type I, the quartz grains are relatively free from postcrystalline strain. In the quartzites of Type I, however, all the grains show a high degree of undulatory extinction, and the orientation of [0001] varies, in many instances 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. The [0001] axes 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," as 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 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 mentioned 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, and 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 ribbonlike habit; the average mean grain dimension in the sections normal to the lineation ranges up to 1 mm, whereas in the most deformed specimen (69) the grains are up to 2 cm long in the section parallel to the lineations.

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 a 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 are generally without undulatory 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, D14), X24 (diagrams D16, D17, D18), and X36 (diagrams D19, D20, D21).

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 ($L_1 = L$) generally found in the rocks, there is a crude lineation (L_2), defined by the trace 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 the schists and is approximately normal to the foliation (*S*) and the lineation (*L*) in the specimen. The quartz grains in the vein are of variable size (average mean grain dimension is .2 mm), and are considerably larger than the grains in the mylonite of the specimen. Some of the grains show undulatory 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 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. In this diagram Sander plotted the maxima for nineteen tectonites, oriented so that the foliation (*ab*) and the lineation (*b*) were parallel.*

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 the intersection of the girdles (maximum I of Sander's diagram), and numerous submaxima 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 patterns is triclinic (though tending toward 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 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 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 orienta-

* It is standard procedure to describe patterns of preferred orientation of quartz and other minerals with reference to fabric axes (*a*, *b*, *c*) 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 the folding, and for this reason I have not followed this procedure.

tion of quartz for the three schist specimens are not unlike those for the quartzites and the 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 (L_2) in specimen X36. The girdles in diagrams D17 (specimen X24) and D20 (specimen X36) each contain two submaxima, defining statistical *s*-planes (S_1 and S_2) in the fabric. These *s*-planes are not equally inclined to S. The symmetry of diagram D14 is orthorhombic and that of diagrams D17 and D20 is 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 over-all 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 positions I and IV of Sander's diagram, and the symmetry is almost orthorhombic.

INTERPRETATION

The symmetry of the quartz fabric in all the analyzed specimens is characteristically nearly orthorhombic, and a few of the rocks, notably the quartzites of Type I (diagrams D2 and D3), show perfect orthorhombic symmetry. Moreover, there is a strong resemblance among 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. Such symmetry planes are drawn in the quartz patterns for individual specimens. For the purpose of discussion the symmetry planes are named p_1, p_2, and p_3, and the orientation of p_1, p_2, and p_3 in relation to the girdles is uniquely specified in diagram D15. 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 analyzed 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, oriented with reference to geographical coördinates. 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 analyzed 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 (Phillips, 1937, D24) with paired maxima inclined to the foliation, as in my diagrams D17 and D20. Phillips states that the degree of preferred orientation in the Cambrian and Torridonian rocks below the Moine thrust is not high (1937, pp. 601–603), and the only constructive effect that 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) seemed to confirm these observations. Phillips concludes (1937, p. 603) that "in many of the rocks in immediate association 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*)." My analyses 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 the 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. 217–218); he considers 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 my diagrams, but the angle between the girdles is greatest in some of the Moine schist diagrams (D16, D19) and least in the primary mylonitic rocks and the 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 (Hietanen, 1938); patterns of the crossed-girdle type have also been recorded in Dalradian quartzites (Weiss *et al.*, 1955), in quartz tectonites in the Appalachians (Balk, 1952), and in the basement gneisses of Kenya (Weiss, 1959). Such patterns are so commonly developed that I believe 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. This may be seen in the folded specimens, X21 and 52. The 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 because the fold axis is inclined at a large angle to the regional maximum, though the style is similar to that of the majority of folds in the primary mylonitic rocks. 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 shear fold produced by slip on a single set of *s*-surfaces transecting the fold (Sander, 1930; Knopf and Ingerson, 1938, p. 159). The symmetry axes of the quartz fabric, however, are unrelated to the *B*-axes or to the axial planes of the folds, and it is more likely, in my 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 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 investigation, for, although the so-called "granulites" of the Moine series are, in general, neither mineralogically nor texturally similar to true granulites, there seems 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 instances oriented in crossed (*Okl*) girdles. He interpreted the fabric in terms of a flattening achieved by slip on two equivalent (*h0l*) slip planes, combined with yielding on (*Okl*) planes. Whereas the orthorhombic symmetry of the fabric indicates that there was little tectonic transport while this fabric was being produced, Sander considers that the quartz fabric reflected only the final imprint (*Aufprägung*) of deformation, which may have been preceded by translative movements of considerable 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. The symmetry of the fabric becomes triclinic, however, when the megascopic fabric elements are considered. The quartz orientation is remarkably uniform over the whole area of the granulites, and Sahama attributes the triclinic symmetry of the fabric to a superposition of two deformations; he considers that the quartz was reoriented by a late overprint, obliquely superposed on the preëxisting megascopic fabric during a separate and unrelated deformation. He infers 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 the 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. The symmetry axis $[p_1:p_2]$ of the quartz fabric, however, is statistically parallel to the *B*-axis of the folds in the area (diagram D24), a fact strongly suggesting that the two phases of deformation were genetically related. I believe that the quartz orientation was induced by the final (orthorhombic) imprint of the same deformation that produced the folding in the rocks, as Sander has suggested for the Saxony and the Finnish granulites (1934, p. 41).

