

THE ORDOVICIAN ROCKS
OF THE
RHINNS OF GALLOWAY

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I INTRODUCTION

Since the classical work of Lepworth, geological interest in the Southern Uplands has centred largely on the fossiliferous bands while the clastic rocks have received scant attention. However, the introduction of new techniques, such as "way-up" criteria, and the improvement of existing ones, have now made it possible to examine the greywackes in a detailed and systematic manner. It was in this context that the work described in the following thesis was undertaken.

The primary objectives of the research were the investigation of the petrology of a typical group of greywacke-suite sediments and an attempt to discover the conditions under which these rocks were deposited. It was envisaged that such a study should involve examination of the lateral variation of the sediments and also their variation in time, since it was thought that the stratigraphy and structure of this area had already been established.

However, a few weeks' field-work sufficed to show that, in this area, the accepted theory of the structure was not tenable, and, partly as a consequence of this and partly from independent evidence, it soon became clear that the stratigraphy, also, could not be relied upon.

Thus, at an early stage of the study, it became necessary to widen the scope to include investigation of the structure and stratigraphy, and these aspects of the work have come to assume considerable proportions in this thesis.

There are comparatively few stream-sections in the area described and, apart from the coastline, which is almost completely exposed, outcrops are almost entirely confined to hills and craggy moorland, with a number of old quarries and railway-cuttings. As a consequence of this, most of the conclusions to be presented later are based on evidence collected from shore-exposures, although valuable additional and confirmatory information was obtained from the inland exposures.

A. GENERAL SETTING OF THE AREA

The area embraced in this work is about 70 sq. miles and comprises the northern part of the Rhinns of Galloway, west of a line running roughly north-south through Stranraer and north of a line running west-south-west from Stoneykirk, to Portayew on the west coast (fig. 1 and fig. 2).

Within this area three distinct topographic provinces may be recognised. (1) The coastline; (2) the eastern coastal lowland; (3) the rough, hilly uplands.

(1) At the north end of Wig Bay, near Kirkcolm, a narrow spit of gravel extends for two-thirds of a mile out into Loch Ryan, and mudflats and wide, sandy beaches characterise the coast from here south to Stranraer. The remainder of the coastline, however, consists of precipitous, often lofty, cliffs with only occasional small sandy coves, and presents an almost continuous exposure of rock. Broadsea Bay, on the west coast, has a sandy beach some two

miles long, but it is backed by high, rugged cliffs (Plate Ia). The general height of the cliffs on the east and north coasts is around 100 feet, while the cliffs on the western seaboard are generally higher, averaging about 200 feet, but rising to over 300 feet south of Morroch Bay (Plate Ib).

This coastline strikingly portrays the influence of geology on the scenery. Promontories and headlands are usually formed in hard rocks: coves and bays in soft rocks or along lines of shatter. The last case is well illustrated by Lady Bay and Dounan Bay, both cut in the shattered rocks associated with the Southern Uplands fault; and also by the rugged, serrated north coast with its long, northward-pointing skerries determined by conspicuous north-south joints and small wrench-faults (Plate IIa).

(2) The eastern coastal lowland is a strip of relatively low, rolling country, about a mile wide, sloping down to the sandy beaches and mudflats mentioned above and extending south from Kirkcolm to the head of Luce Bay. This strip is floored by rocks of Carboniferous and Permian age, breccias and sandstones which, because of their relative softness, have been eroded much more readily than the hard greywackes of the upland area. In this region is found most of the rich arable land in the Rhinns (Plate IIb).

(3) This upland area, which comprises the greater part of the Rhinns, is a plateau-like expanse of rough moors, pastureland and /occasional

occasional cultivated patches at a general height of about 350 feet. It is broken by many low hills which become higher and more frequent to the south. The highest of these is Cairn Pat (593 feet above sea-level) and looking south from here the observer cannot fail to notice the gently undulating nature of the upland tract, monotonous in its regularity. This whole area must formerly have lain under a thick cover of peat which is now mainly preserved on the hill-sides and on the wide moorlands, such as Ervie, Galdenoch, Larbrax, Craigenlee, Craigoch and Broad Moors.

Although no large river is found in this district, there are numerous small streams, most of which run roughly east-west, nearly strikewise. The largest of these, the Piltanton Burn, rises to the north-west of Stranreer and flows south-east, entering Luce Bay at its north-eastern end. There are a number of small, but deep, fresh-water lochs, probably of glacial origin, the largest of which is Loch Connell, near Kirkcolm.

The general geology is essentially simple. Steeply-dipping Ordovician rocks, with a dominantly north-east - south-west strike cover most of the northern part of the Rhinns, and are flanked to the east by a thin veneer of Millstone Grit, represented by red and grey sandstones and marls, and Permian red breccias. These beds dip very gently to the south-east and evidently mantle the west side of an ancient north-south valley, of which Loch Ryan and Luce Bay are drowned portions. The general geological setting of

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the area, as related by the Geological Survey to the rest of the Southern Uplands, has been described in the Account of Previous Research.

B. ACCOUNT OF PREVIOUS RESEARCH

The earliest published observations on the geology of this district are those of the celebrated Ami Boue, who regarded the Rhinns of Galloway as forming the western end of his "terrain de grauwacke". He noted that the beds of greywacke had the normal strike of Scottish rocks, ("la direction ordinaire des roches écossaises") and generally had a very steep dip, while, near Portpatrick, he noted many small veins of quartz in the greywackes.

Nearly twenty years passed before any further information about the geology of the Rhinns was published, and it was not until 1839 that there appeared the first of a series of important papers by J. Carrick Moore. This paper gave a brief account of Moore's discovery of graptolites in "slates" (=shales) on the west side of Loch Ryan, a discovery of considerable importance in the history of Southern Uplands geology, since it is one of the earliest records of the occurrence of these fossils in Scotland.

The following year (1840) Moore contributed a longer paper to the Geological Society in which he stated that the rocks of the Rhinns constituted part of the "great greywacke chain", and noted

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the dominant strike of the rocks, the occurrence of graptolites in certain bands of "slate", and the coarse conglomerates to be found near Corsewall Point.

James Nicol, in his "Guide to the Geology of Scotland" (1844), following Jamieson, placed the greywackes and shales of the Southern Uplands in the 'Transition Series' of Werner and stated that an almost complete succession of these strata was to be found in the Rhinns of Galloway. He also noted the presence of the coarse Corsewall conglomerate which, however, he erroneously equated with the coarse breccia which overlies the greywackes on the east side of the Rhinns and which is now believed to be Permian in age.

In 1848 Moore published another paper amplifying his previous accounts of the geology of the Rhinns end of S. Ayrshire, and giving the first geological map and sections of the region. He placed the rocks in the Silurian System of Murchison, and noted that the local 'physical structure' was similar to that of Peeblesshire, as described by Nicol. A fairly detailed description of the succession to be seen on the west coast of the Rhinns was then given, particular attention being paid to the fossiliferous horizons. He described the Corsewall conglomerate and concluded that there were no rocks exposed in the neighbourhood from which the contained pebbles could have been derived, although he did admit that the pebbles of 'serpentine' closely resemble the rock of Bennane Head, Ballantree. In an appendix, Salter described the

/fossils

fossils from the Stinchar valley and the Loch Ryan district and state that the graptolites from the latter district were similar to those found in the black Llandeilo flags of Wexford and Cardiganshire.

Murchison (1851), suggested that "the schistose rocks ranging through Wigtownshire and Galloway" might overlies the fossiliferous limestones of the Girvan-Dallentree district, while, in the previous year, Sedgwick had placed these rocks in an "Arenaceous Group", overlying the basal "Moffat Group" of shales and overlain, in turn, by the South Girvan Group of fossiliferous rocks.

In Moore's last paper (1856) he dealt with the structure of the rocks exposed on the west coast, concluding that they were folded into a series of asymmetrical anticlines and synclines, one limb being near-vertical, the other dipping at low angles, with the axes (axial planes) dipping south. He further concluded that the graptolitic shales (which occur south of the Southern Uplands Fault) were stratigraphically lower than the Corsewall conglomerate. Substantially the same structure and stratigraphy was deduced for the east side of Loch Ryan.

In 1873 the Geological Survey published the first edition of the 1st geological map of the area, together with an "Explanation", both based on the work of D. M. Irvine and A. Geikie. The main points which emerged from this work are as follows:

(a) The whole of the north part of the Rhinns is occupied by rocks of Lower Silurian age ("Llandeilo Series").

(b) A major synclinal axis was considered to run through

Morroch Bay to the north-east and the strata were believed to be "thrown into innumerable minor folds", these folds frequently having reversed limbs.

(c) These rocks were divided into six groups, and equated with similar groups first erected in the type-area to the east.

