PETROLOGY of the MIDDLE OLD RED SANDSTONE
ERORA OUTLIER of NORTH-EAST SCOTLAND:
A Study in Provenance

By

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THESIS submitted to the UNIVERSITY of EDINBURGH
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form of many of the conglomerate pebbles; nor of the fact that, when tested by Wentworth's method, pebbles from the conglomerates are found to plot in an area of his graph-diagram which is indicative of fluvo-glacial derivation, and distinct from that occupied by pebbles of "fanglemerate" type. Accordingly, it is suggested for serious consideration that the fluvo-glacial hypothesis may, on balance, be preferable to what the present author has termed the "fanglemerate" hypothesis.

The sphericity of the pebbles is found to increase from north to south, and this evidence is used to narrow down the number of possible directions of derivation. The fabric of the conglomerates was analysed and found to indicate derivation from the north-west. Examined in thin section, the pebbles are found to be markedly similar to the granitic and granulitic rocks lying to the west and north-west of the Brora Outlier. By a process of elimination, derivation from the north-west is established.

In addition, by sifting the relevant literature, a general provenance map of the Middle Old Red Sandstone sediment of north-east Scotland has been prepared. From a study of this map, reason is found to doubt the supposition that the Old Red Sandstone sediments of the British area ever extended far beyond their present western margins.
ABSTRACT OF THESIS

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The Erra Outlier of north-east Scotland, which comprises conglomerates and sandstones of Middle Old Red Sandstone age, has been studied with a view to determining something of its depositional history. Various techniques have been employed in an attempt to elucidate the desired information, and the methods used are described.

Samples of the sandstones were mechanically analysed and the results obtained compared with those of modern sediments of known origin. On this basis, the Erra Outlier sandstones are shown to be allied to outwash sands, and, in particular, to bear a close resemblance to fluvo-glacial outwash sands, but it is stressed that the validity of evidence of this nature is perhaps ambiguous, and acceptance of it without reservation is not advised. The hypothesis that the Erra Outlier sediments may have been fluvo-glacially derived (in contrast to the current hypothesis which would identify them as "famglomerates" and associated alluvial outwash fan deposits) is nonetheless presented for consideration, and the evidence afforded by certain features of the sandstones and conglomerates weighed with respect to both concepts.

A banded appearance, due to the alternation of darker, finer layers with lighter layers of a coarser texture, is to be observed in some of the sandstones. This feature is fully discussed; a mechanism put forward to account for it, and reason found for believing that the red colour of the sandstones, due to the presence of haematite, is of post-depositional development. Though restricted in variety and amount, the heavy minerals are considered to afford evidence of derivation from areas lying immediately to the west and north-west of the Erra Outlier.

Many of the features of "famglomerates" and alluvial outwash sands are also characteristic of conglomerates and sandstones of fluvo-glacial derivation. It is therefore extremely difficult to establish criteria for distinguishing between the two types of deposit. Thus, in the case of the Erra Outlier sediments, certain features - the angularity of the sandstone grains; the occasional rude stratification of the conglomerates; the large number of grade sizes present in the conglomerates; and the apparent local nature of the constituent pebbles - all afford only equivocal evidence. It is argued, however, that the same cannot be said of the isolated occurrence of pebbles in an otherwise homogeneous sandstone exposure (which can be best explained in terms of ice-rafting); of the typical glacial form.
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ABSTRACT

The Brora Outlier of north-east Scotland, which comprises conglomerates and sandstones of Middle Old Red Sandstone age, has been studied with a view to determining something of its depositional history. Various techniques have been employed in an attempt to elucidate the desired information, and the methods used are described.

Samples of the sandstones were mechanically analysed and the results obtained compared with those of modern sediments of known origin. On this basis, the Brora Outlier sandstones are shown to be allied to outwash sands, and, in particular, to bear a close resemblance to fluvio-glacial outwash sands, but it is stressed that the validity of evidence of this nature is perhaps ambiguous, and acceptance of it without reservation is not advised. The hypothesis that the Brora Outlier sediments may have been fluvio-glacially derived (in contrast to the current hypothesis which would identify them as "fanglomerates" and associated alluvial outwash fan deposits) is nonetheless presented for consideration, and the evidence afforded by certain features of the sandstones and conglomerates weighed with respect to both concepts.

A banded appearance, due to the alternation of darker, finer layers with lighter layers of a coarser texture, is to be observed /
observed in some of the sandstones. This feature is fully discussed, a mechanism put forward to account for it, and reason found for believing that the red colour of the sandstones, due to the presence of haematite, is of post-depositional development. Though restricted in variety and amount, the heavy minerals are considered to afford evidence of derivation from areas lying immediately to the west and north-west of the Brora Outlier.

Many of the features of "fanglomerates" and alluvial outwash sands are also characteristic of conglomerates and sandstones of fluvioglacial derivation. It is therefore extremely difficult to establish criteria for distinguishing between the two types of deposit. Thus, in the case of the Brora Outlier sediments, certain features - the angularity of the sandstone grains; the occasional rude stratification of the conglomerates; the large number of grade sizes present in the conglomerates; and the apparent local nature of the constituent pebbles - all afford only equivocal evidence. It is argued, however, that the same cannot be said of the isolated occurrence of pebbles in an otherwise homogeneous sandstone exposure (which can be best explained in terms of ice-rafting); of the typical glacial form of many of the conglomerate /
conglomerate pebbles; nor of the fact that, when tested by Wentworth's method, pebbles from the conglomerates are found to plot in an area of his graph-diagram which is indicative of fluvio-glacial derivation, and distinct from that occupied by pebbles of "fanglomerate" type. Accordingly, it is suggested for serious consideration that the fluvio-glacial hypothesis may, on balance, be preferable to what the present author has termed the "fanglomerate" hypothesis.

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In addition, by sifting the relevant literature, a general provenance map of the Middle Old Red Sandstone sediment of north-east Scotland has been prepared. From a study of this map, reason is found to doubt the supposition that the Old Red Sandstone sediments of the British area ever extended far beyond their present western margins.
INTRODUCTION

With the exception of its extreme north-west corner, the Brora Outlier, which comprises conglomerates and sandstones of Middle Old Red Sandstone age, is wholly contained in one-inch Sheet 103 of the Geological Survey of Scotland. A copy of Sheet 103 is included for reference at the end of this work.

The Brora Outlier proper extends nearly 14 miles in a north-easterly direction from Strath Lundie. At its widest part it measures 4½ miles. Its western margin is defined by the escarpment which runs from Silver Rock north-westwards to Cnoc na Gaimhne, and thence north-eastwards by Beinn Smearail and the Craggan to Kilournan in Sheet 109. The eastern margin is partly defined by the escarpment of Ben Uarie, Cnoc na h-Iolaire and Killin Rock, and in part by the Jurassic Boundary Fault and its continuation. The Brora Outlier succession is as follows:

1. Basal conglomerate and arkose.
2. Mudstones and sandstones
3. Pebbly sandstones and massive conglomerate
4. Flaggy sandstones

The writer has largely confined his attention to that part of the Brora Outlier lying to the south-west of Loch Brora, including the conglomerates of Mound Rock, Creag an Amalaidh and Ben /
Ben Tarvie, which are thought to be the equivalents of the lower members of the Brora Outlier (Mem. Geol. Survey, 1925, p. 63).

The Ben Lundie conglomerate, and the sandstones of Beinn a' Bhragie into which it passes upwards, lie undisturbed, dipping at gentle angles to the south-east. Further north, the strata of the two lower groups have been synclinally folded. The fold-axis runs north-eastwards from Glen Rock, almost parallel to the western margin, and terminates at Kilournan, where the two sides of the syncline come together. Parallel to the axis of folding is a line of faulting which can be traced from Glen Rock to the western side of Carrol Rock, is probably continuous, though not apparent, along the line of Oldtown Burn, but then reappears on the eastern side of Meallan Liath Beag, and runs north-eastwards past the eastern face of The Craggan to the termination of the outlier in Sheet 109. As a result of the folding and faulting which followed upon the deposition of Groups 1 and 2, the sandstones of the latter group, between Ben Horn and Carrol Rock dip to the south-east at angles up to 40°, and on the eastern side of The Craggan, dip to the west at angles up to 50°. In this latter locality, these westerly dipping sandstones, which form the eastern limb of the syncline, are brought down abruptly against the easterly dipping basal conglomerate /
conglomerate which forms the western limb. In a depression which occupied the trough of this syncline, Groups 3 and 4 were deposited. The sandstones and conglomerate of Group 3 rest unconformably upon the steeply dipping deposits of Group 2, overlap on the eastern margin of the outlier on to the basal arkose of Group 1, and, between Creagan Mor and Killin Rock rest directly upon the Moine rocks. On the western margin of the outlier, the conglomerate of Group 3 forms Beinn Smeorail and the high ground to the north-east of it. Further north it extends from the east side of Meallan Liath Mor eastwards to a point near Druim Dearg, then south-eastwards to Creag a' Chrionnaich. South of Loch Brora, the conglomerate-outcrops on the northern and south-western flanks of Meall Coire Aghaisgeig may be regarded as a continuation of the massive conglomerate which outcrops on the western margin of the northern half of the outlier. These outcrops are limited to the west by the Glen Rock - Carrol Rock fault, and to the south by the fault which runs south-east from Meall Odhar. The outcrop of the conglomerate of Group 3 on the eastern side of this southern half of the outlier, is truncated by the fault which runs north-eastwards past Dunrobin Wood. The flaggy sandstones of Group 4 build the mass of Col-bheinn in the northern half of the outlier, and in the southern half, those of Meall Coire Aghaisgeig and Cagar Feosaig. Though /
Though never attained in any one locality, the maximum total thickness of the four groups is in the region of 4,600 ft.

In the course of the present study, various aspects of the sandstones and conglomerates of the Brora Outlier have been examined, chiefly to ascertain whence these sediments were derived, and under what conditions and by what means they were transported to the area which they now occupy. To what extent these aims have been achieved is made evident in the following account, and in the summary of results embodied in the "Abstract" (pp. iii - v) and "Conclusions" (pp. 188-191).
TOPOGRAPHY

The area which includes the sediments here under consideration, is contained in Sheet 103 of the Geological Survey of Scotland, and lies wholly within the County of Sutherland. Topographically, the area lends itself to a natural, tripartite division, closely related to its geology.

The following three units are easily discernible:

(a) the Coastal Platform;
(b) the Coastal Range; and
(c) the Inland Plateau.

The Coastal Platform is a low-lying tract of land which runs from Helmsdale, south to Loch Fleet. It is bounded to the east by the sea, and inland, to the west, by the eastern slopes of the Coastal Range, and by a large fault which brings down the rocks of the Coastal Platform successively, from north to south, against the Helmsdale Granite, against the granulites of Creagan Mor, and against the Old Red Sandstone sediments of Cagar Feosaig, Beinn a' Bhragie and Mound Rock. Loose glacial deposits, raised beach and blown sand, now cover the soft Old Red Sandstone, Triassic and Jurassic rocks which underlie the platform. The only good arable land in this part of the county is confined to this coastal strip, and many fair-sized farms lie within its limits. In addition the towns of Helmsdale, Brora /
Brora and Golspie are situated on the Coastal Platform, together with numerous small villages. Advantage was taken of this level coastal belt in the laying of the Highland Railway.

As the name suggests, the Coastal Range includes the highest ground in the area. It is bounded on the seaward side by the Coastal Platform, and gives way westwards to the Inland Plateau. Except in its north-eastern extremity, where it owes its existence to the Helmsdale Granite, the range is built of the conglomerates and sandstones of the Brora Outlier and its associated sediments. The close relationship between the geology and the topography of the area becomes evident when it is realised that those sediments which form the Coastal Range rest unconformably on the Moine granulites, which themselves underlie the greater part of the Inland Plateau. An unconformable junction also exists between the Old Red Sandstone sediments and the south-western extremity of the Helmsdale Granite massif.

The Coastal Range proper may be considered as running from Eldrable Hill and Ben Uarie, southward to Ben Lundie. The valley of Loch Brora effectively bisects the Coastal Range. The southern half of the range is cut through by Dunrobin Glen, while Glen Loth and Glen Sletdale traverse the northern half. Ben Uarie (2,046 ft.) is the highest peak of the range which includes numerous other summits over 1,500 ft. in height.
Except along those valleys already mentioned, the range is uninhabited, and supports only deer and grouse.

The Inland Plateau, the third topographic unit, is the most westerly of the three, and rises gently from the escarpment formed by the Old Red Sandstone sediments which limit its extension eastward, to the western margin of Sheet 103, where, in places, a height exceeding 1,000 ft. is attained. The peat and moss deposits which mantle large areas of the plateau are underlain by Moine granulites and by granites. Hence, the plateau is in reality, the eroded relic of the floor on which the Old Red Sandstone sediments which now form the Coastal Range were originally deposited.

The Inland Plateau is now largely depopulated, and the present crofter population is concentrated in the Rogart region. Where possible, the land is utilised for sheep-grazing. Wherever this is impracticable, however, as it often is on account of inaccessibility, deer and grouse enjoy an undisturbed seclusion.

Although still preserved, the threefold topographic division of the area is less evident south of Strath Fleet. The Coastal range can be followed via the summits of The Mound, Creag an Amalaich and Cnoc Odhar, as far south as Ben Tarvie. Beyond this point, however, no topographic distinctions can be made /
made in the land which rises gradually from sea level on the coastline between Skelbo Station and Dornoch, to a maximum height of 1,000 ft. in the area of Migdale Granite on the western margin of the map. The An Droighneach ridge, which is formed of Old Red Sandstone sediments, and runs with a W.N.W. - E.S.E. trend on the south side of Strath Fleet, is a discordant feature in both the topography and geology of the area.

The most important river system of the area is that of the River Brora and its tributary the Black Water. The system was initiated on a south-easterly sloping Old Red Sandstone surface. River capture, following on the denudation and subsequent retreat of the escarpment eastward, has resulted in the concentration of the drainage of a large part of the Inland Plateau into the single River Brora, which flows from Loch Brora. The Black Water, the main tributary of the River Brora, runs in a rocky gorge and hangs with respect to the parent river, indicating a scouring of the broad valley of the latter during glaciation. This is concordant with the direction of movement of the ice, estimated by the measurement of striae to have been along a line trending approximately E. 30° S.

Smaller systems include the River Fleet, Torboll River, the River Evelix and the many small streams which flow south-eastward off the Coastal Range, such as the burns of Glen Loth and /
and Glen Sleddale. The northern margin of the area from Cnoc Meadhonach eastward to Helmsdale, is drained by the small tributaries of the River Helmsdale, which flow northward to join the main river.

Loch Brora, the largest loch of the area, is the only one which has been surveyed bathymetrically. It is some 3½ miles in length, and has an average breadth of less than a quarter of a mile. The maximum depth is 11 fathoms, and the mean depth a little over 2 fathoms. It receives the drainage of more than 100 square miles of the surrounding country, and has an estimated content of some 553 millions of cubic feet. Side deltas at Carrol and Oldtown divide the loch into three parts, while the continued growth of the incipient delta of the Allt Smeorail at Gordonbush promises a future fourfold division. Glacial overdeepening of the valley of the River Brora has already been mentioned, and Loch Brora now occupies part of the ice-gouged hollow.

Loch Lundie, which lies to the south, also occupies a basin scooped out by the ice. Loch Horn, which lies midway between Loch Brora and Loch Lundie, on the south-west flank of Ben Horn is a true corrie-loch. The majority of the other lochs in the area, such as Loch Tarvie, are of the shallow, moraine-
moraine-dammed type. Although moraine-dammed, Loch Airidhe Mhor, lying at the western end of the An Droighmeach ridge, occupies a basin, partly determined by the presence of a fault-line.
HISTORY OF PREVIOUS RESEARCH

Throughout the history of geological research in Britain, the assemblage of varied strata known collectively as the Old Red Sandstone has been a subject of controversy. Indeed, early in the nineteenth century, the Old Red Sandstone deposits were not generally recognised as constituting a separate system in their own right. Hugh Miller (1841) quotes a celebrated foreign geologist who referred to the Old Red Sandstone as: "a mere local deposit, a doubtful accumulation huddled up in a corner," and this despite the fact that it was known to outcrop in Herefordshire, Worcestershire, Shropshire, South Wales, Sutherland and Caithness, in which last locality alone the estimated thickness of the Old Red strata is some 18,000 feet.

After the general acceptance of the independent status of the Old Red Sandstone, other problems sprang into prominence; problems which gave rise to sharp divisions of opinion, and to which no conclusive solutions have even yet been found. Mode of deposition, relative age of the different strata within the system, and colouration of the red beds, are but a few of the controversial topics with which this unique system has furnished geologists.

Several different hypotheses have from time to time been /
been advanced by various authors, to explain the conditions of origin of the Old Red Sandstone. Hugh Miller was of the opinion that the Old Red Sandstone deposits were of marine origin and comparable with modern tidal deposits. In his book "The Old Red Sandstone," he writes:

"The first scene in the "Tempest" opens amid the confusion and turmoil of the hurricane, amid thunders and lightnings, the roar of the wind, the shouts of the seamen, the rattling of cordage, and the wild dash of the billows. The history of the period represented by the Old Red Sandstone seems, in what now forms the northern half of Scotland, to have opened in a similar manner --- the vast space which now includes Orkney and Lochness, Dingwall and Gamrie, and many a thousand square mile besides, was the scene of a shallow ocean, perplexed by powerful currents, and agitated by waves."

Dr John Fleming and Dr Mantell, both contemporaries of Hugh Miller, suggested that the Old Red Sandstone deposits were of lacustrine origin. In 1855 Godwin-Austen endorsed this opinion. Even at that time, however, the Old Red Sandstone had not won unanimous recognition as a distinct formation. Godwin-Austen regarded the Upper Silurian and Devonian strata as being equivalent, and the Old Red Sandstone deposits as contemporaneous with the Marwood beds, which last were included in the Carboniferous system.

The concept of the lacustrine origin of the Old Red Sandstone deposits was further developed by Sir Archibald Geikie, and in 1878 he propounded his now well-known hypothesis of the five/
five separate basins of deposition.

"Thus," he states, "agreeing in the now very generally accepted view of the lacustrine origin of the Old Red Sandstone, I shall speak of the separate basins of deposit as lakes, to which, for ease of reference, different names will be given."

The names: Lake Orcadie, Lake Caledonia, Lake Cheviot, Lake of Lorne and The Welsh Lake, are now commonplaces in the literature of British geology.

The matter then lay dormant for almost twenty years; a reflection doubtless of the respect which the opinions of Geikie commanded, and of the prestige which he enjoyed as Director of H.M. Geological Survey of Scotland, and Murchison Professor of Geology and Mineralogy in the University of Edinburgh. In 1896 however, Macnair and Reid revived the concept of the marine origin of the Old Red Sandstone, an hypothesis which Hugh Miller had propounded some sixty years earlier. Without invoking any Shakespearian analogy they state:

"We also in the course of the paper propose to show the "Character of the Strata" is entirely against its supposed deposition in small inland fresh-water lakes; that the absence of unequivocally marine fossils is not so complete as supposed, neither is it fatal to their marine origin; that land plants occur freely in undoubted marine strata; and that the existence of the representatives of ganoid fishes in the rivers and lakes of the present day is entirely out of evidence when we consider the immense number of these fossil fishes found in undoubted marine deposits both in England and Russia, and of their wide distribution over the continents of Europe and America."
Publication of these views appears to have stimulated enthusiasm for the problem, and, in 1904, Goodchild formulated his continental hypothesis. He visualised deposition to have occurred under variable climatic conditions characterised by a markedly low average rainfall, to which latter factor he attributed the "common character" of the Old Red Sandstone. The presence of the dominantly piscine fauna in the Upper Old Red sediments he explained on the basis of migration from upland rivers which would be subjected to excessive evaporation on reaching the lowland plains. The Lower Old Red Sandstone deposits of the Caledonian area were also, he claimed, formed under continental conditions. Thus these deposits were in part lacustrine, in part torrential, in part old desert sands, or had resulted from widespread volcanic activity.

In 1907, J. Darrell, unaware then of Goodchild's paper, published a brief account of the fluviatile nature of the piscine fauna, and of what he considered to be evidence of a great development of floodplain deposits in the Old Red Sandstone. This paper, the forerunner of his more extensive publication of 1916, was followed in 1908 by Walther's volume entitled: "Geschichte der Erde und des Lebens," in which the author draws an analogy between the climatic and sedimentary conditions of his "Old Red Northland", and those obtaining at the /
the present time in the interior of Asia and Australia. He further stresses that under the lacustrine concept, the reader should not envisage enduring bodies of water, but rather lakes of a transient nature whose existence was dependent on the occasional thunderstorms which relieved an otherwise arid climate.

Jukes-Browne, in his volume on "The Building of the British Isles", (1911), recognises the validity of the arguments set forth by Goodchild in support of an intermittently desert climate, but shelves the concept of fluvialite deposition in favour of a lacustrine origin.

Barrell (1916) acknowledges that he is in agreement with Goodchild's views, but adds that:

"he would give first place to true fluvialite deposition, spreading sediments on broad and flat river plains, a form of deposition intermediate between torrential and lacustrine and yet quite distinct from either. It is one which is not, however, specifically mentioned by Goodchild."

Indeed, short of reverting to the marine hypothesis, or postulating a glacial origin for the Old Red Sandstone deposits, Barrell could hardly fail to be in agreement with at least a few of the suggestions embodied in Goodchild's publication.

Barrell cites the work of Dr O'Connel on "The Habitat of the Eurypterida" in support of his views. Dr O'Connel reaches /
reaches the conclusion that since the eurypterids were of dominantly fluviatile affinities, then the Old Red rocks which contain them must of necessity be fluviatile in origin.

Finally, Barrell draws attention to the "Textbook of Geology", published by Pirsson and Schuchert in 1915, in which, referring to the Old Red Sandstone deposits of Scotland, they state:

"They are probably wholly continental, and were accumulated in several independent and subsiding valleys, under a climate more or less arid."

