30. Report *on the* Recent Work *of the* Geological Survey *in the* North-west Highlands *of* Scotland, *based on the* Field-notes *and* Maps *of* Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman, *and* H. M. Cadell. (Read April 25, 1888.)

(Communicated by A. Geikie, LL.D., F.R.S., Director-General.)

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Introduction.

In November 1884 a brief notice or report was published of the results of the work of the Geological Survey in Sutherland*. The object of that report was mainly to announce that the detailed mapping of the region had convinced us that the views entertained by our former chief, Sir Roderick Murchison, were no longer tenable. It was then intended that an official Report should soon be published, embodying the details of the survey work and containing a full digest of all that had previously been done by other observers. But the complicated structure of the region and the necessity of continuing the mapping southward along the great line of disturbance have hitherto delayed the publication of this Report. It is felt, however, that instead of further postponement until the conditions of official publication are fulfilled, it will be of advantage to publish a *résumé* of the chief results which the Survey has up to the present time obtained, and hence the present communication is laid before the Society.

Previous Literature.

In fulfilment of the promise made in the preliminary notice above referred to, we now offer an outline of the work of previous observers, chiefly with the view of showing how far our own labours have been forestalled by theirs.

In 1819 Macculloch described a remarkable development of red sandstone, quartz-rocks, and limestones among the gneiss and schists of the North-west Highlands and Islands. He maintained

* 'Nature,' vol. xxxi. p. 29, Nov. 1884.

that the red sandstones and conglomerates rest unconformably on the western gneiss, and that, in Sutherland, they are overlain by quartz-rocks and limestones, which alternate with and are succeeded by gneiss and schists forming the chief portion of the Highlands of Scotland. He chronicled the important discovery of worm-tubes (named by Salter *Serpulites Maccullochii*) and *Orthoceratites* in the quartz-rock of Loch Eriboll*.

In 1841 Hay Cunningham confirmed Macculloch's observations regarding the unconformability between the red sandstones and the underlying gneiss, and the occurrence of an upper gneiss resting on the quartz-rocks and limestones. He further corroborated the discovery of organic remains in the quartz-rock, and stated that "there are gneisses and mica-slates that have been elaborated after these were called into being"†.

In 1852 a suggestive memoir was published by Mr. Daniel Sharpe on the foliation of the rocks of the Northern Highlands, in which he endeavoured to show that foliation is the ultimate stage of cleavage. He distinguished between the gneiss lying east and west of a line drawn from Loch Eriboll to the head of Loch Maree, the foliation and cleavage of the western area and of Lewis striking N.W. to S.E., and that of the eastern area striking S.W.‡

The discovery of fossils in the Durness Limestone, in 1854, by Mr. C. W. Peach §, imparted fresh interest to these rocks, and led Sir Roderick Murchison to revisit the north-west Highlands, which he had seen with Sedgwick as far back as 1827. He invited Professor Nicol to accompany him, and the two observers went over some of the northern sections together in the autumn of 1855. At the British Association meeting of that year Murchison spoke guardedly of the age of the limestones of Sutherland, but was evidently inclined to regard them as Lower Silurian, the fossil evidence not having yet proved decisive on that question. Next year Nicol returned to the ground and extended his observations. He detected a marked unconformability between the red sandstones and quartz-rocks, which he traced for upwards of a hundred miles. At the same time he was led to the conclusion that the red sandstones of the west of Sutherland and Ross-shire were probably of Devonian age, and the quartzite and limestone Lower Carboniferous. When, in the following year, Peach found better-preserved fossils, which put the Lower Silurian horizon of the limestones beyond doubt, Nicol, abandoning the suggestion he had put forward as to the geological age of the rocks, applied himself with renewed energy

* 'A Description of the Western Islands of Scotland,' vol. i. pp. 1–234, 243, 295 *et seq.*, vol. ii. pp. 89, 104, 508, 515, &c. 'A Geological Classification of Rocks,' London: p. 333. "Supplementary Remarks on Quartz-Rocks," Trans. Geol. Soc. ser. 2, vol. i. pp. 53–60. 'A System of Geology,' vol. ii. chap. 29.

† "Geognostic Account of the County of Sutherland," Trans. Highl. Soc. vol. xiii. p. 73.

‡ "On the Arrangement of the Foliation and Cleavage of the Rocks of the North of Scotland," Phil. Trans. vol. cxlii. p. 445.

§ "Notice of the Discovery of Fossils in the Limestone of Durness," Proc. Roy. Phys. Soc. Edinb. (1885), vol. i. p. 23.

to the investigation of the problem of the "newer gneiss." He had at an early period recognized the possibility that this gneiss might have been "forced over the quartzite;" and this view he endeavoured to establish by the evidence of many natural sections. He was ultimately led to maintain that the limestone is the highest member of the Silurian series in that region, and that the so-called "Upper Quartzite" and "Upper Limestone" of Murchison's sections are merely the repetitions of the lower quartzite and limestone, due to faults or folds. While admitting that in places the quartzite and limestones are overlain by gneiss, he contended that there is no conformable upward succession from the fossiliferous limestone to the overlying schists and gneiss, but "that the line of junction where this conformable succession is said to occur is clearly a line of fault, everywhere indicated by proofs of fracture, contortion of the strata, and powerful igneous action." The igneous rocks, which he erroneously regarded as having been erupted simultaneously with the displacement of the strata, were termed "granulite." Along the line of fault, where the disturbance has been most violent, Nicol further observed that the quartzite is "often much hardened and semifused," though its fragmentary character is still recognizable. From the foregoing data he inferred that the sections in the North-west Highlands are but the counterpart of those in the Alps, where crystalline rocks are seen resting on unaltered strata due to enormous inversion and overthrow, and that a comparatively small amount of inversion and extrusion of older crystalline masses will suffice to explain any of the Scottish sections.

With reference to the strike of the crystalline rocks, Nicol admitted that in the western region the general trend is N.W., and in the central areas N.E.; but this distinction is not universal. He ventured the suggestion that the gneiss of Scotland may belong to distinct geological periods. Regarding the divergence in mineralogical character between the western and eastern gneiss, he conceded that hornblendic varieties of gneiss are very characteristic of this formation in the west of Sutherland, but the more usual kinds also occur; while, in the eastern district, he contended that rocks quite as hornblendic and as thoroughly granitic in character are to be found. In his opinion the peculiar character of the rock has no relation to its age or locality, but to its proximity to the great foci of igneous action. Near the granitic and syenitic eruptions the gneiss appears in the more coarsely crystalline and hornblendic forms *.

* "On the Red Sandstone and Conglomerate, and the superposed Quartz-rocks, Limestones, and Gneiss of the North-west coast of Scotland," Quart. Journ. Geol. Soc. vol xiii. p. 17.

"On the Age and Relations of the Gneiss Rocks in the North of Scotland," Rep. B. Assoc. for 1858, see p. 96.

"On the Relations of the Gneiss, Red Sandstone, and Quartzite in the North-west Highlands," Rep. B. Assoc. for 1859, see p. 119.

"On the Structure of the North-west Highlands, and the Relations of the Gneiss, Red Sandstone, and Quartzite of Sutherland and Ross-shire," Quart. Journ. Geol. Soc. vol. xvii. p. 85.

'The Geology and Scenery of the North of Scotland.' Edinb. 1866.

The marked unconformability between the red sandstones and quartzites detected by Professor Nicol was observed independently by Sir Henry James, and described by him in a letter to Sir Roderick Murchison, dated 26th July 1856*.

The fossils obtained from the Durness Limestone by Mr. Charles Peach were considered by Salter to have strong affinities with certain Lower Silurian forms of North America, ranging from the Calciferous Sand-rock to the Trenton Limestone †. This determination, confirming, as it did, Sir Roderick Murchison's reference of the limestones and quartzites of Sutherland to the Lower Silurian system, gave that geologist a new impetus in his investigation of the structure of the North-west Highlands. After devoting parts of the summer of several successive years to the task, he arrived at what he believed to be the true order of geological succession in that region. The western gneiss, forming the ancient foundation-stone of Britain, he correlated with the Laurentian gneiss of Canada, and the red sandstones and grits with the Cambrian formation of Wales. The great succession of Silurian strata, resting unconformably on the Cambrian sandstones and Laurentian gneiss, were grouped by him in ascending order, (1) Lower Quartz-rock, (2) "Fucoid-beds" with *Serpulites Maccullochii* at the top, (3) Limestone with fossils, (4) Upper Quartz-rock followed in places by (5) an Upper Limestone passing upwards into micaceous flagstones, chloritic schists, and gneissose beds, covered unconformably by the Old Red Sandstone. From this unbroken sequence he inferred that the Highlands are mainly composed of metamorphosed Silurian strata.

In his various papers Murchison maintained that the prevalent strike of the western gneiss is N.W. and S.E., while that of the eastern schists is N.E. and S.W., and further, that this difference is made still more apparent by distinct lithological characters. He called special attention to the contrast between the hornblendic gneiss in the west of Sutherland and the micaceous flaggy strata overlying the limestones and quartzites to the east of Assynt, Loch More, and Loch Eriboll. He naturally held that such a difference in strike and lithological character implied a different geological horizon. It is due to his memory to recognize how clearly he saw the impossibility of accounting for the superposition of the eastern or upper gneiss on the limestone by supposing it to be the western or fundamental gneiss brought up again by mere ordinary faulting or inversion. He was mistaken, as we now know, in regarding this superposition as a normal stratigraphical sequence. But the mistake was hardly avoidable at the time, and was shared in at first by Nicol also. Indeed it could not be completely cleared up until laborious and detailed mapping had been undertaken. To Murchison's mind the fact of prime importance in the geological structure of the North-west Highlands was the position

* Memoirs of Sir R. I. Murchison, by A. Geikie (1875), vol. ii. p. 213.

† Rep. Brit. Assoc. for 1857, p. 83; Quart. Journ. Geol. Soc. vol. xv. p. 374 *et seq.*

of fossiliferous Lower Silurian rocks under enormous masses of gneisses and schists, and the proof thereby afforded of a vast regional metamorphism which could not be other than of Silurian age. He was entirely in error when he believed his younger gneiss to be merely metamorphosed Lower Silurian strata; but that the crystalline rocks of the Eastern Highlands contain the records of a gigantic Post-Lower-Silurian metamorphism is now established beyond dispute on evidence of which he never dreamed *.

The order of succession advocated by Murchison, and supported by Professors Ramsay, Harkness, A. Geikie, and others, seemed to furnish a simple solution of the geological phenomena of the Highlands, and hence met with general acceptance.

In 1878 the controversy was reopened by Dr. Hicks, in a paper "On the Metamorphic and Overlying Rocks in the neighbourhood of Loch Maree"†. While agreeing with Murchison that there is a perfect passage from the quartzites, "Fucoid-beds," and limestones into the overlying flaggy strata of Glen Logan and Glen Docherty, resembling the Lower Silurian flags of Wales, he maintained that the flaggy strata rest unconformably on the Pre-Cambrian Archæan rocks of Ben Fyn. Subsequently Dr. Hicks disputed that the eastern schists rest conformably on the Lower Silurian strata. He arranged the Pre-Cambrian rocks in three groups—(*a*) lower, consisting of massive gneisses (Loch Maree); (*b*) middle, comprising more banded gneisses (Loch Shiel); (*c*) upper, composed of crystalline schists (Ben Fyn); and contended that, between Glen Shiel and the Highland border, there are representatives of various Archæan rocks with patches of Silurian strata resting on them unconformably.

In 1880 an important contribution towards the solution of the

* "On the Relations of the Crystalline Rocks of the North Highlands to the Old Red Sandstone of that region, and on the recent Discoveries of Fossils in the former by Mr. Charles Peach," Brit. Assoc. Rep. 1855.

"The Quartz-rocks, Crystalline Limestones, and Micaceous Schists of the N.W. Highlands of Scotland proved to be of Lower Silurian age through the recent fossil discoveries of Mr. C. W. Peach, with a Note on the Fossils by J. W. Salter," Brit. Assoc. Rep. for 1857.

"On the Succession of the Older Rocks in the north-west counties of Scotland, with some observations on the Orkney and Shetland Islands," Quart. Journ. Geol. Soc. vol. xv. p. 353.

"Some Results of Recent Researches among the Older Rocks of the Highlands of Scotland," Brit. Assoc. Rep. for 1858, p. 94.

"Supplemental Observations on the Order of the Ancient Rocks of the North of Scotland and their associated Eruptive Rocks," Quart. Journ. Geol. Soc. vol. xvi. p. 215.

"On the Altered Rocks of the Western Islands of Scotland and the North-western and Central Highlands." By R. I. Murchison and A. Geikie. Quart. Journ. Geol. Soc. vol. xvii. p. 171.

† Quart. Journ. Geol. Soc. vol. xxxiv. p. 811.

On the Pre-Cambrian Rocks of West and Central Ross-shire," with Petrological Notes by T. Davies. Geol. Mag. dec. 2, vol. vii. pp. 103, 155, 222, 266.

"On some Recent Researches among the Pre-Cambrian Rocks of the British Isles," Proc. Geol. Assoc. vol. vii. p. 59.

"On the Metamorphic and Overlying Rocks in parts of Ross- and Inverness-shires," Quart. Journ. Geol. Soc. vol. xxxix. p. 141.

problem was made by Professor Bonney, who described the so-called "intrusive syenite" of Glen Logan, pointing out the occurrence of foliation in the rock and the N.W. strike; from which he inferred that all the "syenite," with the exception of a few dykes, is simply a rather granitoid variety of the Hebridean gneiss. He showed that its junction with the calcareous series is a faulted one and indicated the direction of the fault. He called attention to a marked fragmental structure in a green schist occurring in the mass, which he attributed to crushing *in situ* *.

Similar views to those of Professor Bonney regarding the "Logan Rock" were advanced by Mr. Hudleston, in 1882, who described it as the local representative in the Ben-More-Assynt range of the fundamental gneiss, and "as the framework or core round which the newer rocks are folded." He disputed the existence of the "Upper Quartzite," but considered that the section at Craig-a-Knockan shows a regular ascending series from the Silurian rocks to the upper gneiss †.

The various papers contributed by Dr. Callaway, embracing his researches in the districts of Loch Broom, Assynt, and Loch Eriboll, still further weakened the belief in Murchison's order of succession. Regarding those areas he maintained that there is no conformable sequence from the quartzites and limestones to the eastern gneiss, that the "Upper Quartzite" is merely a repetition of the lower quartzite, and that the "Upper Limestone" is either a repetition of the dolomite of the "Assynt Series" ‡ or an integral part of the Archæan series, as at Loch Ailsh. Recognizing the lithological distinction between the western and eastern gneisses, he grouped them in two great formations of Pre-Cambrian age—(*a*) the Hebridean, (*b*) the Caledonian, the latter resting unconformably on the former. Though the eastern gneiss (Caledonian) overlies the Silurian strata at certain localities, he contended that it had been brought into this position by overfolding and faulting without materially altering its original structures. In the district round Loch Broom, and in Assynt, the "Logan Rock" (Heddle) is regarded as part of the Hebridean gneiss brought up by faults, showing signs of crushing at the points of junction with other strata; at Loch Eriboll it is regarded as the base of the Caledonian gneiss. At Loch Broom the Hebridean gneiss, by means of faulting, is brought into contact with almost every member of the Silurian series in turn, and slightly overlies them; while in Assynt, where it is sometimes accompanied by the Torridon Sandstone, this gneiss is thrown over on to the Silurian series, "the overthrow increasing in breadth northwards, so that in Glencoul it is more than a mile wide."

In the appendix to Dr. Callaway's paper (Quart. Journ. Geol. Soc. vol. xxxix. p. 416) Professor Bonney describes the microscopic

* "Petrological Notes on the Vicinity of the Upper Part of Loch Maree," Quart. Journ. Geol. Soc. vol. xxxvi. p. 93.

† "First Impressions of Assynt," Geol. Mag. dec. 2, vol. ix. p. 390.

‡ Dr. Callaway applied the term "Assynt Series" to the Quartzites, Fucoid beds, Salterella-grit, and Limestone of Murchison's Silurian succession.

characters of some of the thrust Hebridean gneisses in Assynt and at Ullapool which show indications of crushing and recementation. In some instances these features have so obscured the original structure that it is difficult to determine the true characters of the rocks.

Subsequently Dr. Callaway referred to certain localities where the members of the Silurian series become more highly altered towards the junction with the Archæan gneiss, when the latter, by folding or thrust, has been made to overlie the former. He maintained that there is no material alteration in the Silurian series underlying the Hebridean gneiss in Glencoul, because there is no evidence of extraordinary pressure; but near the base of the Stack of Glencoul, at the junction with the eastern gneiss (Caledonian), the quartzite loses all traces of clastic structure and passes into quartz-schist. He accounts for this progressive alteration by enormous pressure due to the quartzite being "reflexed again and again in closely adpressed folds"*.

The investigations of Professor Lapworth demand special notice, because they involve a departure from Professor Nicol's views regarding the nature and origin of the eastern schists of Sutherland. Selecting the region of Durness and Eriboll, he mapped a large portion of it in great detail during the summers of 1882 and 1883. In the pages of the 'Geological Magazine' he published a series of papers on "The Secret of the Highlands"†, in which he described the geological structure of that region, completely confirming Nicol's conclusions (*a*) that the Durness Limestone is the highest member of the "Ordovician" series (Lower Silurian, Murchison), (*b*) that the "Upper Quartzite" and "Upper Limestone" are non-existent, (*c*) that there is no conformable sequence from the quartzites and limestones into the eastern gneissic series, (*d*) that the line of junction of the unaltered Palæozoic rocks is a line of fault and overthrust. But the results of his work, in so far as they affect the age, composition, and mode of formation of the eastern schists, were read at a meeting of the Geologists' Association, July 4th, 1884‡. As these results are practically identical with those obtained independently by the Geological Survey, and published in the official Report ('Nature,' vol. xxxi. p. 39), it is desirable to give a brief summary of them:—

1. The lithological distinctions between the Hebridean gneiss and the Logan and Arnaboll rocks are primarily due to the mechanical disturbances to which the latter have been subjected.

* "The Limestones of Durness and Assynt," Quart. Journ. Geol. Soc. vol. xxxvii. p. 239.

"The Torridon Sandstone in Relation to the Ordovician Rocks in the Northern Highlands," Quart. Journ. Geol. Soc. vol. xxxviii. p. 114.

"The Age of the Newer Gneissic Rocks of the Northern Highlands," Quart. Journ. Geol. Soc. vol. xxxix. p. 355.

"Notes on Progressive Metamorphism," Geol. Mag. dec. 3, vol. i. no. 5, p. 218.

† Geol. Mag. dec. 2, vol. x. pp. 120, 193, 337.

‡ Proc. Geol. Assoc. vol. viii. p. 438; see also Geol. Mag. dec. 3, vol. ii. p. 97 (1885).

2. The planes of schistosity in the eastern metamorphic schists are not planes of bedding, but planes of shearing and cleavage, along which the rocks have yielded to the lateral crust-pressure.

3. By the action of this lateral earth-thrust, the Archæan, the Plutonic, and included patches of sedimentary rocks have been locally sheared and flattened out into rocks resembling hälleflintas, rhyolites, and finely laminated shales.

4. The eastern metamorphic series of Sutherland and Ross not only contains Archæan rocks, but also local patches of metamorphosed Palæozoic, intrusive, and segregatory rocks, together with local patches of material, probably compounded of all these in different degrees.

5. The eastern metamorphic series has received its present strike, pseudo-bedding, and its present foliated and mineralogical characteristics through the agency of the crust-movements which have operated within the district since Lower Silurian times.

The stratigraphy of the West Highlands, he maintained, is of the same character as that described by Heim, in his work on the Alps of Central Switzerland; while the metamorphic phenomena are identical with those detailed by Lehmann, in his publications on the metamorphic rocks of the Saxon Erzgebirge.