(1) Ardwell Group. Unfossiliferous, well-bedded, reddish greywackes and grits, with bands of hard shale. These were said to occupy three miles of the western coastline, at its southern extremity, the apparent thickness being due to repetition of the beds by wide reversed anticlinal folds.

(2) Lower or Moffat Black Shale Group. 1000 feet of flaggy greywackes, "grey flaggy shales", and thin bands of black shales carrying graptolites. It occurs at one point on the west coast north of the Ardwell Group.

(3) Queensberry Grit Group. Thick series of unfossiliferous thick greywackes and grits, with occasional bands of grey and green shales. Greywackes often pebbly, sometimes conglomeratic. Exposed on the coast, south of Portpatrick, and reappear, through folding, at Corsewall Point, where the group is coarsely conglomeratic.

(4) Dalveen Group. Thick series of well-bedded greywackes, with frequent thick bands of grey and blue shales and one thin band of black shale, with graptolites. This Group was thought to extend from Scarty Head for two miles north, and from Portpatrick

to the Genoch Rocks. This apparently enormous thickness was accounted for by the "extreme plication of the rocks". Occasionally, it was stated, portions of the overlying Lowther shales are found, caught in the cores of the synclines.

(5) Lowther Group. Green and olive shales, with thin greywackes, coarsening to the north. Believed to form cliffs between the south end of Morroch Bay and Knockiensusk Head, and from the north end of Morroch Bay to Portpatrick.

(6) Upper or Black Shale Group. Thick bands of black shales, grey, red and green flags, and lenticular greywackes. Well-exposed in Morroch Bay and repeated, to the east, in Crailloch Burn.

(d) Finally, the rocks of the Portpatrick area were stated to show evidence of considerable (thermal) metamorphism.

Although subsequent work has shown many of the conclusions reached in the "Explanation" to be erroneous, it nevertheless marked a considerable advance in the investigation of the local geology.

In the first place, a systematic and detailed description of the various lithologies to be found in the area was given.

Secondly, this work marked the first attempt to relate the detailed local geology to that of the rest of the Southern Uplands, and although the attempted use of lithology alone as a correlative

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criterion was to prove a signal failure, it pointed the way for the faunal correlation which was to be used, with such spectacular success, by Lapworth.

Finally, it is clear that these early workers realised that apparently enormous thicknesses could be reduced to credible dimensions by invoking repetition by numerous folds with reversed limbs (isoclinal folds).

Twenty-five years later, in 1899, the results of the researches of Peach and Horne were published in the first volume of "The Silurian Rocks of Britain". Their conclusions undoubtedly owed much to the general theories of stratigraphy and structure formulated by Lapworth in the Moffat and Girvan regions.

They concluded that the area at present under discussion lies largely in the Northern Belt, with the southern part occupying the north boundary of the Central Belt. In the part lying in the Northern Belt, the unfossiliferous greywackes, conglomerates and siltstones were thought to be of Glenkiln-Hartfell age (Llandeilo-Caradoc), the lateral equivalents of the typical fossiliferous black shales of the Moffat axial region, which also occur "in the cores of anticlinal folds" on the south margin of the Belt, near Portpatrick. There, the black shales are associated with multi-coloured cherts and mudstones, and thin tuffs, considered to be Arenig in age.

It was postulated that, while in the Morroch Bay section, the Glenkiln and Hartfell divisions are represented by a total of about 100 feet of graptolitic black shales with "flint-ribs" (Glenkiln) and blue-black shales (Hartfell), proceeding northwards the shales become coarser, flaggier, with graptolites confined to thin dark seams and films, and are interleaved with coarser sediments - greywackes, grits and siltstones. This lateral transition, it was believed, occurred further south during Hartfell times than in the preceding period, since, in the Broadsea Bay section, although the Glenkiln graptolites occur in a 12" band of black shales with flint ribs, the overlying beds, believed, on indefinite palaeontological evidence, to be Hartfell, are dark sandy shales with black strains. This was offered as evidence of the gradual shallowing of the geosynclinal sea.

Moreover, owing to the close association of graptolites though to be common to both the Glenkiln and (Lower) Hartfell, in the thin dark seams interleaved with coarser sediments, it was found impossible to draw a boundary between these divisions, in the north part of the Rhinns. All these beds, to the northern extremity of the peninsula, were therefore grouped as Llandeilo-Caradoc in age.

Further south, it was believed, the coarser beds were Hartfell in age, while, still further to the south occurred bands of black shale carrying Lower Birkhill graptolites and overlain by greywackes presumably of Upper Birkhill age. The maximum thickness of the beds involved appears to have been regarded as around 2000 feet.

/Structurally

Structurally, the region was regarded as lying near the junction of the great northerly anticlinorium and the southern synclinorium, which together comprise the greater part of the Southern Uplands (fig. 1). The dominant fold-style was believed to be isoclinal, and repeated folding of this type was postulated, to reduce the apparently enormous thickness of strata observed.

The Southern Uplands Fault was recognised in Lady Bay and Dounan Bay and it may be inferred from the published sections that in this area the fault was regarded as normal, throwing to the south, with a relatively small vertical displacement (approx. 4-500 feet). Other, small faults were said to be associated with the isoclinal folds but considered to be of little tectonic significance. Mention was also made of the sporadic occurrences of highly-cleaved rocks.

Since the publication of this Memoir, no serious research has been devoted to the Lower Palaeozoic rocks of the Rhinns, but accounts have been published of two very brief visits to the region.

In 1953 the Geologists' Association visited Girvan and spent one day on the Rhinns being conducted by G. W. Tyrrell. At Corsewall Point some of the boulders in the conglomerates were considered to be of "Lewisoid" appearance. The single stipe of a graptolite (subsequently identified by Dr. G. L. Elles as the scalariform aspect of a *Dicellograptus*) which was found in a

/greywacke

greywacke boulder, was taken to indicate a post-Llandeilo or post-Ceredoc age for the conglomerate, which was tentatively equated with the conglomerate at the Horse Rock, Girvan.

Finally, in 1952, while visiting Britain (in order to test his theory of the turbidity-current origin of graded greywackes) Kuenen made a reconnaissance of the Southern Uplands, including part of the west coast of the Rhinns. In his published account he claims that the greywacke sequence (in the Portobello area) exhibits the combination of features normal to deep-water graded greywackes. Further south however near Larbrax Bay though the grading is inconspicuous he nevertheless concluded that the "dirty" nature of the greywackes, and the occurrence in them of occasional shale-fragments, together with the sporadic appearance of well-bedded, graded greywacke sequences, indicated that these beds, also were not shallow-water deposits.

He noted the occasional beds of shale carrying irregular lensing slabs of greywacke, and proposed that these might indicate slumping. Without comment, he reported the common presence of laminated siltstones showing good current-bedding intercalated with the greywackes.

The directions of supply as deduced from current-bedding and ripple marking which he noted were very variable, ranging from north-west, due west and south to nearly east, and he accounted for this by postulating oscillation of the geosynclinal slope and deep floor, producing variable directions of flow of the turbidity-currents.

Lastly, he remarked upon the fact that over much of the coast which he surveyed, the bottoms of the beds always faced south, and explained this by saying that "the northern limbs of the isoclinal structures are completely suppressed".

II STRATIGRAPHY

Introduction

The table of successions (table I) indicates the sequence of beds in the area as seen in several critical sections on the west coast.

Since the dip of the beds is usually high and frequently inverted, sequence cannot safely be determined from attitude. Therefore the order of succession is derived partly from fragmentary palaeontological evidence but largely from the order of upward sequence indicated by the sedimentary structures (for these criteria see section IV and Walton, 1956a).

In the course of the field-work certain Groups of rocks were differentiated from one another by means of gross lithology (rock-type, average grain-size, average thickness of bed, greywacke-lutite ratio). Within each primary group certain divisions have been erected, whose rocks are characterised by their distinctive microscopic petrography. (Thus, within the Portpatrick Group, which has a fairly uniform gross lithology, two divisions have been recognised. The rocks of the lower (Acid) division contain numerous fragments of acid igneous rocks while the rocks of the upper (Basic) division are rich in basic-igneous-rock fragments.) A departure from these principles of classification is found in the Corsewall Group, where the rocks are petrographically uniform but have been assigned to two divisions on the basis of their megascopic
/characters

characters. In this case partition into two primary Groups would have obscured their essential unity.

Except where affected by dynamic or thermal metamorphism the microscopic characteristics of the clastic rocks remain virtually unchanged. This greatly assists recognition of the formation present in any outcrop, particularly where because of lateral variation the megascopic character of the Group differs widely from that which it presents elsewhere.

The distribution of the various formations is as follows (fig. 2):

Corsewall Group

(i) Flaggy division: This, the lower of the two divisions comprising the Group, occupies a belt of ground about one mile broad extending north from the Southern Uplands fault to a boundary running from the north end of the Genoch Rocks on the west coast to near Milleur Point on the east.