From a consideration of the foregoing hypotheses, two main concepts can be distinguished: the marine, and the continental. The proposals advanced by the various authors to explain the conditions of origin of the Old Red Sandstone are but variations on one or other of those two central themes. Of the two, the concept of continental derivation has won by far the wider acceptance. Today, Old Red Sandstone sediments which comprise coarse conglomerates and closely associated sandstones are commonly thought to have been laid down as torrential, intermontane deposits and alluvial outwash fans, whereas where the Old Red Sandstone is represented by great areal spreads of fine-grained flaggy sandstones, a lacustrine origin is inferred. The Brora Outlier deposits here considered would therefore fall within the first category, and the Old Red Sandstone deposits of Caithness and Orkney, for example, within the second. The lacustrine hypothesis does in actual fact /

Another controversial question which had to be considered, was the manner in which the Old Red beds might be subdivided within the formation. In 1859, Sir R.I. Murchison had subdivided the Old Red Sandstone deposits of Caithness into the three following groups:

1. Upper Red and Yellow Sandstones
2. Middle Grey and Dark-coloured Flags
3. Lower Red Conglomerate and Sandstones.

Sir Archibald Geikie (1876) however, would not support this classification proposed by Murchison, stating that:

"Never having been able to find any stratigraphical support for this classification, I can hardly resist the suspicion that, plausible though the argument from fossil evidence appears, the threefold subdivision was unconsciously suggested by the seemingly well established arrangement of the true Devonian rocks, and by the natural desire to establish a closer analogy between these rocks and the Old Red Sandstone."

It must be remembered that Geikie himself could scarcely fail to have approached the problem without at least an unconscious bias in favour of a twofold division of the Old Red Sandstone in the north of Scotland; for he had already shown conclusively (Q.J.G.S., 1860) that such a division was /
was unquestionably valid for both the Midland Valley and the south of Scotland.

The main evidence for and against the erection of a middle division rested on the character of the piscine fauna to be found in the strata concerned. Murchison had maintained that the fauna of the flagstone series differed significantly from that of the undoubted Lower Old Red Sandstone, and that the absence of early forms such as Pteraspis and Cephalaspis from these flagstones showed them to be of later date. Sir Archibald Geikie (1878) in reply to Murchison stated that, in his opinion, the palaeontological discrepancies which existed between the faunas of the north of Scotland and the rest of the country could be explained on the basis of isolation and variation in the conditions of deposition, and that consequently the proposed middle division did not in fact exist.

"So strong," he concludes, "does this presumption seem to me that it cannot, I think, be set aside, save by much more convincing reasoning than that by which the Middle Old Red Sandstone of this country was considered to be established."

More convincing evidence was shortly to appear.

Dr John W. Evans (1891) maintained that the fish fauna of the Caithness rocks was more closely allied to that of the Upper Old Red Sandstone than to the fauna of the Lower division. Dr Traquair (1894) in supporting this view, added that three distinct /
distinct fish faunas - a Lower, a Middle and an Upper - could be recognised in the Old Red Sandstone of Scotland, and that the Caithness fossils bore marked affinities to those of the Middle and Upper divisions.

It is interesting to note, however, that in the first edition of one-inch Sheet 103 of the Geological Survey of Scotland, published in 1896, the Old Red Sandstone deposits within its boundaries were placed in the Lower and Upper divisions of that formation. In the Upper division was placed the coastal series of the Loch Fleet - Dornoch area: red and yellow sandstones which had yielded scales of Holoptychius. The rocks of the Brora Outlier, together with the narrow strip of conglomerate which skirts the south side of Strath Fleet between Craig-a-bhlair and Corryachvrail, and the fringe of flaggy red sandstone downfaulted against the Helmsdale Granite massif between Lothbeg and Gartymore, were assigned to the Lower division.

The evidence afforded by the fish fauna was supported by that yielded by the fossil plants. Dr Kidston (1902) recognised three main divisions of the Old Red Sandstone floras, each with its unique assemblage. Macnair and Reid had stated in 1897 that the flora of the Caithness strata was distinct from that of the Old Red Sandstone deposits south of the Grampians.
Grampians. At variance with Geikie on this matter, as they had previously shown themselves to be on the question of origin, they concluded:

"any theory which makes those two deposits contemporaneous and demands for them a common land-barrier is, in our opinion, wholly unscientific and untenable."

The authors of "The Geology of Caithness" (1914), after consideration of the foregoing evidence, regarded the existence of a Middle Old Red Sandstone division in Scotland as definitely proved.

The present interest in this controversy rests on the fact that H.H. Read (Mem. Geol. Survey, 1925) has, on the basis of lithological similarity, correlated the barren rocks of the Brora Outlier with the rocks of the Berriedale and Morven districts. The rocks in these last two localities are themselves placed in this disputed Middle Old Red division.

Mention has already been made of the colouration of the red beds as a further topic of controversy. The Old Red Sandstone rocks lend themselves naturally to the study of this colour problem, which is, of course, inseparable from the conditions of origin of the sediments concerned. The writer hopes to return to this question later, so it will suffice for the present to state that there are two prevailing concepts; the first that the red colour of the sediments is indicative of derivation from a deeply weathered, red-coloured source rock /
rock, the second that the red colour testifies to ancient aridity.

The foregoing account will perhaps serve to indicate some, but by no means all of the major problems with which any general study of the Old Red Sandstone is confronted. Other questions, such as the relation of the Old Red Sandstone and its parts to tectonics, remain to be answered. Is the lower part akin to Flysch and the upper to Molasses? Again, the analogy with the Torridonian suggests further problems. The Old Red Sandstone is a natural accompaniment of the Caledonian orogenic belt. With what orogenic belt are the Torridonian sediments associated? A successful theory which will satisfactorily resolve all those problems, will be concerned, not merely with the rocks of any one area, but with those of the Old Red Province as a whole, and will itself be a group of interrelated hypotheses. So great is the magnitude and complexity of producing such a theory, however, that it will be effected, not so much through the work of any one observer, as from a consideration of a large number of individual contributions.
The starting-point, marked by a cross, was arbitrarily fixed. Samples were then collected at the points indicated by the black circles.
METHODS USED IN STUDYING THE SEDIMENTS

The methods employed in the study of sediments are easily separable into a number of distinct operations. For the sake of clarity, the following account is therefore given under a series of appropriate headings.

(1) Sampling

The sandstones of the Brora Outlier are too indurated to allow of sampling by the method of channelling. Instead, samples had to be taken at intervals along an assigned line. The method adopted in the case of a quarry face is illustrated in Figure 1 opposite. Where sandstone was exposed over a wider area, as, say on a hill face, the same method of sampling was practised, but in such cases samples were collected at 25 ft. horizontal and 50 ft. vertical intervals. The closely similar nature of the cumulative frequency curves for the sandstones of any one locality, indicates that the sandstones are sufficiently homogeneous for samples collected by this method to be representative of the locality as a whole. Specific specimens exhibiting such features as ripple-marks or sun-cracks were also collected. As far as possible, an attempt was made to apply the method of random-sampling to the conglomerates /
conglomerates, but these deposits are so indurated that the collecting of a sample at a precise point on the assigned line is often difficult, and sometimes impossible. Some latitude in the distance between samples had therefore to be allowed. The method was not adhered to in collecting pebbles which exhibit to advantage the typical features of glacial pebbles. Because of the difficulty of extracting whole pebbles, the conglomerates were not analysed mechanically. The obviously large number of grade sizes represented, would, in any case, have rendered the collecting of a representative sample for analysis well-nigh impossible.

(2) Mechanical analysis of the sandstones

(a) Preparation

By the method described, several samples of sandstone were obtained for a given locality. From this number, four pieces of sandstone were chosen at random. Each of these samples was subjected in turn to a mechanical analysis. In preparation for this analysis, the sandstone had to be disintegrated to free the individual particles. A pestle and mortar was used for this operation, and the disintegration accomplished in as gentle a manner as possible to avoid fracturing the individual grains.

(b) /
(b) **Splitting and Sieving**

When a given sample of sandstone had been reduced to a sand, it was then ready to be sieved. Fifty to a hundred grams of sand was sieved in every case. If, after disintegration, the quantity of sand was found to be too great, it was reduced, before sieving, by splitting. The method used in splitting a sand was that described by Pettijohn (1931). This method entails cutting four rectangular pieces of paper of which the length is twice the width. These pieces of paper are then placed so that each piece overlaps half of the next, and together, the four pieces form a square surface. The sand is then poured on to the centre of this square, and spread out into a circular area. Pulling the four rectangles apart then effectively quarters the sample. Of these quarters, two alternate ones are retained for sieving, and the remaining two are rejected.

The quantity of sand to be analysed was first weighed, then passed through a series of seven Rotap Testing Sieves. The nominal size of aperture is given in each case, and this can be correlated with Wentworth's Grade Scale (1922). Much time and effort was saved by using the Rotap Automatic Shaking Machine fitted with an automatic time-switch. Each sample was given ten minutes on the mechanical shaker. After sieving, the /
the separate fractions were weighed, and these weights calculated as percentages. Since the loss of weight during sieving was never greater than 0.5%, no compensating allotment of weight was made to any of the fractions. The fine-fraction, that quantity of sand which passed through the 200 mesh sieve, had then to be analysed.

(c) Analysis of the fine-fraction

An attempt was made to analyse the fine-fraction using the Andrews Elutriator shown in Figure 2 opposite. It was found that analysis by this method gave an extremely small weight of material in the 1/64 mm. - 1/128 mm. grade, thus producing a kink in the cumulative frequency curve, which did not look at all natural. To ascertain whether this feature might have been caused by some chance fracturing of the grains during disintegration, a sample of sandstone was broken down by the method of oven-treatment. This method entails heating the sandstone to red-heat, and maintaining it at this temperature for several hours. On cooling, the sandstone has been rendered so friable as to disintegrate under the fingers. The chances of individual grains being fractured during this process are small. On elutriation of the fine-fraction of a sandstone disintegrated by this method, the drop in the 1/64 mm. - 1/128 mm. grade was still apparent. Next, the fine-fraction of /
### Times of Settling Computed According to Stokes' Law*

<table>
<thead>
<tr>
<th>Diameters in Millimeters</th>
<th>Velocity $(\text{cm./sec.})$</th>
<th>$h$ $(\text{cm.})$</th>
<th>Hr.</th>
<th>Min.</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16 ..........................0.0625</td>
<td>0.347</td>
<td>20</td>
<td>0</td>
<td>9</td>
<td>58</td>
</tr>
<tr>
<td>1/32 ......................0.0312</td>
<td>0.174</td>
<td>20</td>
<td>0</td>
<td>1</td>
<td>56</td>
</tr>
<tr>
<td>1/64 ......................0.0156</td>
<td>0.0869</td>
<td>10</td>
<td>0</td>
<td>1</td>
<td>56</td>
</tr>
<tr>
<td>1/128 ........................0.0078</td>
<td>0.0433</td>
<td>10</td>
<td>0</td>
<td>3</td>
<td>53</td>
</tr>
<tr>
<td>1/256 ........................0.0039</td>
<td>0.0217</td>
<td>10</td>
<td>0</td>
<td>7</td>
<td>44</td>
</tr>
<tr>
<td>1/512 ........................0.0019</td>
<td>0.0109</td>
<td>10</td>
<td>0</td>
<td>15</td>
<td>..</td>
</tr>
<tr>
<td>1/1024 ........................0.00098</td>
<td>0.0058</td>
<td>10</td>
<td>0</td>
<td>31</td>
<td>..</td>
</tr>
<tr>
<td>1/2048 ........................0.00049</td>
<td>0.00054</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>...............................0.00021</td>
<td>0.00034</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>

*The values in this table are based on temperature of 20° C. and an average specific gravity of the sediment equal to 2.65. Seconds are neglected in lower part of table.

---

**Figure 3**

Adapted from Krumbein and Pettijohn (1938) p. 166.
of a sandstone disintegrated by the usual method of pestle and mortar was analysed by the pipette method. No drop in the 1/64 mm. - 1/128 mm. grade was recorded. The phenomenon was therefore ascribed, not to an inherent quality of the sandstones, but to faulty elutriation. The fault was probably caused by fluctuations in the flow of water through the instrument. The pipette-method was thereafter employed in the analysis of the fine-fractions.

The pipette-method is based upon the settling velocities of grains of limiting sizes. These velocities are computed according to Stokes' Law. A table giving the different times of settling is shown in Figure 3 opposite. The pipette-method of analysis fully described by Krumbein (1932, 1935) is simple, but tends to be time-consuming. The weighed fine-fraction, together with 0.67 gm. of sodium oxalate which acts as a dispersing-agent, is made up with distilled water to exactly 1 litre of suspension in a measuring-cylinder. The suspension is thoroughly stirred and placed at rest. Exactly 1 minute and 56 seconds later (see Figure 3) 20 cc. of the suspension are drawn into a pipette inserted 10 cm. beneath the surface. The withdrawn suspension is then discharged into a weighed beaker and evaporated to dryness on a hot plate, care being taken to avoid spattering. The beaker plus residue is weighed, the /
the weight of the beaker subtracted, and the weight of the residue corrected for the amount of sodium oxalate which it contains. This corrected weight, multiplied by 50, gives the total weight of the fine-fraction less than 1/32 mm. in diameter. This total weight, subtracted from the original weight of the fine-fraction which was dispersed, gives the weight of sediment in the 1/16 mm. - 1/32 mm. grade. A typical first set of readings for the sandstone samples is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Weight (gm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of beaker plus residue</td>
<td>37.314</td>
</tr>
<tr>
<td>Weight of beaker</td>
<td>37.132</td>
</tr>
<tr>
<td>Weight of residue</td>
<td>0.132</td>
</tr>
<tr>
<td>Less 0.013 gm. sodium oxalate</td>
<td>0.119</td>
</tr>
<tr>
<td>Weight of material finer than 1/16 mm.</td>
<td>17.011</td>
</tr>
<tr>
<td>Weight of material finer than 1/32 mm.</td>
<td>(0.119 x 50)</td>
</tr>
<tr>
<td>Weight of material in 1/16 mm. - 1/32 mm. grade</td>
<td>11.061</td>
</tr>
</tbody>
</table>

To find the weight of material in the 1/32 mm. - 1/64 mm. grade, the suspension is again thoroughly stirred, and 20 cc. withdrawn from a depth of 10 cm. after an interval of 7 minutes and 44 seconds (see Figure 3). The calculation is then similar to the one shown. The weight of material in subsequent, finer grades is found by the same method, stirring the suspension and allowing the appropriate time of settling for each determination.
When the weights in the finer grades thus determined for a given sample had been expressed as percentages, the cumulative weight percentage for each Wentworth grade present in the sample was calculated, and the frequency curve drawn (see pp. 55-78). The sandstone samples from the Brora Outlier were determined down to the 1/128 mm. - 1/256 mm. grade, although finer grades are certainly represented, as witnessed by the fact that a suspension was found still to be settling after an interval of more than two days. For this reason, in constructing the cumulative frequency curves, the writer refrained from allotting the remaining weight to the various fractions, and thus bringing the cumulative weight up to 100% on the 1/256 mm. diameter line.

(3) Cleaning

To examine the minerals present in a given sample one of the fractions obtained by sieving was chosen and the iron oxide coating removed. The darkest fraction, usually the 85 or the 120 fraction, was always chosen as being probably the richest in heavy minerals. The grains were cleaned through the agency of hydrogen produced by the action of oxalic acid on aluminium (Leith, 1950). The chosen fraction was placed in a beaker containing 10 gm. of oxalic acid in 100 cc. of distilled water. A small cylinder of sheet aluminium was then /
then placed in the beaker, the mixture was heated, and allowed to boil gently for about 20 minutes. If by that time the grains were clean, the aluminium cylinder was removed, and the liquid decanted from the beaker. The sand was then washed and decanted several times, until the supernatant wash water remained clear. After washing, the sand was thoroughly dried, then weighed. If the first boiling failed to entirely remove the iron oxide coating, the aluminium cylinder was removed and cleaned, the liquid decanted from the beaker, a fresh quantity of oxalic acid and distilled water added, the cylinder replaced, and the process repeated.

The percentage of iron oxide present in the sample was taken as the difference in weight between the coated and the cleaned sand. The value thus obtained is slightly high, as some material other than iron oxide is removed during the cleaning process. The percentage of iron oxide present could of course be accurately determined by retaining and analysing the washings. The value of the information gained however would not, in this instance, warrant the time consumed.

(4) Separation of heavy minerals

The heavy minerals were separated by pouring the cleaned, dried fraction into bromoform (S.G. 2.39 at 10° C.) contained /
Figure 4

To show its position, the trap has been filled with black ink.
contained in a separating funnel of special design (see Figure 4 opposite). The heavy minerals sank into the trap contained in the stopper. On turning the stopper through 90 degrees, they were then effectively cut off from the bromoform and the light minerals above them. The light minerals were filtered off, washed with benzene to remove all bromoform, then dried and weighed. The heavy minerals were treated in the same way. Filtering of the heavy minerals is not considered advisable, because of the difficulty, or, as some authors have it, the impossibility of recovering all the washed heavy minerals from the filter paper. The writer found no difficulty in this respect, provided that care was taken to ensure that minerals and filter paper were thoroughly dry before recovery was attempted. The heavy and the light minerals were mounted on separate slides for microscopic study.

(5) Preparation of rock sections

From the samples of sandstone from each locality, a random selection was made, and thin sections of those chosen were prepared in the normal manner. A number of oriented specimens of sandstone was collected in the field and specially cut along definite directions (see p. 83). Rock sections were also made from a large number of conglomerate pebbles from different /
different localities, and a few sections of the matrix prepared. The manner in which the sphericity and other properties of the pebbles were examined is explained in the appropriate sections of the work.
EXPLANATION OF THE STATISTICAL DEVICES USED, AND
RESULTS OF THE MECHANICAL ANALYSIS OF THE SANDSTONES

In all, sixteen specimens of sandstone, four from each of four areas, were subjected to a complete mechanical analysis. Two areas were chosen from each of two sandstone groups of the Brora Outlier. It will be remembered (see p. 1) that the sequence in the Brora Outlier is as follows:

(4) Flaggy sandstones
(3) Pebbly sandstones and massive conglomerate
(2) Mudstones and sandstones
(1) Basal conglomerate and arkose.

Specimens of the Cagar Feosaig and Duchary Rock Sandstones were analysed as representative of Group (4), while specimens from Kirkton Quarry and Beinn a' Bhreagie were taken as examples of the sandstones of Group (2). For comparison, an analysis was made of a random specimen of the Berriedale sandstone, thought to be the lithological equivalent of the sandstones of Group (4) of the Brora Outlier. Further, five sands from widely scattered areas were analysed. These included a Scottish beach sand and a Scottish loch sand, a specimen from an Irish sand dune, an African river sand, and sand from Argand's Glacier in East Greenland. (See p. 54 for exact localities).
The results of the mechanical analysis of these sediments are shown in tabular and graphical form at the end of this section (see pp. 53-78). The methods by which these results were obtained have already been outlined (see pp. 23-35). Also, included in this section, are tables of the statistical values calculated from the cumulative frequency curves.

Largely to facilitate comparison with published results, quartile measures (Trask, 1930 and 32) have been preferred to moment measures (Krumbein, 1936). It must however be realised, that while quartile measures are, perhaps, the more readily visualised, they differ from moment measures in being almost wholly insensitive to curves which are open-ended beyond the 75 per cent line in the one direction, and beyond the 25 per cent line in the other. These terms, and those which follow, will be more readily understood after an examination of Figure 5 overleaf. The meaning, and inter-relationship of the calculated quartile measures must now be explained. The following account may be amplified by reference to any of the standard works on sedimentary petrology. (See, for example, Krumbein and Pettijohn, 1938, or Twenhofel and Tyler, 1941).

The median diameter, Md, is defined (Mills, 1924) as the middle member of the distribution: that is, it is that diameter /
Figure 5
diameter larger than 50 per cent of the diameters in the distribution, and smaller than the other 50 per cent. Its numerical value can be obtained graphically, by reading off the diameter value at that point where the 50 per cent line and the cumulative frequency curve intersect. (See Figure 5).

The quartiles, Q1 and Q3, lie on either side of the median diameter, and are numerically equivalent to the diameter values at those points where the cumulative curve is intersected by the 75 per cent, and the 25 per cent lines respectively. The first quartile, Q1, is, by convention, numerically smaller than the third quartile, Q3.

Three types of quartile deviation: arithmetic, geometric and logarithmic, are commonly used. All three values have been computed for the sediments under consideration.

The arithmetic quartile deviation, QDa, may be expressed as half the spread between the two quartiles. Thus:

\[ QDa = \frac{(Q3 - Q1)}{2} \]  

(1)

From the above equation it is obvious that, since Q3 is numerically greater than Q1, the value of QDa will always be positive.

The geometric quartile deviation, QDg, may be expressed as the square root of the ratio between the two quartiles, so chosen as to give a value greater than unity. Thus:

\[ QDg = \sqrt{\frac{Q3}{Q1}} \]  

(2)

More /
More commonly, Trask's sorting coefficient, originally \( S_0 = \sqrt{Q1/Q3} \) (since Trask reversed the definition of the first and third quartiles already given) is used in place of \( QDg \). The value of \( S_0 \) is identical with that of \( QDg \) when the proviso is made, that in computing the value of \( S_0 \), the larger quartile, \( Q3 \), shall form the numerator of the ratio under the root sign.

Whereas the value of \( QDa \) is dependent on the size of the particles and the units of measurement employed, \( S_0 \), being a ratio, is uninfluenced by these factors, and is thus admirably suited to express the spread of a curve. Trask has already shown, that a value of \( S_0 \) greater than 4.5 indicates a poorly sorted sediment. He gives 3.0 as the approximate value of \( S_0 \) for average sorting, and takes a value of less than 2.5 as being indicative of a well-sorted sediment.