In 1885 * a valuable paper was published by Mr. Teall "On the Metamorphosis of Dolerite into Hornblende-schist," as displayed by two more or less parallel dykes in the Archæan gneiss, near the village of Scourie, in Sutherlandshire. From a careful examination of the phenomena presented by the dykes in the field and by microscopic sections of the rocks, he concluded (1) that the hornblende-schist has been developed from a dolerite by causes operating after the consolidation of the dolerite, and that the metamorphosis has been accompanied by a molecular rearrangement of the augite and felspar; (2) that the molecular rearrangement has in certain cases taken place without the development of foliation; (3) that the plasticity which has led to the development of foliation is that due to high pressures at ordinary temperatures. These deductions are of far-reaching importance in interpreting many of the phenomena of the Archæan rocks.

The Geological Survey began the detailed mapping of the North-west Highlands in 1883, by tracing out the structure of the limestone district of Durness and Eriboll in the north of Sutherland. Since that time the work has made considerable progress, chiefly along the belt of extraordinarily complicated ground from Eriboll southwards through Assynt to Dundonald—a distance of fifty-five miles. To the west of that belt the tract between Cape Wrath and Lochinver, mainly occupied by Archæan rocks, has been surveyed. To the east, large districts of the eastern or newer schists between Tongue and Loch Broom have also been examined in detail. A large mass of evidence bearing on the nature and extent of the ancient terrestrial movements in the North-west Highlands, and throwing much light on the origin of the schistose structure in

* Quart. Journ. Geol. Soc. vol. xli. p. 133.

Archæan rocks and regional metamorphism in general, has been gathered together. The chief parts of this evidence are now laid before the Society.

The field-work of the Geological Survey in the region has been executed by Messrs. Peach, Horne, Gunn, Clough, Hinxman, and Cadell, under the immediate supervision of Mr. Peach. Mr. Cadell mapped that portion of the line of complicated structure extending from the head of Loch Eriboll to Loch More; Mr. Clough, from Loch More to the northern base of Glasven; Messrs. Peach and Horne, from Glasven to Elphin and the Cromalt Hills; Mr. Hinxman, from Elphin to Strath Kanaird; and Mr. Gunn, from the latter point to Little Loch Broom.

I. Archæan Rocks.

The detailed examination of the Archæan rocks lying between Loch Laxford and Lochinver has led to the conclusion that they have been subjected to enormous mechanical movements in Pre-Cambrian time. In attempting to unravel the history of these ancient rocks, it is best to follow the chronological order of the movements, as it enables us to interpret the successive modifications which the crystalline rocks have undergone.

1. *Original Types of Gneiss.*

1. Throughout the region referred to there are certain tracts where foliated rocks occur, evidently representing the original types of Archæan gneiss. From Lochinver south to the river Kirkaig and northwards along the coast to Loch Rooe, and again near Kylesku by the shores of Loch A'Chairn Bhain, these typical gneisses are admirably displayed. They are arranged in gentle anticlines and synclines, the axes of which usually run N.N.E. and S.S.W. or N.E. and S.W. Occasionally the angle of dip of the foliation is so low that the outcrop of the bands forms a series of parallel escarpments along the hill-slopes (Kylesku). Structurally they occur either as massive, rudely foliated crystalline rocks, with few divisional planes, or as well-banded gneisses in which the constituents have a distinct parallel arrangement. Both varieties are traversed by segregation-veins and pegmatites. The prominent minerals are plagioclase felspar, pyroxene (augite, diallage), hornblende, quartz (frequently opalescent), and magnetite. It is worthy of note that mica is a rare constituent of these original types of gneiss. On close examination it is apparent that the bands present certain lithological varieties of variable thickness; some consisting mainly of pyroxene or hornblende and a small quantity of plagioclase felspar; some of plagioclase, pyroxene, or hornblende and opalescent quartz; others of opalescent quartz and felspar. These varieties frequently cross the lines of schistosity and are evidently due to differences in the nature of the materials prior to the development of the foliation *.

* The term gneiss, as applied to these rocks, may be regarded as a misnomer, but for the sake of convenience we in the meanwhile use the generally accepted name.

2. *Unfoliated Igneous Rocks in original Gneisses.*

A remarkable feature of these original gneisses is the occurrence among them of numerous masses of highly basic igneous rocks (gabbros, peridotites, palæo-picrites, pyroxene-granulites, and diorites), either possessing no foliation, or foliation of such an imperfect type that it is impossible to tell its angle of inclination. They occur as lenticular zones or belts running for several hundred yards more or less parallel with the foliation, or as irregular patches covering about a quarter of a square mile of ground. Many of the dark bands of gabbro or diorite are highly garnetiferous (pyroxene-granulite), the garnets having no special arrangement except in those cases where they have been affected by later Pre-Cambrian movements.

These patches of non-foliated igneous rock are intersected by veins of grey pegmatite varying in thickness from a few inches to several yards, consisting mainly of felspar and quartz usually opalescent. Occasionally a small quantity of pyroxene or hornblende is associated with the quartz and felspar. In some instances the pegmatites are so prominently developed that they form a large proportion of the mass, and in such cases it frequently happens that "eyes" or bosses of the basic rock have been isolated from the parent sheet. Where the basic rocks are non-foliated, the pegmatites have no regular arrangement; where, on the other hand, incipient foliation is displayed in the former, the latter are drawn out parallel with the direction of movement.

In tracing the boundaries of many of these non-foliated masses and their pegmatites, it is observable that the dark eruptive rocks pass gradually into the rudely foliated basic gneisses; while the pegmatites merge into the grey highly quartzose bands, consisting mainly of opalescent quartz and felspar. The conclusion is, therefore, obvious *that the original types of gneiss in the west of Sutherland have been formed out of eruptive basic rocks and the pegmatites developed in them prior to the foliation.* It is equally apparent also that the relative proportion of pegmatite and other segregation-veins to basic rock in the non-foliated areas should generally correspond with the proportion of grey highly quartzose gneiss to the more basic varieties.

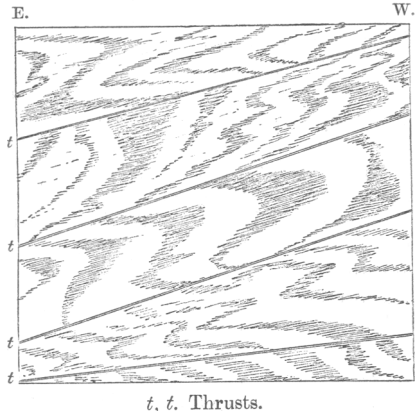
3. *Evidence of mechanical Movements in the Formation of the original Gneisses.*

A careful study of the coast-sections at Lochinver and Kylesku reveals the fact that these original gneisses possess certain structures analogous to those met with in the quartz-schists overlying the fossiliferous limestones and quartzites produced by the Post-Lower-Silurian movements. The planes of schistosity traverse the various basic rocks and pegmatites, irrespective of the boundaries of the original materials. Such a result could not have been produced if the foliation had been due to the deformation of a mass of half consolidated Plutonic rock at the time of the intrusion. The

foliation must have been developed after the consolidation of the igneous rocks and after the segregation of the pegmatites and other veins.

Of equal moment is the evidence supplied by the existence of thrust-planes, oblique foliation, and overfolding in these original gneisses. When the thrust-planes are traced along the face of a cliff, it is observable that they truncate folia lying at an oblique angle to them, thus producing a phenomenon resembling current-bedding. On the surfaces of these movement-planes there is no trace of brecciation, the line being sharply defined after the manner of the Post-Lower-Silurian thrusts in the Moine schists. The oblique foliation viewed in connexion with the prevalent overfolding indicates a gradual movement and piling up of the materials as the Plutonic rocks underwent enormous pressure. Further, it is possible to detect on the foliation-surfaces subparallel lines in-

Fig. 1.—*Section of original Archæan Gneiss, showing Thrust-planes, oblique Foliation, and Overfolding.*



t, *t*. Thrusts.

The figure represents an area of several hundred square yards, the plane being vertical, and the observer facing the south.

dicating the direction of the movement of the particles over each other. The latter, however, are by no means so common in the original gneisses as in those which have been affected by the later Pre-Cambrian movements to be described presently. From these data it would appear that even the first or original foliation of the Plutonic rocks was produced by mechanical movement.

4. *Igneous Rocks injected into the Archæan Gneiss after the first Foliation and prior to the later Pre-Cambrian Movements.*

After the development of the first foliation, the original gneisses were pierced by a remarkable series of igneous intrusions,

mainly in the form of dykes, which may be grouped in the following order:—

a. Basalt-rocks, comprising dolerites, basalts.
b. Peridotites and palæo-picrites.
c. Microcline-mica rocks.
d. Granites.

(*a*) One of the most striking features of the Archæan rocks in the west of Sutherland is the extraordinary series of basic dykes, composed mainly of members of the first group (Basalt-rocks), throughout the tract extending from Lochinver to Loch Laxford. Between Lochinver and Kylesku their general travel is W.N.W. and E.S.E; between Kylesku and Loch Laxford the direction is more northerly, and in some instances it is nearly E. and W. Frequently they occur in groups, upwards of fifteen dykes being met with in the course of a mile. So persistent are they, that many of them have been traced for a distance of ten or twelve miles from the west coast of Sutherland, across the Archæan area, till they are buried underneath the Cambrian sandstones and Silurian quartzites. Sometimes they send forth branches or veins, which maintain separate courses for a considerable distance, and ultimately re-unite with the parent dykes. Sometimes basalt-veins traverse dykes of dolerite, the peculiar lithological characters of each being preserved at the points of intersection. In all cases they possess the various zones characteristic of these igneous intrusions: the outer parts are more fine-grained than the centre and along the edges patches of tachylyte are occasionally met with. Only a very few of the dykes preserve the original prisms running at right angles to the walls; but their absence is satisfactorily accounted for by the extraordinary amount of deformation which they have undergone owing to the later Pre-Cambrian movements. Attention will be directed presently to the evidence in proof of the metamorphosis of many of these dolerites into diorites and hornblende-schists resulting from these later movements. But notwithstanding these facts, it must be admitted that many of the phenomena presented by this grand series of Archæan dolerite-dykes are but the counterpart of what may be seen in the splendid development of basalt-dykes of Tertiary age connected with the volcanic plateaux of the Inner Hebrides.

(*b*) The trend of the peridotite- and palæopicrite-dykes, which are best displayed in the Canisp deer-forest and westwards by Brackloch, Torbreck, and Riecairn near Lochinver, is more nearly E. and W. than that of the dolerites. As they traverse the various dolerite-dykes in their path, there can be no doubt that they were erupted after the basalt-rocks; and the evidence is also conclusive that their date of intrusion was prior to the later Pre-Cambrian movements. Weathering into a dark brown earth, they usually form long narrow clefts or hollows, thus giving rise to conspicuous features in the scenery of the Archæan area.

(*c*) On the south side of Loch Glendhu, a dyke consisting mainly of felspar and mica appears in the coast-section trending N.E. and

S.W. Under the microscope it is found to contain microcline, black mica, calcite, and garnet. It deserves special notice because it is believed to represent the unfoliated form of certain thin veins of mica-schist in the Archæan gneiss, to be afterwards referred to.

(*d*) Equally interesting are the intrusive dykes and sheets of granite (or syenite), containing quartz, felspar, mica, and frequently hornblende, traceable from Loch Stack westwards to Loch Laxford. Their general trend is W.N.W. and E.S.E., and they often coalesce, occasionally forming belts upwards of 500 yards across. Along their lines of outcrop they give rise to conspicuous "slacks" or hollows. From the evidence already obtained in the field, there can be little doubt that they were intruded into the older gneisses after the eruption of the dolerite-dykes; but whether the injection was prior to the foliation of the dolerite-dykes is not quite so certain.

5. *Later Pre-Cambrian Movements and their Direction.*

We have now reached an important stage in the history of the Archæan rocks in the west of Sutherland; for after the eruption of these various igneous materials the whole area was subjected to enormous mechanical movements, which exercised a powerful influence both on the dykes and on the crystalline rocks which the dykes traverse.

These lines of movement run in certain definite directions and may be described as thrust-planes, crush-lines, or lines of shearing, resulting in a newer foliation. They may be grouped in three systems:—(1) those running more or less parallel with the dykes of basalt-rock, viz. W.N.W. and E.S.E. or N.W. and S.E.; (2) those trending nearly E. and W. at an oblique angle to the basic dykes; and (3) those running N.E. and S.W. or N. and S. Of these systems the first and second are by far the most important. For the sake of convenience of description it will be desirable to indicate the effects of these movements first on the dykes, and secondly on the gneiss.

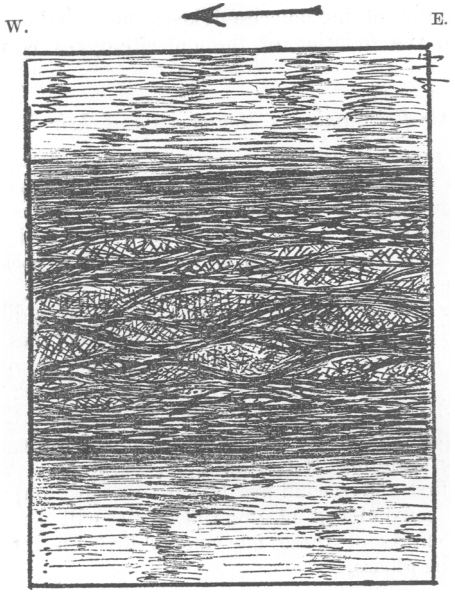
6. *Effects of these Movements on the intrusive Dykes.*

When the lines of movement are more or less parallel with the direction of the basic dykes, the dolerites gradually merge into diorites without the development of foliation. Under the influence of enormous pressure the dolerites have undergone complete molecular reconstruction; the felspars become opaque white and the augite is replaced by hornblende, recognizable in the field by its cleavage-angle. Indeed, this molecular change has been so extensively developed in these basic dykes that much of the existing rock deserves the name of diorite. But this type of metamorphosis is only a stage in the conversion of the rock into hornblende-schist.

When lines of movement coincide with the margins of one of the dolerite-dykes, it usually happens that portions of the outer parts—it may be a few inches or a few feet—are converted into hornblende-

schist. So characteristic is this feature that few of the dykes do not display the marginal strips of schist. A further stage of change is met with when a broad dyke is traversed by several lines of shearing, in which case lenticular or eye-shaped masses of diorite are formed, round which curve in wavy lines beautiful bands of hornblende-schist (Canisp deer-forest).

Fig. 2.—*Diagram Sketch, showing Formation of 'Eyes' of Diorite in Hornblende-schist, from shearing of Dolerite-dyke intrusive in Gneiss.*



The gneiss has been modified by a secondary foliation parallel to the walls of the dyke.
The arrow indicates the direction of movement.
Area represented, about 600 square yards.

Finally the 'eyes' of diorite disappear, and the whole of the original dyke is converted into a zone of hornblende-schist. This extreme alteration is almost invariably accompanied by a complete reconstruction of the surrounding gneiss to be described presently. The bands of hornblende-schist consist mainly of secondary felspar and hornblende with a small quantity of mica, and can be split into thin laminæ from a quarter to half an inch thick, the direction of foliation being parallel with the lines of movement, viz. W.N.W. or N.W. An examination of the foliation-surfaces shows that the

parallel lines or "striping" indicating the direction of movement are usually inclined at angles varying from 15° to 25° to the horizon. It is also observable that the north wall of the dyke has in most cases advanced further to the west than the south wall.

An important feature connected with the metamorphosis of the diorite into hornblende-schist is the occurrence of segregations of vitreous quartz, varying in width from a few inches to several yards. When best developed the direction of the segregation-veins usually coincides with that of the foliation of the schist.

In the neighbourhood of Loch Glencoul thin veins of mica-schist traverse the gneiss, which are believed to represent in a foliated form the dykes of microcline-mica rock near Loch Glendhu.

The result of these movements trending N.W. on the dykes of peridotite and palæopicrite has been to convert them, either wholly or in part, into soft talcose schists which can be easily cut with a penknife, the direction of the foliation being determined by the lines of shearing.

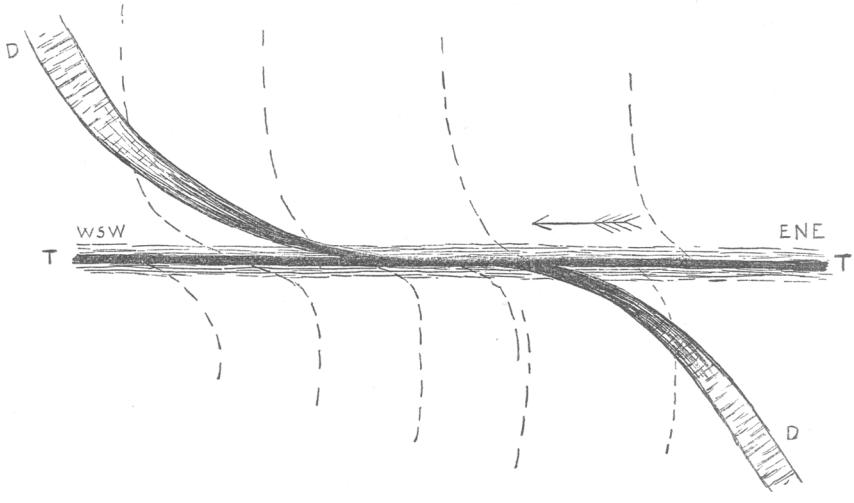
The veins and belts of granite have been changed by the same series of movements into granitoid gneiss, the general trend of the foliation running W.N.W. Of special interest is the appearance of massive pegmatites in connexion with these intrusions. From their mineralogical character there can be no doubt that the constituents have been mainly, if not wholly, derived from the granite. They may occur in the heart of the bands of granitoid gneiss, or the former may run parallel with the latter for long distances, and in some cases portions of the dykes have been completely isolated by the pegmatites. Occasionally the latter have been sheared with the granitic dykes in which they occur, but in such instances the shearing of the pegmatites was subsequent to the first foliation of the granitic intrusions; for there is clear evidence to show that the latter were subjected to a second series of movements, resulting in a modification of the first foliation. Some of the quartz-veins in the hornblende-schists have been similarly affected by this later series of movements.

The lines of movement trending E. and W. are either vertical or nearly so. When one of these typical thrusts crosses the path of a dolerite-dyke running W.N.W. or N.W., the dyke is gradually deflected from its normal course till it coincides with the line of thrust. On leaving it, the dyke resumes its natural trend. In some of the more striking examples the dykes are wrenched out of their normal course for nearly a mile (N. of E. of Ben Strome).

Where the gradual deflection takes place, the diorite begins to lose its granular character and eventually passes into a black, compact, flinty rock in the line of crush; or the dyke is completely recrystallized and converted into a fine hornblende-schist. These changes are accompanied by a remarkable attenuation of the basic intrusions, for in some cases dykes measuring 50 or 60 yards across shrink into bands 4 feet wide in the crush-lines. They are not reduced to the same uniform width, however, as they frequently form eye-shaped masses, completely isolated from each other and

enveloped in crushed or reconstructed gneiss. In most cases the northern portion of the dyke has been moved further towards the west than the southern portion.

Fig. 3.—*Ground-plan, showing Deflection and Disruption of Dykes by vertical Thrust-planes.*



T. Thrust-plane.
D. Dyke, becoming attenuated and deflected and increasingly schistose as it approaches the plane, and being reduced to a "crush-rock" in immediate vicinity of the thrust. Displacement about ¼ mile.
Dotted lines indicate the strike of the gneiss, the planes being deflected as they approach the thrust.
The arrow shows direction of movement.
The parallel lines indicate the newer schistosity produced in the gneiss within the influence of the thrust.