(ii) Conglomeratic division: This division extends across the northern extremity of the peninsula in a belt about two-thirds of a mile in breadth.

Kirkcolm Group

Apart from two narrow belts of Galdenoch rocks in Glenstockdale and the Galdenoch-Leswalt area, rocks of the Kirkcolm Group are believed to occupy all the ground between the Southern Uplands Fault

/and

and the Portpatrick Group northern boundary (Killantringan-Crailloch Burn), each division recurring on several major folds.

Galdenoch Group

This Group outcrops in two narrow belts each about half a mile broad, one extending from the west coast near Galdenoch through Craigoch Tor the other occupying most of north Glenstockdale. In each case the Galdenoch rocks appear to lie in a constricted synclinal trough.

Portpatrick Group

Rocks belonging to this Group occupy all the southern part of the area described, from the supposed Silurian boundary north to the Killantringan-Crailloch Burn line, apart from several small areas where black shales, cherts and tuffs are exposed. The Basic division appears to be almost confined to the area north of the Portpatrick-Lochans line while the acid division, whose area of outcrop is greatly extended by gentle folding, is restricted to the region south of Portpatrick.

A strong NW-SE trending fracture probably of the nature of a dextral wrench-fault apparently runs through Portpatrick harbour and has shifted the Basic/Acid division boundary by half a mile to the south-east on its east side. This explains the presence of Basic division rocks in the inland exposures around Portree farm while along the strike, on the coast at Dunskey Castle, rocks of the

Acid division are exposed. This fault would also account for the pronounced shattering and the general disruption of bedding in the rocks exposed at Portpatrick harbour. Further evidence for the presence of this major fault is offered in section V.

The detailed evidence for the tabulated successions is now described, followed by the main megascopic features of the various Groups. The extent and nature of the lateral variations within each Group is also indicated.

A. GENERAL ACCOUNT OF SUCCESSION

Morroch Bay. (Plate IIIa, cf. Peach and Horne, 1899, pp. 402-408.) The thick sequence of green, blue and dark grey chert underlain by red and green mudstones and ? tuffs, which occurs at the south end of Morroch Bay (loc. 1, fig. 3) are believed to be the oldest rocks exposed in the Rhinns, south of the Southern Uplands fault. This is deduced from two facts. First, the cherts and mudstones appear to underlie the thick band of rusty-weathering black shales with chert-ribs which occurs immediately to the north and which has yielded Glenkiln graptolites. Moreover the topmost (black) cherts are interbedded with the basal black shales. Secondly wherever these cherts and mudstones (usually represented by the uppermost, black chert, member) are encountered in the Rhinns they are overlain by Glenkiln black shale.

Previously these variegated cherts and mudstones have been considered to be largely Arenig in age (Peach and Horne, 1899, fig. 98). However, the interbedding of the upper members with Glenkiln black shales and the fact that elsewhere Peach and Horne recognised very similar rocks as close associates of the Glenkiln shales (see Peach and Horne, 1899, p. 83), indicates that at least the upper part of the chert-sequence must be of later date, probably U. Llandeilo-Caradoc. Recently Lindstrom (Lamont and Lindstrom, 1957, p.61) suggested from the conodont evidence that certain of the "red shales" (mudstones), which occur about half way down the chert-mudstone succession in Morroch Bay are probably Llandeilian.

Beyond the band of Glenkiln black shales mentioned above the main part of the foreshore is occupied by sooty-black shales with chert-ribs, laminated green and pale blue mudstones and siltstones and blue-black shales with blocky mudstones, all intensely folded and fractured and cut by several porphyrite intrusions (loc. 2, fig. 3). The sooty black shales yield Glenkiln graptolites while the blue-black shales contain an ambiguous fauna referable to U. Glenkiln or L. Hartfell horizons. Some of the fairly thick beds of fine to medium-grained greywacke which occur in the midst of the blue-black shales are tectonically defined slices, but in other beds there is strong evidence of inter-digitation and gradational (upper) contacts with the shales, indicating original inter-bedding.

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This conclusion is amply confirmed at the north end of the bay where, on the foreshore, there are several thick (5-10 ft.) bands of blue-black shales, containing abundant U. Glenkiln - L. Hartfell graptolites clearly interbedded with greywackes which are the basal members of the Portpatrick (Acid) Group* (loc. 3, fig. 3). The numerous sedimentary structures afford clear evidence that the upward sequence is consistently to the north, across the shale-bands. Thus the Portpatrick Group must be largely of post U. Glenkiln - L. Hartfell age. Unfortunately, since no graptolites have been obtained from the rocks within the upper part of the Group, no upper limit can be set to its age.

The upward sequence is again northerly in the greywackes of the Portpatrick (Acid) Group forming the south headland of Morroch Bay, and thus there can be no true anticlinal structure across Morroch Bay. A fault with a downthrow to the south has been postulated to separate these greywackes from Glenkiln black shales immediately adjacent to the north.

On the north side of Port of Spittal Bay 8 ft. of Glenkiln black shales (Plate IIIb) are overlain by about 12 ft. of blue-black shales containing Glenkiln-Hartfell graptolites. These in turn pass up into blue siltstones and Portpatrick (Acid) Group greywackes which "young" to the north but are considerably faulted (loc. 4, fig. 3).

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*For convenience the name of the division is bracketed after the name of the Group. Thus Portpatrick (Acid) Group means the Acid division of the Portpatrick Group.

On the south side of the bay several feet of green shales are followed upwards to the south by about 25 ft. of black and blue-black shales with thin greywackes. These are unfossiliferous but are probably of U. Glenkiln - L. Hartfell age. The dark shales pass up into pale-blue siltstones and then into Portpatrick (Acid) Group greywackes, which young to the south. An anticline therefore exists in Port of Spittal Bay.

Portayew. Greywackes and siltstones of the Portpatrick (Acid) Group are exposed south of Port of Spittal as far as Portayew. Here about 20 ft. of Glenkiln black shales with nodular black-cherts (Plate IVa) are accompanied by 60 ft. of blue-black shales, with inter-bedded thin greywackes, containing Hartfell graptolites. South of Portayew the greywackes appear to young north near the erstwhile-mapped Ordovician-Silurian boundary. Interpretation is rendered difficult by the thermal effects of the Cairngarroch porphyrite, but along the line of the mapped boundary, near Garryhar there is pronounced shattering and shearing of the rocks, indicating that the junction may be strongly faulted. Further evidence of dislocation is provided by a consideration of the implications of the stratigraphy. The total thickness of pre-Silurian rocks in this region is probably about 2500 ft. and north-younging rocks with Silurian graptolites occur about half a mile south of the mapped boundary. Folding alone cannot dispose of the estimated thickness of Ordovician rocks in the distance and lateral thinning would have to amount to a

/ratio

ratio of 1 foot of thickness for every 3 feet of original horizontal distance, which appears quite impossible.

Killantringan and Portslogan. In the tectonically disturbed coastal section around Portpatrick harbour, the proportion of basic rock-fragments in the greywackes of the Acid division of the Portpatrick Group increases rapidly, providing a transition into the demonstrably overlying Basic division. Rocks of the latter division extend north as far as Killantringan and in this distance they young to the north consistently, apart from minor flexures.

In Killantringan Bay the pebbly Portpatrick (Basic) greywackes appear to be folded with thick bands of dark blue micaceous shale, with thin films of black shale which contain fragmentary ?Climacograptids. At the north end of this bay lenticular beds of pebbly greywacke of the Kirkcolm Group (Metamorphic division) occur in the midst of the shales and appear to be older than nearby Portpatrick (Basic) greywackes. Since the Kirkcolm Group is believed to be older than the Portpatrick this juxtaposition of Metamorphic and Basic greywackes is anomalous, implying the absence of the entire thickness of the Acid division of the Portpatrick Group and the Upper Barren division of the Kirkcolm Group.

This junction may be disconformable, the U. Barren and Acid divisions wedging out before Killantringan is reached. In support of this view, the Acid rocks appear to have been derived from the south and would therefore be expected to thin out to the north, whereas the U. Barren rocks have a northerly derivation and should thin

out to the south. However it seems rather coincidental that the areas of non-deposition of these two divisions should overlap. Moreover, if the Galdenoch Group is the equivalent of the Acid division - and the evidence seems strongly in favour of this correlation - it is difficult to see how rocks of the former Group could be deposited further north while there was no deposition in the Killantringan area.

From these considerations and from tectonic evidence presented elsewhere (Section V) it seems probable that along its northern boundary the Portpatrick (Basic) Group is in faulted contact with the Kirkcolm rocks.