Since the values of \( S_0 \) are geometric, they do not lend themselves to direct comparison. Thus, it cannot be said that a sediment with \( S_0 = 2.0 \) is twice as well sorted as one which gives \( S_0 = 4.0 \). This difficulty of comparison is surmounted by calculating the logarithmic quartile deviation, \( \log QDg \).

\[ \log QDg = (\log Q3 - \log Q1)/2 \quad \text{......... (3)} \]

Or \[ \log QDg = \log S_0 \]

The /
The values of logQDg can be compared directly. Thus it can be said that a sediment with logQDg = 0.200 is twice as well sorted as one with logQDg = 0.400.

The quartile skewness expresses the extent to which the arithmetic mean of the quartiles departs from the median diameter. Thus the arithmetic quartile skewness may be represented as:

\[
S_{ka} = \frac{(Q_1 + Q_3)}{2} - Md
\]

\[
= \frac{1}{2}(Q_1 + Q_3 - 2Md) \quad \text{(4)}
\]

The quartile skewness can be expressed in a geometric form, to obviate the influence of particle size and units of measurement used. The geometric quartile skewness, Skg, may be expressed as the square root of the ratio of the product of the quartiles, to the square of the median diameter. Thus:

\[
S_{kg} = \sqrt{\frac{Q_1 \times Q_3}{Md^2}} \quad \text{(5)}
\]

Trask's value for the quartile skewness, Sk = Q1.Q3/Md^2, is of course the square of Skg. Considering now the logarithmic quartile skewness, we have the relationship:

\[
\text{LogSkg} = \frac{1}{2} \left( \log Q_1 + \log Q_3 - 2 \log Md \right) \quad \text{(6)}
\]

which is obviously the log of equation (5). Furthermore, since Sk = (Skg)^2 we have:

\[
\text{LogSk} = 2 \text{LogSkg}.
\]
When a curve is symmetrical, the skewness is equal to unity. In practice, values greater or less than unity are common. Since values less than unity bear a reciprocal relationship to values greater than unity, the spread is greater on one side of the curve in the one case, and on the opposite side in the other case. The introduction of the term logSk, which has a negative value when Sk is less than unity, and a positive value when Sk is greater than unity, effectively does away with this reciprocal relationship which is often difficult to visualise.

A final value, Skqφ, expresses the skewness directly in terms of its definition, that is, the extent to which the mean of the quartiles departs from the median diameter. The value of phi terms rests in the deliberate choice of φ to satisfy the conditions that the limits of the Wentworth grades (Wentworth, 1922) are simple numbers on the phi scale, and that each phi unit is one Wentworth grade. A conversion chart for logSk and Skqφ is the most convenient means of determining the value of the latter term.

The quartile kurtosis (Kelley, 1924), KQA, measures the degree of peakedness of the cumulative curve, by comparing the spread of the central portion of the curve with the spread of /
of the curve as a whole. It may be expressed as the ratio of the arithmetic quartile deviation, to the difference between the diameter values at those points where the curve is intersected by the 90 per cent and the 10 per cent lines, P90 and P10 respectively. Thus:

\[
Kqa = \frac{(Q3 - Q1)/2}{P90 - P10}
\]

\[
= \frac{(Q3 - Q1)}{2(P90 - P10)}
\]

Equation (7) is known as Kelley's equation (Kelley, 1924). The arithmetic quartile kurtosis, since it is expressed as the ratio of two spreads, differs from the arithmetic quartile deviation and the arithmetic quartile skewness, in being uninfluenced by either the size factor or the units of measurement employed.

The graphical representation of sediments, and the calculation of statistical values from these graphs is done with two chief aims in view:

(a) that the physical characters of the sediments may be easily visualized; and

(b) that these physical characters may be readily compared with those of other sediments.

In attempting to determine the mode of deposition of ancient sediments, an obvious method is to endeavour to equate statistical /
statistical values calculated for these sediments with like values determined for modern deposits of known origin. In the present case, however, considering the paucity of quantitative data on sands and gravels, inferences as to the conditions of deposition of their consolidated equivalents in a geologically older formation must be drawn with considerable caution. In the following account of comparisons of statistical data for the Brora Outlier sandstones with those for modern deposits of known origin the warning that the validity of inferences drawn from such comparisons is perhaps open to question, is not reiterated, to avoid undue repetition. It should none the less be kept constantly in mind and considered relevant to the remainder of this section.

Without, at this stage, entering into a discussion of the actual conditions of deposition of the sandstones concerned, attention is first drawn to the close similarity which exists between the results for the Berriedale sandstone and those for the sandstones of the Brora Outlier, given in graphical and tabular form at the end of this chapter (pp. 53-72). The likeness is particularly pronounced in the case of the analysed samples from Duchary Rock (pp. 59-62). Lithological similarity is not therefore the only relationship between the two sandstones.
It can now be inferred that the two sandstones were deposited under similar environmental conditions, and for the purpose of this comparison it is unnecessary to stipulate any specific set of conditions.

A comparison can now be made between the statistical values calculated for the sandstones of the Erora Outlier and those published by various workers for different modern deposits. Much of the data on modern sediments has been collected together by Pettijohn, and presented in convenient tabular form in his book, "Sedimentary Rocks". To facilitate comparison in this present case, a cumulative frequency curve was drawn, and from it, a series of statistical values calculated, for an "Average Sandstone" representative of the sixteen analysed samples from the Erora Outlier.

The principal mode of the sandstones falls within the one quarter to one eighth grade of the Wentworth scale. The calculated average weight percentage in this modal class is 33.32%. Reference to Pettijohn (Table 60, p. 235) shows that outwash sands differ significantly from beach and dune sands in that nearly two thirds of analysed samples have between 20% and 39% of the total weight in the modal class. It may be inferred therefore, on this count, that the sandstones here considered approximate more closely to outwash deposits than to beach or dune sands.

Comparison /
Figure 6

A, outwash sands; B, river sands; C, beach sands; D, Brora outlier sandstones; E, dune sands.
Comparison of the present results with those given by Pettijohn in Table 59, is, however, equivocal. Here he shows, that of 97 beach sands, 35 had their principal mode in the one quarter to one eighth grade, while the modal class of 51 of 53 dune sands, 14 of 100 river sands and 4 of 50 outwash sands, fell within these diameter values. This apparent closer similarity to dune and beach sands rather than to river and outwash deposits, is counterbalanced by the remaining information given in Table 59. The average percentage in the modal class for the beach sands is 68.4%, and for the dune sands, 65.7%. The outwash deposits have 34.7% in the modal class, thus showing by far the closest resemblance to the Brora Outlier sandstones in this respect. These similarities and differences are represented diagrammatically in Figure 6 (p. 46) and in Figure 7 (p. 48). Unfortunately, Pettijohn gives no average percentage for the river sands.

Considering the range of the Brora Outlier sandstones, it is found, that of the sixteen analysed samples, one sample had 6 Udden Size Classes (Udden, 1898) with more than 1% of the total weight, seven samples had 7 Classes, and eight samples had 8 Classes. In Table 58, Pettijohn shows that outwash and related alluvial sands are less restricted in range than dune and /
Figure 7

A, outwash sands; C, beach sands;
D, Brora Outlier sandstones;
E, dune sands.
and beach sands. Dune sands normally have 4 Udden Size Classes with more than 1% of the total weight, while beach sands usually have 3 such Classes. Fluvial, outwash, and alluvial sands have, characteristically, a markedly greater range of 6 or 7 Classes. The evidence is therefore again in favour of the Brora Outlier sediments being more closely allied to these last mentioned types of deposit.

In Tables 56 and 57 respectively, Pettijohn gives the average value for the median diameter of 162 beach sands and for 146 river sands. For the beach sands, this value ranges from 0.21 mm. to 0.57 mm. This is slightly coarser than the river sands, which have a corresponding range of 0.16 mm. to 0.40 mm. The average value for the median diameter of the Brora Outlier sandstones is 0.12 mm. Again, this statistical value bears a closer relationship to that of river rather than of beach sands. The fact that the value for the Brora Outlier sandstones is somewhat lower than the lowest average figure quoted by Pettijohn, is in accordance with the evidence outlined above in support of the supposition that these sands are outwash deposits. It is known to be true that sediments tend to become more fine-grained in the downcurrent direction. An outwash deposit, related to river transport, should therefore be slightly finer than the true river sands nearer the source rocks.

An /
An interesting point emerges from a consideration of the median diameter values for the four chosen localities from the Brora Outlier. These values are:

- Beinn a’Ehragie = 0.185 mm.
- Kirkton Quarry = 0.097 mm.
- Cagar Feosaig = 0.117 mm.
- Duchary Rock = 0.088 mm.

Now Kirkton Quarry lies to the east of Beinn a’Ehragie, and Duchary Rock is also east of Cagar Feosaig. On the assumption that sediments tend to become finer with increasing distance from source, it would seem probable, in the light of the above results, that the sandstones in question were transported originally from west to east. This matter is more fully discussed in dealing with the sphericity of the conglomerates (see p. 117).

The average value for the coefficient of sorting, So, for the Brora Outlier sandstones is 1.91. The values quoted by Pettijohn for river sands (Table 57) range from 2.08 to 1.09; the highest average value being 1.49. The poorer sorting of the Brora Outlier sandstones would again suggest that they may be outwash deposits. Deposition of sand over a basin or plain subjected to sporadic currents from different directions, would doubtless tend to impair the degree of sorting that would normally be attained under true fluvial conditions.

From the foregoing comparisons there has emerged an indication /
indication that the Brora Outlier sandstones may be consolidated outwash sands such as are presumably envisaged by the hypothesis which explains the emplacement of Old Red Sandstone sediments in terms of torrents depositing their load in intermontane basins. Comparison of the cumulative frequency curve and statistical data for the Brora Outlier sandstones with those for a fluvio-glacial sand from Argand's Glacier in Greenland indicate a further resemblance between these Old Red Sandstone sediments and a modern, unconsolidated deposit. The curve for the "Average Sandstone" of the Brora Outlier is shown on page 71, that for the fluvio-glacial sand on page 77, and a comparison of the statistical data for both sediments is presented in tabular form on page 53c. It is apparent that there is a close similarity between the results of the analysis of these two sediments, but the danger of arriving at a too hasty conclusion on the basis of such comparisons is even greater in this case, for data on fluvio-glacial sands are extremely scarce. The suggestion that the Brora Outlier sandstones may be consolidated fluvio-glacial outwash sands is therefore advanced most tentatively, and with full realization that further corroborative evidence relevant to the assessment of these sediments would be necessary before such a suggestion could be regarded as a formal working hypothesis of deposition.
For further comparison, two other fluvio-glacial sands were analyzed: one from Pentland Mains, and one from Loan Head. The cumulative frequency curves for these two sediments, for the "Average Sandstone" of the Brora Outlier, for a river sand, and for a glacial till (after Krumbein, 1936) are shown together in the last graph (p. 78) included at the end of this section. Consideration of this graph shows that the curve for the "Average Sandstone" occupies an intermediate position between that for the river sand and that for the till.

This observation is not offered as any strong corroboration of the suggestion that the Brora Outlier sandstones may be fluvio-glacial sediments. It should be pointed out, however, that given fluvio-glacial sands from different areas and different formations, it is to be expected that their cumulative frequency curves would show a gradational variation between two end-points; that fixed by the known river sand on the one hand, and by the known glacial sand on the other. Further, this variation might be interpreted as reflecting differences of degree, determined by the relative importance of glacial to fluvial conditions during the transportation and deposition of such sediments. In the present instance, therefore, it is perhaps reasonable to assert that the observed, relative position of the curve for the "Average Sandstone" in the graph on p. 78 is not inconsistent with the indication of possible fluvio-glacial origin.
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
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<tbody>
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<td>Md</td>
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<td>0.106</td>
<td>0.098</td>
<td>0.094</td>
<td>0.193</td>
<td>0.205</td>
<td>0.167</td>
<td>0.168</td>
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<tr>
<td>Q1</td>
<td>0.040</td>
<td>0.042</td>
<td>0.044</td>
<td>0.046</td>
<td>0.104</td>
<td>0.104</td>
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<td>0.196</td>
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<td>0.300</td>
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<tr>
<td>QDa</td>
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<td>0.074</td>
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<td>0.098</td>
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<td>0.083</td>
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<tr>
<td>So</td>
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<td>1.699</td>
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<td>0.230</td>
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<td>0.234</td>
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<td>0.009</td>
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<td>0.022</td>
<td>0.022</td>
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<td>0.036</td>
<td>0.039</td>
<td>0.034</td>
<td>0.034</td>
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<tr>
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**K.Q.** = Kirkton Quarry  
**B.B.** = Beinn a' Bhragie
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<tr>
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<th>C.P.1</th>
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<th>C.P.3</th>
<th>C.P.4</th>
<th>D.R.1</th>
<th>D.R.2</th>
<th>D.R.3</th>
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<td>0.006</td>
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C.F. = Cager Peosaig  
D.R. = Duchary Rock
TABLE III

<table>
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<tr>
<th></th>
<th>Av. S</th>
<th>B. S.</th>
<th>Bh. S</th>
<th>L. S.</th>
<th>D. S.</th>
<th>R. S.</th>
<th>G. S.</th>
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<td>0.071</td>
<td>0.020</td>
<td>0.076</td>
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<td>So</td>
<td>1.911</td>
<td>2.057</td>
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<td>1.252</td>
<td>1.119</td>
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<td>0.049</td>
<td>0.138</td>
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<td>-0.041</td>
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<td>0.651</td>
<td>0.909</td>
<td>1.122</td>
<td>0.788</td>
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<tr>
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<td>+0.15</td>
<td>+0.06</td>
<td>+0.14</td>
<td>+0.06</td>
<td>-0.02</td>
<td>+0.17</td>
</tr>
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<td>F90</td>
<td>0.025</td>
<td>0.019</td>
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<td>-0.255</td>
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For localities of samples see overleaf.
### Localities of Samples in Table III

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<td>Av.S</td>
<td>&quot;Average Sandstone.&quot; Average values computed from the sixteen analysed samples of the sandstones of the Brora Outlier.</td>
</tr>
<tr>
<td>B.S.</td>
<td>Berriedale sandstone. Berriedale, Caithness.</td>
</tr>
<tr>
<td>Bh.S.</td>
<td>Beach sand. ½ mile N.E. of Nigg Pier, Ross.</td>
</tr>
<tr>
<td>L.S.</td>
<td>Loch sand. Loch Langabhat, S.W. side of Point at Drum na Coarich.</td>
</tr>
<tr>
<td>D.S.</td>
<td>Dune sand. Fortstewart, N. Ireland.</td>
</tr>
<tr>
<td>R.S.</td>
<td>River sand. Sapeki Stream, Lower Shire District, Nyasaland.</td>
</tr>
</tbody>
</table>
Macroscopic characters

The sandstones of the Brora Outlier are fine-grained and reddish-brown in colour. Increase in the fineness of the texture is accompanied by progressive darkening in colour. The value for the dominant colour of the sandstones as determined by the use of the Rock-Color Chart (1943) is 10R5/3. The sandstones are, in the main, flaggy, but are sometimes massive with occasional jointing.

A large slab of sandstone showing ripple-marking on the surface was found on the floor of Kirkton Quarry (Plate 30 Fig. E). Although the writer was unable to discover ripple-marking in situ in the quarry, the slab gave every appearance of being indigenous. Ripple-marking has already been recorded from a different locality of the Brora Outlier by H.H. Read (Mem. Geol. Survey, 1925, p. 57). The mere occurrence of ripple-marking in the Brora Outlier sediments is of significance in that it affords some indication of the conditions under which these sediments accumulated. As no fossil aeolian ripple-marking has ever been recorded, the evidence is against desert conditions having been operative during the deposition of the Brora Outlier sandstones. The ripple-marking displayed in Kirkton Quarry was examined and measurements taken. The marking /
marking is asymmetrical, and the crests of the ripples rounded. The wave-length is approximately 10.5 cm., and the amplitude 1.2 cm., giving a wave-index of 8.75. These features and measurements are in keeping with those of low velocity, aqueous current ripple-marks (Pettijohn, 1948).

In Kirkton Quarry and on Beinn a' Bhragie, sun-cracked surfaces were observed at several horizons. The surfaces are in the nature of a thin leathery skin, rather browner in colour than the rest of the sandstone, and traversed by ill-defined polygonal cracks. The cracks are filled with coarser material than constitutes the rest of the surfaces. This cracking is presumably indicative of occasional drying-out of the sediments during the course of deposition. Sandstones exhibiting what might be termed a "chocolate drop" appearance are occasionally to be observed. This feature is due to the presence of small, dark brown bodies of finer material lying within an otherwise "normal" sandstone. It seems probable that these patches are fragments of the leathery skin already mentioned, broken-off and re-deposited elsewhere.

There is one feature of the Brora Outlier sandstones which merits special attention in that it would appear to be of some value in attempting to ascertain the depositional history of these sediments. This is the occurrence, in the Kirkton /
Kirktone Quarry exposure, of a few pebbles of quartz-felspar-biotite-granulite in the body of the sandstone (Plate 37 Figs. A & B). In the course of field-work in the area, during which many sandstone outcrops were studied in considerable detail, no other occurrence of this feature was noted. Consequently, it is felt that the presence of these isolated pebbles in Kirktone Quarry can be explained only in terms of a special process consistent with, but not necessarily required to account for, the mode of deposition of the sandstones in general.

It cannot be supposed that these few isolated pebbles constituted the entire supply of detritus of this magnitude available for transportation. Even if they did, which is manifestly absurd, their present position would still pose a problem, for they are obviously far beyond the transporting power of the agent which deposited the fine-grained sands all around them (see pp. 103-5 in which a study of the competence of the transporting medium of the sandstones is presented in discussing the banded effect which they exhibit). Further, occurring where they do, it is certain that these pebbles have not descended from an overlying conglomerate. Irrespective of their present position, their very rarity is strongly against such a supposition.

Two feasible explanations which would account for
the presence of these pebbles in the sandstone mass spring readily to mind: either that they were entangled amongst the roots of a floating tree and so carried to their present position and dropped, or that they were ice-rafted to the spot where they are now found. The first explanation has nothing to offer in attempting to determine whether the Brora Outlier sandstones were deposited as alluvial outwash fans or as fluvio-glacial outwash sediments, for a floating tree might exist equally well in either depositional environment. There is, however, one serious objection to this explanation, and that is that it is extremely doubtful if trees as such existed in Middle Old Red time, especially trees with a sufficiently sturdy root-system to enmesh and support fairly large pebbles. Even one floating tree implies a large number of trees in the general area, and there is no trace whatsoever of fossil wood tissue in the Brora Outlier sediments. The author therefore considers that, on balance, it is more feasible to explain the presence of these pebbles in the Kirkton Quarry exposure in terms of ice-rafting: he sees in this occurrence a further indication that the Brora Outlier sandstones may be fluvio-glacial outwash sediments. In this respect it is interesting to note that it was similar evidence that led Horne (1874) to agree in part with the hypothesis advanced by Cumming (1848) that /
that ice action had played a part in the derivation of the Old Red Sandstone sediments of the Isle of Man.

It has already been noted (p. 34) that a number of oriented specimens of sandstone were specially collected. These specimens were cut along two lines at right angles to each other, one bearing N 45°W, and the other bearing N 45°E. The surfaces obtained by this method were examined for any structures which might give some indication of the direction of transport. Very little information was gained by this method due to the lack of interpretable structures. One specimen of sandstone from Kirkton Quarry did, however, exhibit concave cross-bedding on the face bearing N 45°E. According to Anderson (1931) the direction of transport has been at right angles to such faces. According therefore to the evidence afforded by this sandstone specimen, the sediment may have been derived from the north-west or from the south-east. Considered in conjunction with the evidence from the relative sphericities of the conglomerate pebbles (p. 113) whereby a source lying to the north of Silver Rock is indicated, derivation of the sandstone from the north-west is to be preferred.

Microscopic characters

Thin sections of sandstones from Kirkton Quarry, Beinn a'bhragie, Duchary Rock and Cagar Feosaig were examined under /
under the microscope. It was found that the sandstones from these four areas are petrologically similar. Consequently, the following general account of the petrology is equally applicable to all four localities, except where definitely stated otherwise. Differences in the average grain size of the sandstones from the various localities do exist, but such differences have already been made evident by the results of the mechanical analysis (pp. 36-78).

The average value for the median diameter of the sandstones from these four localities is 0.122 mm., and the variation in diameter of the constituent particles is from values greater than 0.5 mm. but less than 1 mm., to values less than 0.004 mm. (see values given for "Average Sandstone" on p. 53c). The textural classification of a sedimentary rock occasions some difficulty. If the "Average Sandstone" for the Brora Outlier were disintegrated, over 50% of the constituent grains would fall within the sand grade (1/16 mm. - 2 mm.) as defined by Wentworth (1922). The aggregate could, therefore, according to Twenhofel (1936-37) be termed a sand, and the indurated equivalent a sandstone. Since, however, the value of Q1 for this aggregate is 0.058 mm., and that of Q3 is 0.202 mm. (see p. 53c) it should, according to Niggli (1938), be termed a silty sand. To classify the sediments in question as fine-grained sandstones appears to be the most satisfactory solution.
In shape, the constituent grains of the sandstones are dominantly sub-angular to angular (Plate 31 Fig. D). Pettijohn (1954) in an article devoted to the classification of sandstones has this to say of glacial outwash sands:

"glacial outwash sands, which have travelled for only a very short distance and for a very brief time, may be well sorted, though they remain highly angular".

It will be remembered (p. 50) that the average value for the coefficient of sorting of the Brora Outlier sandstones was calculated to be 1.91 on a scale which gives values less than 2.5 as indicative of well-sorted sediments. Reference has just been made to the angularity of the constituent grains, and it will be seen (p. 97) that several lines of investigation serve to indicate that the sediments of the Brora Outlier were not derived from a distant source. Evidence such as this, is, of course, by no means conclusive, but it does suggest that the observed characteristics of the sediments in question are not inconsistent with the hypothesis of fluvio-glacial derivation.