TABLE 4

TYPES OF HOMOGENEOUS STRAIN WITHOUT TRANSPORT

Type of strain	Changes of dimension parallel to three mutually perpendicular axes		
	A	B	C
1. Biaxial	Shortened	Unchanged	Elongated
2. Triaxial	Shortened	Elongated	Elongated
3. Triaxial	Shortened	Shortened	Elongated

In view of the diversity of opinions on the mechanism by which quartz acquires a preferred orientation (Fairbairn, 1949, pp. 117–133), no attempt is made to account for the quartz orientation. The orthorhombic symmetry of the patterns and the homogeneity of the fabric over the area denote, however, 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 described in terms of shortening or elongation parallel to three mutually perpendicular axes, A, B, and C (the principal axes of strain), and there are three shape transformations that a body may undergo as a result of such a strain (see table 4).

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 symmetry evidence, but the dimensional orientation in some of the rocks is instructive in this connection. In quartzites of Type I, the large "relict" quartz grains have almost certainly developed from the original grains of the orthoquartzite.* The grains in the undeformed 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

* The granules between the large quartz grains in quartzites of Type I (pl. 9) may have originated by mechanical granulation or by recrystallization; from the appearance of the grains and the texture, the latter mechanism seems likely. These quartzites, however, represent a stage in the transition from undeformed orthoquartzites to rocks consisting entirely of granulated or "crush" quartz; moreover, the large size of the 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 clastic grains of the orthoquartzite by a process involving plastic deformation and perhaps some recrystallization.

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" (*Plättung*). The degree of flattening and elongation parallel to the lineation and the 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 shear movement (transport) relative to the foreland in this direction.

It is probable that there was a gradual transition during the deformation from the translative (monoclinic) movement normal to 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 this flattening will be parallel to the horizontal axis that is normal to the direction of shortening, that is, the fold axis. I consider that such an evolutionary sequence of deformations occurred in the Moine schists and the 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 B and elongation parallel to 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 maximum in each of the mica diagrams defines the foliation, which was passive during the final orthorhombic stages of the deformation. Thus these maxima are relics from the early (monoclinic) phase of movement. However, the *s*-planes S_1 and S_2, defined by submaxima 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 northeast-trending quartz veins in the primary mylonitic rocks and the 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 quartz in the vein in specimen 66 (diagram D5) is similar to that in the primary mylonitic rocks and the schists; the symmetry of the pattern is almost orthorhombic and there are 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 final

orthorhombic phase of the primary deformation, and must therefore have been emplaced before the close of the deformation. It has been inferred above that there was some degree of elongation parallel to $[p_1:p_2]$ $(=B)$ during this phase of deformation, and the veins were probably formed by infilling of extension fissures normal to the direction of elongation.

The quartz fabric of the primary mylonitic rocks and the 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 the folds were passive. The movement during this phase of deformation was extremely penetrative and homogeneous, and was probably achieved by indirect componental movement (Knopf and Ingerson, 1938), that is, by recrystallization of quartz and feldspar. The relationship between the symmetry axes of the early monoclinic movements and the late orthorhombic imprint is such that there would be little change in the orientation of early-formed linear structures during the later stages of deformation. Flattening of the rock mass, however, 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 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.

TECTONIC SYNTHESIS

Introduction

From the evidence described in the foregoing sections, 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 sections separate phases of deformation in the Moine schists, 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.

Structural Correlations

Figure 24, *a*, 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 the close relationship between the folds in secondary mylonitic rocks (B_n, B_s) and the Ben More thrust. The planes S_n and S_s represent the mean orientation of the foliation in the primary mylonitic rocks in the northern and southern areas respectively; the plane representing the Ben More thrust is based on the average orientation of the thrust at several localities where it is exposed in the zone of dislocation. The axes of folds in the secondary mylonitic rocks at the Stack of Glencoul (B_n) and Cnoc a' Chaoruinn (B_s) are parallel to the intersection of the thrust and the foliation in the primary mylonitic rocks in both areas. This fact confirms the hypothesis advanced above, that the later folding about approximately north-south axes was contemporaneous with movement on the Ben More thrust, and that the folds were formed by kinking of the *s*-surfaces in the primary mylonitic rocks (S) along surfaces that are parallel to the thrust and associated reverse faults.