Rocks of the Kirkcolm (Metamorphic Group), heavily folded, occur in Knock Bay and pass down into the greywackes of the Lower Barren division near the northern headland. A thin band of highly contorted unfossiliferous black shale occurs near the top of this division and in the cliffs of Bere Holm there is exposed the core of an anticline with 910 ft. of shattered black cherts and 4 ft. of contorted black shales. What appears to be another band of black shale, 3 ft. thick, occurs on both north and south limbs of the fold and is separated from the first band by about 15 ft. of thin fine-grained greywackes. This second band is overlain by soft blue fissile mudstones. Due to the intense crushing of the rocks only traces of graptolites were obtained here. However, the aspect of the rocks is typical of the Glenkiln shales and this, combined

/with

with the fact that Peach and Horne recorded Glenkiln graptolites from this locality, indicates the horizon.

From this section it appears that there are at least two bands of Glenkiln black shale, separated by thin greywackes, the lower band being associated with a thick bed of black cherts. Further evidence to support this contention is provided by the coastal section at Portslogan, half a mile north of Bere Holm (see fig. 4 and cf. Peach and Horne, 1899, p. 413-414).

Commencing from Cave Ochtree Point, where thin greywackes of the Kirkcolm (Lower Barren) Group are heavily jointed, and moving south, the next beds encountered across a small fault, are interbedded greywackes, siltstones and soft blue fissile mudstones. The proportion of lutite increases down the succession, to the south.

In the cliff near the south-west corner of this bay there occurs a 2-foot seam of shattered and contorted black shales with thin lenticles of black chert. From this seam various Glenkiln graptolites including Nemagraptus gracilis were obtained. The black shales are faulted on their north side against the thin greywackes and mudstones which contain, in the cliff, a bed of greywacke conglomerate, 3 ft. thick. On their south side the black shales appear to pass conformably down into exceedingly amygdaloidal spilite (Plate IVb) which contain thin black shale partings. In turn the spilite passes down into pale blue fissile mudstones then into thin greywackes, which young north.

After passing down through about 20 ft. of thin greywackes another exposure of contorted black shale is encountered in the cliff. This band is at least 3 ft. thick, carries numerous nodular ribs of black chert and has no associated spilite horizon. This is thought to be the second or lower band of black shale, normally underlain by black cherts which, in this instance, appear to have been excised by a strike-fault bringing the shales, on their south side, against thin graded greywackes with siltstones, similar to those of Cave Ochtree Point.

At the north end of the next bay in a series of greywackes of the Kirkcolm (L. Barren) Group there are several thin tuff-bands and at least two thin (6 and 18 inches) lenticular bands of spilite agglomerate. Beyond this, to the south, there is a 50 ft. sequence of soft blue and blue-green shales. Then, on a prominent skerry, a 4 ft. bed of "chert-agglomerate", overlain by eight inches of spilite, is exposed. Lying on top of the spilite is a band of sulphurous black shales, about 12 inches thick and a similar, much thinner seam occurs beneath the agglomerate. Within a few feet the agglomerate lenses out and in its place appears three feet of greywackes and siltstones which are bounded top and bottom by thin seams of black shale.

So far these black shales have proved unfossiliferous but from a fragment in the "agglomerate" Peach and Horne recorded graptolites of the N. gracilis zone and concluded that the age of the agglomerate

is Caradoc (Hartfell). However, it seems equally likely that the highly angular fragments of black shale were torn off their parent bed as the result of contemporaneous volcanic activity, in N. gracilis times. It is postulated that this agglomerate and associated black shales are on the same horizon as the black shales with amygdaloidal spilite, just described (fig. 5).

South of the agglomerate, on the shore, there is about 45 ft. of highly faulted thin greywackes, then a stretch of shingle. About 15 ft. of contorted nodular black and dark grey cherts, with thin intercalations of fissile greenish mudstone, form the skerry at the south end of the bay and on the south side there occurs a thin tuffaceous mudstone. Along the strike, in the recessed cliff a thin seam of black shale with chert-ribs lies conformably above the cherts.

The cherts on the foreshore are evidently faulted against the greywackes forming the headland but reappear in the cliffs of the next cove where they pass up into a two-foot seam of black shales with chert-ribs, from which an abundant fauna was obtained, typical of the Glenkiln N. gracilis zone. Below the cherts there is a band of shattered black shale, 3 inches thick, with traces of indeterminable graptolites, possibly diplograptids. This would indicate that the cherts are at least post-Arenig in age. Although the bedding of the adjacent greywackes is parallel to that of the cherts, it seems that there is a large fault separating these two

rocks since the greywackes belong to the Kirkcolm (Metamorphic) Group at a horizon considerably above that of the cherts. Microscopic cataclasis of the greywackes adjacent to the cherts supports this conclusion.

An important feature of this section is that, apart from minor flexures, the beds consistently young to the north. Thus any repetition must be the result of fracturing not folding.

In a complex area north of Salt Pans Bay the greywackes of the Metamorphic division of the Kirkcolm Group pass up into the Upper Barren division, the boundary being arbitrarily drawn at a 30 foot band of fissile grey and blue siltstones and mudstones, which immediately overlies a series of pebbly greywackes.

In turn, the gently folded Upper Barren division rocks show a transition into the overlying Galdenoch Group. The characteristic lithology of the latter Group is well displayed in the exposures near the mouth of the Galdenoch Burn. Only the lower part of this Group, petrographically similar to the upper part of the underlying division, is exposed on the coast, since this development of the Group is abruptly truncated by a large fault at the south end of Slouchnowen Bay. This fault brings the Galdenoch rocks into contact with shales and greywackes of the Lower Barren division of the Kirkcolm Group.

While no diagnostic graptolites have been found within the Galdenoch Group, its position in the succession and its petrographical

/characteristic

characteristics strongly suggest that it is to be correlated with the Portpatrick Group, and probably the Acid division of that Group.

No direct evidence of age has been gained from the exposures between Portslogan and Portobello. The black shales of the former area do not reappear to the north and seem to be replaced by bands of fissile mudstone and siltstone with dark films. The few graptolites obtained were either indeterminable or ambiguous in determining horizon.

However, in the northerly inlet of Portobello Bay abundant Glenkiln graptolites were obtained from a shale-band containing numerous blocky mudstones. This band is believed to occupy a fairly low position within the Kirkcolm (Lower Barren) Group.

From Portobello north to Dally (or Dounan) Bay there is an almost complete succession in the Kirkcolm rocks, practically undisturbed by folding or major faulting. The Lower Barren division extends from Portobello to Swallow Port where another thick shale-band has been chosen as the boundary between this and the overlying Metamorphic division which is exposed as far north as Castle Butt. A thick band of siltstones immediately above a series of pebbly greywackes marks the boundary between the Metamorphic and the Upper Barren divisions and rocks of the latter division occupy the coast from Castle Butt north to Dally Bay where they contain a thick band of fissile and blocky mudstones and siltstones

(Plate Va) which is highly contorted and is cut off by the Southern Uplands Fault. This shale-band contains Glenkiln graptolites.

In the coastal section just described there are ten thick "shale-bands" several of which yield Glenkiln graptolites. Peach and Horne evidently regarded these as repetitions of one band of "Dounan" shales (see Peach and Horne, 1899, p. 412) such repetition being produced by isoclinal folding. Since, with very local exceptions, the rocks in this section all young north^{*}, since the various shale-bands are lithologically very variable (such variations being irregular in direction) and since the greywackes adjacent to the bands are often petrographically distinct, it follows that folding alone cannot have produced the duplication of shale-bands. There is very little field-evidence for extensive and repetitive thrusting of these rocks and it is therefore concluded that this is a normal non-repeated succession of considerable thickness and that these shale-bands are, for the most part, discrete.

From the evidence of the graptolites it contains and its position in the succession, it appears that the Kirkcolm Group is entirely of Glenkiln age. It is probably equivalent to the Barr Series of Girvan on the one hand and the black shales with part of the blue-black shales of Morroch Bay on the other.

/The

*Kuenen also noted this (1953b, p. 45)

The order of succession in the rocks north of the Southern Uplands Fault is simple. There is a lower Flaggy division in which, on the east coast of the Rhinns, the upward sequence is always to the north. These rocks pass rapidly up into a Conglomeratic division and the two members which are petrographical identical are collectively termed the Corsewall Group.

However, the age-relations of the Group are not so readily determined. No graptolites have as yet been discovered in this Group but on the east side of Loch Ryan in the Finnarts conglomerate which appears to be the continuation of the Corsewall conglomeratic division and also in the underlying rocks, equivalent to the Flaggy division, Walton (1956b) discovered graptolites indicative of a Lower Glenkiln horizon. On the other hand, during the Geol. Assoc. visit to the Rhinns in 1933 one specimen of a scalariform graptolite was obtained from a boulder of greywacke in the Corsewall conglomerate. This was tentatively identified as Dicellograptus and on this basis it was suggested that the conglomerate was post-Llandeillian in age. However the identification was tentative and furthermore the greywacke containing the graptolite could have been deposited, partly indurated, eroded (not necessarily sub-aerially) and re-deposited as a boulder in the conglomerate, all within Glenkiln times.