The sandstones are composed essentially of quartz and felspar grains set in a matrix of red haematite. Variations in the amount of haematite present in different layers of some of the sandstone samples give such rocks a banded appearance. This feature is fully discussed on pp. 98-111. Referring once more to Pettijohn (1954) we find the following statement:

"glacial /
"glacial outwash sands, deposited from silt-laden glacial waters ("glacial milk") after a brief and short transport, are relatively clean".

By "clean sands" are meant those in which the grains are cemented together by a precipitated mineral material, as opposed to those in which the matrix comprises primary, interstitial detritus of a claylike nature. We have therefore another feature of the Erora Outlier sandstones at least not discordant with the idea of their possible fluvio-glacial origin.

The majority of the quartz grains show a sharp, well-defined extinction, but in all the rock sections examined, grains exhibiting the undulose extinction indicative of strain have been observed. Inclusions have been noted within a number of the quartz grains in every section of sandstone examined. Gas and fluid inclusions, and inclusions of zircon and black iron ore have been recognised. Grains of quartz showing outgrowths of silica in optical continuity with the nuclei on which they have developed are of common occurrence throughout the sandstones (see Plates 31-32). In those cases where the original grain of quartz has been bounded by haematite, the outgrowth of secondary silica beyond this red margin is easily seen.

On the assumption that the haematite is authigenic (see pp. 108-111) the outgrowths of silica are then obviously of post-depositional origin. No good examples of quartz grains having attained /
attained euhedral outline through the development of secondary silica have been observed; the outgrowths appearing rather merely to have filled in the interstices between the parent grains and those surrounding them. Occasional, small clusters of quartz grains having no cement-filled interstices, but instead the mosaic-like appearance of fragments of quartzite have been observed. It is reasonable to infer that quartz grains of both igneous and metamorphic origin are present in the Brora Outlier sandstones.

Three types of felspar are found in the sandstone: orthoclase, microcline and plagioclase. Almost invariably the felspars show some signs of alteration, and many have been almost totally kaolinised or replaced by sericitic material. Alteration to chlorite has been observed, but is less common. The turbid, slightly gelatinous appearance of altered orthoclase serves to distinguish it from quartz. Microcline, showing typical cross-hatching is usually confined to a few small grains in each rock section. The microcline has proved more resistant to the processes of alteration which have affected the other felspars, and remains remarkably fresh (Plate 32, Fig. D). This insusceptibility of microcline to alteration was noted by Mackie (1899) when he suggested that the felspars in sedimentary rocks might be used as indices of climate. This assumption /
assumption has, however, been largely disproved by the work of later observers, notably that of Barton (1916) and Krynine (1935). Grains of plagioclase, comparatively unaltered and showing multiple twinning were readily distinguished from the other constituents of the sandstones. In those cases where it was possible to determine the composition of the plagioclase grains by the method of symmetrical extinction, it was found that they invariably fall within the oligoclase-andesine range.

The constituent grains of the sandstones are cemented together by haematite, which is easily recognised in thin section by its typical red colour in reflected light. The haematite is largely confined to the periphery of the grains, around which it forms a thin skin. Occasionally, however, in the case of an altered grain, it is found to have penetrated to the interior. The acid-cleaning of the grains showed that the haematite constitutes, on the average, some 4% of the total weight of the sandstones. Secondary carbonate material filling up the interstices between the grains is fairly common (Plate 32, Figs. A - B). This is especially true of the Kirkton Quarry sandstones, in which some grains of carbonate showing twinned lamellae were observed. Measured on the universal stage, the angle between [0001] and the lamellae poles was found to be 25° to/
to 30°, and the angle between these lamellae poles to be approximately 46°. The crystals are therefore probably calcite, and the lamellae \{01\bar{2}\}. It is probably safe to assume that the carbonate material which could not be determined by this method is also calcite. It is of interest to record that a few grains of quartz appear to have been "eaten into" by the calcite (Plate 32, Fig. C).

The accessory minerals include black iron ore, muscovite, biotite and apatite. Both magnetite and ilmenite are present in every section of the sandstones, occurring as small, sub-angular grains. The significance of the presence of these iron ores is discussed in a later section (pp. 98-111). Muscovite occurs as colourless flakes and stringers of varying length, polarising in bright pinks, blues and greens. There are two types of biotite present in the sandstones, one form being pleochroic from a pale, yellow-green to a dark green, and the other from a yellow-brown to a dark brown. Some of the flakes of biotite show alteration to chlorite, but magnetite is the more common alteration product. Where a flake of biotite has been partially replaced by magnetite, the black ore is present either as a small composite mass within the flake, or as a number of minute specks peppered through it. Some of the flakes of mica are warped, probably in response to compression /
compression during lithification. Apatite is present usually as small, fairly well-rounded grains, often with determinable negative elongation. Many of the grains have what might be termed a crinkly surface, which has probably been caused by solution. In addition to these constituents, occasional grains of yellowish anatase are to be observed in the sections. Secondary anatase encrusted upon a fragment of ilmenite is more frequently observed than these isolated grains.

Apart from its occurrence as inclusions in some of the quartz grains, zircon appears to be almost completely lacking from the sandstones, only a very few small grains having been observed. The presence of carbonate material in the sandstones may account, at least in part, for this paucity of grains of zircon. Strock (1941) has shown that solutions of calcium bicarbonate are capable of dissolving considerable amounts of zirconium from zircon, the zirconium being probably carried in solution as a dicarbonatezirconylate ion. Later work by Carroll (1953) suggests that both acid and alkaline leaching may be effective in the corrosion and final removal of zircon.

These then are the main features of the sandstones which may be determined by a study of thin sections. This study was amplified by a separate examination of the light and heavy minerals present. The method of cleaning and separating the /
the grains has already been described (pp. 31-34) and an account of the examination may now be given, together with such inferences as may be drawn concerning the provenance of the sandstones.

Light minerals

The light minerals of the sandstones, those with a specific gravity less than that of bromoform (2.9) comprise quartz, felspar and muscovite in the following approximate proportions:

Quartz ...... 90%
Felspar ...... 7%
Muscovite .... 3%

The quartz grains can usually be readily distinguished from those of felspar and muscovite by the "concentric ring" of bright interference colours which all but basal grains of quartz exhibit. Both quartz and felspar grains differ markedly from the flakes of muscovite which show a blue-grey interference colour in polarised light. The majority of the plates were found to give a well-defined acute bisectrix figure from which the negative sign is easily determinable. The fragments of muscovite are often larger and more rounded than the associated grains of quartz and felspar. Seen as individual /
individual grains, the obvious angularity of the quartz and felspar militates strongly against the concept of an aeolian derivation.

**Heavy minerals**

The sandstones of the Brora Outlier yield a rather restricted suite of heavy minerals. It is difficult to estimate what percentage weight of heavy minerals is present in the sandstones, since examination has shown, that many of the black iron ore grains, which constitute by far the greatest proportion of the heavy mineral suite, are either adhering to, or partly penetrating grains of quartz. The specific gravity of these composite grains is such that they sink in bromoform, and give a totally wrong impression of the weight of heavy minerals present. Making allowance for this factor, it was estimated that the sandstones carry approximately 0.25% by weight of heavy minerals.

Taken to include ilmenite, magnetite and leucoxene, the black iron ore grains constitute some 95% by number of the heavy minerals present. As far as could be estimated, ilmenite is at least twice as plentiful as magnetite. The ilmenite occurs as irregular, sub-angular grains. Alteration of ilmenite to leucoxene is comparatively rare in the sandstones, alteration /
alteration to anatase being more frequently observed. The precise chemical composition of leucoxene is not known (Milner, 1940) but it is suspected to be, in the main, a form of titanium dioxide. The two alteration products, anatase and leucoxene, are therefore closely related. Much of this secondary anatase which encrusts the grains of ilmenite is of euhedral outline. The anatase is commonly yellow, but rare outgrowths of the green variety have been noted.

Most of the grains of magnetite are anhedral, but rare grains showing at least a partial development of the octahedral form have been observed. A number of magnetite grains show an encrustation of red haematite, presumably too well established to be removed by the acid cleaning.

The remaining heavy minerals (5% by number) are made up of apatite, mica, anatase, garnet and zircon, in that order of abundance. The apatite occurs as small, well-rounded grains, with a whitened, frosted appearance. Apatite is the mineral which suffers most severely under the oxalic acid cleaning (Leith, 1950). The negative elongation of the grains can however in some cases be determined, using a sensitive tint plate.

Coloured plates of biotite are of rare occurrence among /
among the heavy minerals, only a few brown fragments being ob-
erved. Colourless flakes of mica are rather more plentiful, and the question arises whether these are plates of muscovite
or biotite, since some varieties of muscovite are of sufficiently
high specific gravity to sink in bromoform (S.G. 2.9). The
value of 2V for muscovite however is in the region of 45° and
that for biotite approximately 10°. Estimation of 2V from the
curve of the isogyres in the interference figures yielded by
some of these colourless plates suggests that they may be flakes
of leached biotite.

Anatase occurs, not only as secondary outgrowths from
ilmenite, but as discrete crystals of a yellow-brown colour.
No crystals of green anatase occurring independently of the
ilmenite were observed. Garnet, which is a very minor consti-
tuent of the heavy mineral suite, appears to be present in two
varieties; one of a dark purplish-red colour, and the other
lighter, and rather more pink. The scarcity of grains of
zircon has already been recorded (p. 90). It has been occa-
sionally observed, occurring as small grains of modified cu-
hedral outline.

Inferences /
Inferences as to provenance

Such is the uniformity and restricted nature of the heavy mineral suite yielded by the sandstones of the Brora Outlier, that any subdivision of the sediments on a petrographic basis would be extremely difficult, and even if accomplished, of questionable significance. To prove the existence of equivalent horizons in the sandstones at different localities would involve the most detailed work in an attempt to show minor vertical variations in the physical characters of those heavy minerals present. Further, large quantities of sandstone would have to be disintegrated and cleaned before anything approaching a significant quantity of heavy minerals could be obtained for study. The difficulty is increased by the nature of the sandstone outcrops on hillsides, as, for instance, on Beinn a' Bhragie and Cagar Feosaig, where fracturing of the flaggy sandstone, and differential downhill movement has rendered the collecting of samples along a given horizon an extremely uncertain procedure. For these reasons, in interpreting the significance of the heavy minerals present in the sandstones, the writer has attempted merely to ascertain from what parent rock such minerals are most likely to have been derived and where such rocks are at present to be found in relation to the Brora Outlier.
The evidence afforded by the heavy minerals as to the derivation of the sandstones may be briefly assessed. None of the heavy minerals is sufficiently unique in character to indicate derivation from one specific area of the surrounding rocks. On the basis of what might be termed negative evidence, however, one region may perhaps be excluded from the possible provenance areas. The Moine rocks of the Srath Carnaig area which lies to the south of the An Droighneach ridge are rich in epidote and in long, slender, crystals of staurolite (Mem. Geol. Survey, 1925, p. 10). Neither epidote nor staurolite has been recorded as occurring among the heavy minerals of the sandstones, and in consequence, it is feasible to discount the possibility of derivation from the area south of the An Droighneach ridge. The southermost end of the An Droighneach ridge is due west of Silver Rock, and if the Moine rocks to the south of the ridge are to be excluded, then the provenance area must have lain to the north of Silver Rock.

For a possible source of the heavy mineral suite determined in the sandstones, it is unnecessary to look beyond the region immediately to the west and north-west of the Brora Outlier, where it is separated by a strip of Moine rocks from the Rogart and Coirefrois granodiorite masses. No mineral present in the sandstone is absent from the rocks of this region.
region, and the obvious conclusion is that derivation was of an entirely local nature. This conclusion is fully in accord with those reached after a study of the sphericity (pp. 113-118), fabric analysis and fabrication (pp. 123-129), and of the petrology of the conglomerates (pp. 161-162).
OBSERVATIONS ON THE OCCURRENCE OF DARKER BANDS
IN THE SANDSTONES

In the petrological description of the sandstones of the Brora Outlier, attention has been drawn to the frequency with which a banded effect, caused by the alternation of darker with lighter red layers, is to be observed. From this observed effect may be deduced something of the nature of the climatic conditions under which these sandstones were deposited.

Reference was made on page ii to the question of the coloration of the red beds. The origin of the red colour in sediments has, for many years, been one of the most widely discussed problems in the field of sedimentary petrology. When considering the relationship between climate and terrestrial deposits, Barrell (1908) expressed the opinion that the chief conditions necessary for the formation of red sediments was an alternation of dry seasons with periods of flood. Under such conditions, the oxidation and hydration of ferruginous material could be accomplished after deposition. Such a secondary, or post-depositional origin of the red colour in sediments had already been suggested by Crosby (1891). Opposed to this view, Tomlinson (1916), Dorsey (1926), Raymond (1927) and Hager (1928), maintained that the red colour of a sediment was indicative of a/
a red source rock, and was therefore, in this sense primary.

Wherever the darker bands are observed in the sandstones here under consideration, three main points are to be noted:

(a) the dark bands are typically finer-grained than their lighter counterparts;
(b) equally characteristic, and probably more striking, is the obvious concentration, in the darker bands, of detrital grains of magnetite and ilmenite; and
(c) haematite is more abundant in the darker bands than in the lighter.

These three statements can now be amplified.

Statement (a) follows directly from an examination of rock sections under the microscope. By actual measurement it is found that the average diameter value for the black ores and other constituent minerals of the darker bands is of the order of 0.06 mm. The constituent grains of the lighter bands average 0.17 mm in diameter. It is further to be observed that the darker bands are more constant in thickness than the lighter. The average thickness for the darker bands is 0.3 mm, while the lighter bands vary between one and five times this measurement. Finally, within the darker bands it is found that the diameter value for the black ore grains equals, and more often exceeds, that of the other constituents.
The presence of black ores in the sandstones is obvious even in hand specimen. The identification of these ores however, necessitates some investigation. To differentiate between magnetite and ilmenite in thin section is troublesome. To facilitate recognition of the two minerals, recourse was made to an examination of a separated sample of the heavy minerals of the sandstones. It was found that a large number of the black ore grains could easily be removed from the sample, using a small horseshoe magnet. These highly magnetic grains were assumed to be magnetite. The less magnetic residue, which still carried a considerable proportion of black ore grains, was now dissolved in concentrated hydrochloric acid. A drop of the resulting solution was then added to a solution of phenol in concentrated sulphuric acid. The red colour given on the mixing of these two acid solutions is indicative of the presence of titanium (Winchell, Pt. II, p. 67) and consequently confirms that the black ore grains of the residue were ilmenite. A further indication that ilmenite is present in the sandstones under consideration can be seen in those few observed cases where the partial alteration of a grain of ilmenite to anatase is evident under the microscope. This is a phenomenon already noted by Mackie (1920) and by Brammall and Harwood (1923).

Statement /
Statement (b) refers to "detrital grains of magnetite and ilmenite". It is necessary for the purpose of this present discussion to establish the mode of genesis of these grains; that is, whether they are allogenic or authigenic. From several considerations it must be assumed that the magnetite and ilmenite grains are, at least in the vast majority of cases, detrital. It might be argued that the black iron ore which commonly replaces, to a varying degree, flakes of biotite in the sandstones, was of authigenic origin. Assuming however, that the conglomerates and sandstones of the Brora Outlier were derived from the same source rocks, then the prevalence of similarly altered flakes of biotite in many boulders of fresh granite found in the conglomerates, would lead to the supposition that this replacement of biotite by black iron ore was accomplished within the body of the parent rock. As regards the grains of black iron ore proper, reference to standard textbooks on sedimentary petrology indicates the probability of their being allogenic or detrital, as opposed to authigenic. Thus Twenhofel ("Principles of Sedimentation", pp. 265-267) lists magnetite and ilmenite among the common, metastable allogenic minerals, and excludes them entirely from his lists of authigenic minerals. The average diameter value for the grains of black ore in the sandstones here considered, may be taken /
taken as in the order of 0.07 mm. Pettijohn ("Sedimentary Rocks", Fig. 33, p. 85) indicates that ores of this dimension are most likely to be allogetic. Subsequently (Table 23, p. 89) he lists magnetite and ilmenite as two of the more common detrital minerals. In the absence therefore, of any direct evidence to the contrary, there is no reason to suppose that the magnetite and ilmenite grains under consideration are other than detrital.

The concentration of black ores in the darker bands would indicate, that for any given lighter band, there will be an underlying, darker equivalent, since, by virtue of their higher specific gravity, grains of black ore would be expected to sink to the floor of a basin of deposition more readily than any of the other detritals. The association of these black ore grains with the smaller detrital constituents of the sandstones, suggests that the depositional history of these banded sediments could be most readily explained in terms of the fluctuation in velocity of the transporting medium, due perhaps, to climatic variations.

Considering each dark band and the associated lighter band lying immediately above it as a sedimentary unit, a description of the probable depositional history of these two layers may be attempted.

The /
The small grains found in the dark layer would be deposited by a transporting medium moving too slowly to incorporate larger fragments in its suspension load. As the velocity of the transporting medium increased, so larger fragments would be introduced into the area of deposition. If the Brora Outlier sandstones are alluvial fan deposits, then this increase in the velocity and competence of the transporting medium might be due to increased rainfall, if fluvio-glacial outwash deposits, due perhaps to increased rainfall coupled with increased melting of ice. Only the smallest grains of black ore would be deposited by the initially slowly moving river, the bulk of ore fragments appearing among the coarser detrital material. In support of this last statement, the following evidence can be submitted: Mackie (1920) records the relationship that: "the pressure required to move a particle varies directly as the product of its diameter into its specific gravity", and, accordingly, gives the following equation:

\[ P = kx \text{sp.g.} \]  
\[(1)\]

(Where \( P \) = the pressure required; \( k \) = a constant; \( x \) = the diameter of the particle in question; and \( \text{sp.g.} \) = its specific gravity).

It should be noted that the value \( P \) is the maximum pressure or force which must be exerted on a given grain in order to remove it.
it from the area of provenance and to convey it to the area of deposition, since, the force required to overcome the initial inertia of a stationary body is greater than that required to maintain movement once initiated.

A full description of the sandstones in question has just been given (see pp. 79-97). In this present enquiry, it is only necessary to make two distinctions in the constituent minerals of the banded sandstones:

(a) that between the quartz and felspar grains of the lighter bands and those of the darker bands, and

(b) that between the quartz and felspar grains of the darker bands and the associated black ore.

The mean apparent diameters of the different types of grain were calculated from the measurement of some forty grains in a rock section of a typical banded sandstone. Though these average values will doubtless show some slight variation in different rock sections, the same proportional relationship exists in each case between the diameter values for the grains of different type. In estimating the specific gravities in the following calculations, an average value was taken for magnetite and ilmenite in the case of the black ores, and for the light material, the average for quartz, orthoclase and andesine was adopted. It may be noted that for the purpose of this /
this investigation, the value of the constant $k$ and the units in which the final result should be expressed, are immaterial. We have therefore:

For the black ores:

Substituting in equation (1):

$$P = k(0.07)(4.95)$$

$$= 0.34k$$

For light material of fine (dark) layers:

Substituting in equation (1)

$$P = k(0.06)(2.63)$$

$$= 0.16k$$

For light material of coarse (light) layers:

Substituting in equation (1)

$$P = k(0.17)(2.63)$$

$$= 0.45k$$

The results shown above bear out mathematically, what has just been stated empirically, namely, that the current responsible for the deposition of the light material of the darker layers was not competent to incorporate any but the very smallest of the black ore grains in its suspension load. Further /
Further, it is seen that the current necessary for the transport of the light material of the coarser, lighter layers, is also adequate to transport the black ore grains now concentrated in the darker layers of the sandstones.

In the light of the foregoing evidence, the postulated sinking of the detrital grains of magnetite and ilmenite from the light, coarser layers into the underlying, dark, finer layers would appear to be valid. It is to be expected, that if this were indeed the true picture, then not only would the darker layers carry a concentrate of the black ore grains, but also, that they should be richer than the lighter layers in the heavy minerals of the sandstones. That the heavy minerals are concentrated in the darker layers can easily be seen on examining the rock sections under the microscope, and the hypothesis of the emplacement of the black ore grains is accordingly strengthened.

Professor Backlund (1932) referring to pairs of micro-beds in the recent iron ore deposits of the Baltic Shield area, points out the difficulty of deciding whether these micro-beds are equivalent to varve deposits, and thus measure an annual rate of deposition, or whether they are merely subdivisions of some greater rhythm which might itself be annual. Bubenoff (1947) /
(1947) states that any rhythmic sedimentation is but the reflection of a corresponding, externally imposed rhythmical change of conditions on the surface of the earth. In the case of the Brora Outlier sandstones, viewed in the light of rhythmic sedimentation, it appears most likely that the necessary rhythmical changes in external conditions were climatic. It does not seem feasible that such small changes in grain size as have been observed in the different layers can in any way be a reflection of a periodic uplift of the area of provenance. It is impossible to state whether in the case of these sandstones, a given pair of light and dark beds approximates to, or is the equivalent of, a varve. Consideration of the thickness of the different layers, in conjunction with the grain size of their constituents would indicate that the period of accumulation of each layer was of approximately equal duration, bearing in mind that increased melting of the ice or increased rainfall would result, not only in greater competency of the transporting river, but also in an increased supply of detritus.

The previously noted third feature of the darker bands (p. 99), the high concentration of haematite, is, perhaps, the most important of the three, in that it has a direct bearing on the problem of red coloration. Both concepts of the origin of the haematite may be considered in conjunction with the depositional /
depositional history outlined for the red banded sediments of the Brora Outlier.

The haematite of the sandstones, as has already been described (p. 88), acts as a cement, and as such, forms a finely powdered, red pellicle of varying thickness round the constituent grains. No crystals of haematite have been observed. If the idea that this haematite be of primary derivation, that is, that it was formed in the provenance area, be accepted, then it must also be allowed that it would be deposited in a pronounced state of sub-division. Supposing first, that haematite was deposited in a finely divided state in the initial fine-grained bottom layer; it does not seem at all probable, despite the high specific gravity of haematite, that it would remain in the marked concentration in which it is now found in such layers, with the advent of the currents of higher velocity responsible for the deposition of the coarser, overlying band. Further, the absence of any boulders of a suitable red source rock in the conglomerates associated with the sandstones, militates against this concept of primary derivation of the haematite.