The diagram also indicates 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 Moine thrust and intersect in an axis plunging toward the east, parallel to B; 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-southeast–plunging axis B. The foliation surfaces in the primary mylonitic rocks and the schists in the northern and southern parts of the bulge are analogous to the limbs of a large fold (about the axis B) with small amplitude. Thus the em-

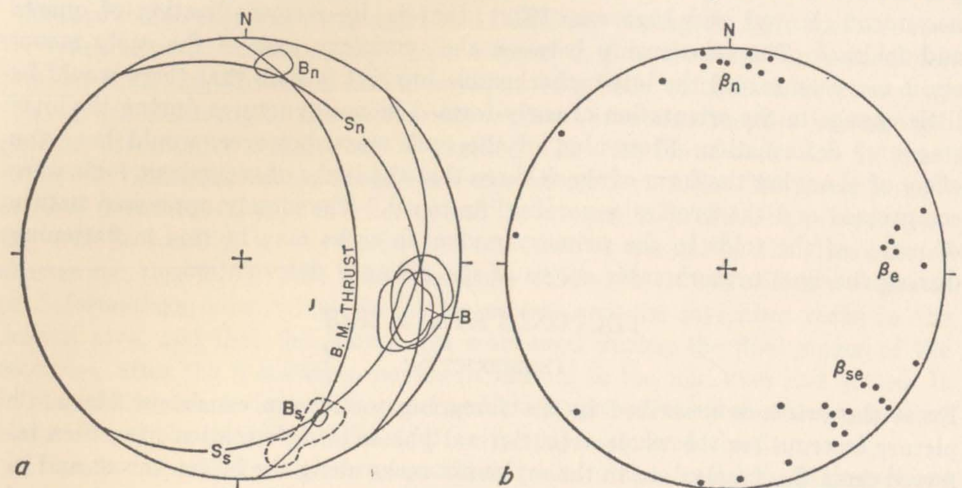

Fig. 24. *a*. Synoptic diagram showing maxima of fold axes in Stack of Glencoul area (B, B_n), Loch Ailsh area (B), and Cnoc a' Chaoruinn area (B, B_s). S_n and S_s represent the mean orientations of the foliation in the northern and southern areas, respectively. The mean orientation of the Ben More thrust is also shown. Full lines are 10 per cent contours, and the broken line is a 6 per cent contour. *b*. Synoptic diagram showing the orientation of β-axes in Cambrian and Torridonian rocks in zone of dislocation (from fig. 20, in pocket).

bayment of the thrust is not due to an "axial culmination," as claimed by Bailey (1935), but to an anticlinal fold of the thrust about the regional fold axis 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 (approximately 500 feet) are scarcely reflected in the outcrop of the Moine thrust.

The B_n- and 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 (fig. 24, *b*, β_n) in the zone of dislocation. Thus it is evident that folding about north-trending axes in the Torridonian and Cambrian rocks of 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 the thrust masses were transported toward 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.

It has been shown that the southeast- and east-plunging fold structures in the zone of dislocation (fig. 24, *b*, β_e, β_{se}) and the widespread east-southeast–plunging folds in the primary mylonitic rocks and the Moine schists (fig. 24, *a*, B) are earlier than the westward movements.

It is not clear whether the β_{se} and β_e groups of folds in the zone of dislocation date from different phases of deformation or were formed contemporaneously. In view of the parallelism of the β_e-folds and the eastward-plunging minor folds in the dolomite at Loch Ailsh (figs. 15; 16, *b*; 21, in pocket, D6, D15), these were probably formed contemporaneously. The minor folds in the Loch Ailsh dolomite are overturned to the north (p. 375), and it has been suggested (p. 384) that they, along with some small kink zones in the overlying mylonites, might represent a distinct phase of deformation during which the overlying rocks moved to the north.

The β_{se}-folds in the zone of dislocation must certainly have formed during the extensive movements that produced the east-southeast–plunging folds (B) in the primary mylonitic rocks and the Moine schists. The divergence of orientation between the B-folds above the Moine thrust and the β_{se}-folds below the thrust must be due to one 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 wide variation in the physical properties of the rocks; under these conditions irregularities in the movement pattern are to be expected. The variation in the orientation of the folds probably stems mainly from this cause, but it is not impossible that the folds in the zone of dislocation were modified by the late movements.

The structural picture obtained from the analysis of the microscopic fabric of the Loch Ailsh dolomites agrees very closely with that obtained from the megascopic fabric. The B-axis determined from the grain orientation plunges toward the east, parallel to the axes of most of the folds in the area. The sense of rotation about the eastward-plunging axis in the dolomites is opposite to that indicated by the majority of the folds in the overlying primary mylonitic rocks. It has already been stated, however, that there may have been slight movement toward the north along the Moine "movement horizon" near the end of the primary deformation. It has tentatively been inferred from the microscopic and megascopic data that the dolomites were later affected by slight deformation about a north-trending B-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 B-axis after the movement that produced the east-plunging B-axis.

Discussion of the Movements

The current controversy regarding the relative age of the Moine metamorphism and of 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 sections proves that at least two and perhaps three separate phases of dislocation and movement are recognizable in the rocks of the thrust zone. These have been referred to as the primary and secondary phases of deformation; the east-trending folds (β_e, and B in the dolomite) are here referred to the primary deformation in view of the near parallelism of their axes with B in the primary mylonitic rocks. 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 mostly produced during the secondary phase of deformation, and this cataclastic breakdown affects the earlier-formed primary mylonitic rocks as well as the Moine schists (Christie, 1960). It has not generally been recognized that the primary mylonitic rocks, which include the true mylonites of Lapworth and the Survey geologists (Peach *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 primary mylonitic rocks. Petrographic evidence indicates that this was contemporaneous with the regional metamorphism of the Moines. The thrust was only locally an active movement surface during the secondary phase of deformation, when the "brittle" structures were produced.