When the hornblende-schist is extremely fine-grained there is a considerable development of black mica along the divisional planes, the direction of the foliation being more or less parallel with that of the thrust-planes; but variations commonly occur as the folia curve round the patches of diorite or granular igneous rock. When the orientation of the minerals in the hornblende-schist is examined, it is found to point towards the west; and when this fact is viewed in connexion with the deflection of the dykes, it is clear that, with one or two exceptions, there must have been a powerful movement towards the west, on the *north* side of these thrust-planes.

Similar schistosity is produced by the third system of disruption-lines, running N.E. and S.W., the direction of the foliation in this case also being determined by the trend of the lines of shearing.

An interesting example occurs on the hills to the east of Stoer, where a dolerite-dyke trending N.W. is traversed by a thrust-plane nearly at right angles to its course. Wrenched out of its path for some distance in accordance with the line of shearing, the dyke has been completely recrystallized and converted into hornblende-schist, which is not continuous. Along the path of the newer shearing the dyke is represented by lenticular strips of schist, the dip of the foliation being the same as that of the adjacent gneiss, which at this point has also undergone reconstruction owing to the same movement.

In all the cases above described belonging to these three systems of disruption-lines, the divisional planes developed in the hornblende-schist are either vertical or highly inclined. But we have yet to call attention to the presence of nearly horizontal foliation in these basic dykes.

In the neighbourhood of Stoer various dolerite-dykes, trending N.W. and occurring in the heart of gently inclined gneiss, are traversed by divisional planes crossing them at low angles and curving downwards towards the edges. The adjacent gneiss, though nearly flat or lying at low angles, has also been reconstructed. In such cases the dykes lose many of their characteristic features; they no longer present their wall-like form, but weather with much the same contour as the gneiss.

These horizontal movements, resulting in gently inclined thrust-planes and the development of horizontal schistosity, are not uncommon throughout the Archæan area. But there can be no doubt that they have an intimate relation with the vertical disruption-lines, for it sometimes happens that the one merges into the other. A remarkable example of this phenomenon is met with about a mile to the N.N.W. of Kylestrome. The general direction of the thrust-plane is W. 47° S., the hade being sometimes nearly flat, sometimes forming an angle of 30° with the horizon; while on the north side of the dolerite-dyke which it traverses the thrust-plane is inclined at a high angle. This instance is of special importance, because it illustrates those sharp curves so common in the far later disruption-lines which traverse the Silurian limestones and quartzites; nay, further, it shows how the same phenomena were repeated after long cycles of time in the production of the eastern schists.

7. *Effects of these Movements on the Gneiss.*

We now come to consider the effects of these various systems of movement on the original Archæan gneiss.

a. On approaching one of these vertical lines of movement the original gneiss suddenly loses its low angle, becomes highly inclined, and dips either towards or away from the disruption-line. Still more frequently the gneiss is thrown into a series of sharp folds forming a belt of contorted strata close to the lines of shearing. No matter what may have been the strike of the original gneisses, the axes of the folds are always more or less parallel with the

powerful disruption-lines. In the case of the first system of movements, the strike of the gneiss in these contorted belts is W.N.W. or N.W.; in the second system the strike is nearly E. and W.

b. Coincident with this folding and high inclination of the gneiss there is a modification of the constituent bands; the folia are attenuated, and there is a partial reconstruction of the rock. In some cases this reconstruction has been so complete that the orientation of the minerals in the gneiss coincides with that of the minerals in the hornblende-schist in the basic dykes. Where this happens, the movements have given rise to a second foliation of the original types of gneiss.

c. The constituents of the different laminæ have undergone a mineralogical change, the original opalescent quartz-granules, besides being elongated, lose much of their opalescent character and become clear and vitreous; black mica has been abundantly developed out of the original hornblende, and a white hydrous mica out of the original felspar; the hornblende has recrystallized in the form of needle-shaped crystals of hornblende or actinolite; and, lastly, there is a plentiful development of secondary felspar.

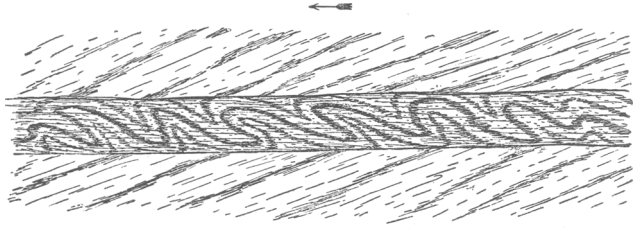
d. The high inclination and folding of the gneiss is usually accompanied by crush-lines, forming sometimes coarse breccias full of irregular fragments, sometimes very thin schistose bands several inches in breadth or even less, the foliation being parallel with the sides. Indeed, along the crests of many of these sharp folds new shear-planes occur, indicating complete disruption.

One of the best examples of the second foliation developed in the original gneisses by these vertical lines of movement occurs in the neighbourhood of Lochinver. It forms a belt from a quarter to half a mile in width, running W.N.W. through the Canisp deer-forest by Torbreck to Loch Rooe and Achmelvich. The strata consist of fine-grained gneiss and schist striking W.N.W., and inclined at high angles to the S.S.E. Indeed, as a general rule, this second foliation, wherever it occurs throughout the area *in connexion with the N.W. vertical movements*, dips at high angles in a south-easterly direction. Excellent examples of narrow zones of newer foliation trending E. and W. are displayed to the north of Kylesku.

In the case of the flat thrust-planes near Kylestrome, the disruptions in the gneiss are prominently marked, being sometimes filled with a layer of soft, rusty micaceous matter, on either side of which the folia of gneiss are inclined at different angles to the thrust. Occasionally there are repeated overfolds of a thin band in the micaceous layer, though the adjacent gneiss shows no trace of similar contortions.

In all the cases observed near Kylestrome the crests of the overfolds point S.W. or S.S.W., so that it would appear that the upper layers had moved over the lower ones in this direction. These layers of micaceous material may reach a few feet in thickness, and the plates of mica may be repeatedly folded by renewed movement along the line. The micaceous matter found in these flat thrust-

Fig. 4.—*Overfolding of Micaceous Layers along Thrust-planes in Archæan Gneiss.*



The arrow indicates direction of movement.

planes is usually of a yellow colour, probably from the weathering of specks of iron-pyrites. The bands of partially reconstructed gneiss sometimes possess the same tint, in particular those trending from Loch na Seilge to the sea-coast near Tarbat (Loch Laxford), which contain a large quantity of mica. The folia of the more micaceous layers in these bands are most frequently arranged at an oblique angle to the planes of schistosity, which seems to indicate that the higher bands of gneiss had moved over the lower ones in a westerly direction. A similar arrangement is met with near Loch na Claise Fearn, where the more quartzose layers of gneiss have been piled over each other; but in this case the laminæ are further apart. These phenomena closely resemble the heaping up of the bands of the eastern schists (Moine), to be referred to on a subsequent page.

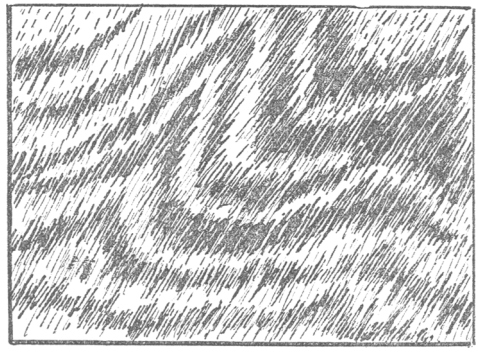
Another important structure resulting from these mechanical movements is the development of incipient newer foliation at an oblique angle to the older one, and rudely parallel with the adjacent lines of movement. This newer schistosity occurs in various stages of development, sometimes so indistinct that it is hardly observable except when the rock-surface is carefully examined, sometimes so well marked that it is quite as conspicuous as the older one; while, again, it may be carried a stage further, when the old foliation is wholly destroyed. The effect of the attempt to establish a newer foliation is to rearrange the constituents of the bands along new planes more or less inclined to the old ones.

Black mica invariably accompanies this structure, and it occurs in greater or less quantity according to the stage of development of the second foliation. When the original folia form an alternation of light- and dark-coloured layers, it is observable that the oblique schistosity is most conspicuous in the dark bands; indeed, in some cases the lighter quartzose parts seem hardly affected at all, even where the adjoining layers, both above and below, show a marked second foliation.

This double foliation is frequently accompanied by intense crumpling and rapid contortions of the bands of gneiss, representing

the effects of mechanical movements, which, along the same line of strike, merge into a disruption-line. Hence it follows that a zone or belt of gneiss with newer foliation trending W.N.W. may cease or disappear, and be replaced along the same line of strike by contorted gneiss with both the first and second lines of schistosity. (Canisp deer-forest, hills east of Scourie.)

Fig. 5.—*Diagram showing Double Foliation in Archæan Gneiss.* (About nat. size.)



This contortion and double foliation of the gneiss are characteristic of the area between Ben Auskaird and Loch Laxford, the general strike of the imperfect second foliation being from 8° to 20° S. of E. and N. of W.

A careful examination of the region near Claisfearn, north of Scourie, points to the conclusion that *the folding and contortion of the original gneiss were subsequent* to the injection of the basic dykes already described. It seems also pretty clear that the reconstruction of the gneiss in that region has taken place more or less along the old foliation-planes. Where this reconstruction has been carried so far as to involve the complete recrystallization of the original ingredients, then the gneiss may be regarded as practically a new rock. Just as the Silurian quartzites have been crystallized and converted into quartz-schists, frequently along the old bedding-planes, by movements later than Lower Silurian time, even so has the original Archæan gneiss undergone reconstruction along the old planes of schistosity.

From the evidence now adduced it is apparent that, owing to the effects of the various systems of movements here described, the Archæan gneiss possessing the first foliation has undergone considerable modification over extensive areas in the west of Sutherland. Its gentle arches and troughs, striking N.E. and S.W., have given place to sharp folds trending N.W., W.N.W., or E. and W., in harmony with the two great systems of disruption-lines. In places

the old foliation has been completely destroyed and we find belts of newer foliation trending W. or N.W., or, it may be, a combination of the old and the new schistosities, accompanied by violent contortion. Or, again, the original gneiss has undergone partial or complete reconstruction along the old foliation-planes, whether they happen to be inclined at high or low angles. Hence it is only within limited areas that we can study the characters of the original gneisses. We believe, and the evidence in the field warrants the belief, that the highly basic, pyroxenic, and hornblendic gneisses at one time extended over the whole area, and that the lithological varieties now met with, so different from the older set, have been produced by the deformation of the original gneisses *.

8. *Evidence proving the Pre-Cambrian Age of these Movements.*

There is an overwhelming amount of evidence to prove that these various mechanical movements, which have so powerfully affected the basic dykes and the Archæan gneiss, took place prior to the deposition of the Cambrian (Torridon) sandstones. The various disruption-planes and the belts of secondary foliation can be traced from the sea-coast, across the Archæan area, till they are buried underneath the pile of Cambrian sandstones and Silurian quartzites. Neither the red sandstones nor the quartzites along the western escarpment show the slightest trace of having been affected by these movements. The disruption-lines, like the basic dykes, disappear at the base of the great cliff of Palæozoic sedimentary deposits. We are therefore forced to conclude that these movements have no connexion with the gigantic Post-Lower-Silurian displacements, and that the rocks had assumed their present characters in Pre-Cambrian time.

The Archæan area is still further complicated by a double system of normal faults, one set trending N.W. and S.E., and the other set N.E. and S.W. Most of these are probably later than the Post-Lower-Silurian movements.

Among the Archæan rocks certain dykes are met with which are all probably later than the deposition of the Cambrian and Silurian strata of Sutherland. These include some of mica-diabase occurring in the Archæan gneiss and Cambrian strata, and the porphyritic quartz-felsites of the same age as the Canisp "porphyry" to be referred to presently, and probably certain dykes of olivine-diabase.

9. *Summary of the foregoing Researches in the Archæan Rocks.*

The series of phenomena revealed by these researches in the Archæan rocks in the north-west of Sutherland may be tabulated as follows:—

(1) The eruption of a great series of igneous rocks of a more or

* From the evidence adduced in the foregoing pages regarding the effects of the *later* Pre-Cambrian movements, it is obvious that they are merely the differential results of an enormous thrust of these Archæan rocks, generally from the E.N.E. towards the W.S.W.

less basic type (gabbros, peridotites, palæopicrites, quartz-diorites, &c.), in which pegmatites and segregation-veins were formed.

(2) The development of foliation in these eruptive rocks and pegmatites by mechanical movement, and their conversion into "gneisses," the axes of the folds running generally N.E. and S.W.

(3) The intrusion of a great series of igneous rocks, mainly in the form of dykes, in the gneisses, consisting of (*a*) basalt-rocks, (*b*) peridotites and palæopicrites, (*c*) microcline-mica rocks, (*d*) granites, &c.

(4) The subjection of the original gneisses to enormous mechanical movements, giving rise to disruption-lines or thrust-planes trending, (*a*) N.W. and S.E., or W.N.W. and E.S.E., (*b*) E. and W., (*c*) N.E. and S.W.

(5) The alteration of the dykes consequent upon these movements :—(*a*) the dolerites being changed into diorites and hornblende-schists, (*b*) the peridotites into talcose schists, (*c*) the microcline-mica rocks into mica-schists, (*d*) the granites into granitoid gneiss. Pegmatites were also formed in the hornblende-schists and granitoid gneiss.

The plication of the gneiss in sharp folds trending E. and W. or N.W. and S.E., the development of secondary foliation running generally N.W. and S.E., or W.N.W. and E.S.E., or E. and W., and the partial or complete reconstruction of the gneiss along the old planes of schistosity.

6. The foliation of the granitoid gneiss and associated pegmatites by a still later series of movements.

II. Cambrian Formation. (Torridon Sandstone.)

1. *Denudation of the Pre-Cambrian Land-surface.*

Between the formation of the Archæan rocks in the west of Sutherland and the deposition of the overlying Cambrian conglomerates and sandstones an enormous interval of time must have elapsed, during which the primeval land-surface was subjected to extensive denudation. In order to form an accurate idea of the outline of this ancient land, the observations must be confined to the area bordering the line of junction between the gneiss and the sedimentary deposits. It would obviously be unsafe to accept the present contour as any indication of the primeval one, in tracts where the Archæan rocks have been stripped of the red sandstones and quartzites, and exposed for long ages to denudation. Indeed, there is clear evidence for maintaining that where such has been the case the agents of waste have been to a large extent guided in their operations by the trend of the basic dykes, the various Pre-Cambrian disruption-lines, and the great series of normal faults that followed the terrestrial displacements of Post-Lower-Silurian date. From the evidence obtained in the district of the Parph, west of the Kyle of Durness, it is apparent that the old land-surface must have been worn down to a comparatively level plane ; while in Assynt it must have been carved into a series of dome-shaped eminences, sometimes

reaching a considerable elevation. In one case, a Pre-Cambrian hill, *about* 700 *feet high*, projects through the lower, and is overlapped by the higher members of the Red-Sandstone series on the north-west slope of Quinaig. Similar evidence, though not so remarkable, is obtained round the margin of the outlier at Stoer north of Lochinver, on the shores of Cama Loch near Elphin, and to the south of Loch Broom.

2. *Order of Succession in the Parph District.*

The general ascending order of succession in the Parph district is as follows:—

Total maximum thickness 1800 feet.

4. Fine-grained, friable, yellow and mottled sandstones and marls.
3. Alternations of coarse sandstones, grits, and beds of conglomerate.
2. Conglomerate, containing well-rounded pebbles of slaggy diabase-porphyrite, quartzite, greywacke, hardened shales, cherty limestone, jasper, &c.
1. Angular basal breccia, occurring at any horizon where the domes of gneiss project through the Cambrian deposits.

Of the foregoing subdivisions, zone 2 presents features of special interest, as the component pebbles have not been derived from the underlying gneiss. They point to the existence of an older series of sedimentary deposits and volcanic rocks, no trace of which has yet been met with throughout the Archæan area*.

3. *Succession in Assynt.*

In Assynt the foregoing subdivisions cannot be traced, as the vast thickness of strata mainly consists of coarse sandstones, grits, and occasional bands of conglomerate corresponding with zone 3 of the above section. Towards the base, however, the beds become flaggy and fine-grained and contain several bands of purple and greenish-grey shales and sandstones. In places there is an important local development of conglomerate named "the Button Stone," which seems to have filled hollows in the old land surface. This horizon has been of great service in the identification of the masses of Cambrian strata thrust forward by the Post-Lower-Silurian displacements.

At Stoer north of Lochinver there is a small patch of Cambrian strata, covering about six square miles of ground, which possesses special interest owing to the discovery of organic remains in grey, green, and black mudstones and cornstones near the base of the series. The fossils consist of calcareous rods, which have as yet defied determination. The total thickness of the members of this formation in Assynt varies from 3800 to 4000 feet.

* The occurrence of rocks foreign to the North-west Highlands, in the Cambrian conglomerates of Ross-shire, has been chronicled by Dr. Hicks (Q. J. G. S. vol. xxxiv. p. 813).

4. *Succession in Loch-Broom district.*

Advancing southwards to the shores of Little Loch Broom, this formation undergoes a still further development by the occurrence of dark and grey flags and shales, occupying a higher position than any of the beds lying to the north. These dark shales have also yielded certain doubtful impressions which may prove to be organic, together with worm-casts. In this region the total thickness of strata is about 8000 feet.

Considering the coarse materials which compose the greater portion of the Cambrian strata and the indications of rapid accumulation, it may be plausibly inferred that they represent a great lacustrine formation.

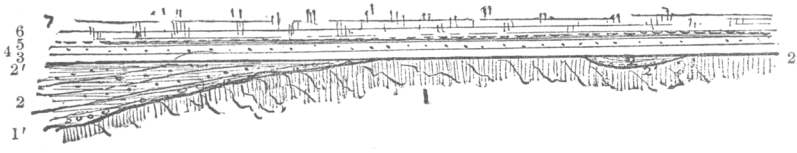
5. *Formation of Outliers of Cambrian Strata in Post-Cambrian and Pre-Silurian time by Folding and Denudation.*

After the accumulation of the Cambrian strata there is clear evidence to prove that they must have been subjected to extensive denudation prior to the deposition of the fossiliferous quartzites and limestones. That there is a marked discordance between the two formations, as originally established by Professor Nicol and Sir Henry James, cannot for a moment be doubted. As the red sandstones are either horizontal or inclined to the E.S.E. at lower angles than the quartzites, it is observable that the former are transgressed, bed after bed, by the basal quartzites, till the latter rest directly on the Archæan gneiss. This double unconformability is admirably displayed on the slopes of Ben Garbh, forming the southern shore of Loch Assynt.

That this was not the original eastern limit of the formation is evident from the fact that several masses of Cambrian strata have been carried from areas lying far to the east by the Post-Lower-Silurian displacements to be referred to presently. The Cambrian age of these thrust-masses is placed beyond doubt (1) by the occurrence of the local conglomerate ("Button Stone"), (2) by the double unconformability of the basal quartzites on the red sandstones and the Archæan gneiss; and (3) by the sheets of intrusive felsite occupying their proper horizon.

It is obvious therefore that during the interval which elapsed between the deposition of the Cambrian sandstones and Silurian quartzites, the former must have been thrown into a series of gentle folds, a vast thickness of strata was then removed, the Archæan rocks were exposed over wide areas, and the surface was reduced to a great plane of marine denudation. By these means various outliers of Cambrian strata were formed, far to the east of the present apparent limit of this formation, which tell an interesting story in connexion with the metamorphism induced by the Post-Lower-Silurian movements (see fig. 6).