That the haematite is of post-depositional, or secondary derivation, as proposed by Crosby and Barrell, seems to be /
be the more feasible explanation. If the outlined pattern of deposition for the sandstones of the Brora Outlier is accepted, then the concentration of black iron oxides in the finer layers finds a ready explanation, and in turn affords the obvious source for this post-depositional formation of haematite. When examined under the microscope, sections of these sandstones afford many instances of a marginal alteration of the black ore grains to red haematite. Again, though not a common feature, the production of authigenic anatase from ilmenite probably proceeds via a ferric oxide complex. Evidently the high concentration of the red iron oxide in the darker bands can most readily be explained on the basis of its being authigenic. The staining of the whole sediment could then be accomplished, partially by diffusion of iron from the finer layers, and in part by the conversion to haematite of the ferruginous material which did not sink to the finer bands, but was trapped in the coarser layers. In this connection, it is of interest to note that Mackie (1920) records the observation that in all cases examined by him, red sediments carry a much higher percentage of iron ore grains than do the lighter coloured sandstones. In Kirkton Quarry, where the typical red sandstone of the Brora Outlier is well exposed, there occurs, interbedded /
interbedded with the normal sediments, a thin band of grey sandstone. Comparison of a rock section from this band with one from the normal red sandstone testifies to the accuracy of Mackie's findings. This high percentage of particles of iron ore in red sediments, led Mackie to suppose that the red colour might be due to the partial solution, followed by what he terms the "running" (migration and re-precipitation) of these constituents.

Finally it may be noted that Barrell suggests as the necessary climatic conditions for the formation of red sediments: intermittent wet and dry periods. A similar set of conditions; dry periods alternating with periods of increased rainfall, or increased melting of ice, or both, has already been proposed (p. 107) to explain the alternation of the coarse and fine, or light and dark bands in the sandstones of the Brora Outlier.

The dangers of generalisation are perhaps nowhere greater or more apparent than in the study of sediments. The processes of sedimentation are too notoriously prone to variation to allow of any degree of valid extrapolation. Consequently, it cannot be claimed that the course of deposition outlined for the red banded sandstones of the Brora-Outlier would
would necessarily be applicable to similar sediments in other areas. All that can be maintained is that in the present case, the mechanism proposed to account for the observed condition is a feasible one, and that the facts on which it is based indicate that the haematite occurring in these sandstones, originated, not in the area of provenance, but in the basin of deposition.
Figure 8

The numerical value of the average sphericity of the pebbles from the four conglomerate outcrops is given.
THE SPHERICITY OF THE PEBBLES IN THE CONGLOMERATES

Waddell (1932) has defined the true sphericity, \( \psi \), of a particle as \( s/S \), where \( s \) is the surface area of a sphere of the same volume as the particle, and \( S \) is the actual surface area of the particle. He has also shown (1932) that sphericity or shape, and roundness, are two independent variables. Due perhaps to the failure to distinguish between these two properties, no great amount of study has been devoted to the changes in the sphericity of a particle with distance of travel. What little work has been done, however, at least bears out the relationship which might be expected to exist between abrasion and sphericity: namely that the sphericity of a particle increases with continued abrasion. The most rapid increase of sphericity occurs during the early stages of transport, and thereafter, further increases take place somewhat more slowly.

In this present work, an attempt has been made to calculate the average sphericity of the pebbles of the four conglomerate outcrops which are shown as black patches in the sketch map opposite (Figure 8). Dealing with indurated conglomerates such as those of the Brora Outlier, great difficulty is often experienced in attempting to obtain samples of unbroken pebbles. To take samples at definite intervals along any given pebble-band
is practically impossible. Accordingly, the author has collected pebbles from these outcrops wherever it was relatively easy to do so, without regard to stratigraphic level. The numerical value assigned to each outcrop in the sketch map is therefore in the nature of an approximate average sphericity for that outcrop as a whole.

The sphericity of some forty pebbles from each of the outcrops shown was calculated, and from these values the average sphericity for the pebbles of the outcrop concerned was obtained. The method used to calculate the sphericity of each pebble was that proposed by Wadell in 1934. This method obviates the difficulty of measuring the surface area of an irregularly shaped pebble. The relationship \( \mathcal{W} = s/S \) has already been given. In the practical formula adopted in this work, the equation \( \mathcal{W} = \frac{dn}{Ds} \) is used, where \( dn \) is the true nominal diameter, that is, the diameter of a sphere of the same volume as the pebble, and \( Ds \) is the diameter of the circumscribing sphere, taken as the longest diameter of the pebble.

In practice, the value of \( dn \) for a pebble is readily obtained when its volume is known. The volume is easily ascertained by noting the displacement when the pebble is dropped into a known volume of water in a measuring jar. The value of \( Ds \) /
Nomograph for computation of sphericity by Wadell's method. For pebbles, the volume value, determined by displacement method, is connected with the $D_m$ (maximum diameter) value measured by gage. Point of crossing of line thus determined, on slanting scale, gives sphericity.

**Figure 9**

Adapted from Krumbein and Pettijohn (1938) p. 293.
De is obtained by direct measurement of the longest diameter of the pebble. The final calculation of the sphericity, \( \psi \), is greatly facilitated by the use of the nomograph shown in Figure 9 opposite.

Before attempting to draw any inferences from the results obtained for the average sphericities of the pebble constituents of the four outcrops shown on the sketch map, it cannot be emphasised too strongly that any conclusions based upon this evidence must be regarded as no more than mere indications, which may or may not have any real significance. The author is well aware of the fact that the average sphericity of a few pebbles taken from a mass of conglomerate which carries many thousands is not likely to be an accurate estimate of the sphericity of the pebble content of that mass as a whole. If it were possible to trace a given pebble band from one outcrop to the next, and if such a band could be sampled at definite intervals along its length, then the results obtained would be of definite moment. Unfortunately however, this ideal method cannot be practised on the conglomerates of the Erora Cutlier. Again, in basing any conclusions as to the direction of transport of the pebbles concerned upon the evidence of their sphericities, it is tacitly assumed that the conglomerate /
conglomerate outcrops from which these pebbles have been taken are related, in so far as they have been derived from the one general provenance area. In actual fact, the petrological similarity which exists throughout the outcrops shown on the sketch map indicates that this is a relatively safe assumption.

Bearing these reservations in mind, the results of the sphericity measurements may now be interpreted. A glance at the sketch map will show that the estimated average sphericity of the pebbles increases from north to south, reaching a maximum average value of 0.747 at Creag an Amalaich. Considering these results on the basis of the principle that the further a pebble has been transported, that is, the longer it has been subjected to abrasion, the more nearly spherical it should be, certain inferences as to the location of the source rocks of the conglomerates concerned may be drawn. Since the pebble constituents of the Glen Rock conglomerate have lower sphericity than those of Silver Rock, the provenance area for these two conglomerate masses could not have been situated at any point south of Silver Rock. Two dotted lines have been drawn on the sketch map, and within the area bounded by these lines, or by their extensions beyond the confines of the map, the source rocks of the four conglomerate masses are, on this evidence /
evidence at least, located, so situated as to lie nearer to Glen Rock than to Silver Rock.

As has already been stressed, the evidence is such, that deductions based upon it cannot be accepted without reservation. It is however worthy of note, that however slender the evidence, this method of attempting to determine the direction of derivation of the conglomerates of the Frera Outlier has yielded results which are in close agreement with those afforded by the petrological examination (see pp. 161-163) of the conglomerates concerned. This may, or may not be coincidental.
THE FABRIC ANALYSIS OF THE CONGLOMERATES

As a possible means of determining the direction of transport of the Brora Outlier conglomerates, several outcrops were subjected to a fabric analysis. The methods used, and the terms adopted in this work are those advocated by Clark and McIntyre (1951). These writers have given the following definitions:

(a) "the fabric of an object is described by all the spacial data (fabric elements) which it contains. A rock is said to have a single fabric when it contains a single fabric element (e.g. lineation or plane). A rock is said to have a compound fabric when it contains more than one fabric element (e.g. lineation plane; 3 planes; &c.).

(b) a face is an exposure-plane, either natural or artificial.

(c) a trace is the intersection of a fabric element with a given plane;

(d) pitch is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal;

(e) plunge is the vertical angle between a lineation, or a trace, and the horizontal;

(f) trend is the strike of the vertical plane containing a lineation or a trace."

In practice, outcrops of conglomerate were chosen where three or more suitable non-parallel faces were present. If traces can be measured on three, or preferably more than three such faces, it is then possible to determine the space orientation /
orientation of the structure responsible, by the use of a stereographic projection. Three measurements were made on each separate face. First, the strike of the face was determined. Second, the dip of the face was measured, and third, the pitch of the trace resulting from the intersection of the long axes of the constituent pebbles with the plane of the face, was determined. Usually, when studying an exposure face, the long axes of the pebbles were marked with chalk. It was then comparatively easy to measure the average angle of pitch of any trace present, or alternatively, to decide that the pebbles exhibited no preferred orientation.

A typical set of readings for the conglomerates here considered is as follows:

<table>
<thead>
<tr>
<th>Face</th>
<th>Strike</th>
<th>Dip</th>
<th>Pitch of Trace</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>341°</td>
<td>70° E</td>
<td>16° NW</td>
</tr>
<tr>
<td>2</td>
<td>265°</td>
<td>90°</td>
<td>8° W</td>
</tr>
<tr>
<td>3</td>
<td>357°</td>
<td>85° E</td>
<td>2° S</td>
</tr>
<tr>
<td>4</td>
<td>50°</td>
<td>72° NW</td>
<td>2° S</td>
</tr>
</tbody>
</table>

These measurements are then plotted on a stereographic projection.

The plotting procedure may best be described by considering the plotting of the data referring to Face 1. A sheet /
sheet of tracing paper is placed upon a Wulff stereographic net, and the centre and north points are marked with a cross and an arrow respectively. The tracing paper is then rotated in an anticlockwise direction, until the north arrow marked upon it has been turned through 241° from the north point of the net. The north-south diameter of the net then marks the strike of Face 1, and the pole of the face-normal lies 20° from the western end of the east-west diameter. The projection of Face 1 itself, is the great circle 90° distant from the pole, measured along the east-west diameter. The trace lies on this great circle, 16° from its north-western end. The pole of the face-normal is marked by a point and the trace by a cross. The readings for every face are plotted in a similar manner.

Before considering the stereographic projection (Figure 10) of the measurements given, several points about simple structures must be made. Clark and McIntyre put the case thus:

"If the structure is planar, the traces on random faces are the intersections of the planes with these faces. In this case all traces have one common feature: viz: they lie parallel to the structure planes. Any two traces define the space orientation of the planar arrangement; the remainder must all lie in this plane. Thus in a stereographic projection, the poles of the traces must lie upon the great circle representing the planar structure.

"If /
Figure 10
"If the structure is linear, the traces are the projections of the lineations upon the faces studied; i.e., any trace is the intersection of the exposure face with the plane which contains the lineation and which is normal to the exposure face. If the orientation of the faces and traces are known, the great circles representing these normal planes are easily constructed on the projection. The point at which these great circles intersect is the pole of the lineation (Lowe, 1946).

"If the poles of the traces lie upon, or are close to a great circle, then the fabric is probably planar. The great circle may be constructed and its strike and dip read directly from the projection.

"Should the traces not lie on a great circle, lineation may be suspected, and the normal planes referred to above must be constructed. For each exposure surface, and for each trace, the required normal plane is represented by the great circle containing the pole of the trace and the pole of the face on which that trace was observed. If these great circles, representing the normal planes, intersect at or near a point, then the fabric is linear and the trend and plunge of the lineation can be determined."

From the foregoing discussion it will be realised that the construction of the normal plane for a given face is effected by rotating the tracing paper until the face-normal and the pole of the trace lie on the same great circle of the underlying net. This great circle is the required normal plane. The procedure is repeated for each face.

In the case of the measurements shown plotted in Figure 10 opposite, it will be seen that the normal planes intersect nearly at a point. On this evidence the structure is /
is linear. A certain ambiguity arises, however, in that it is possible to draw a great circle which passes close to the poles of the traces on Faces 2, 3 and 4. This would suggest that the structure is planar, although the fact that the pole of the trace on Face 1 is somewhat removed from this great circle tends to weaken the case. It is of course possible that the structure is both planar and linear. It cannot however be decided on the strength of measurements from only four faces, whether this is a compound fabric. In the case of a hand specimen, this ambiguity could be resolved by cutting extra faces with definite orientations, but this method is obviously inapplicable to conglomerate-outcrops in the field. As far therefore as the evidence goes, it would appear that the data plotted in Figure 10 reflect a linear structure. The point of intersection of the normal planes gives the pole of the lineation, and the trend is given by the diameter passing through that point.

It must be emphasised that this linear structure is due to the alignment of the long axes of the pebbles, and that it is not a reflection of imbrication. Krumbein (1940) records that stream pebbles usually lie with their long axes dipping upstream, but that the farther a pebble has travelled from /
Figure 11
from its source rock, the more marked is the variation to be expected from this mean direction. Unfortunately, too little is known of the complex mechanics of stream transport to allow of any safe generalisation. Accordingly, in transferring the results of the fabric analysis on to the sketch map (Figure 11) allowance has been made for the possibility that the long axes of the pebbles lay, not parallel to the stream, but at some angle athwart it. The result of the analysis for a given locality is shown on the map by three arrows, the centre arrow corresponding to the trend of the lineation as determined, the other two being inclined at 45° to it.

A glance at the stereographic projection (Figure 10) will show that the transporting agent could, according to this evidence, have moved from approximately N.E. to S.W. or vice versa. The N.E. to S.W. direction is the one which appears on the sketch map. This direction has been favoured for several reasons:

(a) measurement of the sphericity of the pebbles indicates that the provenance area could not have lain to the south of Silver Rock (see pp. 113-118);

(b) measurement of the pebbles by Wentworth's method (see pp. 145-154) gives a similar indication;

(c) H.H. Read (Mem. Geol. Survey, 1925) records imbrication in the conglomerate of Ben Lundie as indicating transportation from the north-west. This is again in agreement with a provenance area situated on the northern side of Silver Rock;

(d) /
(d) the petrology of the conglomerates favours a provenance area on the northern side of Silver Rock (see pp. 162-168).

In the case of all the directions shown on the sketch map (Figure 11) with the exception of that on Ben Lundie, which records the imbrication just noted, the results of the fabric analysis do, of course, offer diametrically opposed alternatives. The directions shown have been preferred on the basis of the other evidence just outlined, with which they are consistent throughout the area.

Many measurements were made in the field at specific points in the conglomerate-outcrops shown in outline in the sketch map (Figure 11). On plotting the data however, it was found that in a large number of cases the poles of the faces measured lay too close together to give a reliable result. It was decided therefore to treat each conglomerate-outcrop as a whole, and the available data were accordingly so selected as to give a wider scatter of poles on the stereographic projection. The stereographic projection of a number of such selected measurements for the Silver Rock conglomerate is shown in Figure 12. In the case of this conglomerate, only two arrows have been drawn on the sketch map. A third arrow 45° distant from the trend of the lineation as determined by the stereographic projection, would indicate a source situated south /
Figure 12

TREND OF LINEATION
south of Silver Rock, and this has been discredited for the reasons already given. The arrows which refer to Glen Rock and Ben Tarvie are based upon projections which do not have as wide a scatter of poles as might be desired, and are therefore somewhat less reliable than the rest.

It has already been noted (p. 126) that the imbrication of the Ben Lundie conglomerate indicates transport from the north-west. Considering the remaining directions shown on the sketch map in the light of this independent evidence, it will be seen that in the case of each of the six other localities, one arrow at least indicates derivation of the conglomerate concerned from the north-west. From the nature of the evidence, it would be unsafe to draw any conclusions of a more specific nature. It is interesting to note, however, that the more southerly of the two arrows referring to the Silver Rock conglomerate and the most westerly of those referring to the Ben Tarvie conglomerate, when produced backwards, meet the conglomerate of the An Droighneach ridge. A connection between the An Droighneach conglomerate and these conglomerates to the east is perhaps indicated.
EVIDENCE OF ORIGIN AS REVEALED BY THE CONGLOMERATES

Fully aware of the limitations of the methods of comparison adopted, it may be fairly claimed nonetheless that the results of the mechanical analysis of the Erora Outlier sandstones have suggested two main possibilities concerning the origin of these sediments: first, that they are apparently most closely akin to outwash deposits; and second, and more specifically, that they may be fluvo-glacial outwash deposits. Whatever the precise mode of deposition of these sandstones, it is reasonable to suppose that evidence of this method of derivation should be apparent in the closely associated conglomerates, which, together with the sandstones, comprise the Erora Outlier.

It must be readily admitted that first examination of the conglomerates fails to reveal any characteristic which might be considered inconsistent with the commonly accepted view that these are "fanglomerates" or torrent deposits possibly laid down in intermontane basins. There is nothing discordant with this hypothesis in the large number of grade sizes represented, in the lack of sorting, in the occasional rude stratification of these deposits, nor in the apparent local nature of the constituent pebbles (see pp. 162-168). In the case of the conglomerates /
conglomerates, therefore, are there any grounds for entertaining the suspicion that they have been fluvio-glacially derived? Before deciding, it is necessary to determine what evidence of this mode of origin might be encountered.

While differences of opinion exist as to the exact manner in which the final, distinctive form of a glaciated pebble is produced, geologists are agreed that this final form does correspond to a definite, general type. Von Engeln (1930) states that:

"The type form which apparently evolves (with adequate application of the processes of sub-glacial abrasion to rock fragments carried along by the ice motion and themselves the tools utilized for scour of the bed-rock pavement), is roughly that of a flat-iron minus the handle. As flat-irons vary in shape and size from that of a tailor's goose to many less massive types and forms of special outline, all of which retain nevertheless a general resemblance, so also do the typical, flat-iron shaped, faceted and striated pebbles display differences and keep to one likeness. Another comparison is to the prows of flat-bottomed boats which also are distinctive as between one and the next but conform to a general pattern.

"The characteristic features of such type facetted and striated pebbles are:

(1) the roughly triangular shape in plan with the facet of largest area and that which is flattest down;

(2) the pointed but scour-smudged nose at the apex of the narrowest angle of the bottom facet;

(3) an only slightly scoured or hackly back side above the base line of the bottom triangle;

(4)/
(4) a tendency to a hump form of the top side of the flat iron with
(5) lateral facets running off towards the snubbed point;
(6) chipping or nicking on the underside or at the apex of the point;
(7) a tendency of the striations on the lateral facets to be directed diagonally downward toward the point;
(8) indications that variation from the norm or failure to develop of one of these features in a well-processed pebble are due to particular, and still obvious configuration of the original fragment or to the nature, rock structure and composition of the specimen.

Von Engeln devotes the greater part of his paper to an explanation of the processes which would result in the production of these flat-iron pebbles. He points out that only those fragments which have been subjected to the abrasion processes prevailing at the sole of a glacier can be expected to exhibit the flat-iron form to a marked degree. The fragments not confined to the sole of a glacier will, he contends, have in general an ovoid end-form. Since, however, variation in shape is to be expected, and also, because of the resemblance which these ovoid pebbles bear towards pebbles of other than glacial form, this secondary type of glaciated pebble is less characteristic, and more difficult to recognise than the flat-iron form. He concludes that:

"whatever /
"Whatever objections may be raised to the contentions herein set forth regarding the manner in which the flat-iron form is processed, the fact remains that such pebbles are present in considerable numbers in the compact ground-moraine till of Central New York and that, as a pebble form, the facetted, striated flat-iron type is unique. Dreikanter from wind action are their nearest counterparts."

Pettijohn (p. 217) summarises the work of Wentworth (1936) and states that:

"Three hundred cobbles selected for perfection of glacial action, were classified according to the general shape as shown in Table 52. Clearly the dominant shape is tabular, owing in part to the original tabular shape of the limestone fragments and to sustained abrasion on the two initially opposed principal faces.

"Study of the marginal profiles (as observed when the pebble lies on its most stable face, i.e. profile normal to the shortest axis), shows the pentagonal outline to be the most common (Table 53). Approximately two thirds of the margins might be described as pentagonal, quadrangular, triangular, polygonal, trapezoidal or reniform. The most characteristic shape of a glacial cobble, therefore, is parallel tabular with a pentagonal outline, and comprises the modal class. The flat-iron shape noted by Von Engeln thus is verified by actual count.

He further notes that:

"When a randomly collected sample was studied, only 10 per cent of the limestone, and scarcely over 1 per cent of all other rocks was found to show striations. The difficulty of removing cobbles intact and the scarcity of striations on typical glacial material, as shown by Wentworth's data, explain the common failure to find striated stones in many ancient non-limestone-bearing tillites."

Finally, Pettijohn summarises the characteristic features of glacial till as follows:

1. /
1. High range of sizes usually unsorted

2. Rock fragments (shape, roundness and surface markings)
   a. Usually subangular or angular with several facets
   b. Some rounded pebbles or boulders
   c. Fragments blunted at one or both ends, or rather pointed at one end and blunted at the other
   d. Fragments bevelled on one or more sides, the sides usually not parallel but making an angle to one another
   e. Concave fractures
   f. Striated fragments, nailhead scratches

3. Rock fragments (lithology)
   a. Greatly varied
   b. More local than foreign

4. Rock fragments (fabric and packing)
   Sparsely distributed pebbles show preferred orientation parallel to flow

5. Matrix usually clay, sometimes sand, usually greatly in excess of fragments

6. Lower part of till has finer matrix and more striated pebbles than top

7. Till often rests on grooved or striated rock pavement

8. Unstratified

9. Near top of till, intercalated stratified lenses may be found; such "nests" and layers are usually contorted

10. No evidence of weathering or decomposition


   Such then are the criteria which must be borne in mind looking to the conglomerates for any evidence of their possible /
possible fluvi-glacial origin. It must be remembered, how- ever, that it is merely the possibility of a fluvi-glacial origin which is being considered, and that the part played by river-action in the transportation of the Brora Outlier sediments has never been denied. Indeed, the two suggested modes of derivation are by no means markedly divergent; what may be termed the "fanglomerate" hypothesis invokes river-action alone as a transporting agent, while in referring to a possible fluvi-glacial mode of origin, the present author envisages a set of conditions in which this selfsame river-action was preceded by ice-action, perhaps relatively unimportant, yet perhaps sufficiently pronounced for some trace of its effects to be retained by the deposits as they are found at the present time.