The primary deformation (I) may be divided into three phases, one following closely on the other. These phases of deformation were probably closely related. The secondary deformation (II) broke down the structures that were formed by the primary deformation, and the two main deformations (I and II) apparently are not related. The structures formed during each phase of deformation and the characteristics of each deformation are summarized in table 5.

During the early monoclinic phase of the primary deformation (I*a*) there was intensely penetrative movement throughout the zone of primary mylonitic rocks, and the Moine schists were transported toward the south-southwest along this "movement horizon." The presence of folds with southeast trend in the zone of dislocation, and the close relationship between these folds and the major thrusts, suggest that the Assynt nappes were transported during this phase of deformation. It has been inferred (p. 000) that there was movement of the lower Assynt nappe along the sole toward the southwest, and it is probable that there was also transport along the Assynt thrust in the same direction (pp. 000–000). These inferences are very significant, for they indicate that the Assynt nappes were derived from the northeast and not from the east-southeast, as claimed by Clough (in Peach *et al.*, 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 (fig. 25) is valid (and I believe it is), the nappe was transported a distance of 6 or 8 miles. Bailey has stated (1935, p. 159): "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 right angles to the abundant flow structure of the district, rather than thirteen miles as closely as possible along the line of flow." The "line of flow" to which Bailey refers, however, does not have the significance that he attributes to it; the lineation is parellel 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.

TABLE 5

Structures Formed during and Characteristics of Deformation Phases

Deformation phase	Moine schists and mylonitic rocks	Zone of dislocation
I*a*	1. Movement with monoclinic symmetry 2. B–folds produced 3. Deformation precrystalline and continuous	1. Movement with monoclinic symmetry 2. β_{se}-folds produced 3. Deformation postcrystalline and discontinuous
I*b*	1. Movement with orthorhombic symmetry (flattening) 2. Quartz and mica (in part) reoriented 3. Deformation paracrystalline and extremely penetrative	1. No evidence in most rocks 2. Possibly original (orthorhombic) fabric of dolomite produced
I*c*	1. Movement with monoclinic symmetry 2. Few east-plunging folds and kink zones produced in primary mylonitic rocks 3. Deformation less penetrative than in phases I*a* and I*b*	1. Movement with monoclinic symmetry 2. β_e- and B-axes produced in dolomite 3. Deformation postcrystalline and discontinuous
II	1. Movement with monoclinic symmetry 2. B_n- and B_s-folds produced 3. Deformation postcrystalline and discontinuous	1. Movement with monoclinic symmetry 2. β_n-folds produced 3. Deformation postcrystalline and discontinuous

Phemister (Read *et al.*, 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 seems to be part of the upper nappe, and the Loch Borolan mass belongs to the lower nappe, and I consider that the latter has played an important part in the formation of the bulge, as Phemister has suggested. It is clear from figure 25 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 cir-