Fig. 6.—*Diagram showing the Formation of Outliers of Cambrian Strata by folding and denudation in Post-Cambrian and Pre-Silurian time.*



1. Archæan.
2. Cambrian.
3–7. Silurian.
1'. Pre-Cambrian Plane of Marine Denudation.
2'. Pre-Silurian Plane of Marine Denudation.

III. The Silurian Formation.

1. *Uniformity in the Order of Succesession.*

The results of our researches along the line of complicated structure from Eriboll to Ullapool demonstrate the remarkable uniformity of the order of succession of the Silurian formation. All the various zones and even the minor subdivisions, from the basal quartzites up to the horizon of the Eilean Dubh limestones (Group II. of vertical section of Durness limestones), have been traced for a distance of nearly 60 miles with very small variations in their respective thicknesses.

2. *Subdivision of the "Pipe-Rock" Zone.*

The detailed mapping of the Assynt region and the tract north to Ben Arkle has enabled us still further to subdivide the "Pipe-Rock" zone of the quartzites into five horizons. At the top of the fourth subzone (see vertical Section II. p. 406) an interesting discovery was made of a thin band containing Serpulites (like those in the Serpulite-grit) on Ben Arkle. This band, however, seems to be local; for though it has been carefully searched for to the south, it has not yet been met with.

The lowest group of Limestones (Group I., vertical section of Durness Limestone) has been also subdivided into eight zones, which have been of the greatest service in unravelling the complicated structure of the limestone plateau at Inchnadamff. A recent examination of the representatives of this group in Eriboll has proved their occurrence in that region also.

In order to compare the vertical section of strata at Durness and Eriboll with that along the line of complicated structure from Loch More to Ullapool, we have drawn out a vertical table of the strata in the latter region (vertical Section II. p. 406), showing the various subdivisions and the horizons of the numerous sheets and dykes of intrusive rocks in Assynt.

Vertical Section I. *of Silurian Strata at Durness and Eriboll.*

C. Calcareous Series.	VII. Durine Group.	Fine-grained, light-grey limestones, with an occasional dark fossiliferous band.
	VI. Croisaphuill Group.	*c.* Fine-grained, cleaved, lilac-coloured limestones, full of flattened worm-casts; fossils distorted by cleavage. *b.* Alternations of black, dark-grey, and white limestone, with an occasional fossiliferous band, like zone (*a*) of this group. *a.* Massive, dark-grey limestone, chiefly composed of worm-casts which project above the matrix on weathered surfaces. Near the base are several lines of small chert nodules. This is one of the most highly fossiliferous zones in the Durness basin.
	V. Balnakeil Group.	Alternations of dark- and light-grey limestone, highly fossiliferous, with occasional impure, argillaceous, unfossiliferous bands. Most of the beds are distinctly cleaved, and contain few worm-casts.
	IV. Sangomore Group.	Fine granular dolomites, alternating near the top with cream-coloured or pink limestone. Near the base are two or more bands of white chert, one of which is about 5 feet thick.
	III. Sailmhor Group.	Massive, crystalline-granular, dolomitic limestones, occasionally fossiliferous, charged with dark worm-castings set in a grey matrix; large spheroidal masses of chert near the base. This limestone is locally known as "the Leopard Stone."
	II. Eilean Dubh Group.	Fine-grained, white, flaggy, argillaceous limestones and calcareous shales. As yet no fossils have been found in this division.
	I. Ghrudaidh Group.	Dark leaden-coloured limestones, occasionally mottled, alternating near the top with white limestone. About 30 feet from the base there is a thin band of limestone charged with *Serpulites Maccullochii*, and a similar band occurs at the base.
B. Middle Series (partly calcareous and partly arenaceous).	Upper Zone.	At the base lies a massive band of quartzite and grit, passing upwards into carious dolomitic grit, crowded in patches with *Serpulites Maccullochii*, more especially in the decomposed portions (Serpulite-grit).
	Middle Zone.	Alternations of brown, flaggy, calcareous, false-bedded grits and quartzites with cleaved shales.
	Lower Zone.	Calcareous mudstones and dolomitic bands, weathering with a rusty brown colour, traversed by numerous worm-casts, usually flattened, and resembling fucoidal impressions. These beds are often highly cleaved. This and the overlying zone form the "Fucoid-

Vertical Section I. (continued).

A. Arenaceous Series.	Upper Zone.	Fine-grained quartzites, perforated by vertical worm-casts and burrows, becoming more numerous towards the top of the zone ("pipe-rock" of previous authors).
	Lower Zone.	False-bedded flaggy grits and quartzites, composed of grains of quartz and felspar. At the base there is a thin brecciated conglomerate, varying from a few inches to a few feet in thickness, containing pebbles of the underlying rocks, chiefly of quartz and orthoclase, the largest measuring about 1 inch across.

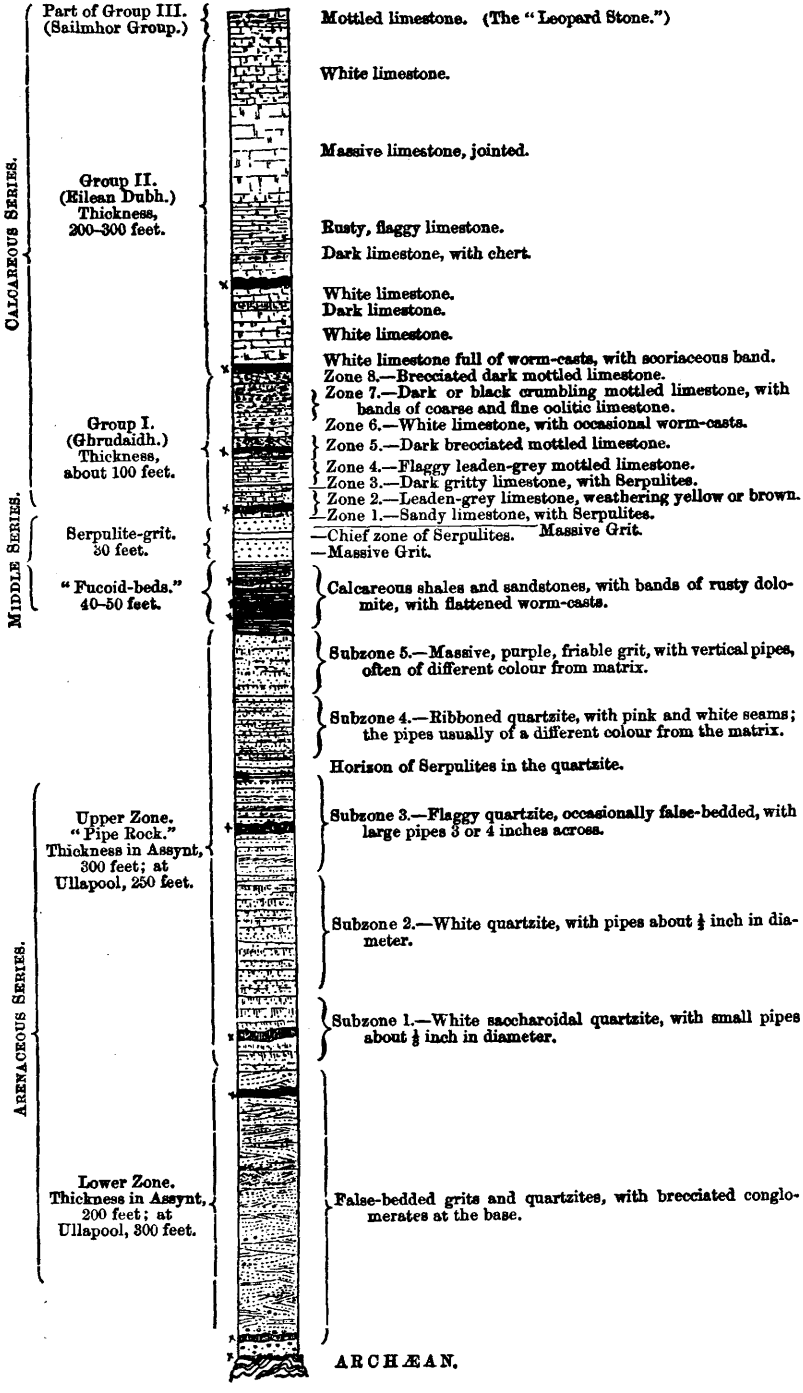
The highest beds which occur along the line of complicated structure belong to the Sailmhor Limestones (Group III. vert. Section I.). These dark mottled limestones, representing only the basal beds of this group, occur on the limestone-plateau of Inchnadamff, and nowhere else along the line. None of the rich, fossiliferous zones of Durness is met with anywhere between Eriboll and Ullapool, because they all occupy higher horizons. The *Orthoceras* found by Mr. Charles Peach in Assynt must have been obtained from one or other of the bands of Serpulite-limestone at the base of the Ghrudaidh Group.

3. *Physical Conditions during Deposition of Silurian Strata, and Horizon of the latter.*

Mr. B. N. Peach thus summarizes the physical conditions indicated by the Silurian strata in Sutherland. In the case of the basal quartzites, where there is a passage from a land-surface to a sea-bottom, there is little or no organic matter mixed with the coarse siliceous sand, which, from its texture and the false-bedding of the layers, bears evidence of rapid accumulation. There would therefore be no food for the support of Annelides under these conditions. But with the slower accumulation indicated by the "pipe-rock" there was evidently time for the fertilization of the sand by the shower of minute pelagic organisms which is ever falling on the sea-floor, so that it could afford food for the burrowing Annelides whose casts now form the stony pipes.

Different species of errant Annelides make their appearance in the "Fucoid-beds" along with the survivors of those that formed the vertical burrows in the quartzite, the surfaces of the beds presenting a matted network of their flattened excrements, thus misleading the older observers, who regarded them as the remains of seaweeds. The zone of Serpulite-grit indicates a shallowing of the area of deposit and the introduction of coarser sediment; but after its deposition hardly any sediment derived from the land entered into the composition of the overlying limestones. Eventually nothing seems to have fallen on the sea-floor but the remains of minute organisms,

Fig. 7.—*Vertical Section* II. *of Silurian Strata from Eriboll to Ullapool, showing horizons of Intrusive Rocks* (*marked* ×) *in Assynt.*



whose calcareous and siliceous skeletons have slowly built up the great mass of limestone and chert so conspicuously developed at Durness. That small pelagic animals played the chief part in the formation of this accumulation of limestone, is rendered almost certain by the fact that most of the beds are traversed by worm-casts in such a manner that nearly every particle must have passed through the intestines of worms. It is evident from the prevalence of these Annelid traces that the limestones cannot be due to coral-reefs, but must be of detrital origin. Only one undoubted specimen of coral, resembling a *Michelinia*, imbedded in a fine calcareous sediment, has been obtained from the series. That shell-banks had little to do with the accumulation of the limestone, is apparent from the mode of occurrence of the shells which are found in it. The most abundant forms are chambered shells, such as *Orthoceratites*, *Lituites*, and *Nautilus*; next in order are the Gasteropods, chiefly *Maclurea* and *Pleurotomaria*, while the Lamellibranchs and Brachiopods rank last in point of number. The two latter are found with their valves attached, and the Lamellibranchs occur in the position in which they lived and died. All the specimens show that every open space into which the mud could gain access and the worms could crawl is traversed by worm-casts. In the case of the *Orthoceratites*, they seem to have lain long enough uncovered by sediment to allow the septa to be dissolved away from the siphuncles which they held in place. Many of those siphuncles are now found isolated; indeed Salter established his genus *Piloceras* on such large examples as those found in *Endoceras*. Sponges of the genera *Archæocyathus* and *Calathium* occur at intervals in the muddy matrix. One example is preserved in chert; but the larger masses of chert in the limestone do not seem to be derived from sponges, but more probably from the siliceous skeletons of Diatoms, which, in all likelihood, were as abundant in that ancient ocean as they are now. No undoubted remains of Foraminifera have been discovered, though on several horizons there are zones of limestone made up of small rounded bodies, probably oolites; but owing to the fact that the limestones are crystalline, and that many of them have been more or less dolomitized, it is now almost impossible to decide definitely as to the nature of these spherules. For the same reasons it is almost hopeless to find minute organisms in this formation. The shell-substance of the larger fossils has in almost every case been dissolved out, and the spaces have been filled with calcite and, in some cases, with beekite, so that all the finer markings on their surfaces are obliterated.

The fossils, as Salter long ago pointed out, are distinctly of an American type, and do not resemble those found in the contemporaneous deposits of Wales and England. So far as the order of succession of the beds and their fossil contents are concerned, we have almost an exact counterpart of the strata exposed along the axis of older Palæozoic rocks, stretching from Canada through the eastern States of North America. In the latter region the Silurian strata of Sutherlandshire are represented by:—(1) the Potsdam Sandstone,

always described as being vertically piped by *Scolithus* like the "pipe-rock," and (2) the Calciferous Group; in other words, the highest beds of the Cambrian and the lowest members of the Silurian formations. There can be little doubt that some old shore-line or shallow sea must have stretched across the North Atlantic or Arctic ocean, along which the forms migrated from one province to the other, and that some barrier must have cut off this area from that of Wales and Central Europe.

IV. Igneous Rocks in Cambrian and Silurian Formations.

1. *Evidence of their Intrusive Character.*

The Lower Palæozoic strata of Assynt furnish evidence of an outburst of volcanic activity after the deposition of the Limestone series. The crystalline rocks which contain the records of this episode in the geological history of the North-west Highlands are all intrusive and occur in the form of sheets extending for miles along the bedding-planes.

That these igneous rocks are intrusive and not contemporaneous will readily be admitted for the following reasons:—first, when the sheets are followed along the line of outcrop they pass transgressively from lower to higher members of the same group; second, where they reach a considerable thickness, both the overlying and underlying strata are altered by contact-metamorphism; and third, they frequently contain patches of the sedimentary beds which they have traversed, as, for example, fragments of altered quartzite in the diorites associated with the limestone.

2. *Horizons.*

The phenomena presented by these intrusive sheets are admirably displayed on the slopes of Ben Garbh and Canisp, south of Loch Assynt, where they have been injected along the bedding-planes of the Cambrian sandstones and Silurian quartzites, and again in the great limestone cliff at Stronechrubie (Inchnadamff) on the horizon of the Ghrudaidh Group. For long distances the foregoing masses keep to the same horizon, even where the strata are dipping at low angles, but eventually they leave it and pierce the beds above or below. On the western face of Canisp, a large mass of porphyritic felsite rises from the old platform of Archæan rocks, passing upwards into the Cambrian sandstones and ultimately spreading along the bedding-planes of the strata. Several important sheets are also found on higher horizons both on Canisp and Ben Garbh.

The foregoing vertical Section II. (fig. 7) shows the prevalent horizons of these intrusive masses in the Silurian rocks of Assynt, from which it will be seen that they occur in both zones of the quartzites, the "Fucoid-beds," and in the two lowest limestone groups. It ought to be remembered, however, that though they generally occupy the particular horizons indicated in the table, they not unfrequently appear either in higher or lower subdivisions of the same group.

The thickness of these dykes and sheets varies from 10 to 50 feet. But towards the southern limits of Assynt there is quite an exceptional development of one of these intrusive masses extending continuously for a distance of five miles from Ledbeg to a point near the road leading to Loch Ailsh. Occurring within the area affected by the Post-Lower-Silurian movements, it is traversed by numerous thrusts which have had the effect of repeating portions of the mass. It is highly probable that it resembles the others in its mode of occurrence, and was originally injected along the bedding-planes, forming a sheet not less than 600 feet thick. As might naturally be expected, such a great thickness of igneous material has developed important changes in the lithological characters of the strata by contact-metamorphism.

3. *Area of Distribution.*

The area of *undisturbed* Lower Palæozoic strata penetrated by these sheets is limited, extending from Loch Assynt to near Elphin, a distance of about nine miles; but their development in the territory affected by the Post-Lower-Silurian movements is somewhat remarkable. Indeed from the evidence obtained by the detailed mapping of the displaced masses, it is clear that originally the igneous rocks must have spread over a large area, stretching from Glencoul to Ullapool—a distance of twenty-four miles. In the latter district they occur near the base of the limestone or between the limestone and the Serpulite-grit; while in Strath Kanaird (north of Ullapool) they are met with apparently about the junction of the "pipe-rock" with the basal quartzites. It is further evident that they must have extended far to the east (though how far it is impossible to say), because they occur in the Cambrian sandstones and Silurian strata carried westward along the higher thrust-planes.

4. *Macroscopic Characters.*

A detailed description of the petrographical characters of these igneous rocks is not contemplated in this paper. It will be sufficient if we indicate their general macroscopic characters and the types to which they belong. In his papers published in the 'Mineralogical Magazine'*, Dr. Heddle has called attention to some of their lithological features, and has figured some of the beautiful crystals of felspar and hornblende; Professor Bonney† has described the microscopic characters of certain specimens from the Traligill burn, Inchnadamff, and near Alltnacallagach, naming the former a hornblendic porphyrite; while Mr. Teall‡ has contributed notes on the macroscopic and microscopic characters of several dykes taken from different horizons in the Silurian series, giving the chemical analyses of three varieties, which show a considerable variation in chemical composition, the most basic being obtained from the series

* Mineralog. Mag. vol. iv. p. 233, vol. v. pp. 137–145.
† Quart. Journ. Geol. Soc. vol. xxxix. p. 419.
‡ Geol. Mag. dec. 3, vol. iii. p. 346.

in the limestones. He has called attention to the presence of augite in addition to the hornblende, and suggests that the pyroxene may be due to the absorption by the igneous magma of a certain amount of the dolomite-limestone into which the rock has been intruded.

These interesting observations of Mr. Teall are confirmed by the results of the detailed examination of the Assynt region. Indeed, during the season of 1885, when the limestone-plateau of Inchnadamff was mapped, it became sufficiently obvious that, with few exceptions, the intrusive rocks in the limestones are more basic than those in the quartzites. It was also noted that the development of pyroxenes is a characteristic, not only of the thinner bands in the calcareous series, but of those portions of the great sheet of igneous material east of Ledbeg which are in immediate contact with the marble.

The following varieties are met with in the lower and upper zones of quartzite:—(*a*) compact, fine-grained, pink or grey felsite, with or without porphyritic quartz; (*b*) porphyritic felsite, with crystals of felspar and hornblende set in a felsitic ground-mass; (*c*) the former shades into a highly crystalline rock in which large crystals of orthoclase and albite, with beautiful zonal banding, occur in a micro-crystalline ground-mass consisting of felspar and hornblende; (*d*) porphyritic diorite in which hornblende-crystals are porphyritically developed in a crystalline matrix of plagioclase felspar with some hornblende.

The igneous sheets and dykes in the Ghrudaidh limestones (Group I.) consist mainly of diorite, some of them being fine- and others coarse-grained. With the hornblende and plagioclase felspar augite is occasionally associated. The dyke occurring in the Eilean-Dubh limestone is usually a grey felsite or hornblendic felsite.

The macroscopic characters of the great intrusive mass, extending from Ledbeg eastwards by Loch Borrolan to a point near the Loch-Ailsh road, are somewhat different from the foregoing types. The greater portion is highly granitoid, consisting mainly of crystals of felspar (albite, microcline, orthoclase) with secondary quartz. In those localities where hornblende is present, the rock resembles a hornblendic granite. Where the intrusive mass has come in contact with the limestone, pyroxene has been developed; indeed the molten material must have absorbed a large quantity of calcareous matter, for in many places it effervesces freely.