The lithology and petrography of the Glen App, Finnarts and Corsewall conglomerates are very similar and there seems no reason

to doubt that they are of similar age. This being so, then the weight of evidence strongly indicates a Lower Glenkiln age for the Corsewall Group.

It is not easy to decide the equivalents of the Corsewall Group among the rocks south of the Southern Uplands Fault. The nearest in terms of lithology and petrography is the Portpatrick (and Galdenoch) Group but that appears to occupy a much higher horizon. There seem to be three alternatives to explain this lack of correlation:

(i) There was no deposition in the region south of the Fault during the period when the Corsewall Group was being laid down further north.

(ii) The equivalents of the Corsewall Group are not exposed in the southern area, remaining uneroded at a lower tectonic level than that of the other rocks.

(iii) Due to original lateral variation the equivalents of the Corsewall Group possess petrographic and lithological characteristics which are strikingly different from those of that Group. In this case the Corsewall equivalents would be present but unrecognised south of the Fault.

Explanation (i) seems very improbable. Some sedimentation certainly occurred during Lower Glenkiln times further south in the Rhinns - black shales, cherts and tuffs and probably greywackes. It seems unlikely that there was a depositional lacuna between these

two areas which were originally separated by only a few miles. Moreover it is improbable that 5000 ft. of coarse-grained sediments should thin to zero in less than three miles.

Explanation (ii) implies that the Corsewall equivalents lie underneath the Kirkcolm Group and presumably below the black shales and the variegated cherts and tuffs of Morroch Bay. Although such a view is impossible to disprove within the Rhinns it seems scarcely credible that no part of the Group should be exposed.

However alternative (iii) also presents several difficulties. If the Corsewall Group is represented by coarse clastic sediments in the area to the south then these equivalents are petrographically quite dissimilar to the Corsewall rocks. This is anomalous in view of the fact that despite certain changes in gross lithology the coarse clastic rocks of the other Groups retain their petrographic characteristics throughout the whole area. On the other hand very profound lithological changes might obscure petrographic similarity. This would imply that the Corsewall Group is represented by shales and siltstones south of the Southern Uplands Fault.

Some support for this idea is obtained from the current-directions in Corsewall rocks, which indicate roughly southward flow. Under normal conditions a southward decrease in grain-size and thickness would result from such a current. Moreover the Flaggy division, particularly on the west coast of the Rhinns, contains a high proportion of lutite and could readily become transformed into a shale-siltstone sequence.

From the available evidence it appears that a combination of lateral variation and non-exposure offers the most adequate explanation for the apparent disappearance of the Corsewall Group. The writer believes that this variation is largely in the gross lithology and also, to a lesser extent, in the microscopic petrography so that, while most of the Corsewall Group is represented by a fairly thick series of shales lying below the Kirkcolm Group, part of the Conglomeratic division is probably equivalent to the lower part of the Lower Barren division. The rocks of the latter division, despite pronounced differences in microscopic petrography, exhibit an aspect similar to that of the Corsewall rocks. It is probable that the Corsewall equivalents are not completely exposed at any point north of the Portslogan section. In the southern part of the area these equivalents possibly include part of the Glenkiln black shales.

Because of the tectonic pattern of the area most of the inland exposures merely serve to show that the various Groups and divisions initially erected on the coast continue more or less undisturbed along the strike and help to define their boundaries. In only one case is the occurrence of a particular Group known from the evidence of inland exposures alone. This is the southern exposure of the Galdenoch Group in Glenstockdale. The Group occurs in the core of a syncline which, because of its gentle easterly plunge, closes

a little further west so that the Group is not exposed on the west coast at this point.

However there are a number of inland exposures involving greywackes and graptolitic shales which possess considerable stratigraphic interest.

In Glenlaggie Burn, south of Lochans and on the line of strike of the Morroch Bay shale-bands, hard black shales with occasional chert-ribs, shattered and contorted, occur among thick bands of red-stained, rather soft dark shales with blocky mudstones. Graptolites occur only as silvery traces in these shales and are indeterminable but lithological comparison with Morroch Bay and other exposures indicates that these are the representatives of the Glenkiln and Hartfell shales. As in Morroch Bay the shales are cut by a number of porphyrite intrusions which appear to be much more numerous in the shale-bands than in the greywackes.

There are no exposures on the line of strike between Glenlaggie and Morroch Bay but a little to the north of this line, in Colfin Burn and Colfin quarry, platy dark blue shales are associated with quartzose greywackes of Portpatrick (Acid) Group aspect. In the entrance to the quarry a band of these dark shales at least 15 ft. thick has yielded L. Hartfell graptolites.

Along the strike of the Bere Holm rocks, in Crailloch Burn, there are exposures of black shales and black cherts which occur on the crests of at least two anticlines, and intervening greywackes

of the Kirkcolm (Lower Barren) Group. Glenkiln graptolites are plentiful in the shales. In an old quarry, 200 yards southwest of Knockquhassen Farm, Glenkiln graptolites were obtained from a 6-inch seam of black shales interbedded with thin Kirkcolm greywackes.

The total maximum thickness at any point in the area is 6,600 feet for the Kirkcolm and Galdenoch Groups in the Portobello region. This succession probably represents a time-period from Lower Glenkiln to Middle or Upper Hartfell. Such a thickness can only be approximate and may be reduced by several hundred feet by concealed or unobserved faulting. Even so, the postulated thickness is greatly in excess of the 2,200 feet proposed by Peach and Horne for the maximum thickness in the Northern Belt of rocks of Glenkiln-Hartfell age.

However, such a thickness is not unusual in geosynclinal sediments of other Caledonian regions. For example Vogt (1945) calculated a maximum thickness of over 3000 metres (10,000 ft.) for a Girvan-like succession in the Trondheim region of equivalent age to the British Llandeilo-Caradoc. A thickness of over 6,000 ft. is also claimed for geosynclinal sediments of Upper Trentonian-Cincinnatian age (approximately Llandeilo-Bala) in part of the eastern Appalachians (Key, 1951).

B. DESCRIPTION OF LITHOLOGIES

Corsewall Group

(1) Flaggy division: This division is characterised by the thin and very even bedding of the rocks (Plate Vb). The typical lithology consists of alternations of flaggy and blocky grey siltstones and blocky dark grey mudstones, with occasional thicker (6-12 inches) bands of fine-grained* greywacke. Frequently the siltstones are crudely laminated with alternate quarter-inch bands of coarse and darker fine-grained siltstone. Sometimes the greywackes occur in beds up to four feet thick and are then much coarse in grain. Towards the upper boundary of the division these greywacke beds predominate. Occasionally the mudstones and siltstones are fissile but these fissile bands nowhere exceed a few feet in thickness.

Small-scale current-bedding and ripple-lamination commonly occur in the siltstones and convolute-lamination in the mudstones. Many of the greywackes are poorly laminated but graded-bedding is rare and poorly developed. Ovoid nodules of highly calcareous siltstones are sometimes conspicuous in the more massive greywackes.

/Since

*Greywackes are here regarded as coarse-grained if the average grain-size is more than 1 mm., medium-grained if it is between 1 and 0.25 mm. and fine-grained if it is less than 0.25 mm.

Since it is well exposed on both east and west coasts of the Rhinns, the Corsewall Group furnishes excellent opportunities for the study of strikewise variation in lithology. The Flaggy division, in particular, undergoes several interesting lithological changes as it is traced across the peninsula.

The most striking change is in colour for the predominantly red and brown colours of the rocks on the east coast are replaced by grey and blue-grey in the rocks on the west coast. However, this change probably possesses little environmental significance, since the red colouring is due to a limonitic staining presumably derived by leaching from the Permian rocks which formerly must have blanketed all the east side of the Rhinns.

More important is the accentuation of the flaggy character of the rocks and the decrease in the average thickness of the greywacke beds, with a concomitant decrease in the greywacke/lutite ratio, as the division is traced west. Furthermore the proportion of true mudstone increases to the west and simultaneously some of the siltstones become appreciably calcareous (Plate VIa and fig. 6)

(ii) Conglomeratic division: There is a fairly rapid passage from the thin greywacke sequence at the top of the flaggy division into the thick coarse-grained greywackes at the base of the overlying division. On the east coast this change is not reversed but on the west coast, within the lowest two to three hundred feet

of the Conglomeratic division the typical flaggy lithology recurs several times, in bands from 20-50 feet thick.

The transition from the Flaggy into the Conglomeratic division is marked:

- (a) by a considerable increase in the average thickness of the greywacke beds,
- (b) by a corresponding decrease in the proportion of lutite in the succession, and
- (c) by a great increase in both the maximal and average grain-size of the rocks, culminating in the appearance of "conglomerates" and boulder-beds.