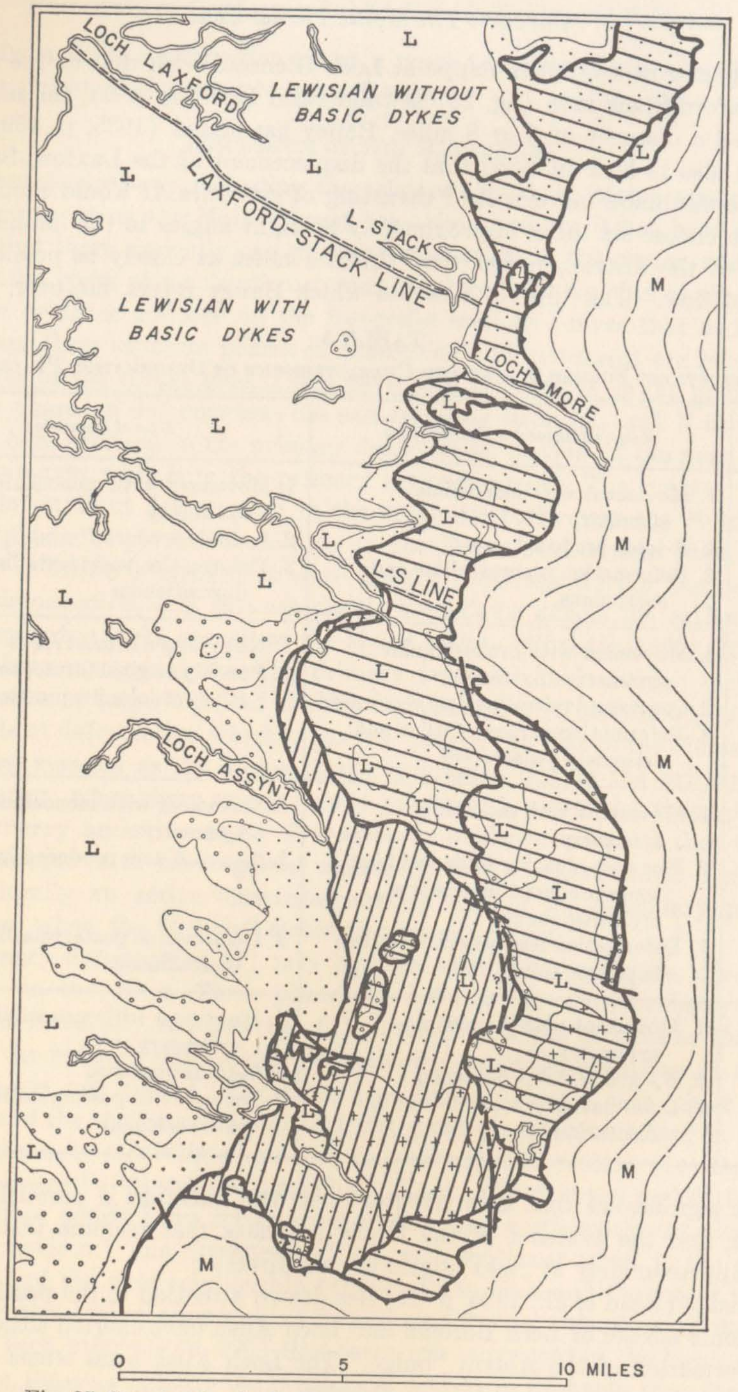

Fig. 25. Structural units in the Assynt and Loch More area, as interpreted by the present author (cf. fig. 1, in pocket). The upper Assynt nappe is shaded with nearly horizontal lines; the lower Assynt nappe, with nearly vertical lines. The Laxford-Stack line in the foreland and the upper Assynt nappe are shown (after Clough, in Peach *et al.*, 1907, and Bailey, 1935). Lewisian rocks are designated by L; Moine schists, by M; Torridonian rocks, by circles; Cambrian rocks, by points. The plutonic masses of Loch Borolan and Lock Ailsh are shaded with crosses.

cumstantial 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-southwest along the movement horizon (Moine thrust), and was dragged along under the moving Moine rocks until its progress was impeded by the upper portion 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 force 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 southwest along with a slice of the sedimentary rocks in which it is emplaced. The bulge is due to a gentle anticlinal fold of the movement zone 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 this fold was contemporaneous with the primary movements along the Moine movement horizon.

In the transitional stages of the primary deformation between the monoclinic movement and the orthorhombic imprint, there was probably slight shear movement normal to B combined with flattening normal to the foliation and extension parallel to B. But, during the ensuing stages of this deformation, the foliation was no longer an active slip surface, and the flattening and the elongation parallel to B were not accompanied by tectonic transport normal to B. In the final phase of the primary deformation (Ic), there was slight movement of the overlying rocks to the north.

Whereas the movement in the Moine schists and the mylonitic rocks throughout the primary deformation was pre- and paracrystalline, the movements during the later secondary deformation were postcrystalline. The sense of movement during this phase of deformation was toward the west, and the Ben More thrust and other eastward-dipping reverse faults were formed. The only zones of imbrication I recognized in Assynt 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 B-structures, the approximately orthogonal relationship between B and B_n, B_s, and β_n suggests that there may be a connection between the two phases of deformation. It is possible, in my 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 B in the Moine schists farther to the east. That is, the movement may be of the $B \perp B'$ type 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 B in a zone between the schists and the rigid foreland; the north-trending folds (B_n, B_s, β_n) in the thrust zone may have originated in this fashion.

Balk (1936, 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 submaximum of fold axes with trend parallel to the strike of the thrusts (Balk, 1953). Balk regards the lineation as a type of slickensides, parallel to the direction of movement on the thrust. He considers 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 block generated these supplementary stresses, producing slight movements of small masses sideways [1953, p. 102].

Cloos (1946) holds a similar view on the origin of what he describes as "folds in *a*." He cites the Assynt area and certain areas in Scandinavia and Lapland as affording examples of folds of this type (pp. 26–29). He states 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" (p. 28). Cloos considers that the main movement *and transport* in the Moine schists of the Assynt area were toward the northwest, parallel to the lineation; the orientation of the lineation varies slightly in different parts of the area, and the author attributes this to variations in the direction of movement, produced by local restriction of transport in certain parts of the area. Cloos also concludes that there may have been subordinate movement perpendicular to the general west-northwest direction of advance.

The movement postulated by Balk and Cloos is similar to that I infer for the second (orthorhombic) phase of the primary deformation, but my analysis of the fabric of the Moine schists and the 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 the style of the folding in the other areas examined indicate that there was considerable translative movement normal to the fold axes before the orthorhombic imprint.

Age of the Movements

My conclusions on the relative age of the different groups of fold structures in the Moine schists and the mylonitic rocks are essentially the same as those advanced by Read (1931), but the evidence set out in the foregoing sections proves that the geological ages of the two phases of deformation are not as Read inferred. It has been shown above that the east-southeast–plunging folds and lineations (B) were produced during the regional metamorphism of the Moine schists, and also 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). There was movement along the Moine thrust during the Moine metamorphism and deformation; the primary mylonitic rocks formed a movement horizon or zone along which the deforming and recrystallizing Moines were transported over the rigid basement. The "dislocation" effects described by Read (1931), and the "brittle" structures referred to by 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; they may, as McIntyre has suggested, be of Hercynian or even Tertiary age, for the Permian dike in the mylonitic rocks of A'Mhoine (McIntyre, 1954, pp. 216–217) cuts primary mylonitic rocks. If, however, there is a genetic ($B \perp B'$) relationship between the B-structures in the Moine schists and the north-trending folds in the thrust zone, as suggested above, then the westward movement on the thrusts must have followed closely on the primary movements. Thus it is possible that the secondary deformation of the Moine schists and the mylonites and the westward movements on the thrusts also date from the Caledonian orogeny.