5. *Contact-Metamorphism.*

Where the bands are comparatively thin, not much alteration is observable in either the quartzites or the limestones, except a slight induration of the strata along the edges of the intrusive masses. But where they reach a considerable thickness, some remarkable changes occur. For example, on the slopes of Ben Garbh, south of Loch Assynt, the quartzites, traversed by a massive sheet of porphyritic felsite, have been so altered that the two rocks are welded together. In the case of the great granitoid mass at Ledbeg and

Loch Borrolan the limestone, as is well known, has been converted into a beautiful white marble, which is found over a considerable area. At Ledbeg the marbles underlie the intrusive sheet, and to the east of Alltnacallagoch they are found resting on it in small isolated patches. The marble is again traceable across the moor southwards to Loch Urigill, while far to the north it is met with on the southern slope of Sgonnan More, immediately below the outcrop of the Ben-More Thrust-plane to be afterwards referred to. Along the eastern margin of the Loch-Borrolan sheet, it appears close by the road leading to Loch Ailsh. The lithological characters of the marble have been well described by Professor Heddle, who calls attention to the presence of malacolite, serpentine, Wollastonite, magnetite, and margarodite in the calcite-matrix. That the marble is merely a portion of the limestone-series altered by contact with the intrusive igneous rocks, as pointed out by Professor Heddle, can be proved by most conclusive evidence. Passing outwards from the margin of the intrusive mass, the observer can trace all the stages of change from the crystalline to the unaltered bands of the calcareous series. Nay, further, it is possible to identify some of the zones of the limestone even in the midst of the marble. In places, however, the alteration has been so extreme that all traces of bedding have been destroyed. Finally, sheets and dykes of granitoid rocks occur in the marble, apart from the great Loch-Borrolan sheet.

6. *Sheets injected prior to Post-Lower-Silurian Movements.*

While these igneous rocks have been intruded after the deposition of the limestone, there is satisfactory evidence to prove that the injections took place prior to the Post-Lower-Silurian movements. Throughout the whole of the area affected by the displacements the dykes and sheets are truncated by numerous reversed faults, like the strata in which they occur. Further, they have in many cases been made schistose by these displacements, and there can be no doubt, therefore, that this phase of volcanic activity had ceased before the great terrestrial movements began.

V. Physical Relations of the Strata between Eriboll and Ullapool.

The conclusions to which the Geological Survey was led in the district of Eriboll, regarding the nature and extent of the terrestrial movements of Post-Lower-Silurian date, have been confirmed by the examination of the line of complicated structure southwards to Ullapool.

1. *Modification of two Inferences announced in former Official Report.*

There are two points, however, in the former official Report which, in the light of recent evidence, require modification. First, it was stated that during the incipient stages of the movements the strata were thrown into folds, which became steeper along the western fronts, till they were disrupted and the eastern limbs pushed

westwards. The folds were believed to have culminated in reversed faults; but it is now apparent that the latter need not necessarily be preceded by folding. Secondly, in the horizontal section illustrating the previous report, the reversed faults in advance of the great thrust on Ben Arnaboll are represented as extending downwards, till each pierced the buried platform of Archæan rocks. But from the evidence obtained between Foinne Bheinn and Ullapool, it is clear that such may not be the case. Numerous sections demonstrate the fact that the strata, piled up by minor thrusts, have been driven along a major thrust-plane, separating the underlying undisturbed masses from the overlying displaced materials.

2. *Classification of Terrestrial Movements.*

With the view of simplifying the description of the extreme complications of this region, the following classification of the various terrestrial movements is proposed. They may be arranged in three groups, according to the magnitude and importance of the displacements:—

a. Minor thrusts or reversed faults.
b. Major thrusts.
c. Maximum thrusts.

a. The reversed faults included in group (*a*) repeat the strata by bringing lower to rest on higher beds, and lie at oblique angles to the major thrust-planes. By means of them, the Silurian strata are piled up to an enormous thickness.

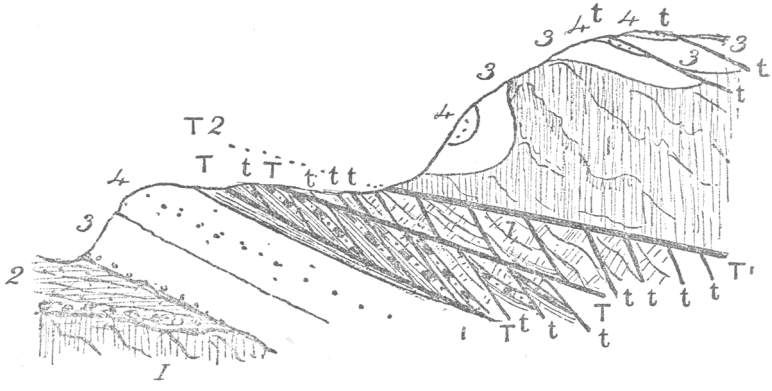
b. The major thrusts have driven the piled-up strata westwards, along planes separating the displaced materials from the underlying undisturbed strata. They always truncate the overlying minor thrusts and may nearly coincide with the lines of bedding of the strata over considerable distances.

c. The maximum thrusts are by far the most powerful, because they bring up and drive westwards portions of the old Archæan platform with the Cambrian and Silurian strata resting on it, and likewise usher in the eastern schists. The accompanying horizontal section (fig. 8) shows the characteristic features of these various displacements.

3. *Chief Maximum Thrusts.*

There are several maximum thrusts throughout the area affected by the movements, but three of them are of special importance because they enter into the geological structure of the complicated tract between Loch More and Ullapool. Stated in order, passing from west to east, they are—1, *the Glencoul Thrust*; 2, *the Ben-More Thrust*; 3, *the Moine Thrust*. The first is magnificently displayed in dip section on Loch Glencoul and Loch Glendhu, near Kylesku; the second, on the great cliff of Ben More in the Bealloch of Coinne-mheall; the third, at Knockan near Elphin and on the coast-section of the Moine between Loch Eriboll and the Kyle of Tongue.

Fig. 8.—*Diagrammatic Section in West Face of Glasven, near Loch Gamnheach, to show Minor Thrusts or reversed Faults, Major and Maximum Thrusts.* (Horizontal distance 1½ mile.)



t, Minor, T, major, T′, maximum thrusts. T². Glencoul Thrust.

There are certain features characteristic of these maximum thrusts which ought to be enumerated before proceeding to describe the geological structure of the line of complication.

a. The outcrops of these maximum thrust-planes resemble the boundary lines between unconformable formations, because (1) there is always a complete discordance between the strata lying above and below the planes of disruption, and (2) each successive thrust may be overlapped in turn by the higher one. In other words, *the Glencoul Thrust-plane may be overlapped by the Ben-More Thrust-plane, and the Moine Thrust-plane may overlap both these and all major and minor thrusts, till the materials lying above it rest directly on the undisturbed Silurian strata.* A remarkable example of the latter phenomenon will be described in the sequel as occurring at Craig-a-Knockan, south of Elphin.

b. By means of denudation, outliers of the materials lying above these planes are formed. Perhaps the most extraordinary instances are the two prominent outliers, resting on the limestone-plateau at Inchnadamff, of Archæan rocks with Cambrian and Silurian strata, separated by two circular faults from the underlying limestones!

c. The planes of these powerful thrusts along which the materials have been driven are not always inclined at low angles, indeed they are frequently very irregular. In some cases the thrusts may be inclined at a gentle angle to the horizon and may suddenly become vertical.

d. Owing to the movements of the strata from east to west and also to the friction along the unyielding lower plane or "sole" of the thrust, there was a tendency in the materials to fold over and curve under, thus producing inversion of the beds. As a result of

this tendency, the Cambrian and Silurian strata resting on the Archæan rocks brought forward by one of these powerful thrusts, fold over the western face of the displaced gneiss and actually underlie the Archæan rocks in inverted order.

e. From the foregoing phenomenon (*d*) it follows that along the line of outcrop of a maximum thrust the materials above the plane, in contact with the underlying strata, may consist of either Archæan rocks, Cambrian sandstones, or some zone of the Silurian series. For example, along the outcrop of the Glencoul Thrust, in Loch Glencoul and Loch Glendhu, the Archæan gneiss rests directly on the piled-up Silurian strata; but when it is traced southwards towards Inchnadamff, the thrust brings the quartzites to overlie the limestones along the base of the western slope of Glasven. In like manner, along the outcrop of the Ben-More Thrust, at one point the Archæan gneiss is made to overlie the piled-up Silurian strata, at another point the Cambrian sandstones are brought in contact with the heaped-up beds, while at a third point different members of the Silurian series are thrown against each other.

All these various features are beautifully illustrated along the line of complicated structure between Eriboll and Ullapool.

5. *Horizontal Sections illustrating the Physical Relations of the Strata between Eriboll and Ullapool.*

In order to show the remarkable variations in the geological relations of the strata and the extraordinary complexity of the structure, we propose to describe a series of horizontal sections drawn across the general strike of the sedimentary deposits and the eastern schists, leaving out minute details.

Section from Ben Arkle to the Moine Thrust-plane (fig. 9).—Beginning with the tract lying to the north of Loch More, there is a magnificent example of the abnormal thickness of the quartzites, due to the piling-up of the beds by minor thrusts or reversed faults. Indeed there is no finer instance along the line to Ullapool. So deceptive is the structure that, were it not for the subdivisions of the "pipe-rock" recently established, the task of unravelling the complications would be hopeless. Along the western base of the mountain, the basal quartzites rest unconformably on the old Archæan platform; but a short distance up the slope a great major thrust-plane occurs, separating the underlying undisturbed quartzites from the overlying displaced beds. Along the "sole" of this major thrust the zones of the quartzite, chiefly of the "pipe-rock," have been driven, piled on each other by minor thrusts or reversed faults, the latter being truncated by the former. In tracing these reversed faults, the band of Serpulite-quartzite in the "pipe-rock" has been of the utmost service. Advancing eastwards to Loch-an-na-Faoilege, the same phenomenon is met with, viz. the constant repetition of various zones of the quartzites by minor thrusts. Eventually the "pipe-rock," "Fucoid-beds," and Serpulite-grit are repeated by similar displacements, till they are overlapped by a maximum thrust, bringing forward a slice of Archæan rocks with the basal quartzites. By means of another maximum thrust a belt of green schist and sheared gneiss, with recognizable bands of

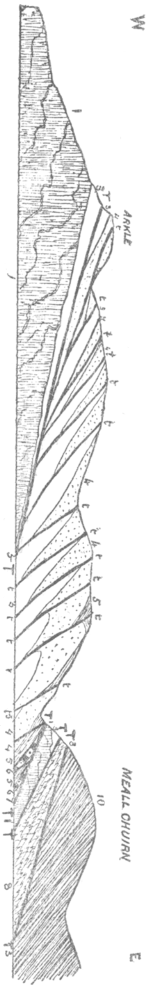


Fig. 9.—*Horizontal Section across Ben Arkle to the outcrop of the Moine Thrust-plane.* (About 5 miles in length.)

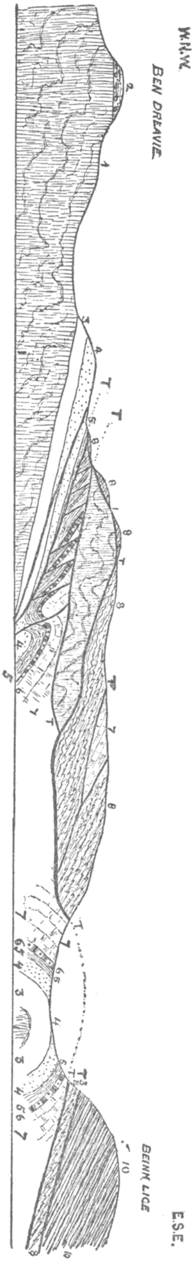


Fig. 10.—*Horizontal Section showing Structure of Ground between Loch More and Strath nan Carran.* (About 6 miles in length.)

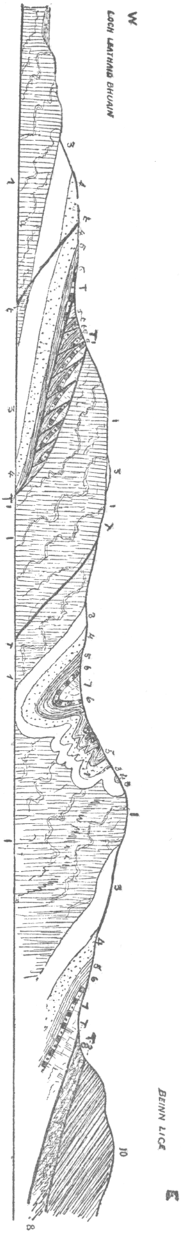


Fig. 11.—*Horizontal Section showing the Structure of the Ground between Strath nan Carran and Loch Glendhu.* (About 5 miles in length.)

Archæan gneiss at the base and in the heart of the mass, is made to overlie these displaced materials. Within a short distance this belt of green schist and sheared gneiss is succeeded by the Moine Thrust, ushering in the micaceous and quartzose flagstones belonging to that horizon.

Section south of Loch More (fig. 10).—On the ridge south of Loch More Lodge the Archæan gneiss *with the basic dykes* is covered by the basal quartzites and the "pipe-rock" in natural order, the latter being traversed by a powerful thrust. The "pipe-rock" and "Fucoid-beds" are eventually truncated by a major thrust-plane, along which the Fucoid-beds, Serpulite-grit and limestones, piled on each other by reversed faults, have been driven, till they are overlapped by a maximum thrust bringing up the Archæan gneiss of a red, massive, granitoid type. These recognizable Archæan rocks are abruptly truncated by a second maximum thrust ushering in reconstructed gneiss and schists, the prominent planes, dipping E.S.E., having been determined by the Post-Lower-Silurian movements. The general colour of the rock is light or dark grey, forming a marked contrast to the underlying red, granitoid gneiss. As the inclination of the thrust-plane is variable, numerous outliers of the reconstructed gneiss and schist have been formed. In the heart of the main mass, however, there is a patch of Silurian limestone belonging to the Eilean Dubh and Ghrudaidh groups. The occurrence of this large mass of Silurian limestone is of special importance, as it shows how calcareous bands are formed among the eastern schists, their geological relations being determined by mechanical movement. Advancing still further eastwards, this belt of crushed and reconstructed gneiss and schist is buried underneath the dark micaceous flagstones lying above the Moine Thrust-plane.

Along this line of section, the geological relations of the strata are somewhat different from the foregoing. Towards the southern margin of Loch an Leathaid Bhuain, the basal quartzites rest unconformably on the Archæan gneiss, followed by the "pipe-rock," "Fucoid-beds," and Serpulite-grit. These are traversed by a major thrust-plane, along which the "Fucoid-beds," Serpulite-grit, and basal limestones have been piled up by minor thrusts. To these succeed the Glencoul Thrust-plane, above which there is a great slice of Archæan rocks with no basic dykes. This mass has been laid bare for a distance of nearly two miles, from Ben a Ghrianain to Ben a Bhutha; but to the east of the latter hill there is a splendid development of Silurian rocks resting naturally on the slice of the old Archæan platform. All the Silurian zones, from the basal quartzites up to the horizon of the Eilean Dubh limestones, are met with, thrown into a series of inverted synclinal folds. On the hill to the west of Lochan nan Ealachan, a small patch of the old Archæan gneiss has been exposed on the crest of the arch by the denudation of the basal quartzites. Advancing eastwards, the Silurian zones are met with up to the horizon of the limestone, the latter being truncated by the maximum thrust bringing in the sheared gneiss and green schist; and within a short distance the micaceous flagstones above the Moine Thrust-plane appear on the slopes of Ben Licc.

As the observer passes southwards to Glendhu and Glencoul (fig. 11), the outcrop of the Glencoul Thrust-plane is magnificently displayed in dip-section in these sea lochs. To the west lies the natural escarpment of the basal quartzites and "pipe-rock," resting unconformably on the undisturbed Archæan platform; and within a distance of half a mile to the east occurs an enormous slice of the old crystalline rocks, which has travelled for miles along the "sole" of the Glencoul Thrust. Underneath this maximum thrust, however, there is a powerful major thrust driving forward the "Fucoid-beds," Serpulite-grit, and basal limestone piled up by numerous reversed faults, the latter being admirably seen in dip-section in Loch Glencoul.

The great mass of Archæan rocks brought forward by this maximum thrust rises from the sea-level like a wall round the head of Loch Beag, to a height of over 1750 feet, presenting the typical features of the Archæan gneiss to the west with the basic dykes. Ascending the ridge of Archæan rocks on the south side of the Glen to the Stack of Glencoul, various Silurian zones dip towards the E.S.E., piled on each other by minor thrusts. A careful examination of the sections shows that these zones are separated from the Archæan rocks by a powerful thrust-plane which descends the slope at a high angle. There can be no doubt whatever that these Silurian zones have been driven westwards along the "sole" of this thrust.

At the base of the Stack of Glencoul the Silurian quartzites have undergone important changes, due to the movements which will be refered to presently. They are overlain by a thin belt of green schist, the latter being rapidly succeeded by the micaceous flagstones above the Moine Thrust-plane.

Advancing south-eastwards towards Cnoc an Fhuarain Bhain (fig. 12), across an area of intense complication, all the

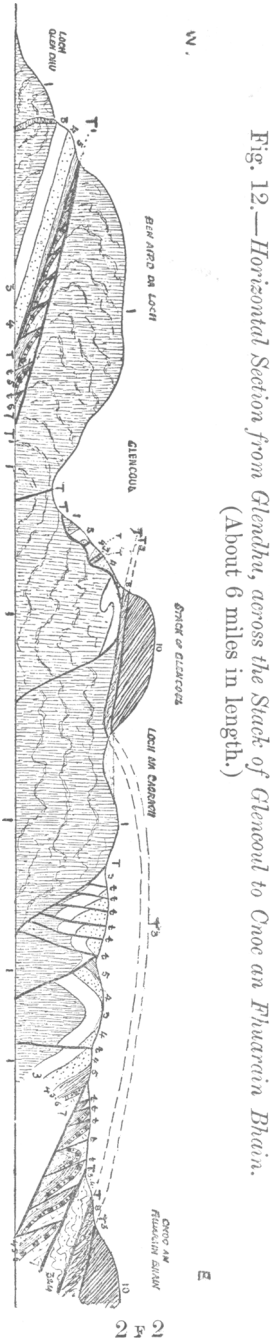


Fig. 12.—*Horizontal Section from Glendhu, across the Stack of Glencoul to Cnoc an Fhuarain Bhain.* (About 6 miles in length.)

Fig. 13.—*Section from Quinaig east by Achumore, Glasven, and Ben Uidhe, to the Ben-More Thrust-plane.* (Distance about 7 miles.)

Silurian zones from the basal quartzites up to the limestone are repeated by thrusts of more or less magnitude, till we reach the maximum thrust which brings in the green schists and sheared gneiss with strips of highly altered quartzites.

These are overridden in turn by the micaceous flagstones above the Moine Thrust-plane.

On the southern slope of Quinaig (fig. 13) the unconformability between the quartzites and the Cambrian sandstones is well exposed in the great escarpment skirting Loch Assynt, the sandstones being nearly flat, while the quartzites are inclined to the E.S.E. at angles varying from 15°–20°. Both zones are succeeded by the "Fucoid-beds" and Serpulite-grit in natural order; but close to the highroad leading to Kylesku the strata are truncated by a major thrust-plane, along which the "Fucoid-beds," Serpulite-grit, and basal limestones have been driven, repeated by numerous minor thrusts. Generally the piled-up strata belonging to these horizons are tilted at high angles to the plane of the major thrust. Owing to the extraordinary number of these minor thrusts, there are no fewer than thirteen outcrops of the Serpulite-grit in the course of one third of a mile. Close to Achumore another powerful major thrust ushers in the basal limestones, lying at gentle angles and resting on the highly inclined thrust-strata just described. They are repeated by numerous minor and major thrusts, and thrown into a series of arches and troughs, as shown in section, till they are overridden by the materials brought forward by the Glencoul Thrust-plane. The outcrop of this thrust-plane has been traced continuously from the shore of Loch Glencoul, southwards by Loch na Gainmhich along the base of the western slope of Glasven, to the Poll an Droighinn burn, thence by the base of Ben Fhuarain and Coinne-mheall of Ben More, till it is eventually overlapped by the Ben-More

Thrust-plane. For several miles of its course, from a point near Loch na Gainmhich to Cnoc an Droighinn, this maximum thrust brings various members of the quartzites to overlie different subdivisions of the Ghrudaidh and Eilean Dubh limestones. These quartzites have been driven westwards with the great slice of Archæan rocks above this thrust-plane, the latter rocks being exposed, with their characteristic basic dykes, to the north of the Chalda Lochs. But it ought to be borne in mind that the quartzites along the western face of the disrupted gneiss do not lie in regular inverted order: they are traversed by numerous thrusts, bringing different subdivisions of the quartzites with their intrusive sheets against each other. The extreme complications resulting from these minor thrusts and subsequent folding in the quartzites and their associated igneous rocks are splendidly displayed in Cnoc an Droighinn near Inchnadamff.