As previously noted (see p. 114) pebbles from the conglomerates were collected at Glen Rock, Silver Rock, Mound Rock and Creag an Amalaidh. A special collection was made of specimens which appeared to conform most closely to the type of glacial pattern as described by Von Engeln and others. This process of selection was considered justified in view of the fact that pebbles bearing the recognizable imprint of ice-action are in a minority in true glacial deposits: all the more so in that it is to be anticipated that if the Brora Outlier pebbles were /
were ever subjected to ice-action, the visible effects of such action may well have been somewhat modified by subsequent river transport.

A series of representative photographs shows that the pebbles from the Brora Outlier bear a closer resemblance to the true glaciated pebbles of Von Engeln than to the specimens of dreikanter. The facetting of the dreikanter appears to be more pronounced, and, if anything, rather more haphazard than that of the pebbles from the Brora Outlier. Also, against the possibility of the pebbles in question being examples of dreikanter, and consequently indicative of desert conditions in Old Red times, must be set the fact that no evidence to corroborate this view can be obtained from the associated sandstones, either on the macro or micro-scale. Nothing approaching dune-bedding has been recorded, nor have the micro-sections of the sandstones shown the rounded, millet-seed grains commonly associated with desert sediments. Indeed, the angular nature of the constituent grains of the sandstones has already been recorded, (see p. 85). Further, the relative abundance of flakes of muscovite in the sandstones is not concomitant with deposition under desert conditions. The results of the mechanical analysis of the sediments are even more strongly against their being of desert origin. Not only has it been shown, (see /
(see pp. 44-49), that the cumulative frequency curves for the sandstones of the Brora Outlier, and the statistical values calculated from them are at variance with those of known desert sediments, but it has further been illustrated that a marked similarity exists between the results for the Brora Outlier sediments and those for known outwash deposits.

Transport by ice is automatically associated in the mind with glacial striae. It has been shown, however, by Wentworth (1936) that glacial striae are not of such frequent occurrence as might be supposed. As noted on p. 133 he has recorded that only 10 per cent of a randomly collected sample of glaciated limestone pebbles, and just over 1 per cent of all other glaciated pebbles of different rocks were striated. No examples of striae, which could be, with certainty, definitely dissociated from the inherent fabric of the pebbles concerned, have been observed in the case of the conglomerates under consideration. Since the constituent pebbles of these conglomerates comprise granite, granulite, quartz and schist, the failure to find striae is not, in the light of Wentworth's findings, perhaps surprising. It is even less remarkable when considered in conjunction with some results previously published by Wentworth (1922), when it was shown experimentally that river transport over a distance of no greater than 0.35 miles was sufficient /
sufficient to remove originally well-developed striae on glaciated pebbles.

In the absence of striae, the shape of the pebbles assumes a greater importance, and the presence of facets in so many cases, as may be seen from the Plates, becomes especially significant. Apart from the more obvious facetting, other common features noted by Von Engeln and others, such as snubbing, chipping and the presence of concave fractures are easily observed in many of the photographed specimens. Wentworth has shown (see p. 133) that glaciated pebbles have, most commonly, a pentagonal outline. Over two hundred pebbles from the Brora Outlier were examined and roughly classified as pentagonal, triangular or quadrangular. The results showed that 40.5 per cent of the pebbles examined were roughly pentagonal in outline, 29.5 per cent were triangular, and 30 per cent were quadrangular.

As may be seen from the Plates, the tabular form of pebble flattened on two sides is common, while many examples of pebbles showing the development of the hump form, noted by Von Engeln as being typically of glacial origin, are to be observed. While in the case of some of the tabular or "soled" pebbles, the development of almost parallel, flat surfaces has obviously /
obviously been aided, if not wholly determined by the fabric of the rock, there are many flat-iron pebbles whose tabular form apparently owes nothing to this factor. The facets, as opposed to the flat top and bottom surfaces of the pebbles, have, in the great majority of cases, been produced without reference to the fabric of the rocks.

Small concave fractures, and, less frequently, distinct grooves are fairly common features of the pebbles. Occasionally the whole bottom surface of a pebble is markedly concave in form (see Plate 16). This concavity might have been produced by warping of the pebble due to the pressure of the overlying conglomerate. If so, however, it is to be expected that such warped pebbles would be more numerous than observation has shown them to be. The shape of some of these concave pebbles renders improbable the supposition that the concavity might have been caused by concussion fracturing. While breaking up of the parent rock along curved surfaces (see McIntyre, 1951) might conceivably have produced this concavity, the writer considers that gouging out of the bottom surface of such pebbles on their being forced over some obstacle in their path appears to be the most feasible explanation of this feature.

Pettijohn's /
Pettijohn's summary of the characteristic features of a glacial till has already been given (see pp. 133-134). In pursuing the enquiry into the possibility that the Brora Outlier conglomerates may have been fluvis-glacially derived, it is now necessary to consider in what manner features accepted as evidence of ice-action might be modified through exposure to the fluvial and outwash environment, and to what extent such modified features are represented in the conglomerates.

It is known that characteristically a glacial till carries unsorted pebbles varying greatly in size. The effect of superimposing a short period of fluvial transport upon unconsolidated glacial debris would be to improve, to a certain extent, the degree of sorting, and, in deposition, to introduce at least a rude stratification. The marked discrepancy in size between the largest and the smallest fragments would only slowly disappear. These features: a rudimentary stratification, a partial sorting and a high range in pebble size, are all present in the Brora Outlier conglomerates (see p. 161) and Plate 33).

As regards the effect upon individual pebbles, the removal of striae has already been noted (see pp. 137-138). This effect would doubtless be coupled with a small increase in /
in the degree of roundness of the pebbles. The Plates show that a slight rounding of the corners, and a smoothing of the line of intersection of opposed facets are common features of the pebbles under consideration.

The point noted by Pettijohn: that the constituent pebbles of a glacial deposit are of local rather than of foreign origin, would, in the case of short-lived fluvial transport, obviously still be valid. Examination of the constituent pebbles of the Brora Outlier conglomerates has led to the conclusion that they are of local derivation. No fragments of far-travelled material have been recognised (see pp. 162-163).

In a true glacial till the matrix is usually greatly in excess of the fragments. That this is not true of the Brora Outlier conglomerates does not necessarily militate against the possibility of their fluvio-glacial origin. In such a hypothesis, the sandstones associated with the conglomerates must be considered as the washed out, fine material, which, in the absence of fluvial and outwash conditions, would otherwise have consolidated as part of the matrix of the conglomerates. In this respect, it is interesting to note that Krumbein (1933), in recording the results of the mechanical analysis of a number of glacial tills, includes several cases where the principal mode falls within the one quarter to one eighth grade of the Wentworth /
Wentworth scale. It has already been shown (see p. 45) that the sandstones of the Brora Outlier have their principal mode in this grade. Further, it is characteristic of glacial till that it possesses a large range of grade sizes; usually twelve or more. It can readily be seen that the conglomerates of the Brora Outlier satisfy this condition (see for example, Plate 33). If the sandstones be considered as part of the matrix of the conglomerate, then the number of grade sizes which would originally have been present becomes characteristically large, especially when it is remembered that in the sandstones themselves as many as eight grade sizes are represented.

A till may or may not rest upon a glaciated rock pavement. In the case of the Brora Outlier sediments, if they are of fluvio-glacial origin, then a grooved and striated floor may have existed at one time beyond the present limits of the Outlier. Whether or not such a floor did exist, however, is a question which must as yet remain unanswered. Even a minute fraction of a period of more than three hundred million years during which erosion might have occurred would doubtless suffice to remove any grooves or striae which might once have been present.

Attention /
Attention must be drawn to another significant feature; namely the common association of varved sediments with tillites. A section of this work has already been devoted to a discussion of the banded sandstones of the Erora Outlier, and mention was then made of the resemblance which these banded sandstones bear to varved deposits (see pp. 106-107).

Of the remaining salient features of a glacial till which have been noted by Pettijohn (see p. 134), little need be said. The chemical composition is, as he himself observes, variable, and naturally largely governed by the nature of the local bedrock. It cannot therefore be decided that a given deposit is, or is not of glacial origin, on the basis of its chemical composition. A glacial till does not normally show evidence of weathering or decomposition. Obviously this criterion would be subject to modification in the case of an indurated tillite of great age. Further modification would result under fluvio-glacial as opposed to the glacial conditions proper under which a normal till is deposited. It is then perhaps especially noteworthy that, considering the age of the Erora Outlier conglomerates, the constituent pebbles are remarkably fresh.

In the light of the foregoing discussion, it appears reasonable /
reasonable to assert that although, as has been indicated (see p. 130), many of the observed characteristics of the Brora Outlier conglomerates are not inconsistent with the hypothesis which identifies these deposits as "fanglemerates"; neither are they at variance with the suggestion of fluvio-glacial derivation. In addition, the form of many of the pebbles weighs in favour of the supposition that they may have been fluvio-glacially derived. The equivocal nature of much of the evidence, however, serves only to emphasize the difficulty of differentiating between the two modes of origin, and it becomes increasingly evident that any distinctions which may exist between the two types of deposit are extremely fine-drawn. This is also the opinion of Professor W.C. Krumbein, who, in a personal communication to the author, writes:

"... that it may be rather difficult to make a sharp distinction between glacio-fluvial and alluvial fan deposits. In both instances the streams appear to be heavily loaded, so that deposition from them may well have yielded somewhat heterogeneous deposits. The intimate association of coarse and fine materials, and the wide variety of lithologic components may render it difficult to find any sharp criteria for making critical distinctions."

In the section of the work which follows immediately, one further endeavour is made to determine which of the two suggested modes of derivation of the Brora Outlier sediments might be considered the more probable.
SOME FURTHER EVIDENCE FROM THE PEBBLES

Late in the course of this present investigation, the writer discovered a method developed by Wentworth (1922) for the interpretation of the genesis of pebbles on the basis of shape. This method is described in Bulletin 730-C of the United States Geological Survey. Still in search of evidence which might help to determine the mode of derivation of the Erora Outlier sediments, the author examined forty pebbles from the Outlier (ten from each of four areas) by this method, and a second group of twenty-five pebbles from City Creek Canyon, to which reference will be made later. The results were thought to be of sufficient interest to merit inclusion in this separate section.

The method entails first, the calculation of three values: $r'$, $r''$ and $R$. $r'$ is the radius of curvature of the sharpest developed edge, and $r''$ the radius of curvature measured in the direction of the most convex edge on the flattest developed face or portion of the surface. $R$ is the mean radius of the pebble, and may, for practical purposes, be taken as half the arithmetic mean of the length, breadth and thickness of the pebble.

By plotting what he termed "the roundness ratio", $r'/R$, against the "flatness ratio", $r''/R$, Wentworth found that fluvial, glacial /
<table>
<thead>
<tr>
<th></th>
<th>r'</th>
<th>r''</th>
<th>R</th>
<th>r'/R</th>
<th>r''/R</th>
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</tr>
<tr>
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<tr>
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<td>10.2</td>
<td>1.30</td>
<td>0.38</td>
<td>7.85</td>
</tr>
<tr>
<td>9</td>
<td>0.38</td>
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</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>12.2</td>
<td>1.98</td>
<td>0.20</td>
<td>6.16</td>
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</table>

Results for Silver Rock Conglomerate
glacial and sand-blasted pebbles fell within three distinct areas of his graph. He further found that a pebble rarely departed far from the mean shape of those of its particular mode of origin. Thus, of over six hundred fluvial pebbles which he examined, only three fell within the area of glacial pebbles. Only forty pebbles from the Brora Outlier conglomerates were examined, partly because the writer did not possess the necessary instruments for the accurate determination of the radii of curvature, and had therefore to estimate these measurements using compasses and dividers, and partly because of the marked tendency for pebbles to plot close to the mean shape of their kind, whereby it was considered that forty should be a sufficient number to give an indication of the nature of the Brora Outlier conglomerates. A table of results for the pebbles from the conglomerate of Silver Rock is shown on p. 146. Similar values were obtained for the pebbles from the other three localities.

Figure 13 on page 148 is an adaptation from the chart included in Wentworth's paper. The dotted lines are the approximate boundaries determined by Wentworth for three principal types of pebble. Area F is that of fluvial pebbles, area G that of glacial pebbles, and area D that of dreikanter or sand-blasted pebbles. It will be seen that the area of glacial pebbles is sufficiently /
Figure 13
sufficiently far removed from that of sand-blasted pebbles to allow of no ambiguity in the interpretation of the plotted points. This is an admirable feature of Wentworth's method, since the possibility of confusing a glacial pebble with a sand-blasted pebble in attempting to distinguish between the two on sight, is a well-known pitfall to which reference has already been made.

The black dots in Figure 13 are the plots of the forty pebbles from the Brora Outlier; ten from Glen Rock, ten from Silver Rock, ten from Mound Rock and ten from Creag an Amalaich. The pebbles were chosen at random from the number shown in the Plates. Of the forty points plotted, twenty-seven lie within the area of glacial pebbles, and the remaining thirteen lie between the boundaries of the areas of glacial and fluvial pebbles respectively. All are completely removed from the area of sand-blasted pebbles.

The clustering of the majority of the plotted points on that side of area G which is in part contiguous with area F, and the location of the remainder between the bounding lines of these two areas, would appear to support the hypothesis that the pebbles may have been derived fluvio-glacially; the impress of initial ice-action being later modified by subsequent river transport. In this respect, it is interesting to note that Wentworth subjected five glacial and five sand-blasted pebbles to /
to abrasion in a tumbling mill. The pebbles were examined from
time to time, and their shapes calculated and plotted in the
manner described, in an attempt to record the process of modi-
fication. It was found that the plots of the end products lay
above, and only slightly to the left of, the plots of the origi-
nal unmodified pebbles. It might therefore be contended that
the results shown in Figure 13 indicate that the conglomerates
of the Erora Outlier are composed of pebbles of modified drei-
kanters, rather than of fluvio-glacial pebbles as has been sug-
gested. While this is perhaps possible, it is in no way pro-
bable. To raise the plot of a pebble from the right-hand part
of area D to the left-hand part of area G requires considerable
modification in the shape of that pebble. The Erora Outlier
conglomerates are of local derivation, and comprise fragments
of granite, granulite and quartz (see pp. ). It is ex-
tremely doubtful whether changes of the magnitude required could
be effected upon such resistant materials during a short period
of transport. If these were modified sand-blasted pebbles,
some indication of their true origin, given by some of the plots
lying between areas D and G, is surely to be expected. Nothing
of this nature is evident, and the interpretation of a fluvio-
glacial origin already given is by far the more feasible.

It /
It was considered unwise, however, to accord too much weight to the apparent support lent by the results of this method of assessment to the fluvio-glacial hypothesis until some attempt had been made to determine where on Wentworth's chart "fangular" pebbles would plot. Some difficulty was experienced in obtaining pebbles lithologically and structurally suited to such a comparison, and unfortunately, Dr C.K. Wentworth, the originator of this method, had no data to offer on material of this type. Eventually, however, the author was able to acquire a sample from City Creek Canyon, near Salt Lake City, Utah. City Creek Canyon is situated in an unglaciated area of the United States, and the pebbles were collected from a modern torrent outwash deposit. The sample was therefore considered to meet the present requirements admirably.

As noted, twenty-five of these pebbles were measured in precisely the same manner as those taken from the Brora Outlier conglomerates, and the positions of the resultant plots on Wentworth's chart determined. To simplify Figure 13, these plots are not shown individually, but all twenty-five fell within that part of area F contained by the rectangle labelled C.C.C. The values obtained for ten of the twenty-five pebbles measured are shown in tabular form on p. 152.

1 Personal communication.
2 The author is indebted to Dr C.T. Walker, Stanolind Oil and Gas Company, Calgary, Alberta, for the City Creek Canyon sample.
<table>
<thead>
<tr>
<th></th>
<th>$r'$</th>
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<td></td>
</tr>
<tr>
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<td>3.08</td>
<td>4.19</td>
<td>2.62</td>
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<td>0.71</td>
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<td>0.81</td>
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</table>

Some Results for City Creek Canyon Pebbles
It would seem reasonable to assert that the plots for the City Creek Canyon pebbles, while not widely separated from those of the Brora Outlier pebbles, are yet distinct; the most significant feature being that no plots of pebbles from the former locality fall within area G of Wentworth's chart. On this evidence, therefore, there is some justification for the claim that, when examined by Wentworth's method, the Brora Outlier pebbles are found to differ from pebbles of "fanglomerate" type, and that by virtue of this distinction the hypothesis of fluvio-glacial derivation is strengthened.

One further point remains to be noted. Of the thirteen pebbles which are plotted between areas G and F, one was from Glen Rock, four were from Silver Rock, three from Mound Rock, and five from Creag an Amalaich. Since Mound Rock is situated south of Silver Rock, it cannot be stated that there is a progressive increase of such pebbles from north to south. Many more measurements would in any case have to be made before the existence of such a progression could be proved or disproved. Out of forty pebbles measured however, it is perhaps significant that while only one pebble from Glen Rock, the most northerly of the four localities is plotted outside area G, the plots of five pebbles from Creag an Amalaich, the most southerly of the four localities, lie outside this area. It might therefore be maintained /
maintained that the pebbles of Creag an Amalaidh have suffered greater modification than those of Glen Rock, that is, that they have undergone a longer period of river transport. If this suggestion is correct, then the same conclusion regarding the provenance area of the conglomerates which was reached from a consideration of the sphericity of the constituent pebbles (see p. 117) is arrived at, namely that it could not have been situated at any point to the south of Silver Rock.
GENERAL CONSIDERATIONS

In the foregoing sections of this work, some attempt has been made to weigh the separate merits of two hypotheses of derivation of the Brora Outlier sediments; the first attributing the presence of these sediments to fluvial torrent and outwash action, the second embodying the mechanism of the first, but postulating in addition initial ice action. The two hypotheses are therefore essentially parallel, but for this ice action, the only factor not common to both. At this point it must again be stressed that in suggesting the possibility of a fluvio-glacial origin, the author is not contemplating a glaciation of anything approaching the magnitude of that operative during the Pleistocene epoch, but is merely advancing the idea that ice in high-lying source areas may have contributed detritus to the basin of deposition. Furthermore, it is not denied that if such a mechanism existed, its sphere of influence may have been quite local, confined perhaps to the area of this present investigation.

But what of the possibilities of the presence of ice quite outwith the evidence afforded by the Brora Outlier sediments? From what is known of the physiography of Scotland during the deposition of the Middle Old Red Sandstone beds, the /
the presence of upland ice, which it is suggested, was in part responsible for the transportation of the Erora Outlier sediments, was not only possible, but indeed probable. It is commonly believed that mountain-building and the major periods of glaciation may be in some way related. Umgrove (1947) considers it safe to assert:

"(1) that the periodicity of 250 million years as indicated by the major periods of glaciation is also manifested in the epochs of mountain-building.

(2) that a rhythm of minor amplitude, as observed in the less accentuated deviations from normal climatological conditions in the Ordovician, Silurian, Devonian, (Triassic?), Jurassic and Eocene can probably be said to coincide with epochs of mountain-building of far less geographical importance than those which accompanied the major rhythm of 250 million years referred to above."

The tectonic upheaval which resulted in the building of the Caledonides is believed to have ceased in Scotland early in Devonian times. Just as the Pleistocene glaciation is thought to be related to the Alpine orogeny, so tillites of Devonian age in South Africa and Alaska are thought to be associated with the minor Caledonian folding. It seems probable that before the deposition of the Erora Outlier sediments, valley glaciers had been established in the newly raised mountain chain which towered to the west, and that these sediments were therefore laid down under climatological conditions which deviated from normal /
normal to this extent.

In attempting to describe the mode of transport and deposition of ancient sediments, the earlier British geologists appear to have been extremely chary of the mention of ice. This reticence was probably due in part to the comparative remoteness of the British Isles from areas then undergoing active glaciation, and in part perhaps to the active controversy, in existence during the first half of the nineteenth century, between the advocates of the "iceberg theory" and the glaciologists. Though Hutton had realised, as far back as the end of the eighteenth century, that the erratic boulders observed by Saussure in the Jura Mountains must have been glacier-borne to their position (see Playfair, 1802), it was not until after the publication of two classic papers: one by Jamieson in 1862 and the other by Archibald Geikie in the following year, that the concept of the marine origin of the drift was finally abandoned.

Although the author is original in suggesting a fluvio-glacial origin for the sediments of the Brora Outlier, here and there in the literature there are expressed a few guarded statements on the possibility of ice having played a part in the deposition of the Old Red Sandstone beds of other areas. In this general consideration of the likelihood of ice /
ice action in the present case, it is interesting to review these statements briefly.

In 1848 the Reverend J.G. Cumming described the Old Red Sandstone conglomerates of the Isle of Man as: "a consolidated ancient boulder clay formation". It soon becomes evident as he indulges in speculation as to the nature of the climatic conditions obtaining at the time of deposition of these beds, that he believed them to have been deposited by floating icebergs. That the precise mode of ice transport proposed by Cumming has long since been proved wrong is immaterial. The important point in this present discussion is that ice was thought to have been active in the transportation of these Old Red Sandstone sediments. It is of interest to note that in 1874 John Horne subscribed to Cumming's opinion that these conglomerates had been derived through the agency of ice.