The characteristic rock-type of this upper formation is very coarse-grained greywacke or "conglomerate" (average grain-size 0.5-1.5 cms.) which occurs in beds ranging from six to twenty feet in thickness, often pebbly at the base and poorly graded. These are separated by thinner beds of medium-grained greywacke and thin blocky siltstones. In places the greywackes are platy, alternating with thin bands of siltstone, but generally they occur in thick poorly laminated beds.

where the greywackes and rudaceous rocks have escaped the Permian-derived limonitic staining they have a distinctive colour, dark grey with a faintly purple hue. The lutites are generally somewhat darker in colour and lack the purple tint.

/Graded-

Graded-bedding is seldom well developed in the greywackes although lamination is common. Scour-fill structures, small wash-outs and other erosional features are frequently found in the coarse-grained rocks while small-scale ripple-lamination occurs in the siltstones.

Within this general lithological framework there occur numerous coarser-grained bands, ranging from pebble-conglomerate to boulder-beds. The first of these bands is found about 300 ft. above the base of the division on the east coast of the Rhinns, near Milleur Point, and in a slightly higher position on the west. To the north the division becomes increasingly conglomeratic.

These boulder-beds consist of a matrix of fine-grained "conglomerate" in which are embedded numerous fairly well-rounded pebbles, cobbles and boulders ranging in diameter from a fraction of an inch to several feet (Plate VIIb). The average thickness of these beds is about 6-10 ft., but occasionally they are much thicker attaining a known maximum thickness in excess of 20 ft. near Boak Port, on the north coast.

True graded-bedding is usually absent from these beds although sometimes present in the inter-bedded greywackes. However a coarse pebbly fraction (average grain-size 10 mm.) is frequently found at or near the base, sometimes forming the basal six inches or so of the bed. Moreover the matrix of the boulder-beds, like the

/associated

associated greywackes is often well-laminated with units from 0.5-1.0 inches thick. In some instances the beds immediately underlying a boulder-bed have been thoroughly disrupted, the material of the boulder-bed wedging apart these earlier deposited layers (fig. 28 and Plate XXIVb). In other cases the boulder-bed lies with apparent conformity on thin-bedded greywackes. Some of these boulder-beds can be followed for several scores of yards along the strike and in many cases they are found to be lenticular, passing laterally into thick-bedded greywackes.

In the boulder-bed, the first boulders generally appear about a foot above the base and are seldom found in a lower position. Frequently the cobbles and boulders are not scattered randomly throughout the bed but are concentrated into layers, perhaps two or three boulders thick. There is some slight tendency for the frequency of boulders to decrease upwards.

The boulders occurring in these beds, like those which occur sporadically in the interbedded rocks are generally large with an average maximum diameter of about 12-15 inches. The largest boulders observed were of granitic rocks which were up to 5.8 feet in maximum diameter. The vast majority of the boulders are igneous, with the acid representatives dominant, and are normally coarse-grained. The rock-types which occur as boulders include: granite, quartz-porphyry and other microgranitic rocks; quartz-
/diorite

diorite; "gabbro", dolerite and spilite; greywacke, fine-grained conglomerate, siltstone, shale and chert; hornblende-granulite, epidosite and quartzite. These will be described more fully in section III.

Kirkcolm Group

The typical development of this Group is exposed in the coastal section from Portobello to Dally Bay. The megascopic characters of the rocks of this Group are rather variable but distinctive in aggregate. The dominant lithology consists of massive and fairly thick (3-6 ft.) beds of medium and coarse-grained greywacke which are separated by thin seams (2-18 ins.) of fissile siltstone (Plate VIIa). The beds of greywacke are often conspicuously graded and display numerous other sedimentary structures, notably ripple-mark, convolute-lamination, flute- and groove-casts, load-casts of various types and occasionally current-bedding on a fairly large scale. Scour-fill structures are much less common than in the Corsewall Group. Pebbles up to 15 mms. in diameter are found in many greywackes and may be scattered uniformly throughout the lower part of a graded bed or concentrated into "pebble-bands" up to 18 inches thick, which may occur at the base of a greywacke or at various levels within the bed. Such pebble-bands can sometimes be seen to grade laterally into greywacke of finer grain (fig. 29).

This massive greywacke sequence is often interrupted by a thin-bedded succession which consists of beds of fine to medium-grained greywacke from one to three feet thick interbedded with bands of fissile and flaggy siltstone and mudstone which vary in thickness from six to twenty inches (Plate VIIb). These greywacke may be graded, but are more often laminated and relatively ungraded. The siltstone bands are frequently convoluted throughout their entire thickness and are sometimes appreciably lenticular, in one case lensing from six inches to zero within 45 feet. This sequence is conspicuously even-bedded, the thickness of the greywacke beds remaining fairly constant. Such a sequence may be from 50-200 feet thick.

Perhaps the most characteristic megascopic feature of the Kirkcolm rocks is the frequent occurrence of thick "shale-bands". The average thickness of these bands is about 30-40 feet, but may be as much as one hundred feet. They consist of fissile and flaggy pale or dark blue micaceous siltstone with a variable proportion of fissile and blocky dark blue mudstone which often has shiny films of black shale which may contain traces of graptolites. Thin ribs of fine-grained greywacke are infrequent in these bands. In some shale-bands certain of the flaggy siltstones are calcareous while buff-weathering calcareous nodules with the shape of curling-stones and maximum dimensions of 3 ft. by 1 ft. frequently occur

/where

where there is a thick development of mudstone. The junctions of these bands with the adjacent greywackes are usually abrupt rather than gradational. By means of stream-sections some fossiliferous shale-bands may be traced for several hundred yards along the strike without any appreciable change in thickness or lithology. These bands appear to be particularly common and thick in the lower part of the Lower Barren division but they also occur in the other divisions.

In hand-specimen, greywackes of the Kirkcolm Group are generally dark grey in colour, almost always micaceous with recognisable grains of quartz and fragments of fine-grained siliceous rocks. Apart from very localised areas near major movement-planes the rocks are free from iron-staining. The massive greywackes often carry nodules of highly calcareous coarse siltstone similar in shape and size to those in the shale-bands and these weather out preferentially, leaving characteristic ovoid hollows.

In the field the three divisions of the Kirkcolm Group are almost indistinguishable. The greywackes of the Metamorphic division generally appear to be more micaceous and quartzose than the others, with a rather typical dull glassy appearance on a fresh surface, but the other megascopic characters are identical.

So far as can be ascertained from the meagre inland exposures there is little variation in the lithology of the Group and its

/component

component divisions as they are followed along the strike. However traced across the strike, i.e. from north to south, the Group exhibits several striking changes in megascopic lithology and total thickness whilst the coarse clastic rocks retain their characteristic microscopic petrography. Such changes are discernible not only in the Group as a whole but in individual divisions.

First of all there is a marked southerly attenuation in the thickness of each division and consequently of the Group. This is shown in table II. If the proposed stratigraphic relationships hold the whole Kirkcolm Group is represented in Morroch Bay by a few score feet of black shales and cherts.

In each division and in the Group as a whole the proportion of lutite increases to the south. For example, in the northern exposures the shale: greywacke ratio is about 1:6 while in the extreme south, in the Killantringan region, the ratio is about 1:4. This change appears to be achieved by a marked decrease in the average thickness of the greywacke beds and a concomitant slight increase in the thickness of interbedded lutites which include a higher proportion of mudstone further south (fig. 7).

A southerly decrease in average and maximum grain-size of the greywackes is also apparent in the field although occasional thin "pebble-bands" occur in rocks of the Metamorphic division as far south as Knock Bay.

/Galdenoch

Galdenoch Group

Near the mouth of the Galdenoch Burn, in the upper part of the Kirkcolm (Upper Barren) Group there is a passage from the typical Kirkcolm lithology to that of the Galdenoch Group. This transition is achieved by a slight decrease in the average thickness of the beds of greywacke together with a marked increase in average grain-size and the appearance in the greywackes of numerous large detrital grains of ochreous feldspar. The rocks of this transition zone are petrographically similar to the rocks forming the basal part of the Galdenoch Group, the boundary being placed where the rocks contain appreciable amounts of ferromagnesian minerals (here represented by pseudomorphs) since elsewhere the Galdenoch rocks invariably contain these minerals.

The typical Galdenoch lithology is rhythmic (cf. Robertson, 1952). It comprises several beds - usually four or five - of medium-grained greywacke, the beds being about two to three feet thick and separated by thin bands of fissile and flaggy siltstone. This sequence is followed by a thick bed (four to eight feet) of coarse-grained greywacke than by a further four or five thinner beds, and so on.