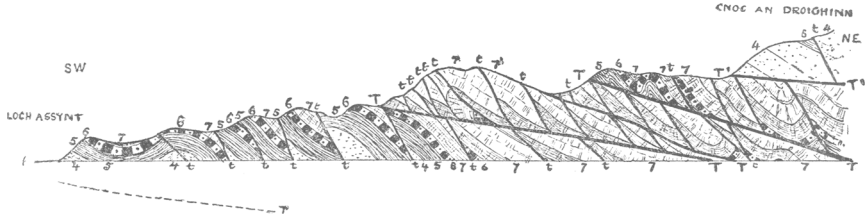
Between Glasven and Ben Uidhe there is a powerful maximum thrust driving westwards the Archæan gneiss with the basal quartzites and the "pipe-rock," while on the crest of the latter mountain both zones of the quartzites are repeated by various thrusts. On the northern shoulder of Mullach an Leathaid Riabhaich several powerful thrusts and extraordinary flexures of the strata are met with, until we reach the horizon of the Ben-More Thrust-plane, at the head of Glenbeg.

The Limestone Plateau at Inchnadamff.—The great development of Silurian limestone at Inchnadamff occurs almost wholly within the area affected by the Post-Lower-Silurian movements. Indeed it is rather remarkable that only one small patch, belonging to the lower subdivision of the Ghrudaidh group, lies in the undisturbed area, viz. on the north shore of Loch Assynt near the mouth of the Skiag burn. Between Achumore and Inchnadamff the belt of limestone is nearly a mile wide, but to the east of the great Stronechrubie cliff it forms a broad plateau about two and a half miles in width. As indicated in the foregoing vertical Section II. (p. 406), the beds belong mainly to the two lowest groups of the Durness limestones, only a small portion of the Sailmhor group being represented. Owing to the extraordinary complications of the strata, due to the number of minor and major thrusts, it is difficult to estimate accurately the thickness of the limestones, but it cannot exceed 450 ft. or 500 ft.

That the calcareous beds are not arranged in an inverted synclinal fold can be demonstrated in the most conclusive manner. Taking first that portion of the plateau between Inchnadamff and Achumore, the following horizontal section (fig. 14) shows the general relations of the strata. Starting from the shore of Loch Assynt, about half a mile north of the mouth of the Traligill, the "Fucoid-beds," Serpulite-grit, and a portion of the basal limestones are repeated by numerous minor thrusts, till we reach a powerful major thrust-plane, along which the Eilean Dubh limestones have been driven westwards, over the underlying Ghrudaidh Group. Within a distance of half a mile of the shores of the Loch, the piled up limestones are truncated by another major thrust, bringing up the "Fucoid-beds," Serpulite-grit, and basal limestones to overlie the Eilean Dubh beds.

This powerful thrust can be traced northwards to the Chalda burn and southwards across the Poll an Droighinn and Traligill burns to the great plateau east of Stronechrubie. Following the line of

Fig. 14.—*Horizontal Section from Loch Assynt, across the Silurian Limestones, to Cnoc an Droighinn.* (About $\frac{3}{4}$ mile in length.)



section east to Cnoc an Droighinn, various subdivisions of both the lowest limestone groups with their dykes are repeated by reversed faults, till they are overlapped by the "pipe-rock" above the Glencoul Thrust-plane.

Between Ardvreck Castle and Achumore the relations of the strata are still more complicated. Briefly stated, the principles involved in the structure are as follows:—(1) the occurrence of a series of major thrusts running roughly parallel with each other, producing great horizontal displacement; (2) the piling up of the limestones along the planes of these thrusts by minor reversed faults; (3) the subsequent arrangement of the strata in a series of gentle arches and troughs, *the axes of the folds being quite independent of the trend of the major thrust-planes.*

Precisely the same principles are illustrated in the broad plateau east of Stronechrubie. The first great major thrust in the limestone is well seen in dip-section in the great cliff about half a mile south of the Inchnadamff Hotel, where it drives forward the Eilean Dubh limestones, the latter dipping at a high angle to the plane. Again, on the slope south of the Traligill burn at Glenbain about six major thrusts are admirably seen in dip-section, the beds between these planes being piled up by minor reversed faults. Occasionally outliers of the "Fucoid-beds" and Serpulite-grit are found, capping the Eilean Dubh limestones in the north-east part of the plateau, separated from each other by major thrusts. But subsequent to these various displacements driving the strata together, the area along the north-eastern and eastern margins of the limestone-plateau was elevated in the form of a great dome; and hence we find, at intervals, various sections showing the natural passage from the "pipe-rock" to the "Fucoid-beds," Serpulite-grit, and basal limestones, the strata being inclined towards the west. This feature has given rise to the belief, advocated by several observers, that the limestones were arranged in a great synclinal fold. But the examination of the great quartzite range of Braebag, to the east of the limestone plateau, points to the conclusion that the quartzites were piled on each other by numerous thrusts prior to the formation of the great

anticline. Along the western side of the arch, where the quartzites and limestones dip to the west, the thrust-planes are inverted, so that the observer has, metaphorically, to stand on his head to realize the effect of the displacements.

Geological Structure of Ben More.—Along the line of complicated structure between Eriboll and Ullapool, Ben More stands unrivalled for the extreme intricacy of the geological relations of the strata, for the striking evidence in proof of the existence of two maximum thrust-planes, and finally for the brilliant light which it throws on the metamorphism induced by these mechanical movements.

This mountain has two peaks, one, Ben More (3273 ft.), the other, about a mile to the west, named Coinne-mheall (Coniveall) (3234 feet). Between the latter peak and Braebag there is a col or narrow pass termed the Bealloch, separating the head-waters of the Oykel from the sources of the Traligill. In order to illustrate the structure of the mountain, we propose to describe three horizontal sections traversing it in various directions (figs. 15, 16, 17).

Fig. 15.—*Section across Coinne-mheall from one of the sources of the Traligill east to Corrie Mhadaidh.* (About 1½ mile in length.)

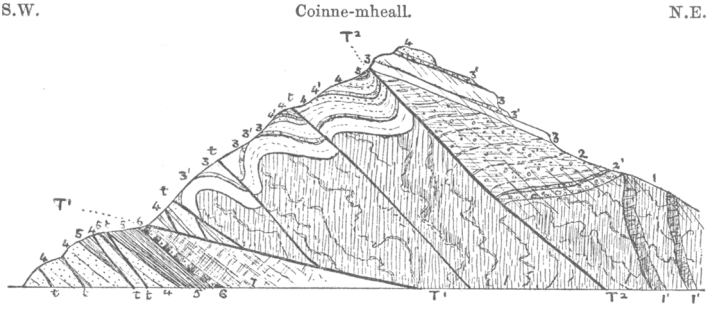
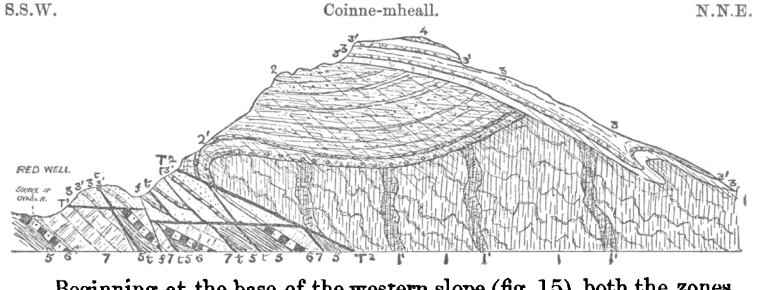


Fig. 16.—*Horizontal Section from the Bealloch across Coinne-mheall to Corrie Mhadaidh.* (About 1½ mile in length.)



Beginning at the base of the western slope (fig. 15), both the zones of the quartzite, the false-bedded grits, and "pipe-rock" are driven on to the Silurian limestone by the Glencoul Thrust. Ascending the slope, the false-bedded grits are made to overlie the "pipe-rock" by means of a reversed fault, and for some distance upwards, to near

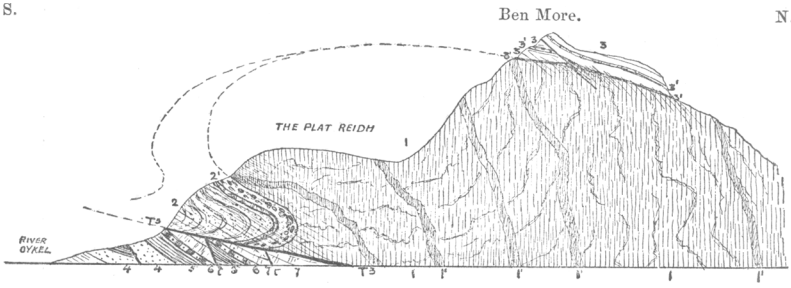
the 2500 feet contour-line, the strata exposed in the stream-section consist wholly of the lower zone of quartzites with their dykes, repeated by inverted folds and minor thrusts. Indeed, from the various arches exposed, it is clear that the basal quartzites only form a thin veneer over the concealed Archæan rocks. Were the slope denuded further back, there can be no doubt that the latter would be revealed. About the 2500 feet contour-line the basal quartzites are followed in regular order by the various subdivisions of the "pipe-rock," with their intrusive sheets, and the "Fucoid-beds," until they are abruptly truncated by the great Ben-More Thrust-plane. At the point where this line of section is drawn the effect of this maximum thrust is to bring the basal quartzites to overlie the highest zone of the "pipe-rock" and "Fucoid-beds." When the false-bedded quartzites (Zone 1) are traced along the crest of the mountain they are found to overlie unconformably both the Cambrian sandstones and the Archæan rocks. The false-bedded quartzites are succeeded by the lowest subdivision of the "pipe-rock," exposed on the mountain top. Descending the north-eastern slope of Coinne-mheall (fig. 15), the observer crosses (1) the unconformable junction of the basal quartzites and the Cambrian sandstones, and (2) the boundary line between the latter and the Archæan gneiss.

Owing to the high inclination of the Ben-More Thrust-plane at this point, the outcrop descends from the crest of the mountain to the Bealloch, where it is well seen on the great cliff in dip-section. As a result of the friction along the unyielding "sole" of the thrust, causing the upper layers to move more rapidly than the lower, we find that the Cambrian sandstones fold over the western face of the disrupted gneiss, as shown in the foregoing section (fig. 15). By means of the local conglomerate ("the Button-stone") at the base, the line of junction with the old Archæan platform is easily traced, and the proof of inversion is beyond all doubt. The basal conglomerate and the overlying grits, sandstones, and shales can be followed continuously from the Bealloch, round the south-eastern spur of Coinne-mheall, to the southern shoulder of Ben More, where they are unconformably overlain by a cake of the basal quartzites. That these grits and sandstones are really a portion of the Cambrian sandstones to the west, as originally maintained by Prof. Nicol, is apparent from the fact that the double unconformability is admirably seen along the ridge between Coinne-mheall and Ben More, and further from the presence of the various intrusive dykes on their proper horizons. The area occupied by the Cambrian strata is about half a square mile, about half of which is buried under the basal quartzites. In the corrie on the north-east side of the mountain they reappear with the conglomerate at the base, resting on the old platform. The general inclination of the Cambrian strata is towards the W.N.W., at an average angle of 20°; the greatest thickness is about 1500 feet.

In the Bealloch of Coinne-mheall (fig. 16), the hade of the Ben-More thrust-plane becomes almost flat, and hence the outcrop can be followed for two and a half miles down the river Oykel. Along the line of outcrop, the Cambrian sandstones reappear above the

thrust-plane, dipping underneath the Archæan gneiss in inverted order (see section), as previously described by Mr. Callaway. There can be no doubt, however, that this strip of Cambrian strata, extending nearly two miles down the valley, is merely a continuation of the mass on Coinne-mheall, as shown in section.

Fig. 17.—*Horizontal Section from the Oykel Valley across Ben More.* (About 2 miles in length.)



The slice of Archæan rocks bearing these Cambrian sandstones and Silurian strata, driven westwards by the Ben-More Thrust, is of large dimensions. The Archæan gneiss and basic dykes form a grand cliff about 1500 feet high overlooking Dubh Loch More, and they sweep across the lofty peaks separating the Oykel from the Gorm Lochs. Though still recognizable as a part of the old Archæan platform, the rocks have undergone important changes due to the movements, as will be shown further on.

The outcrop of this great thrust-plane can be followed southwards from the Oykel valley, round the western slope of Sgonnan More, by Strathsheaskich, thence to Allt an Loin Dubh, curving round Cnoc na Glas Choille to the base of the Cromalt Hills, where it is overlapped by the Moine Thrust-plane.

Of special interest, however, are the numerous outliers of the materials lying above this thrust-plane, left by denudation in the most extraordinary situations. The most important occur on Cnoc an Leathaid Bhuidhe west of Loch Awe, on the moor south of Loch Urigill, and on the limestone plateau south-east of Stronechrubie. The two isolated masses, resting on the limestones to the north and south of Allt nan Uamh, are of great importance, as they show the original folding of the Ben-More Thrust-plane over the quartzite range of Braebag, and the overlap of the Glencoul Thrust-plane by the former (see fig. 18).

Descending the slopes of Canisp the double unconformability of the quartzites on the Cambrian sandstones and Archæan rocks is well exposed, the lower zone being overlain by the "pipe-rock" in natural sequence. Crossing the Loanan, the "pipe-rock" is followed by the "Fucoid-beds," Serpulite-grit, and basal limestone, the latter three zones being repeated by reversed faults. Ascending the west declivity of Beinn an Fhuarain, the two lowest groups of limestone are repeated by minor thrusts till we reach the outcrop of the Ben-More Thrust-plane. Just above the plane, on the north-west face

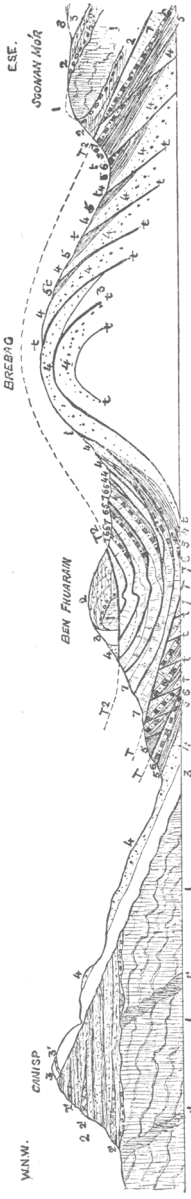


Fig. 18.—*Horizontal Section from Canisp east by the River Loanan, Ben Fhuarain, Brabag to Sgonnan More.* (About 8 miles in length.)

of the hill, the "pipe-rock" appears with an inverted dip, plunging underneath the basal quartzites, the beds being inclined to the E.S.E. at tolerably high angles. Near the hill-top the unconformable junction of the basal quartzites on the Cambrian sandstones is exposed, and when followed southwards *the false-bedded quartzites pass transgressively across the Cambrian strata and rest directly on the Archæan gneiss.* Only a small exposure of the gneiss is met with, but it presents the normal characteristics and contains one of the basic dykes.

This remarkable outlier is about a mile in length, from north to south, the outcrop of the thrust-plane forming a striking feature round the hill. The limestones are exposed in the various swallow-holes adjoining the plane, and the actual disruption-line is seen in dip-section on the north-west shoulder of the ridge. The Allt nan Uamh has carved a deep channel through the underlying limestones and has isolated the outlier on Beinn Fhuarain from that on Beinn nan Cnaimhseag on the north side of the stream. In the case of the latter, the Archæan rocks are not exposed, but the basal quartzites rest unconformably on the Cambrian sandstones. By means of these and other outliers, originally continuous with the strata lying above the main outcrop on Sgonnan More, we can form a clear conception of the enormous extent of these terrestrial displacements and also of the vast amount of denudation which has since taken place.

Only a brief reference can be made to the large number of thrust-planes repeating the Silurian strata, with occasional wedges of Archæan rocks, to the east of the Ben-More Thrust-plane. The alteration produced by these movements in advance of the Moine Thrust-plane is remarkable. So striking is the change, as will be shown presently, that Mr. Callaway grouped the Loch-Ailsh

limestones with the Caledonian series, thus regarding them as of Pre-Cambrian age. But in the course of the survey of that region we found that the false-bedded quartzites, the "pipe-rock," the "Fucoid-beds," the Serpulite-grit (with the Serpulites) are associated with the crystalline limestones and the intrusive sheets, the whole series being intersected by numerous thrusts which develop new structures of an important kind.

Advancing southwards to the confines of Assynt, we find evidence of an extraordinary overlap of the Moine Thrust-plane, along the base of the Cromalt Hills to the south of Elphin and Loch Urigill. From the base of the Stack of Glencoul the outcrop of this thrust-plane can be traced continuously, southwards by Loch Ailsh, thence crossing the Oykel and Allt Ealag in a S.S.W. direction. From the latter point *it runs west for a distance of six miles, along the base of the north slope of the Cromalt Hills to the famous Knockan cliff south of Elphin, passing transgressively across the Ben-More Thrust-plane and all underlying thrusts, till the micaceous flagstones rest at various localities on the undisturbed Silurian strata.*

Between Loch More and Glencoul the belt of complicated ground extending from the outcrop of the Moine Thrust westward to the edge of the undisturbed Silurian strata varies from two to four miles; while from Glencoul to the base of the Cromalt Hills, the belt averages about six miles in width. When we reach the Knockan cliff, the southern prolongation of this complicated ground is buried underneath the materials borne along the plane of the Moine Thrust. Indeed, had it not been for the extensive denudation of the strata above the latter thrust-plane, we should never have been able to study the sequence of these terrestrial movements, or the various stages in the production of the Moine schists.

With the view of showing the belt of complicated ground, comprising displaced Archæan, Cambrian, and Silurian strata, along the northern margin of this great overlap, the accompanying horizontal section (fig. 19) has been drawn from Elphin eastwards by Am Pollan and Cnoc na Glas Choille, to the outcrop of the Moine Thrust-plane in Allt Ealag.