In 1855, A.C. Ramsay had noted the similarity between some of the Old Red Sandstone conglomerates of Scotland and the Permian breccias of Worcestershire, which latter he considered to be of glacial derivation. Later, in 1863, referring to the Scottish Old Red Sandstone deposits, he remarks that: "some of these conglomerates possess a character which suggests that they may have had a glacial origin". In an article written in 1876, James Geikie refers to evidence from the Upper Old Red Sandstone /
Sandstone conglomerates of the Cheviot area, which made him "suspect that glaciers may have existed at this early period among the Cheviot and Lammermuir Hills".

It is significant that these earlier geologists, working at different times on Old Red Sandstone deposits of different areas, should all have been of the opinion that ice action is evidenced by the sediments. In the case of the sediments of the Brora Outlier, the author believes that there is sufficient evidence to assert that these earlier suspicions have been aroused in yet another area, and this time for reasons that are more than general impressions.

While much of the evidence yielded by the Brora Outlier sediments may be construed as lending equal support to both the "fanglomerate" and the fluvio-glacial hypotheses, a number of the characteristics of these sediments when assessed have given results which find no ready place among the tenets of the former hypothesis but are consistent with those of the latter.
PETROGRAPHY OF THE CONGLOMERATES

Macroscopic characters

Except in those localities where the conglomerates are basal, and are arkosic, as in Glen Sletdale where they overlie the Helmsdale Granite, or siliceous, as along the western margin of the northern half of the Brora Outlier, they are composed essentially of angular or subangular fragments of siliceous schist and granulite, granite and quartz, set in a red, gritty or sandy matrix. The pebbles average some four inches in diameter, but a wide range in size is to be observed. A granite boulder measuring over three feet in diameter was noted in the conglomerate of Silver Rock. Lenses of sandstone are sometimes found intercalated with the conglomerates, which are themselves occasionally rudely stratified, but more often form compact boulder beds (Plate 34).

An interesting example of one of these intercalated sandstone lenses was found in the shore section of the Mound Rock conglomerate. The relationship between this lens and the surrounding conglomerate is shown diagrammatically in Figure 14 opposite. The sandstone lens passes laterally into a fine pebbly layer, and vertically into the coarser conglomerate proper. As shown, several large pebbles were lodged within the /
the sandstone. Close inspection showed that the overlying conglomerate was slightly downwarped over the pebbly portion of the lens. The explanation of this feature must be that whereas after deposition pebbles were able to sink into the underlying sandy part of the lens, the pebbly portion was sufficiently resistant to prevent any penetration.

No account of the more important physical properties of the conglomerates need be given at this juncture. Descriptions of such features as the sphericity, shape and preferred orientation of the constituent pebbles are to be found under the appropriate headings elsewhere.

Microscopic characters

To give anything approaching an exhaustive account of the constituent pebbles of the conglomerates would be a most ambitious undertaking. Such is the uniformly local nature of the pebbles, however, that such an extensive project would be largely redundant.

The writer has examined a fairly large number of pebble slices from the Glen Rock, Silver Rock, Mound Rock and Creag an Amalaidh conglomerates, and has found nothing of an exotic nature. The pebbles can be assigned to source rocks which lie no farther west /
west than the margin of Sheet 103. Mention has already been made of the local nature of the basal conglomerates of the northern half of the Brora Outlier (p. 161). The conglomerate of Ben Lundie which passes upwards through a series of transition beds into the sandstones of Beinn a' Bhragie in the southern half of the Outlier, has been described by H.H. Read (Mem. Geol. Survey, 1925, p. 54) as consisting of "rock types that occur abundantly in the schist and granite-schist areas lying immediately to the west".

The writer was fortunate in being able to borrow from H.M. Geological Survey nearly one hundred slides cut from the rocks which surround the Brora Outlier. It was possible to compare these with rock sections cut from the conglomerate pebbles. It is not proposed to give detailed petrological descriptions of individual pebbles, for in so far as it is impossible to refer specific pebbles to specific points in source rocks which are themselves only known in a general manner, such descriptions would be of doubtful value. Instead, a less specialised approach has been adopted.

As has been stated (p. 161) the conglomerates comprise pebbles of granite, granulite, schist and quartz. There are two distinct granites in the area which could have supplied detritus to the conglomerates: the Rogart and Coirefrois mass, which /
which for the present purpose may be treated as a unit, and the Helmsdale granite. The writer collected specimens of the Helmsdale granite, and had also available the Survey rock sections. The Helmsdale granite has contributed only to the basal conglomerates which now rest upon it. No pebbles of this granite were encountered in the conglomerates of the southern half of the Brora Outlier. The conglomerates would therefore appear not to have been derived from the north-east.

The pebbles of granite in the conglomerates can, however, almost certainly be referred to the Rogart and Coirefrois masses which lie to the west of the Brora Outlier. These two masses can be partially distinguished in that the Rogart mass consists of a central zone of granodiorite, surrounded by a zone of inclusions in which granitic material is intimately associated with the Moine rocks, whereas the Coirefrois mass consists entirely of this granite-granulite complex (Mem. Geol. Survey, 1925, p. 21). The central granodiorite of the Rogart mass is rich in hornblende and biotite, but the rock in small areas near the margin is hornblende-free. The zone of inclusions consists, in the main, of a complex of biotite-granite and siliceous granulites.

Examined in thin section the pebbles were found to be biotite-granites /
biotite-granites, often showing a contact with siliceous granulite. They would appear therefore to have been derived from the zone of inclusions, or, in the case of the pebbles of biotite-granite which are not apparently associated with the granulite, from the above-mentioned marginal patches in the central granodiorite. None of the granitic pebbles examined were found to carry hornblende, from which it may perhaps be assumed that the central granodiorite proper did not contribute material to the conglomerates. It is significant that hornblende has not been detected among the heavy minerals of the sandstones (see p. 93) which would appear to indicate that no rock in which hornblende is present in appreciable quantities supplied detritus to the sandstones. In attempting to delimit the direction of transport of the sediments, mention may be made of a pebble which was collected from the Glen Rock conglomerate. This pebble shows stringers of splitic material which occasionally swell into augen, insinuated between the foliation-planes of what was originally a biotite-schist, and so compares closely with the rocks described from the "augen-injection" complex of the Lochan Dubh area (Mem. Geol. Survey, 1925, p. 37). Lochan Dubh is situated in the south-east corner of the Coirefrois mass, and the line of transport indicated would be from N.W. - S.E. This result is
fully in accord with inferences drawn from the estimation of sphericity (pp. 113-118) and the fabric analysis (pp. 119-129) of the conglomerates.

Pebbles of quartz-felspar-biotite-granulite and pebbles of siliceous schist, which exhibit a poorly-developed schistosity and are richer in biotite than the granulites, may be referred to the belt of Moine rocks which separates the granite masses from the Brora Outlier. The apparent absence of sillimanite-schists from the conglomerates, and of sillimanite from the heavy minerals, suggests that the area north-east of Rogart Station, where sillimanite-schists occur, may not have been encountered on the line of transport of the sediments. Quartz veins are abundant throughout both the granitic and the Moine rocks, which would account for the presence of quartz pebbles in the conglomerates.

The matrix of the conglomerates was examined in this section. Apart from being slightly coarser in texture, it does not appear to differ significantly from the sandstones associated with the conglomerates. This is consistent with the hypothesis that the sandstones represent the washed out, fine material of the original conglomeratic sediment (see pp. 141-142). From the point of view of direction of derivation, it is significant to note that the conglomerate of Ben Lundie passes upwards /
upwards into the sandstones of Beinn a' Bhregie from the north-west to the south-east. This relationship also holds at points farther north in the Erera Outlier.

A sketch map, Figure 15, is shown on p. 167. It embodies the place-names mentioned, and the conclusions reached during the study of sandstones and conglomerates. The symbols Si, E, H and St represent respectively sillimanite, epidote, hornblende and staurcrite. The direction of derivation of the sediments is indicated, in a general manner, by the dotted lines. Plates 23-36 show some of the features of the pebbles described in this section of the work.
Figure 16
PROVENANCE MAP OF THE MIDDLE OLD RED SANDSTONE DEPOSITS OF N.E. SCOTLAND

In constructing the map shown opposite, the chief aim has been to present a rough, general picture of the sources from which some of the material constituting part of the Middle Old Red sediments of the area shown has been derived. If the work possesses any merit, it rests in the presentation, as a composite whole, of what have been heretofore merely references of no more than individual significance scattered through the relevant literature. To that extent, and in the manner of interpreting some of the data, it is original.

The bulk of the information has been culled from the Memoirs of the Geological Survey of Scotland, with additional reference to certain individual papers. Provenance studies of the area considered are aided by the occurrence of the sediments in question as outliers, wholly, or at least largely surrounded by rocks of greater age. The black circles on the map indicate the respective source areas of pebbles or heavy minerals found at those points in the sediments where the lines drawn from the circles end. These lines, showing the direction of transport, follow the shortest possible route. Where a pebble or mineral has been referred to a parent rock which outcrops over a considerable /
considerable area, the circle marking that source has been located centrally with respect to the parent mass. While this method introduces obvious inaccuracies, it is the only feasible means of presenting the recorded data. For clarity, the different directions of transport shown on the map have been numbered, and these are now dealt with in turn.

Directions 1 to 7 inclusive, are based on the findings of Mackie (1923), when working on the Turriff Outlier. Directions 1 and 2 record the occurrence of pebbles of Corrennie and Bennachie granite respectively, in the Slack o' Causeway conglomerate near Fyvie Station. Direction 3 is based on the occurrence of zircons in the Ardin sandstones, believed by Mackie to have been derived from the Wardhouse syenite. Directions 4 and 6 record respectively the occurrence of pebbles of the Huntly garnetiferous norite and the Inchbae gneiss in the Slack o' Causeway conglomerate. Concerning directions 5 and 7, a certain difficulty arises, and these cases become clearer if directions 8, 9 and 10 are first considered. Direction 8 arises from the occurrence of boulders of the Ardlach granite in the conglomerate of Muckle Burn (Mem. Geol. Survey, 1923, p. 72). The small strip of conglomerate to the south-west of Muckle Burn, at Drynachan Lodge, carried "angular and subangular fragments /
fragments of schist and porphyritic granite". (op. cit., p. 76). This "porphyritic granite" may be either Ardlash granite (direction 9), or Moy granite (direction 10). Since the Moy granite is the nearer of the two to the conglomerate in question, and since this direction of transport is more in keeping with those already discussed, the author believes that direction 10 is to be preferred to direction 9. The latter direction is therefore queried on the map. Returning now to directions 5 and 7, it must be noted that both directions refer to Mackie's finding of the one set of granite pebbles, which he recognises as being from either the Abriachan granite (direction 5), or the Helmsdale granite (direction 7). Although both directions have been mapped, the Abriachan granite appears to be the more likely source. The map serves to bring out a significant feature in favour of derivation from this source: namely the close agreement of this direction with direction 4 from the Huntly norite, and with direction 10 from the Moy granite. Again, since the sediments of the Turriff Outlier are of such a nature as to suggest that they are flood-plain deposits (Geology of Banff, Huntly and Turriff, 1923, p. 176), acceptance of the Helmsdale mass as the source of these granite pebbles would involve obviously doubtful physiographic changes of considerable magnitude. Direction 7 is therefore queried on the map.

Three /
Three other directions remain to be noted in this eastern area of the map. Direction 11 records the occurrence in the conglomerate near Delnabo, of pebbles of quartzite and mica schist, together with "a few rounded pebbles of Cairngorm granite". (Mem. Geol. Survey, 1896, p. 29). The outlier is composed of sediments which appear to have been locally derived under torrential conditions. In constructing direction 11 therefore, the author has referred these "pebbles of Cairngorm granite" to the southern extremity of the small granite mass near Dorback Lodge, west of Delnabo, and separated from the sediments of that latter area by outcrops of quartzite and mica schist. Direction 12 is based on the occurrence in the conglomerate between Auchinleith and the Burn of Glenny, of pebbles of quartzite, mica and knotted schist, granite, gneiss, felsite and black slate (Mem. Geol. Survey, 1890, p. 28). The author has chosen the small granite mass cut by the Livet Water northeast of Tomintoul, as the most likely source of the granite pebbles found in the outlier concerned. The resulting line of transport (direction 12), then passes either over, or extremely close to, those rocks necessary for the completion of the pebble suite noted above. Finally, direction 13 records the occurrence in the conglomerate at Pennan, of a boulder from a minette dyke, which is found in situ, cutting the slates to the west, near /
Institute of Geology for the personal communication.

The author is indebted to Dr. Robert Campbell of the Great

although it is generally probable that they may have been derived
places of which neither have been referred to the Isthmus region.

Is not large enough for these purposes, but the scale of the map
carry a similar accommodation of populations, but the scale of the map

ranean Gates and people of eastern section in the Stetin River

frequently referred to. Direction 17 refers to the occurrence of outcrops of
zone of the three black strata concerned have been fixed early

the occurrence of outcrops at the points shown. The post-

They merely indicate the present local nature of

To special reference need be made of the junction to

be examined extensively.

have drawn from the evidence furnished by the several authorities
some of the interferences which the Survey authorities

been taken from the Geodetical Survey records on the area of

between the Portuguese and the Border River, the

and recessional outcrops" and which occupy the breadth

the middle old sandstone formations which form the crest of

near their junction with the middle old sandstone formations.

174
from the closely associated Carn Chuinneag mass lying immediately to the north-east. The petrological similarity between the two masses is such that it is impossible to refer a given pebble to any specific point within them.

The two directions included under number 18 are based on the local derivation of the conglomerates of Allt Dearg and of the Strathcroy River section. Both these conglomerates are largely composed of boulders of Fearn granite, with a small admixture of schist fragments (Ben Wyvis Memoir, p. 134). The conglomerate of Struie Hill, on the other hand, to which direction 19 refers, carries only a few small pebbles of the Fearn granite in an assemblage largely composed of fragments of the metamorphic rocks of the Moine Series, together with pebbles "of coarse muscovite pegmatite and others of a purple felsitic rock" (op. cit., p. 134). A feasible explanation of this paucity of Fearn granite pebbles might be, that the transporting agent of the sediments now forming the conglomerate of Struie Hill largely by-passed the granite mass, touching but briefly upon its northernmost extremity. This is the interpretation which the author has put upon the available data: direction 19 has been mapped accordingly, and a hypothetical source point has been located somewhere to the west.

Before /
Before proceeding further, it is necessary now to consider some of the inferences which the Survey authors have drawn from their observations in this area. They state that:

"while certain upper conglomerates, to be shortly described in the Alness and Evanton area, contain abundant pebbles of Cambrian and Torridonian rocks derived from areas to the west, beyond the Moine thrust, no fragments of the augen gneiss have yet been detected in them. This gneiss enters largely into the composition of the conglomerates in the western outliers, and the inference may perhaps be drawn that the augen gneiss, though to a large extent exposed while those western beds were being formed, had subsequently become wholly, or almost wholly, covered by succeeding Old Red Sandstone strata before the upper conglomerates of the Alness and Evanton area were laid down. If this inference be correct, we may conclude that all, or a very large proportion of the schistose area within the map was at one period covered by the Old Red Sandstone." (Ben Wyvis Memoir, p. 131).

There are several points raised by this argument. First, while evidently concerned over the absence of pebbles of augen gneiss from the upper conglomerates, the Survey authors are quite unperturbed by the fact that such pebbles also fail to appear in the basal beds. Directions 14 to 16 inclusive emphasise the local nature of the beds concerned. If the basal beds of the western outliers and those of the Alness and Evanton area are contemporaneous, then the absence of pebbles of augen gneiss in the latter can best be explained by the presence of an effective barrier between the mass of augen gneiss and the western margin of these Alness-Evanton deposits. The Inchbae and Carn Chuinneag /
Chuinneag massifs, and the sediments of the Alness and Evanston area are, at the present time, separated by the high ridge of Meine rocks which runs parallel to both, much of which rises considerably above the 2000 ft. contour. It seems probable that this great barrier was in existence during the deposition of the Old Red Sandstone beds, and that it effectively governed the drainage system then in operation.

Concerning the absence of pebbles of augen gneiss from the upper conglomerates, a different line of reasoning to that followed by the Survey authors may be advanced. Returning for the moment to direction 19, it will be seen that if the interpretation of the data on the conglomerate of Struie Hill is accepted, then what in actual fact is implied by the drawing of this direction, is the presence of a through-valley at the northern end of the Pearn granite mass, that is, beyond the northern extremity of the dividing ridge to which reference has just been made. Directions 20, 21 and 22 all refer to the "upper conglomerates" concerned, and record the occurrence within them of pebbles of Durness Limestones, Fucoid Beds and Terriconian Grits and sandstones. Significantly, these conglomerates also carry many pebbles of Pearn granite (Ban Wyvis Memoir, p. 138). Since the conglomerate of Struie Hill is basal, the postulated valley would be in existence before the deposition of the upper conglomerates.
conglomerates. The transporting agent which deposited these later sediments may well have followed this pre-existing course. More active erosion of the Fearn granite mass by this transporting medium would account for the occurrence of the granite pebbles in the conglomerates concerned. Of the three directions which emanate from possible areas of derivation of the pebble suite recorded, number 20 seems to be the most probable. If, however, any of the three directions of transport is accepted, then the absence of pebbles of augen gneiss in the upper conglomerates is explained simply by the fact that the transporting agent did not pass over either the Inchbae or the Carn Chuinneag massif.

The observed facts from both basal and upper conglomerates of the Alness and Eventon area can be satisfactorily explained on the assumption that in neither case was augen gneiss being contributed to the sediments concerned. It has, the author hopes, been shown that there is no adequate reason for the assumption that the Inchbae and Carn Chuinneag massifs were ever covered by Old Red Sandstone deposits. The supposition that the Strath Rannoch and its associated outliers were ever joined to the main sheet of sediments east of Ben Wyvis is not at all convincing. Whether it is assumed that the boulders of augen gneiss found in the western outliers were derived from the /
the Inchbae area (as shown on the map), or from the Carn Chuinneag mass, the resulting line of direction in either case is quite at variance with the general trend of those connected with the sediments of the Alness and Evanton area. Again, there is no palaeontological evidence for the assumed Old Red Sandstone age of the western outliers, which may therefore be purely local deposits, laid down perhaps long after the deposition of the proved Old Red Sandstone sediments of the main outlier. On the basis of such questionable evidence as has been advanced by the Survey authors, the hypothesis of the supposed former westward extension of the Alness-Evanton outlier is hardly tenable.

The sediments of the Alness and Evanton area continue northward on the northern side of the Dornoch Firth to form the Brora Outlier. The provenance of this area is fully discussed in another section of this work (see pp. 162-168), and all that need be noted for the purpose of the general map under consideration, is the local nature of the pebbles in the conglomerates. The directions included under numbers 23, 24 and 25 indicate, in a general way, derivation from the granitic and schistose rocks which lie to the west of the sediments.

Passing northward into Caithness, the first group of Old Red Sandstone sediments encountered are those of the Berriedale /
Berriedale Outlier, which is separated from the main mass of the Caithness sediments by a narrow strip of crystalline schists which reach the coast at Badsallach. In connection with the Berriedale Outlier, three sources have been located and several directions drawn. The sediments of this area are of local derivation.

Direction 26 records the derivation of the Ousdale arkoses largely from the Ord or Helmsdale granite, and in part from the adjacent crystalline schists of the Moine Series (Mem. Geol. Survey, 1914, p. 20). The two directions included under number 27 are again based upon the occurrence of pebbles of granite and schist within the conglomerates at the points indicated. The more northerly of the two directions records the greater proportion of schist to granite pebbles in the conglomerate concerned (op. cit., p. 21). Under number 28, two directions have also been included, both referring to the presence of pebbles of quartzite, schist and granite within the Badbea breccia. To account for the occurrence of the quartzite pebbles, the source has been located in the Scaraben area, which is separated from the sediments at Badbea by strips of schist and granite. The more northerly of the two directions passes over the narrower stretch of granite, in accordance with the /
the lower percentage of granite pebbles found in the Creag an Turnail breccia, to which it refers. The conglomerates which outcrop to the north of the Ferriedale Water are also composed of pebbles of granite and schist. The scale of the map is, however, too small to include another local source in this area.

The various directions included under number 29 record the occurrence of pebbles of the local granite, augen gneiss, schist and quartzite, in the conglomerates of the Braemore and Norven district. Not all the conglomerates carry the full pebble-suite just noted, as might be inferred from the presence of only one source-circle on the map. This method of presentation has been adopted merely to emphasise the local derivation of those rock fragments present in each deposit.

Moving northward along the western margin of the Old Red Sandstone outlier, the purely local nature of the pebbles in the conglomerates is still in evidence, as indicated by directions 30, 31 and 32, which record the presence of strictly local material in the conglomerates of Gnoc na Saobhaidhe, Beinn Glas-cchoire and Ach Forsiesoye respectively. Owing to the large area covered by the Old Red Sandstone deposits of Caithness, no directions based upon the evidence from the conglomerates of the east coast can be drawn. Thus the pebbles of black /
black porphyritic basalt which are present in the Sarclet con-
gglomerate (Mem. Geol. Survey, 1914, p. 26) may have been derived
from any point within the area mantled by the outlier.