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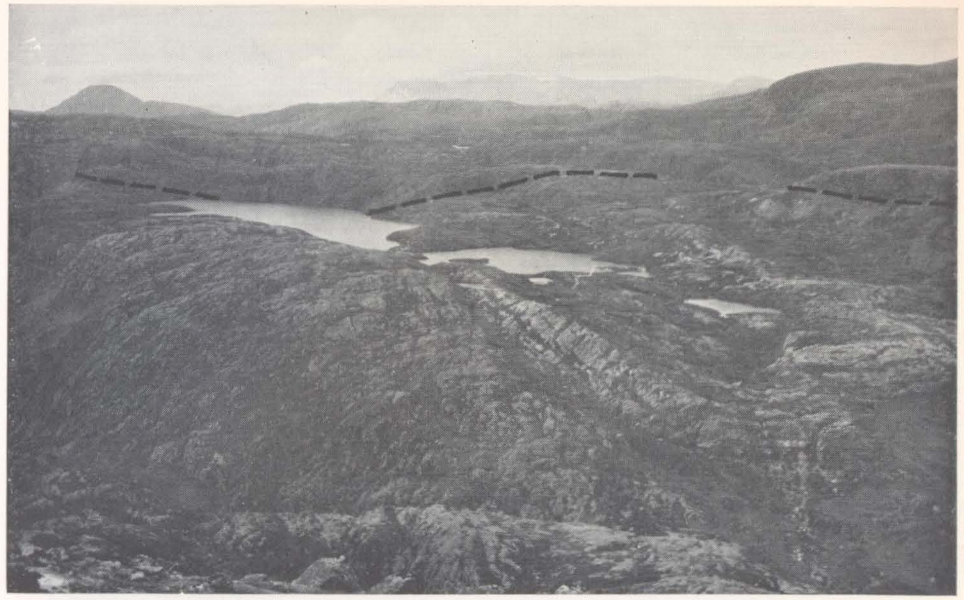
PLATES

PLATE 1

a. The Stack of Glencoul area, viewed from the south, showing the outcrop of the Moine thrust. The stack and Loch nan Caorach are in the middle distance. Note the gentle anticlinal fold in the thrust. One of the steep reverse faults west of the Ben More thrust shows in lower right.

b. Specimen of primary mylonitic rock from the Stack of Glencoul, showing the characteristic intrafolial type of folding. Specimen is approximately 1 foot long. (Specimen in the Royal Scottish Museum, Edinburgh; photographed by permission of the Director.)



a

b

PLATE 2

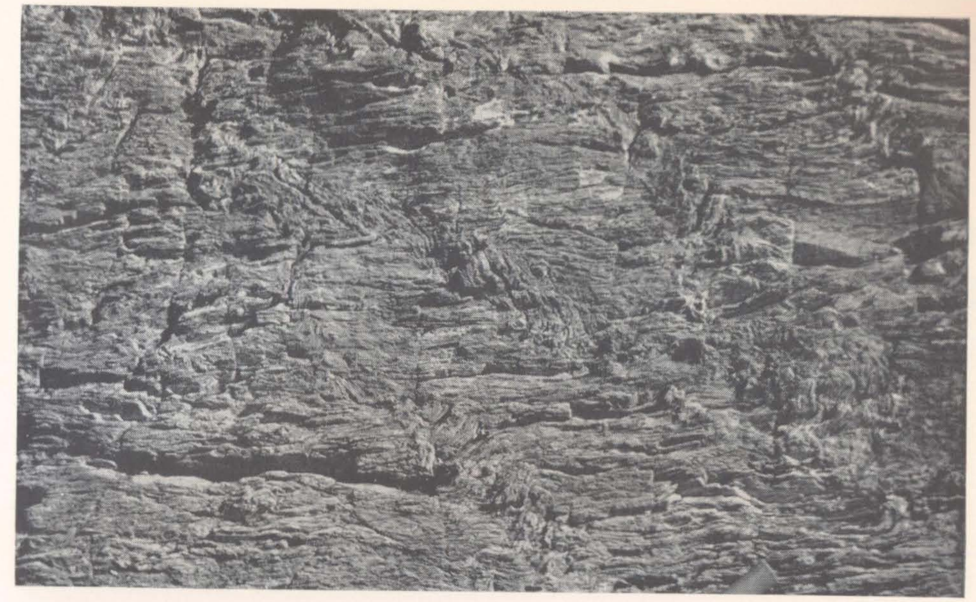
Folding in primary mylonitic rocks at the Stack of Glencoul, viewed in profile toward the east-southeast.