At Elphin, close to the road leading to Ullapool, the "Fucoid-beds" and Serpulite-grit are truncated by a powerful major thrust, bringing forward the piled-up "Fucoid-beds," Serpulite-grit, and basal limestone. The latter are abruptly cut off by another major thrust-plane, along which the Eilean Dubh limestones have been driven, repeated by innumerable minor thrusts, for a distance of two miles. At Am Pollan, these displaced limestones are capped by an outlier of the materials lying above the Ben-More Thrust-plane, consisting of Archæan rocks covered unconformably by the Cambrian sandstones and the basal quartzites, the latter resting unconformably on both. Advancing eastwards, the strata are mainly composed of piled-up limestones, which, at the base of the west slope of Cnoc na Glas Choille, are overlapped by the Silurian strata lying above the main outcrop of the Ben-More Thrust-plane. In the

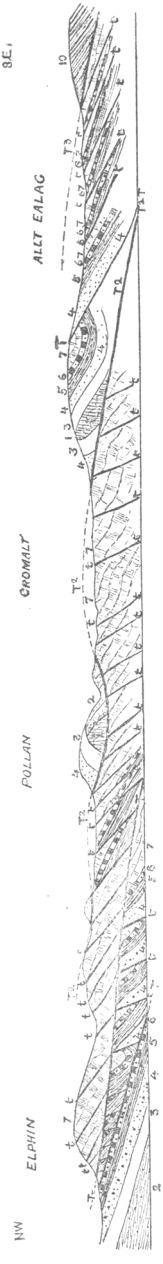


Fig. 19.—*Horizontal Section from Elphin to Allt Ealag.* (About 6 miles in length.)

heart of the latter displaced materials a small patch of Archæan rocks has been exposed by the denudation of the basal quartzites. In addition to the latter, all the Silurian zones, up to the horizon of the Eilean Dubh limestones, have been borne westwards along this disruption-plane, comparatively unaltered in places, till we approach the micaceous flagstones above the Moine Thrust-plane, where the quartzites have been converted into quartz-schists, and the dykes have also been rendered schistose.

Advancing southwards to the Knockan cliff, about two miles to the south of the foregoing line of section, there is a remarkable difference in the order of succession of the strata.

On the eastern slope of Coul More the basal quartzites rest unconformably on the Cambrian sandstones, followed in natural order by the "pipe-rock," "Fucoid-beds," and Serpulite-grit, the latter being exposed on the Knockan cliff east of Lochan Fasaig. Overlying the Serpulite-grit in natural sequence, there is a small portion of the basal limestone of the Ghrudaidh group, which is abruptly truncated by a major thrust-plane, bringing forward the white limestones and marble of the Eilean Dubh group. The latter are succeeded by the finely laminated micaceous flagstones above the Moine Thrust-plane.

Following the outcrop of this thrust-plane southwards to Strath Kanaird, a distance of nearly six miles, the Moine micaceous flagstones rest, now on the basal limestones, now on the Serpulite-grit, and again on the "Fucoid-beds," passing transgressively from one horizon to the other, thus showing the complete discordance between the materials above and below the thrust-plane (fig. 20). As the flagstones lie on the undisturbed beds, there seems at first sight to be a natural passage from the Silurian strata into the eastern schists; but the apparent conformity is entirely deceptive.

That such is the true explanation of the relations of the strata along this line of section is still further confirmed by the remarkable evidence in Strath Kanaird, near Langwell. *About a mile to the east of the normal outcrop of the Moine Thrust, the river has cut down through the thin cake of micaceous flagstones, and exposed on the south side of the valley a large mass of Archæan gneiss, covered unconformably by the*

basal quartzites (fig. 21). There can be little doubt, from the evidence obtained at Am Pollan (Loch Urigill), in the valley of the Achall, and at Ullapool, that this mass of Archæan rocks and basal quartzite has been borne along by the Ben More Thrust, and that the materials rest on the piled-up Silurian strata underneath.

Passing southwards to the Achall valley, there is a regular ascending series from the basal quartzites, resting unconformably on the Cambrian sandstones, up to the Serpulite-grit and a portion of the basal limestone. The latter zones are abruptly truncated by a powerful major thrust driving forward nearly all the zones of the Ghrudaidh and Eilean Dubh limestone-groups, repeated by numerous reversed faults. The limestones are overlapped in turn by the materials lying above the Ben-More Thrust-plane, consisting of a great development of Archæan gneiss with the basic dykes covered unconformably by the Cambrian conglomerate and sandstones, with the basal quartzites resting unconformably on the latter. The serpentine referred to by Prof. Nicol as occurring in the Achall valley is one of the ultrabasic dykes in the thrust Archæan gneiss. The Ben-More Thrust-plane in the Achall valley is inclined to

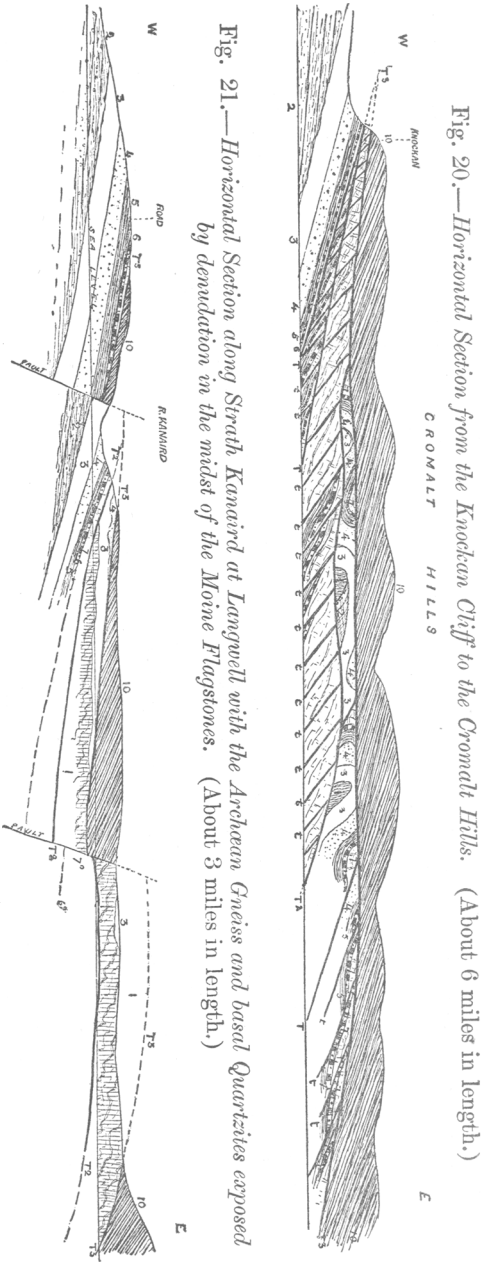


Fig. 20.—*Horizontal Section from the Knockan Cliff to the Cromalt Hills.* (About 6 miles in length.)

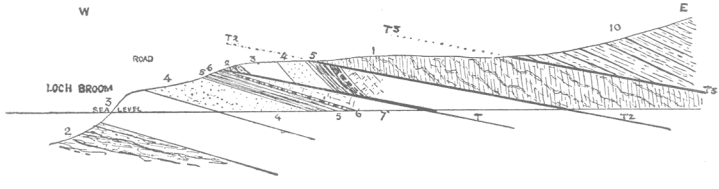
Fig. 21.—*Horizontal Section along Strath Kanaird at Langwell with the Archæan Gneiss and basal Quartzites exposed by denudation in the midst of the Moine Flagstones.* (About 3 miles in length.)

the east at an angle of 35°; but in places it has been folded, and the materials lying above it have been denuded away. Hence we find, to the west of Glastullich, that it is overlapped by the Moine flagstones, which there rest directly on the thrust Silurian limestones.

From the Achall valley southwards to Ullapool the outcrop of the Ben-More Thrust-plane can be traced almost continuously by means of the Archæan rocks. In two places, however, it is overlapped by the Moine Thrust, which ushers in the micaceous flagstones.

To the east of Ullapool there is an undisturbed order of succession from the basal quartzites to the Serpulite-grit. Along this latter horizon there is a powerful major thrust, bringing in a portion of the Cambrian sandstones overlain unconformably by the basal quartzites and succeeded by the various members of the Silurian series up to the limestone. Following the line of outcrop of this major thrust, southwards by the Braes of Ullapool to the shore of Loch Broom, a large mass of Cambrian sandstone appears above the plane, resting on the Serpulite-grit and spreading over a considerable area to the north of Corry Point. Near the latter locality the basal quartzites, in several places, rest unconformably on the Cambrian sandstones (fig. 22).

Fig. 22.—*Horizontal Section south of Ullapool.*
(About 1 mile in length.)



Passing eastwards, the Cambrian and Silurian strata borne along by this major thrust are abruptly truncated by the Ben-More Thrust-plane, well exposed at various localities. Along the western face of the disrupted gneiss, small patches of Cambrian strata rest unconformably on the latter with an inverted dip towards the plane of disruption. Eventually within a short distance the Archæan gneiss is overlapped by the micaceous flagstones above the Moine Thrust-plane.

To the south of Loch Broom the major thrust, which forms such an important feature in the geological structure of the Ullapool and Achall districts, is entirely overlapped by the Ben-More Thrust-plane, bringing forward a large slice of the old Archæan platform, consisting of gneiss with numerous basic dykes, covered unconformably by patches of Cambrian conglomerate and sandstone. Advancing southwards towards Little Loch Broom, the materials lying above the Ben More Thrust-plane consist almost wholly of Cambrian strata, which, at Dundonald, have been converted into schists. Indeed, so striking is the metamorphism developed by

these movements in the Cambrian strata near Dundonald that it is difficult to trace the line between the schistose sandstones and the eastern schists.

VI. Metamorphism resulting from the Post-Lower-Silurian Movements.

Having described the evidence in proof of enormous terrestrial movements along the chain of mountains between Eriboll and Ullapool, we now proceed to consider the relation of these displacements to regional metamorphism *. In reviewing the effects of these movements, we will describe the evidence furnished by (1) the Archæan, (2) the Cambrian, (3) the Silurian, and (4) the igneous rocks intrusive in the Cambrian and Silurian strata. From these various lines of evidence it will be seen that with each successive maximum thrust there is a progressive alteration in the displaced materials as we pass eastwards to the horizon of the micaceous flagstones overlying the Moine Thrust-plane.

1. *Metamorphism of Archæan Rocks.*

The great slice of Archæan rocks brought forward by the Glencoul Thrust does not present any striking evidence of deformation except close to the lines of disruption. To the north of Glencoul the original banding of the gneiss is as distinct as that in the Archæan area to the west of the Post-Lower-Silurian displacements, the general strike being W.N.W., and the dip of the foliation being S.W., at high angles. It is a significant fact that although the north-west dolerite-dykes are numerous in the undisturbed Archæan area between Ben Stack and Glencoul, none is met with in the thrust-gneiss, above this thrust-plane, till we pass southwards to Glencoul. Indeed the absence of these basic dykes and the presence of broad veins of red pegmatite point to the conclusion that the displaced gneiss between Strathcarran and Glencoul resembles that in the Archæan area to the north of Ben Stack. By protracting the angle which the basic dykes in the undisturbed gneiss on Ben Stack make with the direction of movement in the displaced masses, it is clear that the disrupted rocks must have travelled for several miles from the east.

Overlying the thrust-plane, a thin band of slaty schist or highly sheared gneiss is frequently met with, the strike of the foliation being more or less parallel with that of the thrust-plane. Advancing eastwards towards the limit of the displaced mass, these new divisional planes are more strikingly developed, owing to the number of more or less powerful thrusts. In the latter case, the new planes of schistosity may be either parallel with those of the

* It ought to be borne in mind that, though the movements affecting the Cambrian sandstones and the fossiliferous quartzites and limestones are now regarded as of Post-Lower-Silurian date, it may ultimately be possible to fix their age with greater precision, when the fossils from the Durness Limestone have been correlated with those of other countries.

thrust-planes or inclined at a higher angle. The basic dykes on the northern slope of Glasven show no perceptible alteration except where they have been traversed by some of the powerful Post-Lower-Silurian disruption-lines; but they show in a marked degree the foliation produced by the Pre-Cambrian movements.

The alteration of the Archæan rocks is more pronounced above the horizon of the Ben-More Thrust in Assynt. Along the unconformable junction of the gneiss with the Cambrian and Silurian strata, the former has entirely lost its original structure, and has been converted into greenish epidotic schist, the dip of the foliation being E.S.E. In one remarkable case, to be immediately described, where the gneiss is overlain by the Cambrian conglomerate, the schistosity developed in the latter passes downwards into the former, irrespective of the original bedding of the Cambrian beds or the original foliation of the gneiss. The new structures in the gneiss, along the junction-line, have been produced by the more rapid movement of the upper layers of displaced materials, without destroying the geological relation between the two. In other words, there has been a differential movement of the several layers of the thrust-masses as well as of the constituent particles over each other. Along the eastern slope of the Ben-More range, northwards to Glendhu, where powerful thrusts follow each other in rapid succession, bearing forward slices of the old Archæan platform with the quartzites, the new divisional planes are very prominent. Further, in the case of the dolerite dykes, new foliation-planes have been produced along the disruption lines, which are much more conspicuous than in the displaced dykes above the Glencoul Thrust-plane.

Advancing eastwards to the belt of sheared gneiss and green schist underlying the Moine Thrust-plane the evidence relating to regional metamorphism is of a most remarkable kind. The gneiss occupying this horizon between Loch More and Strathcarran possesses new divisional planes, the old ones having been almost wholly effaced. The dip of the foliation is E.S.E., being more or less parallel with that of the thrust-plane. On the foliation-surfaces close parallel lines, like those of slickensides, are met with, indicating the direction of movement, varying from 20° to 40° S. of E. The divisional planes are also coated with a thin film of sericite-mica, while "eyes" of felspar are drawn out in the direction of the movement. The pegmatites, too, have been sheared, so that their foliation-planes coincide with those of the gneiss, the original quartz and felspar appearing now as thin, close, red and white parallel streaks in the direction of the movement lines. Notwithstanding this extreme alteration of the Archæan rocks south of Loch More, the patch of limestone occurring in the heart of the mass is still recognizable as belonging to the two lowest limestone groups of Durness.

Along this same belt of sheared gneiss and green schist between Assynt and Loch Eriboll the Archæan gneiss has been rolled out into a finely laminated slate or slaty schist (mylonite), breaking into thin folia like leaves of paper. All the various stages of deformation,

from the crushed Archæan gneiss on the one hand, to the laminated slate on the other, can be clearly traced. The original constituents of the gneiss have been comminuted, but here and there broken fragments of the felspars occur, which are invariably drawn out in the direction of movement. The colour of the slaty schists has been determined by the nature of the materials out of which they have been made. Where the Archæan gneiss contained much epidote, the slates or "crush-rocks" are light green; where it contained much hornblende, they are dark green; where pegmatites or granitoid gneiss have been the chief materials employed, the resultant slates are red or pink. These finely laminated schists or slates show beautiful examples of fluxion-structure; and their foliation-surfaces display closely set lines or "striping," indicating the direction of movement of the particles over each other, the general trend of the latter being E.S.E. Associated with these slates are certain belts of "frilled" dark-green schists, of precisely the same character as those so well exposed on the coast-section east of Whitten Head, Loch Eriboll. A detailed study of the remarkable structure presented by these "frilled" schists points to the conclusion that they have been formed by Post-Lower-Silurian movements mainly out of dark hornblendic gneiss, the folia having been piled on each other by minute major and minor thrusts.

Occasionally, along this belt of sheared gneiss and schist, there are lenticular masses of the original Archæan rocks, which only show partial deformation, and, in addition to these, strips and wedges of Silurian and Cambrian strata which have been completely converted into schists.

2. *Metamorphism of Cambrian Strata.*

It is interesting to note that no Cambrian strata occur among the displaced masses brought forward by the Glencoul Thrust in Sutherlandshire. They do not appear till we reach the horizon of the materials lying above the Ben-More Thrust-plane. The various changes produced by these movements in the Cambrian conglomerates, sandstones, and shales are strikingly exemplified on Ben More, on the north side of the Oykel valley, and on Sgonnan More.

Beginning with the basal conglomerate, or "Button-stone," we find that it has undergone extraordinary changes, both where it underlies the gneiss in the Oykel valley and where it overlies that rock in Corrie Mhadaidh. In its unaltered form, throughout the undisturbed Cambrian areas, this characteristic band of conglomerate is composed of more or less well-rounded pebbles of quartz-rock, gneiss, pegmatite, diorite, &c., imbedded in a loose, gritty matrix. But where it has been subjected to mechanical movement, the softer pebbles of gneiss and the fragments of the basic Archæan dykes have been crushed, flattened, and elongated in the direction of movement. Indeed, in some cases, they have been drawn out to such an extent as to form thin lenticular bands of micaceous or

hornblende-schist flowing round the harder pebbles of quartz-rock. The latter still preserve their rounded form, but they are traversed by small "step" faults, tending to elongate them in the direction of movement. The original gritty matrix has been converted into a fine micaceous or green chloritic schist, showing exquisite "flow-structure," winding round the elongated pebbles in wavy lines. In short the matrix has been converted into a fine crystalline schist, and but for the presence of the deformed schistose pebbles it would probably be impossible to tell that the schist had a clastic origin.

No less remarkable is the phenomenon displayed in Corrie Mhadaidh (see fig. 23), where the foliation passes downwards from the Cambrian conglomerate into the underlying gneiss, irrespective of the bedding-planes of the former and the original foliation of the latter. The conglomerate is inclined to the W.N.W. at an angle of 20°. Along the line of junction it is welded to the old Archæan platform, so that rocks of widely different geological age practically form one mass. The planes of schistosity in the conglomerate dip to the E.S.E., more or less parallel with the plane of the Ben-More Thrust, and they are continued downwards into the gneiss, the original structures of which have been entirely effaced.

The Cambrian grits, sandstones, and shales have also been profoundly affected by these movements. Throughout them all cleavage-planes have been developed, dipping towards the E.S.E., more or less parallel with the plane of the Ben-More Thrust, at an average angle of 45°; while the original lines of bedding dip towards the W.N.W. Owing to the variable nature of the Cambrian strata, however, the cleavage is very unequally distributed, the beds of coarse grit being less distinctly cleaved, and the planes being more highly inclined than those in the finer sandstones and shaly bands. In fact, there seems to be a constant relation between the inclination of the cleavage-planes and the texture of the strata. The fine flags and shales behave, so to speak, like lines of weakness, their constituent particles having been drawn out or dragged much further than those of the grits. The planes of schistosity in the grits, flags, and shales form a series of sigmoidal curves, as represented in the accompanying section (fig. 23).

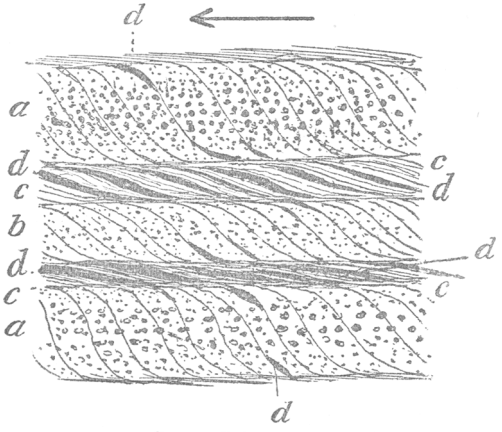
In addition to the cleavage, new minerals have been developed in the Cambrian strata. Sericite is abundant in the finer bands, so much so, indeed, that they might fitly be termed sericite-schists. At regular intervals too, along finer bands between the grits, lenticular veins of pegmatite occur, more or less parallel with the new schistose planes.

Again, on the slopes of Sgonnan More, the Cambrian flags and shales have been rendered schistose and show minute spots or knots resembling those in the knotted schists. This phenomenon is observable above the outcrop of the Ben-More Thrust-plane.

Finally, in the neighbourhood of Little Loch Broom, along the margin of the eastern schists, the Cambrian sandstones have been converted into schists, in which mica has been developed, and wherein the folia show beautiful wavy lines analogous to those in

the belt of green schist already described. At this locality these Cambrian schists seem to merge into the eastern schists without any well-marked boundary line.

Fig. 23.—*Diagram of Cambrian Strata on Coinne-mheall, illustrating differential cleavage, schistosity, and formation of pegmatite in Cambrian Grits and Shales above Ben-More Thrust-plane as seen in Coinne-mheaell and River Oykel.* (Area shown about 12 yards square.)



a. Coarse Grits or Arkose.
b. Finer Grits or Arkose.
c. Shales.
d. Pegmatites.
The arrow shows the direction of movement.