As a rule the greywackes are poorly graded but well laminated and they often show large-scale current-stratification, even near the base of a bed. Scour-fill and other irregular erosive

/structures

structures are common, particularly at the base of the thick beds of greywacke, while many of the upper surfaces carry current ripple marks. The intercalated pale-blue siltstones often exhibit convolute-lamination and small-scale ripple-lamination and there are also at least two "slumped beds", each about three feet in thickness.

Rounded pebbles of spilite, quartz and siliceous rocks up to 5 mms. in diameter are common and may occur at the base of a graded bed or as discrete bands within the greywacke. At Galdenoc the greywackes are slightly red-stained because of their proximity to a large fault but elsewhere they are blue-grey in colour.

The character of the Group remains virtually unchanged within the areas exposed and no lateral variation within the Group has been discerned. Since the Group occupies the cores of synclinal troughs its true thickness cannot be computed but the maximum observed thickness is in the region of 300 feet.

Portpatrick Group

Where typically developed as, for instance, on the beach and in the old quarry south of Portpatrick old lighthouse, the lithology of the Portpatrick rocks is quite distinctive. Beds of coarse or medium-grained greywacke from two to four feet in thickness alternate with thick seams (one to three feet) of fissile

/and

and blocky or laminated dark blue siltstone and mudstone and within this sequence there are occasional much thicker beds of coarse greywacke, up to 15 ft. thick (Plate VIIIa).

The greywackes are usually rather poorly graded and contain numerous scattered pebbles of spilite, chert and granitic rocks up to 30 mms. in diameter. Discrete bands and lenses of similar pebbles are frequently encountered, especially in the thicker greywackes, and may occur at almost any level in the greywacke. Such bands are highly lenticular and often occupy small scour-structures excavated in the adjacent sediment of finer grain - even within a greywacke bed. Grading is common in these pebble-bands and is often inverted. Within the bands there are often swarms of large (up to 5-6 inches long) angular and twisted or frayed pieces of fissile and laminated dark siltstone and mudstone similar to the intercalated bands of lutite. At several localities and especially at the north end of Morroch Bay, thin layers of dark lutite lying immediately below a pebble-band have been disrupted, the pebbly greywacke penetrating between the layers or forming long thin vertical veins which are transcurrent to the laminae in the mudstone. Large slivers of shale are often conspicuous in the lower part of such a pebble-band.

A thin-bedded sequence of well-graded fine-grained greywackes and fissile dark siltstones is often intercalated in the normal

/succession

succession and is in fact the dominant lithology of the lower part of the Basic division. Within this sequence thin shale-bands are occasionally developed. These consist of fissile and flaggy dark blue siltstone and fissile and blocky dark blue mudstone in approximately equal proportions, with numerous very thin (1-2 inches) ribs of fine-grained greywacke. There are several of these bands in the Acid division but only four are known from the Basic rocks. Such shale-bands may be forty feet thick.

Lamination of the greywackes is often pronounced with current-bedding and small-scale ripple-lamination rather less common. Scour-fill and other irregular erosional structures are frequently developed but directional current-structures such as groove- and flute-casts appear to be rare in the Portpatrick rocks. Another interesting feature of the greywackes is the prolific occurrence of large greyish-white calcareous nodules. These are similar to the nodules in the Kirkcolm greywackes but appear to be richer in carbonate. Lamination was occasionally observed in these nodules, particularly in those within the greywackes at the north end of Port of Spittal Bay. This lamination is usually oblique to the bedding of the greywacke and is abruptly truncated at the margins of the nodules implying that at least some of the nodules are probably eroded blocks incorporated within the greywacke.

In hand specimen the Portpatrick Group greywacke is usually recognisable because of its characteristic "smoky-blue" colour and unique dull matt appearance on fresh fracture. In the coarser Basic greywackes dark ferromagnesian minerals can usually be detected while the Acid rocks are generally more siliceous and less homogeneous in appearance. Only by such petrographic properties can the two divisions be differentiated in the field.

Lack of adequate marker horizons within the Group renders detection of lateral variation rather difficult. The problem is further aggravated by the pronounced effects of cleavage, extensive fracturing and tight folding in the rocks of the Acid division in the area south of Port of Spittal Bay. However the thickness of the Acid division appears to increase to the south and the siltstones and mudstones become pale or olive-green in colour, in contrast to their dark hue further north. There are also certain changes in the mineralogical and petrographical composition of the greywackes and these will be dealt with in section IIIB.

C. PALAEONTOLOGY

In common with other parts of the Southern Uplands where greywackes predominate, precise determination of age-relationships in this area is made difficult by the paucity of fossiliferous horizons and the fragmentary nature of the graptolites. Because of the rather crude zonation in the Glenkiln-Hartfell, even where determinable graptolites were found it often proved impossible to determine the exact horizon. This was particularly true of the upper part of the Glenkiln and the lower part of the Hartfell.

With respect to the wider age-relationships, as Pringle (1948, p. 14) demonstrated, the fauna of the basal member of the Glenkiln black shales is very similar to that of the basal Caradoc in the Welsh area, but his further inference that the Llanvirn and Llandeilo periods were unrepresented in the Southern Uplands has recently been refuted by Lamont and Lindstrom (1957). These workers showed that on the evidence of the conodonts many of the so-called Arenig cherts are actually of Llandeilo age.

The fossils collected by the writer, together with the localities, are listed below. Many of the graptolites were identified by Dr. Isles Strachan who also commented on the probable horizons of the material. Dr. Strachan's help and advice is gratefully acknowledged here.

/Assiduous

Assiduous search was made at all fossiliferous localities mentioned in the account by Peach and Horne (1899) and several new localities were also found. At many of the localities listed by Peach and Horne the material obtained was either indeterminable or determinable only to the generic stage. It is highly probable that re-examination of the material collected by these workers, using the refined methods of identification now in use, would result in a drastic decrease in the number of specific and possibly also of generic names. (See Lemont and Lindstrom, 1957, p.62 for a case in point.)

In the following lists a fossiliferous locality hitherto unrecorded is prefixed by an asterisk. The suffixed numbers indicate the position on the locality-map (fig. 2).

*Band of red shales on shore 300 yds. SSE of small cottage at Jamieson's Point (1).

Orthograptus sp.
cf. Climacograptus sp.

Thick band of dark shales, small cliff at Dounan's Nose, Dounan Bay (2).

Dicellograptus sextans var. exilis ELLES and WOOD
Climacograptus sp.
Dicranograptus sp.



/Thick

*Thick band of dark blue shales, shore 120 yds. south of
Burn root, Dounen Bay (3)

Dicranograptus cf. nicholsoni HOPKINSON
cf. Orthograptus sp.

Shale-band at south end of Salt Pan Bay (4)

Dicellograptus cf. sextans (HALL)
Climacograptus sp.

*Dark shales in northerly inlet of Portobello Bay (5)

Dicellograptus sextans var. exilis ELLES and WOOD
Glyptograptus teretiusculus var. euglyphus (LAPWORTH)
Climacograptus cf. antiquus LAPWORTH
cf. Corynoides sp.
Didymograptus sp.
Ostracodes

Northernmost band of black shale, in small cliff 150 yds.
south of Cave Ochtree Point (6)

Nemagraptus gracilis (HALL)
Dicellograptus sextans var. exilis ELLES and WOOD
Climacograptus cf. bicornis (HALL)
Dicranograptus sp.

Band of black shale immediately above black cherts, inland
cliff 60 yds. north of Dove Cave (7).

Nemagraptus gracilis (HALL)
Dicellograptus cf. sextans HALL

/Climacograptus

Climacograptus sp.
Dicromograptus sp.
 cf. Corynoides sp.
Lingula cf. alternata SOW.

*Thin black shale below black cherts, inland cliff 60 yds.
 north of Dove Cave (7)

Fragments of ?diplograptid graptolites

*Thin band of dark shale interbedded with greywackes, old
 quarry 200 yds. SW of Knockquhassen Farm (8).

cf. Didymograptus superstes LAPWORTH
Nemagraptus gracilis (HALL)
Didymograptus sp.
Orthograptus sp.
Dicromograptus sp.

Black shales in Crailloch Burn at sharp bend in stream
 180 yds. SE of small bridge near Knockquhassen (9).

Diplograptus cf. foliaceus (MURCHISON)
Dicellograptus sextans var exilis ELLES and WOOD
Climacograptus cf. antiquus LAPWORTH
Climacograptus sp.
Corynoides sp.
 cf. Orthograptus sp.

*Blue black shales interbedded with greywackes at entrance
 to old quarry near Colfin Farm (10).

/Glyptograptus

Glyptograptus teretiusculus var. euglyphus (LAPWORTH)
Amplexograptus cf. perexcavatus (LAPWORTH)
Climacograptus scharenbergi (LAPWORTH)
Orthograptus cf. calcaratus (LAPWORTH)
Climacograptus sp.
Orthograptus sp.