The several small outliers on the north coast of
Scotland occupy valleys with a north-south trend. During the
deposition of the Old Red Sandstone sediments, drainage was to
the north (op. cit., p. 69). The two directions included under
number 33 record the occurrence of a largely granitic suite of
pebbles in the outlier which occupies the tract between Sand-
side Burn and the Bay of Bighouse, while those directions in-
cluded under number 34 record a similar pebble assemblage in
the conglomerates of the Strathy outlier (Mem. Geol. Survey,
1914, p. 78). In both cases, the source from which the lines
of direction emanate has been located on the nearest point of
the Strath Halladale granite concomitant with an approximately
northern drainage. Direction 35 records the purely local
nature of the conglomerates of the Kirktony area (see op. cit.,
p. 77). Of the five directions included under number 36, all
but the most westerly refer to the four isolated outcrops of
Old Red Sandstone sediments on the eastern side of the Kyle of
Tongue, and record the occurrence within these deposits of
pebbles of granite probably referable to the Beinn Laoghal mass,
together with fragments of the local schists.
Attention may now be drawn to the small outliers of central Sutherland, to which directions 37 and 38 refer. The more northerly of the outliers includes Ben Grian More, Ben Grian Beg, and Meall a' Ehuiirich, while the southern outlier extends southward from Creag Sgoilteach through Meall Odhar to Meall a' Chnoic. The two directions included under number 37 refer to the occurrence, within the upper conglomerates of the Ben Grian area, of a pebble-suite which comprises fragments of the underlying injection-complex, granulites, vein quartz, and a few pieces of hornblendeic gneisses, together with pebbles of the Scaraben quartzite, and of the hybrid rocks of Ach'uaine type (Mem. Geol. Survey, 1931, p. 207). The source-circle has been centred upon the nearest mass of Scaraben quartzite, and the lines of direction so drawn as to pass over the only area of hybrid rocks occurring between the quartzite and the Ben Grians. Perhaps more reliance can be placed upon the recognition of the hybrid rocks, rather than upon that of the Scaraben quartzite, but provided that only one of these rock types has been identified correctly, the lines of direction shown on the map remain unaltered. The most important fact is that the source rocks of the Ben Grian deposits are to be found to the east of the outliers, and that in this case, transport has consequently occurred in an east-to-west direction. The same /
same is probably true of the small outlier in the Meall Odhar area, although in this instance the evidence of derivation from the east is not so strong. Within this outlier, conglomerates of a seemingly local nature occur, composed of blocks of the underlying injection-complex (Mem. Geol. Survey, 1931, p. 207). Since the greatest mass of this injection-complex lies to the east of the outlier, and since the basement rocks to the east are at a higher level than the outlier, and those to the west at a lower, the author has tentatively located the source-circle for the sediments close to their eastern margin. It may however be maintained that the Meall Odhar outlier is a local deposit, and not likely ever to have extended much beyond its present limits in any direction.

No palaeontological evidence of age has been recorded for the outliers of either the Ben Griam or the Meall Odhar area (Mem. Geol. Survey, 1923, pp. 206-7).

It appears therefore, that these outliers of central Sutherland are similar to those of the Strath Rannoch area already discussed (see pp. 174-179), in that there is no adequate reason for believing that they were ever joined to the main sheet of sediments to the east. Almost certainly in the case of the Ben Griam outliers and possibly in the case of the Meall Odhar /
Odhar outlier, the direction of transport of the sediments is diametrically opposed to that of the main outlier to the east. As in the case of the Strath Rannoch outliers, so also in this case might it be argued, for all that is known to the contrary, that the western outliers of Sutherland are not necessarily of Old Red Sandstone age. It is at least evident, that the westward extension of the main Sutherland and Caithness outliers is open to question.

Attention must finally be drawn to the sediments of the three small islands in the Kyle of Tongue: Eilean nan Ron, Eilean Iosal, and Meall Halm. The scale of the map is too small to show these islands separately, and they have therefore been grouped together. It is to these deposits that direction 39, and the most westerly of the directions included under number 36 refer. The latter direction is based upon the occurrence, within the lowest conglomerates of Eilean nan Ron, of pebbles of hornblende-granite, hornblende-schist, hornblende-gneiss, and quartz granulites (Mem. Geol. Survey, 1914, p. 78). In constructing this direction, the author has referred the source of the hornblende-granite to the Beinn Laoghal mass, and has thence drawn the line over the rock types necessary to complete the pebble-suite just noted. Direction 39 records the occurrence /
occurrence of boulders of Cambrian dolomite and limestone in the conglomerates of all three islands. In particular, the conglomerate of Eilean Iosal carries boulders from recognisable zones of the Durness Limestone, together with fragments of the Serpulite Grit, Pipe Rock, and Basement quartzite, and pieces of mylonised rocks of the Moine Series (Mem. Geol. Survey, 1914, p. 79). It is unfortunate that none of the outliers west of Strathy has yielded fossils, since, if these pebbles have been correctly identified as mylonite, and, in particular, mylonite associated with the Moine Thrust, then their occurrence in a conglomerate of Old Red Sandstone age would fix an upper limit for that great movement. It is not even certain however, that these outliers are of Old Red Sandstone age.

These then are the main directions of transport which may be constructed for the Middle Old Red Sandstone deposits of the area shown on the map. Considering the map as a whole, the local nature of the sediments is the most striking feature. So marked is this impression, that the lines of direction derived from distant sources seem to strike a discordant note in the general picture. They cannot of course be condemned on this count alone, but it is unlikely that directions 7, 21 and 22 have any real significance. Similarly, it is possible that the /
that the pebbles of the Turriff Outlier, which Mackie has referred to the Abriachan and Inchbae masses (directions 5 and 6) have in actual fact been derived from less distant sources.

It is important to note, that while the mere presence of the isolated western outliers of supposed Middle Old Red Sandstone age does lead naturally to the supposition that the main sheets of sediment had a former extension westward, the evidence from these western outliers, far from corroborating this supposition, rather militates against. It may well be that the large eastern outliers as known today, never extended far beyond their present western limits.

In preparing the map however, the main object, as was stated at the outset, has been to synthesise the available information, and to present it as a composite whole. If the map does give a general picture of the provenance of the Middle Old Red Sandstone sediments, then it has fulfilled its purpose.
CONCLUSIONS

Throughout this present study of the Brora Outlier, relatively new techniques have been brought to bear upon an old problem: that of the history of deposition of Old Red Sandstone sediments. The writer has been concerned only with the southern half of the Brora Outlier and would hesitate to claim more than local significance for any of the results which have been gained. Some may indeed be applicable to the outlier as a whole, but the value of extrapolation has so often proved doubtful that extreme caution must be exercised in attempting it. The Brora Outlier sediments are thought to be the equivalents of the Berriedale sediments and of those of the Morven area (Mem. Geol. Survey, 1914, pp. 19-31); it is therefore possible that these three sequences accumulated under similar conditions. In this respect, the close agreement between the results of the mechanical analysis of the Brora Outlier and the Berriedale sandstones (see pp. 44-5) may be advanced as supporting evidence.

The most important aspect of the work is the emergence of the hypothesis that the Brora Outlier sediments may have been fluvio-glacially derived. In putting forward the case for this interpretation, the current hypothesis that these sediments are "fanglomerates" /
"fanglomerates" and alluvial outwash fans has been kept con-
stantly in view, and the evidence weighed with respect to both
modes of deposition. As a result, it has become apparent that
the two hypotheses are by no means widely divergent, and that
much of the evidence must be considered to lend equal support
to both. The author has attempted to show, however, that in
his opinion, certain features of the Brora Outlier sediments
afford evidence of a somewhat less equivocal nature which weighs
in favour of the fluvio-glacial hypothesis; but in view of the
essential parallelism of the two concepts derivation under
fluvio-glacial conditions is suggested as a possibility worthy
of further investigation rather than as a locally established
conclusion.

That the sediments have been derived from the north-
west has been amply indicated. In this respect, the most
direct and strongest evidence is, of course, the matching of
pebbles from the conglomerates with the surrounding country
rocks. In the case of the Brora Outlier, the problem of deter-
mining the area of provenance is somewhat simplified in that
the sediments are almost wholly surrounded by rocks of greater
geological age. The corroborative evidence yielded by measure-
ments of the sphericity and by the fabric analysis of the
conglomerate /
conglomerate pebbles is none the less important, in that not only does it strengthen the present case, but it also indicates that these indirect methods might be relied upon to give a fairly accurate result in the case of, say, an inlier where the method of pebble-matching would be inapplicable.

The occurrence of banded sandstones, in which dark coloured layers of fine texture are found to alternate with lighter layers of a coarser texture, occasioned an enquiry into the possible mode of origin of such sediments. A mechanism to account for the observed features has been formulated (pp. 102-106). On the basis of this outlined pattern of deposition, and on other evidence, the red colour of the sandstones due to the presence of haematite is thought to be a post-depositional development.

A general provenance map of the Middle Old Red Sandstone deposits of north-east Scotland has been prepared, based upon information culled from various sources (see pp. 170-187). The embodiment of hitherto uncorrelated records within the framework of a general picture, constitutes the most important feature of the map. During its preparation, reasons were found for doubting some of the interpretations based upon the recorded facts, and some alternative suggestions have been advanced.

That /
present work may contribute to the advancement of this end.

It is the author's hope that the proposed can be achieved. It is the middle of the reed sentence where the proper understanding of the complex and the advances that much detailed work is required before redimensioning the to the south and to the south-west of the outlier, really large feature of the author. Nothing equivalent to the detailed development of redimension compared with the vast spread of redimension in gathered and exceeded. The proper outlier is of utmost importance, have been repeatedly be or no more than Local distinction have been repeatedly.

The results obtained in this present study may
ACKNOWLEDGEMENTS

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Finally, I wish to record my gratitude to the University of Edinburgh for the grant of a Studentship, to the Carnegie Trust for assistance in the payment of fees, and to my mother for financial support.


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ROCK-COLOR CHART, 1948. Distributed by the National Research Council, Washington, D.C.


TRASK /


The pebbles shown in Plates 1-26 inclusive have been photographed against a scale graduated in millimeters.
PLATE I

Fibbles from Glen Rock conglomerate

Figure A
Tabular pebble with fairly well developed pentagonal outline.

Figure B
Hump-backed pebble flattened on under-surface; modified pentagonal outline.

Figure C
Wedge-shaped pebble with elongate, pentagonal outline.

Figure D
Tabular pebble with modified pentagonal outline.
PLATE 2

Pebbles from Glen Rock conglomerate.

Figure A
Facetted, tabular pebble with quadrangular outline.

Figure B
Wedge-shaped pebble of modified quadrangular outline.

Figure C
Markedly tabular pebble with quadrangular outline.

Figure D
Quadrangular pebble with well-defined, longitudinal ridge on top surface.
PLATE 3

Pebbles from Glen Rock conglomerate

Figure A

Hump-backed, triangular pebble with well-developed facets.

Figure B

Snub-nosed, triangular pebble with nicked back-edge.

Figure C

Triangular pebble with faint grooving on back facet.

Figure D

Tabular pebble of modified triangular outline.
PLATE 4

Pebbles from Glen Rock conglomerate

Figure A
Tabular pebble of pentagonal outline with well-developed facets.

Figure B
Wedge-shaped, triangular pebble, with well-developed facets and distinct grooving on top surface. The back-edge is nicked.

Figure C
Quadrangular pebble with well-developed facets and gouged-out top surface.

Figure D
Tabular pebble of triangular outline.
Figure A: Markedly tabular pebble of well-rounded pentagonal outline.

Figure B: Sub-rounded, tabular pebble of triangular outline.

Figure C: Tabular pebble of rounded quadrangular outline.

Figure D: Wedge-shaped pebble of modified triangular outline.

Legend:
- Tabular: flat on one face
- Sub-rounded: rounded edges
- Wedge-shaped: pointed at one end
PLATE 6

Pebbles from Glen Rock conglomerate

Figure A

Four of the smaller pebbles of pentagonal outline. The specimen in the top, left-hand corner has well-developed facets and indistinct grooving.

Figure B

Small, faceted pebbles of quadrangular outline.

Figure C

Four small, faceted pebbles of different shapes. The specimen in the top, left-hand corner has grooving which is just discernible in the photograph.

Figure D

Four small, faceted pebbles of triangular outline.
PLATE 7

Pebbles from Silver Rock conglomerate

Figure A
Tabular pebble with well-developed pentagonal outline.

Figure B
Wedge-shaped pebble of pentagonal outline, with concave, right-hand surface.

Figure C
Tabular pebble with elongate pentagonal outline and marked groove on top surface.

Figure D
Tabular pebble with elongate pentagonal outline and nicked back-edge.
PLATE 6

Pebbles from Silver Rock conglomerate

Figure A
Tabular pebble of modified pentagonal outline.

Figure B
Facetted, quadrangular pebble with nicked back-edge.

Figure C
Hump-backed pebble of rounded pentagonal outline.

Figure D
Snub-nosed, tabular pebble of quadrangular outline.
Pebbles from Silver Rock conglomerate

Figure A: Tabular pebble of quadrangular outline.

Figure B: Many-faced, faceted pebble of quadrangular outline, with convex bottom surface.

Figure C: Sub-rounded, tabular pebble of quadrangular outline.

Figure D: Tabular pebble of quadrangular outline, with slightly concave surface.
PLATE 10

Pebbles from Silver Rock conglomerate

Figure A

Facetted, snub-nosed, triangular pebble.

Figure B

Tabular pebble of triangular outline.

Figure C

Snub-nosed, tabular, triangular pebble, with nicked back-edge.

Figure D

Hump-backed, facetted pebble of triangular outline, with nicked back-edge.
PLATE II

Figure A. Facetted pebble of modified pentagonal outline, with concave bottom surface.

Figure B. Facetted pebble of triangular outline.

Figure C. Sun-nosed, facetted pebble of quadrangular outline.

Figure D. Facetted pebble of modified triangular outline, with convex back-edge.
PLATE 12

Pebbles from Silver Rock conglomerate

Figure A
Four of the smaller pebbles of pentagonal outline, three of which show nicking of the back-edge.

Figure B
Four small pebbles of quadrangular outline, the two lower specimens showing nicking of the back-edge.

Figure C
Four small, faceted pebbles of different shapes. The specimen in the top, left-hand corner is elongate pentagonal, that in the top right-hand corner is quadrangular, and the remaining two are triangular.

Figure D
Four small, faceted pebbles of triangular outline.
PLATE 13

Pebbles from Mound Rock conglomerate

Figure A

Hump-backed, faceted pebble of pentagonal outline, with concave bottom surface.

Figure B

Hump-backed, faceted pebble of pentagonal outline, with nicked back-edge.

Figure C

Wedge-shaped pebble with modified pentagonal outline.

Figure D

Hump-backed, faceted pebble, with nicked back-edge and rounded pentagonal outline.
PLATE 14

Pebbles from Mound Rock conglomerate

Figure A
Tabular pebble with well-developed pentagonal outline and nicked back-edge.

Figure B
Tabular pebble of modified pentagonal outline.

Figure C
Tabular pebble of quadrangular outline.

Figure D
Tabular pebble of quadrangular outline with well-developed facets.
PLATE 15

Pebbles from Mound Rock conglomerate.

**Figure A**
Hump-backed, well-faceted pebble of pentagonal outline.

**Figure B**
Tabular pebble of triangular outline, with concave back-edge.

**Figure C**
Wedge-shaped, faceted pebble with elongate pentagonal outline.

**Figure D**
Tabular pebble with modified pentagonal outline.
Figure A
Side-view of pebble shown in Plate 15, Fig. A, to show markedly concave bottom surface and hump-backed form.

Figure B
As in Plate 15, Fig. B.

Figure C
Side-view of pebble shown in Plate 15, Fig. A, to show concave bottom surface and poorly developed wedge-shape.

Figure D
As in Plate 15, Fig. D.
PLATE 17

Pebbles from Mound Rock conglomerate

Figure A
Hump-backed, facetted pebble of triangular outline.

Figure B
Wedge-shaped, facetted pebble of triangular outline.

Figure C
Poorly-facetted pebble of modified triangular outline, with chipped back-edge.

Figure D
Wedge-shaped, facetted pebble of modified triangular outline.
**PLATE 18**

**Pebbles from Mound Rock conglomerate**

**Figure A**

Well-faceted, tabular pebble of quadrangular outline.

**Figure B**

Hump-backed, well-faceted pebble of pentagonal outline.

**Figure C**

Hump-backed, faceted pebble of quadrangular outline.

**Figure D**

Hump-backed, sub-rounded, faceted pebble of modified quadrangular outline, with faint trace of grooving on the back-facet.
PLATE 19

Pebbles from Mound Rock conglomerate

Figure A

Four of the smaller pebbles showing variations in the pentagonal form.

Figure B

Four small pebbles of quadrangular outline.

Figure C

Four small, facetted pebbles of different shapes. The specimen in the top, right-hand corner shows grooving of the back-facet.

Figure D

Four small, facetted pebbles of triangular outline. The specimen in the top, left-hand corner shows nicking of the back-edge.
PLATE 20

Pebbles from Creag an Amalaidh conglomerate.

Figure A-B

Large, wedge-shaped pebble of pentagonal outline.

Figure C-D

Five smaller pebbles which show progressive rounding of the pentagonal outline. The specimen in the top, left-hand corner is the most obviously pentagonal of the five. From left to right, the remaining pebbles are progressively more rounded, until, in the case of the pebble in the bottom, right-hand corner, the remnants of a former pentagonal outline are only just discernible.
Pebbles from Creag an Amulaich conglomerate

Figure A
Tabular pebble of modified quadrangular outline.

Figure B
Snub-nosed, tabular pebble of triangular outline.

Figure C
Tabular pebble of triangular outline, with slightly concave bottom surface.

Figure D
Hump-backed, facetted pebble of triangular outline, with nicked back-edge.
PLATE 22

Pebbles from Creg an Amalaidh conglomerate.

Figure A
Hump-backed, facetted pebble of pentagonal outline.

Figure B
Tabular pebble of modified pentagonal outline, with signs of chipping on bottom surface.

Figure C
Tabular pebble of much-rounded pentagonal outline. The top surface is deeply grooved.

Figure D
Well-rounded pebble of modified pentagonal outline.
PLATE 24

Pebbles from Creag an Amalaidh conglomerate

Figure A
Faceted, tabular pebble of quadrangular outline.

Figure B
Hump-backed, faceted pebble of quadrangular outline, with grooved top surface.

Figure C
Hump-backed, soled pebble of rounded, elongate pentagonal outline.

Figure D
Hump-backed, faceted pebble of modified quadrangular outline.
PLATE 25

Pebbles from Creag an Aulaich conglomerate

Figure A

Four of the smaller, faceted pebbles showing variations in the pentagonal form.

Figure B

Four small, faceted pebbles of quadrangular outline.

Figure C

Four pebbles of different shapes. The specimen in the top, left-hand corner has a modified pentagonal outline, and is grooved on the back-facet.

Figure D

Four small, stub-nosed pebbles showing variations in the triangular form. Nicking of the back-edge is particularly obvious in the top, left-hand pebble.
Figures A - D

Four specimens of dreikanter included for comparison with the pebbles from the Brora Outlier conglomerates. The facets on these pebbles are more sharply defined than on the conglomerate pebbles. None of these pebbles is tabular, nor does any of them have a pentagonal outline; both features commonly associated with pebbles of glacial origin.
A reproduction of the Plate appearing in the paper by Von Engel (1930). These pebbles resemble those from the Brora Outlier conglomerates much more closely than do the specimens of dreikanter shown in Plate 26. Note the facets in pebble 1, the tabular form of pebbles 3, 5 and 8, and the pentagonal outline of pebbles 9 and 10. These features are common in the pebbles from the conglomerates.
Figure A
Mound Rock, Silver Rock and Beinn a’ Bhragie (with Monument) as seen from the road near Creag an Ailaidh.

Figure B
Looking up Dunrobin Glen from the slope of Cagar Feoasaig. Glen Rock, in the middle distance, is centrally situated in the photograph. The sporadic nature of the sandstone outcrops on Cagar Feoasaig is apparent.
PLATE 50

Figure A

View of part of Kirkton Quarry.

Figure B

Slab of ripple-marked sandstone in Kirkton Quarry.
PLATE 31

Figure A
Quartz grain in sandstone from Cagar Fecosaig, showing outgrowth of secondary silica beyond the rim of haematite. (Nicois crossed, magnification approximately x 6).

Figure B
The same grain rotated to the extinction position, showing the outgrowth to be in optical continuity with the nucleus on which it has developed. (Nicois crossed, magnification approximately x 6).

Figure C
Another quartz grain in sandstone from Beinn a'Bhragie, showing the development of secondary silica. (Nicois crossed, magnification approximately x 6).

Figure D
Section of banded sandstones from Duchary Rock, showing a darker, finer layer, between two lighter, coarser layers. (Magnification approximately x 5.5).
Section of Eikston Quarry sandstone showing large grain of calcite in sandstone from Eikston Quarry (microscope x 60).

Section of Eikston Quarry sandstone showing smaller grain of calcite in sandstone from Eikston Quarry (microscope x 60).

Section of Bichury Rock sandstone with grain of mica and showing typical cross-hatching.

Section of Bichury Rock sandstone with grain of mica and showing typical cross-hatching.
Figure A

View of the conglomerate of Mound Rock.

Figure B

View of the conglomerate of Mound Rock.
Figure A
View of the conglomerate of Silver Rock.

Figure B
View of the conglomerate of Silver Rock.
Figure A

Pebble of injected schist found in Glen Rock conglomerate. Flakes of biotite are moulded round augen of aplitic material. (Magnification approximately x 1.2).

Figure B

Section of pebble shown in Figure A. (Magnification approximately x 5).

Figure C

Junction between granite and granulite as seen in pebble from Silver Rock conglomerate. (Magnification approximately x 1.3).

Figure D

Section of pebble shown in Figure C. (Nicols crossed, magnification approximately x 5).
Figure A

Junction between coarse and fine-grained biotite-granite, as seen in pebble from Mound Rock conglomerate. (Magnification approximately x 1.1).

Figure B

Section of biotite-granite pebble from Mound Rock conglomerate. (Nicol's crossed, magnification approximately x 1.2).

Figure C

Section of pebble of fine-grained biotite schist from Mound Rock conglomerate. (Magnification approximately x 5).

Figure D

Section of pebble of quartz-felspar-biotite-granulite from Silver Rock conglomerate. (Nicol's crossed, magnification approximately x 5).
Figure A

Occurrence of pebbles in otherwise homogeneous sandstone of Kirkton Quarry; largest pebble approximately 5 inches in diameter.

Figure B

Another view of pebbles in Kirkton Quarry exposure; largest pebble approximately 3 inches in diameter.
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Degree: PhD Year: 1956

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