3. *Metamorphism of the Silurian Strata.*

The various members of the Silurian series underlying the Glencoul Thrust-plane show little alteration, even where they have been piled on each other by minor and major thrusts. The "Fucoid-beds" are occasionally cleaved, the planes being determined by the adjacent thrusts. Not till we pass eastwards to the horizon of the materials above the Ben-More Thrust-plane is much change observable. The various powerful thrusts above this horizon, repeating wedges of the Archæan platform with various members of the Silurian series, produce marked changes in the latter. Both zones of the quartzite have been attenuated by the elongation or dragging-out of their constituent mineral particles. In the case of the false-bedded grits, the small pebbles of quartz and felspar have been drawn out to a length of three inches near Loch Strath nan Asinteach. The felspar pebbles are often cracked in the direction of the movement and the fissures are filled with secondary quartz. Again, in the "pipe-rock," the quartz-grains have been elongated and the vertical "pipes" or Annelide-tubes have been bent over, flattened, and drawn out into ribands parallel with the direction of movement. Along the

divisional planes sericite has been abundantly developed, so that the strata lose all their normal characters and merge into quartz-schists. As a result of these changes, the quartzites have been reduced to a third of their usual thickness. At the base of the Stack of Glencoul and near Loch Ailsh, underneath the outcrop of the Moine Thrust-plane, these new structures are strikingly displayed. At the latter locality other members of the Silurian series share in the metamorphism. Advancing outwards from the Loch-Ailsh road to Cnoc Chaoruinn, the Silurian zones, from the false-bedded quartzites to the basal limestones, are repeated by thrusts at intervals of a few yards. At first the various zones are quite recognizable, the pipes in the quartzite being slightly bent over and the Serpulite-grit yielding Serpulites after a careful search; but with each successive displacement their characters are gradually modified, till it is impossible to distinguish them from some of the members of the eastern schists. The false-bedded quartzites merge into quartzose sericite-schists; the "pipe-rock" passes into a fine quartz-schist, in which the pipes are flattened like strips of paper, parallel with the foliation-surfaces; the original lines of bedding of the "Fucoid-beds" wholly disappear and are replaced by divisional planes, coated with white mica; the Serpulite-grit, no longer yielding Serpulites, becomes a quartz-schist, and, finally, the limestone becomes crystalline. On the new divisional planes numerous fine parallel lines are met with, indicating the direction of movement, trending generally E.S.E.; indeed this "striping" is equally apparent in the quartzites at the base of the Stack of Glencoul, at the head of Glendubh, and other localities.

4. *Metamorphism of the Igneous Rocks intrusive in the Cambrian and Silurian Strata.*

The evidence relating to regional metamorphism furnished by the great series of intrusive sheets in Assynt likewise indicates progressive alteration as we pass eastward to the Moine Thrust-plane. In the undisturbed area to the west of the Post-Lower-Silurian movements the igneous rocks of a granitoid type never show the slightest trace of a foliated or banded arrangement. The felsites, on the other hand, frequently show fluxion and spherulitic structures, where they traverse the old Archæan platform, along the margins of the dykes. Passing eastwards to the displaced Silurian zones underlying the Glencoul Thrust-plane, hardly any change is observable in the sheets, except in those instances where they have been driven along the "sole" of a major thrust. In the latter case the diorites in the limestones have been slightly cleaved and rendered schistose.

Crossing the outcrop of the Glencoul Thrust to the slopes of Coinne-mheall, we observe that some of the porphyritic felsites show a flow-structure like that of the rhyolites, and that in one case the rock has been completely reconstructed so as to become a fine-grained schist. On the crest of Coinne-mheall, just above the Ben-

More Thrust-plane, the sheets of felsite injected along the bedding-planes of the basal quartzites have been converted into soft sericite-schists, which can be cut with a penknife; and in Corrie Mhadaidh a felsite dyke on the same horizon has been cleaved parallel with the planes of schistosity in the Cambrian strata and with the plane of the Ben-More Thrust. All these changes have been developed in the dykes without much alteration in the quartzites in which they occur. Again, on the north side of the Oykel valley, a dyke of porphyritic felsite in the inverted Cambrian strata, above the Ben-More Thrust-plane, has been converted into a mica-schist, showing that peculiar "frilled" structure so marked in the green "frilled schists" of Eriboll.

Still further eastwards, in the belt of thrust and sheared Silurian strata stretching southwards from the Stack of Glencoul by the Gorm Lochs to Loch Ailsh and Allt Ealag, nearly all the dykes and sheets are beautifully foliated, the planes of schistosity being parallel with the planes of thrust. The fine-grained diorites in the limestones are now represented by green hornblende-schists and chlorite-schists; the holocrystalline rocks with porphyritic felspars set in a micro-crystalline base appear as bands of "augen-gneiss" and "augen-schist"; and finally, along a line of powerful thrust in the great granitoid sheet east of Loch Borrolan there is a belt of "augen-gneiss" with pyroxenes, which, existing originally as porphyritic crystals, now appear as "eyes" in the foliated rock. Indeed, so striking are the changes in these intrusive sheets close to the Moine Thrust-plane, that it would be almost impossible to identify them, were it not for the still recognizable zones in which they occur. Where the latter lose their distinctive characters, bands of white quartz-schist are then found, alternating with grey or green hornblende-schist.

From these various lines of evidence it is quite apparent that there is progressive metamorphism on a grand scale as the observer passes eastwards from the undisturbed western belt of ground to the horizon of the Moine Thrust-plane. It is also obvious that the crystalline rocks, where they occur in thin sheets, become schistose much more readily than the clastic rocks, and that the Cambrian sandstones and shales are more easily cleaved than the Silurian quartzites. It is also probable that the great thickness of the slice of Archæan rocks above the Glencoul thrust-plane, together with the heterogeneous character of its materials, prevented the development of new divisional planes in the thrust-gneiss, the deformation showing itself mainly in the fracture and crushing of the crystals. Not till we reach the point where powerful thrusts follow each other in rapid succession, repeating thinner slices of the old Archæan platform in the overlying quartzites, is the Post-Lower-Silurian shearing strongly marked in the Archæan rocks. At length in the zone of green schist and sheared gneiss underlying the Moine Thrust each divisional plane or foliation-surface is a shear-plane developed by these Post-Lower-Silurian movements.

5. *Succession of Strata above the Moine Thrust-plane.*

We must now describe briefly the strata overlying the Moine Thrust-plane, stretching eastwards by the Kyle of Tongue to Strathnaver. For nearly six miles there is a belt of strata of remarkably uniform character, consisting of flaggy quartzose mica-schists or fine-grained gneiss, typically developed on the Moine between Loch Eriboll and the Kyle of Tongue. These strata (the "younger gneiss" and "quartzose flagstones" of Murchison) have been traced continuously from the north coast of Sutherland to Loch Broom, showing little variation in lithological character. In the heart of the mass there is a prominent zone of hornblendic and micaceous schist, studded with garnets, traceable from the north coast to the Kyle of Tongue and thence round the north and west slopes of Ben Hope. There can be little doubt that this zone has once been an extensive sheet of igneous rock, because at various localities patches of the original igneous mass are still met with, consisting of diorite or diabase. Overlying this belt of garnetiferous schist, bands which can still be recognized as sheared Archæan gneiss can be followed for some distance.

Like the crushed slates, schists, and sheared gneiss (mylonites) underlying the Moine Thrust-plane, these flaggy crystalline schists and gneisses are inclined at gentle angles to the E.S.E. That they form an enormous pile of material is evident from the fact that they rise from the sea-level to the crest of Ben Hope (3040 feet). But a careful examination of the path along which they have travelled shows that the divisional planes or foliation-surfaces lie at an oblique angle to the thrust-plane (see fig. 20, where the Moine schists are represented as lying at an oblique angle to the plane of the Moine Thrust). It is obvious, therefore, that the thickness of the Moine schists cannot be estimated after the manner of ordinary sedimentary strata. This conclusion is confirmed by a study of the structures presented by these schists. The main divisional planes truncate minor planes, like the major and minor thrusts in the displaced Silurian strata. In other words, as the schists were being driven forward the materials were piled on each other to an enormous thickness. Further, on closer examination, it is observable that the different mineral constituents lie at an angle to the main foliation-planes. There is also evidence to show that the terrestrial movements were intermittent, because the first divisional planes in the Moine schists are frequently truncated by subsequent thrusts. During pauses in the disturbances dykes and thin sheets of various igneous (granitoid) rocks were injected across the foliation-planes, and these intrusions have been in turn sheared by later movements.

These crystalline schists and flaggy gneisses display parallel lines on the foliation-surfaces, indicating the same direction of movement as those in the sheared Silurian strata and crushed slates and schists (mylonites), while the constituent minerals are orientated along these lines. It is obvious, therefore, that the present strike, dip, and lithological characters of these crystalline schists and flaggy gneisses

were developed by movements after the Lower Silurian period. They differ, however, from the mylonites underlying the Moine Thrust-plane in one important feature, viz., that their matrix is holocrystalline. In other words, the formation of the Moine schists, as Professor Lapworth has shown, has been attended by greater molecular changes. Throughout the crystalline matrix numerous "eyes" of felspars and quartz occur, belonging to the original rock out of which the schists have been formed. The holocrystalline character of the Moine schists points in all probability to the conclusion that in their case the movements took place at a more rapid rate, thus producing a higher temperature and giving rise to greater chemical changes after the movements had ceased.

To the east of the Kyle of Tongue, the Moine flaggy schists alternate with occasional bands of hornblende-schist as far as Strathan, where they are succeeded by a belt of undoubted Archæan rocks, two miles in width, stretching eastwards nearly to the river Borgie. Consisting mainly of hornblendic gneiss with masses of rudely foliated diorite and dykes of ultra-basic materials (peridotites, &c.), these rocks present many of the typical features of the Archæan gneiss west of Durness. When followed southwards, this belt thins away till it disappears to the north of Loch Creagach, near Ben Loyal.

To the south of Tongue another belt of Archæan rocks has undergone a great amount of deformation by the Post-Lower-Silurian movements, the foliation-planes coinciding in direction with those of the Moine schists. But here and there throughout the belt patches of gneiss and pegmatite, showing the Pre-Cambrian foliation, may be detected.

Advancing eastwards to the Borgie River, we find alternations of flaggy Moine schist and gneiss, Archæan hornblendic gneiss striking generally north and south and dipping to the east, overlain by a peculiar type of gneiss in Strathnaver. Consisting mainly of black micaceous gneiss in which the mica is very abundant, this zone contains "eyes," "cores," or oval-shaped masses of diorite, whereof the longer axes lie parallel with the strike of the foliation. Round these "cores," both mica and hornblende curve in wavy lines, the latter disappearing as they are followed outwards into the well-foliated gneiss. There can be little doubt that these lenticular masses, or "cores," are patches of a once continuous sheet of igneous rock, out of which the Strathnaver gneiss has been formed. A remarkable characteristic of this foliated mass is the development in it of pegmatites, mainly along the lines of foliation. Beginning as isolated knots of felspar, they gradually become continuous, giving rise to thin strings or veins and eventually increasing in size till they form bands a hundred yards across. The formation of these pegmatites evidently formed a part of the process of metamorphism whereby the eruptive igneous mass was converted into a micaceous gneiss. From the fact that bands of Moine schist or flaggy micaceous gneiss are intercalated with the Naver gneiss, it is

highly probable that the deformation of this Archæan mass was mainly effected by the Post-Lower-Silurian movements.

From Bettyhill to Kirktomy there stretches a belt of flaggy micaceous gneiss, resembling part of the Moine gneiss; but to the east of the latter locality lies an area of undoubtedly Archæan rocks, several miles broad, which have only been slightly affected by the Post-Lower-Silurian movements. They consist of coarse hornblendic and micaceous gneiss with bands of diorite and gabbro, similar to the Pre-Cambrian crystalline rocks at Cape Wrath. Though the area to the east of Strathnaver has not been mapped in detail, we are at present inclined to believe that this broad belt of Archæan rocks resembles the mass of Pre-Cambrian strata at Strathan Skerray in its mode of occurrence. The latter, as we have shown, is intercalated in micaceous Moine schist or flaggy gneiss.

The Archæan rocks east of the Naver are traversed by dykes of pink and grey granite, which have been converted into granitoid gneiss by mechanical movements.

After the Moine schists and gneiss to the south of Tongue had acquired their present strike, dip, and lithological characters, in consequence of the terrestrial movements after the Lower Silurian period, the great sheet of syenite now constituting Ben Loyal was erupted, mainly along the foliation-planes. On the western slope of the mountain the schists and gneiss plunge underneath the intrusive mass with an E.S.E. dip, while along the north and south margins of the area they also pass underneath it. To the east of Ben Loyal the main body of syenite divides into several branching sheets, which are likewise intruded more or less along the foliation-planes. The boundary line traverses the western slope of Ben Loyal at a height of about 1000 feet, while the peak rises to a height of 2504 feet, so that this great intrusive mass is upwards of 1500 feet thick.

Other intrusive igneous rocks pierce the micaceous flagstones of the Moine series, consisting of dykes of diabase and mica-trap. The latter have been followed for miles through the Cromalt Hills, and in one case a dyke traverses both the Moine schists and the underlying Silurian strata of the Knockan cliff.

It is obvious that the facts now brought forward furnish a large amount of evidence in support of the theory *that regional metamorphism is due to the dynamical and chemical effects of mechanical movement acting alike on crystalline and clastic rocks.* It is further obvious that regional metamorphism need not be confined to any particular geological period, because in the North-west Highlands it occurred on a vast scale both in Pre-Cambrian time and at some period subsequent to that in which the Durness limestones were deposited.

6. *Denudation of the Land-surface before the time of the Old Red Sandstone.*

In the neighbourhood of Tongue remarkable evidence is obtained regarding the denudation of the old land-surface before

the deposition of the Old Red Sandstone. Between Ben Loyal and the Kyle of Tongue various outliers of this formation, described by the present Director-General of the Geological Survey, rest on a highly eroded platform of the crystalline schists. The deposits are also met with in the islands at the mouth of the Kyle. One of these outliers, at Cnoc Craggy (1043 feet), about a mile and a quarter to the north of the northern margin of the Ben-Loyal syenite, was grouped by Professor Nicol with the Torridon sandstones, and was believed by him to be overlain by quartzite*. The platform on which it rests is about 800 feet high. Upwards of 40 per cent. of the pebbles in the conglomerate are composed of the syenite of Ben Loyal. It follows, therefore, that the latter intrusive sheet was stripped of the overlying schists, thus proving enormous denudation before the deposition of the Old Red Sandstone.

Some of these outliers, on the east side of the Kyle of Tongue, rest on the Moine flagstones produced by the Post-Lower-Silurian movements, and they contain numerous fragments of these schists. Hence it is obvious that the changes must have been completed before the time of the Lower Old Red Sandstone.

Further evidence that the outliers really belong to the Old Red Sandstone is furnished by their numerous pebbles derived from the Cambrian and Silurian formations. Amongst these, we noted Cambrian sandstones, false-bedded quartzite, "pipe-rock," Serpulite-grit, and limestone belonging to several groups of the Durness limestone, some of the blocks containing *Murchisonia*. From the inclination of the layers in the conglomerate it is evident that the pebbles were borne by currents from the W.N.W.

The detailed examination of the north-west of Sutherland has furnished important evidence regarding the glaciation of the region, showing, for example, that during the greatest extension of the ice the centre of dispersion did not coincide with the existing range of high ground. It has also thrown light on the excavation of the present valley-system, on the relation of disruption-lines and the trend of basic dykes to surface-features, and, finally, on the formation of lofty mountains by denudation. But the description of these and other phenomena is reserved for the detailed official memoirs of the Geological Survey.

Discussion.

The President observed that the communication just made to the Society was remarkable, not only for its importance, but for the mass of details it contained; it was, in fact, four or five papers rolled into one.

Professor Lapworth commented on the wonderfully descriptive character of the paper. The general conclusions arrived at were very similar to those he had himself indicated. There was this difference that when he brought forward his views such notions were novelties and were consequently regarded with suspicion. But so much has the question been ventilated within the last four years that he pre-

* Quart. Journ. Geol. Soc. vol. xvii. p. 92.

dicted for this paper a hearty reception. So well had the subject been worked out by Messrs. Peach and Horne and their colleagues, that it had been made clear that our own country contained structures which were practically unequalled as types of metamorphism. So far from lagging behind, we were now fully abreast of foreign investigation; and when the paper came to be printed, with no stint as to illustrations, it must rank as one of the highest value. Such sections are to a certain extent astounding, yet they do occur. He spoke of the fascination of these studies, and felt sure that they gave promise of a great future for British geology. He was only acquainted with the Durness-Eriboll district; but from his knowledge of the accuracy of the Authors' work there, he had every confidence in their interpretation of the other districts. The paper will also add to our knowledge as regards the theory of the origin of the Archæan rocks. He complimented the officers of the Survey on the interest and excellence of their work.

Dr. Hicks considered that the interest attaching to the district under discussion will hold as far as Loch Carron. One point in respect of the origin of the Archæan rocks he particularly noticed in the paper was the amount of alteration these rocks had undergone in Pre-Cambrian times. These features were seldom obliterated by the new movements. It would be interesting to know to what extent the central area of the Highlands was made up of the old and the new rocks. He imagined that comparatively little of the latter would be found there. He spoke of the evidence afforded in the paper of rocks other than those now known to occur in the area, testifying to an enormous amount of denudation prior to the deposition of the Torridon Sandstone. He had also noticed and referred to the presence of such rocks in the Torridon series further south. He thought the paper a credit to the Survey and to British geologists generally.

Professor Judd also congratulated the Survey on this important piece of work. Before offering any criticisms we must wait till we have an opportunity of studying it in detail. It supplied important evidence in support of a principle which had been maintained by many of the most distinguished members of the Geological Society in past times—namely, that foliation is not coincident with stratification.

Mr. Teall commented on the many points opened up, and on the immense amount of work embodied in the paper. He could say but little. What was the Archæan gneiss originally? what is its most original rock? In many instances the divisional planes are not vertical, but described as rolling at gentle angles. In such cases the strike is represented as being about N.E.; hence the so-called normal, or N.W. strike must be secondary. What do the original planes of division represent? Are they lines of segregation in a plutonic magma? He was glad to find that his petrographical work, more especially in connexion with the development of hornblende-schist out of dolerite, had been confirmed.

Mr. Hudleston said that every one who had paid any attention

to the difficult subject with which this paper deals must have listened with genuine pleasure to the story of the solving of these mysteries, which even a few years ago seemed almost to defy the attempts of geologists. Persons who lived before the discovery of "thrust-planes" might well be excused for not having read aright the section at Craig-a-Knockan. It was to be hoped that in the great future which was promised to British geology some attempt would be made to explain the dynamics of these phenomena. He ventured to point out what seemed to him a discordance between certain sections through the Ben More range and the generalized section through Assynt.

Mr. Peach explained that the apparent discrepancies alluded to by Mr. Hudleston were due to a difference in the direction of the sections and in the level of the datum-line. He thanked the Society for the way in which the paper had been received, and in reply to Mr. Teall assured him that they had thought about these things, but their solution, he considered, must be left mainly to the microscopist.

Mr. Horne alluded to the value of Professor Lapworth's work, of which they had the highest appreciation, seeing that their conclusions were practically identical.

Dr. Geikie also expressed his satisfaction at the reception accorded to the paper. Referring to a remark by Dr. Hicks, the survey of the country had not yet got so far as Gairloch, where Dr. Hicks's observations had been made. He was both ready and anxious to do justice to the work of previous writers. Referring to the future progress of the Survey, he held out hopes that another paper, giving the results of the detailed study of the southern half of the belt of great complication, might be presented to the Society ere long in anticipation of the Survey Memoirs.