PLATE 3

Folding in the zone of secondary deformation,
Stack of Glencoul area

a. Exposure near the eastern margin of the zone of secondary deformation, half a mile northeast of the Stack of Glencoul. Several kink zones dip toward the east.

b. Exposure of phyllonite in the valley of the Glencoul River, showing small-scale folds. The axial planes of the folds (parallel to the hammer shaft) dip toward the east.



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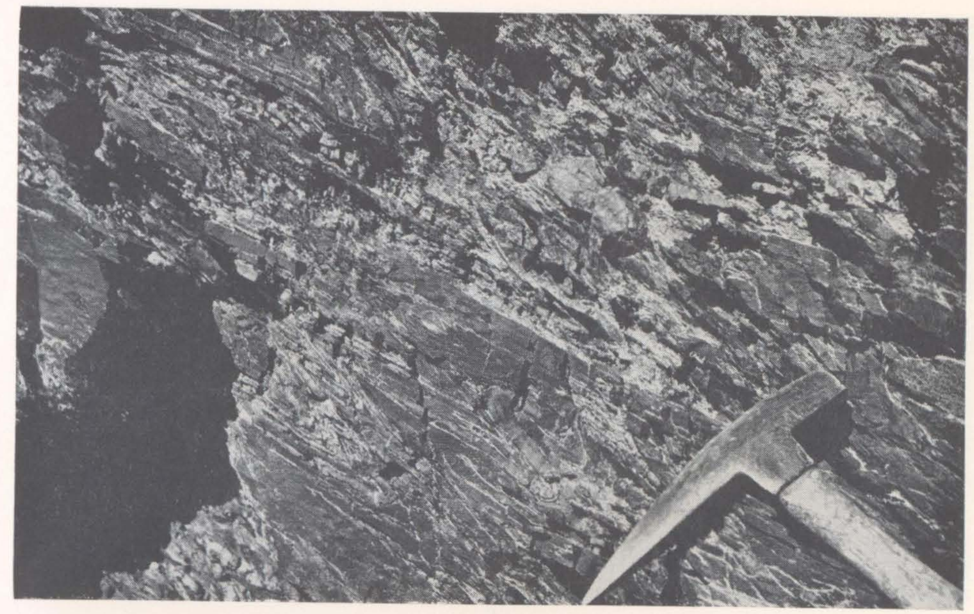


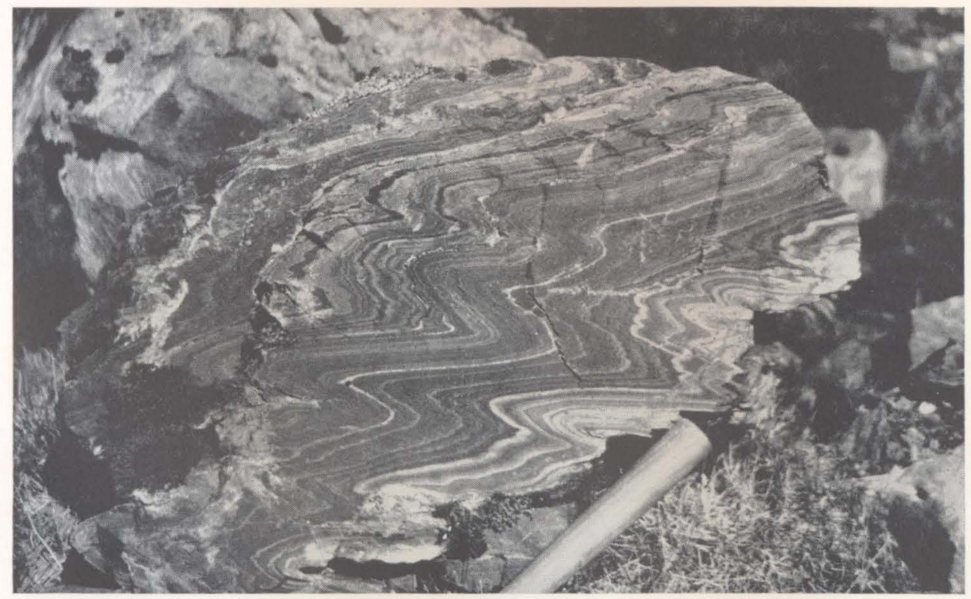
b

PLATE 4

Folds in the zone of secondary deformation, in the Cnoc a' Chaoruinn area

a. Specimen of folded phyllonite from disused quarry, half a mile southeast of Ben More road. Specimen is 4 inches across.
b. Block of folded phyllonite at same locality as *a*, showing the characteristic style of folding. Axial planes of folds dip toward the east.

a



b

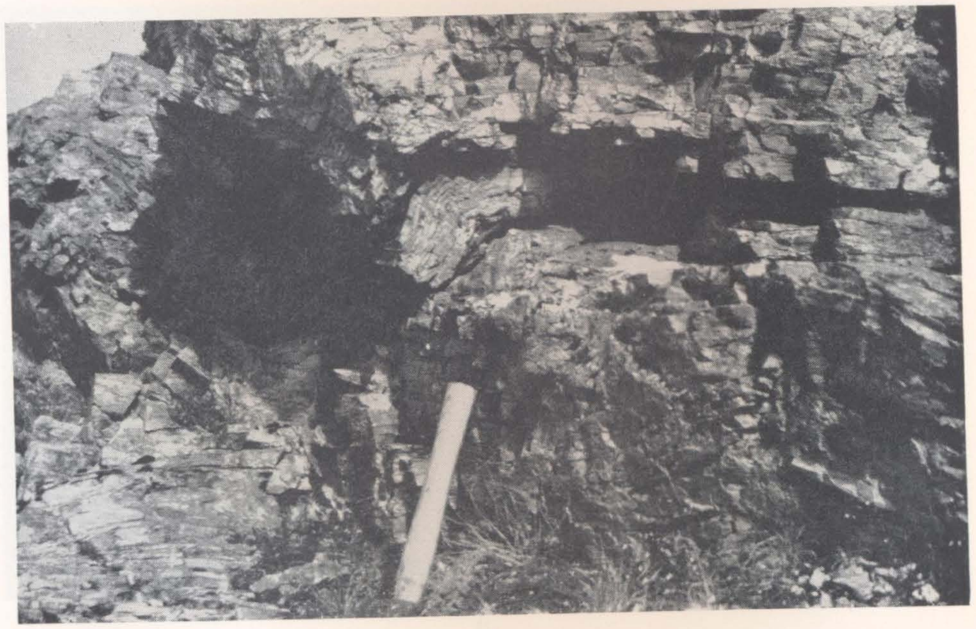
PLATE 5

Moine schists in the Knockan Crag area

a. Low-grade slabby Moine schist east of Knockan Crag. Foliation is evidently bedding. The most prominent set of joints strikes parallel to the lineation.

b. Fold in primary mylonitic rock at Knockan Crag, viewed toward the east. Note the crushing associated with the folding.

a



b

PLATE 6

Thrusts in the zone of dislocation

a. The Assynt (Glencoul) thrust on the south side of Loch Glencoul. Phyllonitized Lewisian gneiss rests on deformed Cambrian dolomite.

b. Gorm Loch Mor and Ben More Assynt from the north, showing the outcrop of the Ben More thrust west of Gorm Loch Mor. Note the folding in the Cambrian quartzites (about north-trending axes) above the thrust.

Inverted

a

b

PLATE 7

Structures in the zone of dislocation

a. 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 subparallel to the Ben More thrust, the outcrop of which is marked.

b. Large-scale fold in Cambrian limestones above the sole, east of Chalda House, Loch Assynt, viewed in profile to the southeast.

a

b

PLATE 8

Photomicrographs of deformed quartzites

a. Quartzite of Type I. Grains represent clastic grains of a Cambrian orthoquartzite. Grains are flattened and show some marginal granulation. Deformation lamellae and planes of minute inclusions are present in some grains. Scale line represents 1 mm.

b. Quartzite of Type II. Recrystallized Cambrian quartzite. The grains are small and relatively free from postcrystalline strain. Scale line represents 1 mm.

a

b

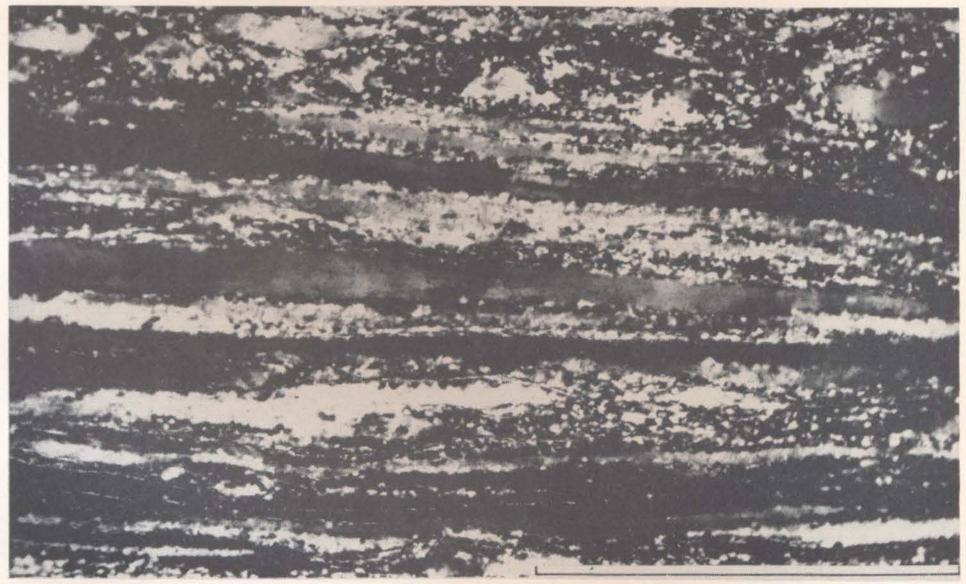
PLATE 9

Photomicrographs of a deformed quartzite

a. Quartzite of Type I, specimen 62. Section cut perpendicular to the foliation and the lineation. Note extreme flattening and undulatory extinction. Scale line represents 1 mm.

b. Same specimen (62). Section cut perpendicular to the foliation and parallel to the lineation. Note the great elongation of the grains parallel to the lineation. Scale line represents 1 mm.

a



b