Bands of blue-black shale interbedded with greywackes on the foreshore at the north end of Morroch Bay, where the cliffs jut seawards (11).

Climacograptus bicornis (HALL)
Climacograptus cf. spiniferus RUMEDMANN
Orthograptus cf. quadrimumcronatus (HALL)
 cf. Leptograptus sp.
Dicranograptus sp.
 cf. Cryptograptus sp.

Orthograptus truncatus (LAPWORTH)
Dicellograptus angulatus ELLES and WOOD, (very abundant)
Orthograptus calcaratus (LAPWORTH)
Orthograptus calcaratus var. vulgatus (LAPWORTH)
Climacograptus cf. bicornis (HALL)
Orthograptus sp.
 cf. Corynoides sp.

Dicellograptus cf. angulatus ELLES and WOOD, (very abundant)
Dicellograptus cf. forchhammeri GRINITZ
Climacograptus sp.
Orthograptus sp.
 cf. Corynoides sp.

Black shale with chert-ribs immediately north of exposure of light-coloured cherts and red and green shales, 110 yds. NNW of southernmost cottage in Morroch Bay (12).

/Nemagraptus

Nemagraptus gracilis (HALL)
Dicellograptus sextans var exilis ELLES and WOOD
Dicranograptus zic-zac LAPWORTH
Glyptograptus cf. teretiusculus (HISINGER)
Corynoides sp.
 cf. Orthograptus sp.

Band of similar shales 50 yds. WSW of southernmost cottage
 in Morroch Bay (12).

Nemagraptus gracilis (HALL) - abundant
Dicellograptus sextans HALL
Dicellograptus sextans var exilis ELLES and WOOD
Hallograptus mucronatus (HALL) - abundant
Glyptograptus teretiusculus var. euglyphus (LAPWORTH)
Orthograptus sp.
Climacograptus sp.
 horny brachiopods

Band of blue-black shales on foreshore at north end of
 Port of Spittal Bay (13).

Climacograptus cf. scharenbergi LAPWORTH
Plegmatograptus cf. nebula BOLMAN
 cf. Orthograptus sp. of calcaratus type
Climacograptus sp.
 cf. Glyptograptus sp.
 ?Retiolitid
 horny brachiopod

Band of black shales 8 yds. to ESE of last locality (13)

Dicranograptus zic-zac LAPWORTH
Nemagraptus gracilis (HALL)
Dicellograptus sextans var. exilis ELLES and WOOD

/Dicellograptus

Dicellograptus cf. sextans HALL
Glossograptus hincksii (HOPKINSON)
Dicellograptus sp.
Climacograptus sp.
Cryptograptus sp.

Blue-black shales interbedded with greywackes on foreshore
 at Isle of Lanna, Portayew (14).

Orthograptus cf. quadrimumcronatus (HALL)
Orthograptus cf. calcaratus (LAPWORTH)
Orthograptus cf. calcaratus var. vulgatus (LAPWORTH)
Climacogreptus sp.
 cf. Dicranograptus sp.

III. PETROGRAPHY

A. PETROGRAPHY OF THE CONGLOMERATES

Under this heading it is proposed to describe the general features of the rudaceous rocks (average grain-size in excess of 2.5 mms.) and also to give a detailed account of the petrography of the various rock-types represented in the boulders, cobbles, pebbles and fragments in these beds.

Corsewall Group. As indicated in a previous section, the Conglomeratic division of this Group contains numerous coarse-grained beds. These are usually "fine-grained conglomerates" which are essentially greywackes of exceptionally coarse grain (but see p. 115) with a variable proportion of pebbles and sporadic boulders. Occasionally such a bed contains large numbers of boulders and pebbles, when it is termed a boulder-bed.

In dealing with these boulder-beds it was found convenient to classify into three parts: boulders, being fragments with a maximum diameter of more than 250 mms.; pebbles, fragments between 250 and 5 mms. in diameter; and the greywacke matrix. Separate counts of the boulders and the pebbles of three boulder-beds were

/taken

taken in the field in order to ascertain the relative proportions of the different rock-types at each size-grade and at different horizons within the Group. Thin-section counts were also made of the fragments between 1 and 5 mms. in the matrix of each boulder-bed.

Histograms expressing the results of these counts are given in fig. 8 and it may be seen from these that in each size-grade the distribution of components remains approximately similar throughout the three beds examined. Since the beds are at different horizons within the Conglomeratic division there appears to be little vertical variation in their composition. With decreasing size-grade, however, there is a pronounced and fairly regular change in composition which results in the dominance of the fine-grained rock-types in the lower grades. Thus while granite is the commonest type of boulder, microgranitic pebbles are dominant and spilitic and microgranitic fragments are almost equally abundant in the thin-section counts. Basic rock-types, too, are more common in the smaller size-grades.

The apparently anomalous "secondary maximum" of granitic fragments in the thin-section counts may be partly accounted for by the mode of weathering of granite. Being very coarse-grained, granite would probably be much more susceptible to mechanical disintegration

/ then

than any of the other rock-types present, which because of their fine-grained nature, possess greater cohesion. On this hypothesis the boulders of granite are blocks defined largely by jointing; once disintegration of these blocks commenced it would proceed with great rapidity, producing relatively few, ephemeral fragments of pebble-size and a great deal of crystalline detritus. This detritus would largely be composed of mineral grains containing small patches of other minerals. In support of this hypothesis, most of the fragments identified in thin-section as "granite" consist of a few crystals of quartz with small adherent patches of feldspar.

Thin-section counts were also taken of the fragments in a number of conglomeratic bands and also in the interbedded greywacke at various points with the Groups. The results of these counts are presented in histogram form in fig. 9 but the counts themselves are discussed in more detail at the end of the sub-section on the petrography of the greywackes.

Since many of the rock-types occurring as boulders, pebbles or small fragments in these conglomeratic bands are also found in the greywackes of this and other Groups, it is proposed to describe their petrography in some detail.

/Granite

Granite: This rock-type forms the largest boulders observed. Generally the granitic rocks are coarse-grained (average 2-3 mms.) and non-porphyrific. When the rock is fresh the colour varies from dull blue-grey, where plagioclase is the dominant feldspar, to pale pink, where orthoclase is abundant. The normal colour on weathered surfaces is buff or light orange. In hand-specimen shiny flakes of dark mica are usually conspicuous, with fairly large prisms of dark green hornblende. A few boulders and pebbles are very coarse-grained, pegmatitic, while intensely pink aplite occurs as small patches and veins traversing granite boulders. Frequently boulders of granite are cut by joints whose orientation is irregular and quite independent of the local joint-system. Such joints must have been imposed on the parent rock-mass. Thin veinlets (up to 0.5 ins. wide) of pale green epidotic material occasionally occur in the granites.

Microscopically the granites consist of a great deal of quartz with a variable but usually large amount of plagioclase and a very variable proportion of potash feldspar, together with micas, hornblende, opaques and secondary minerals. Reference to Table II will show that the average mineralogical composition of these rocks is that of a granodiorite.

/The

The water-clear or smoky grey quartz of the granites commonly forms large anhedral plates, or small interstitial blebs. It is sometimes turbid through the abundance of tiny inclusions, mainly very small, rounded and acicular apatites and zircons and tiny indeterminable granules. Undulous extinction is fairly common while roughly rectilinear cracks, filled with chlorite or limonite, are frequently developed.

There are three different varieties of potash feldspar in the granites, of which microperthite is by far the most abundant. This consists of an orthoclase host with numerous parallel stringers of sodic plagioclase. In some cases microcline is the host-member. The large anhedral patches of microperthite are usually somewhat kaolinised. Pure orthoclase is similar in form to the intergrowth but is seldom found. Microcline is also rare, being most abundant in slightly sheared granites where it forms small inclusion-less anhedral patches.

The plagioclase is usually sodic in composition (albite-oligoclase, An 6-15) and often exhibits slight zoning, from a more calcic core (An 20-10) to a rim of nearly pure albite. The crystals are generally euhedral, tabular or lath-shaped, and twinned according to the Albite Law, the Carlsbad Law, a combination of both or, rarely, untwinned. Advanced alteration is
/characteristic

characteristic of this mineral and usually consists of kaolinisation, although sericite also occurs, particularly along the cleavages. Very occasionally a myrmekitic intergrowth of quartz and sodic plagioclase is observed at the boundaries of crystals of microcline and microperthite.

Biotite is the common variety of mica and forms large or small flakes (max. length 2.4 mms.), sometimes aggregated. Pleochroism is strong, X = yellowish grey; Z = moderate brown. Pleochroic haloes are common and the usual alteration is to a pale green penninitic chlorite. In some cases the biotite appears to have been derived from hornblende through an intermediate pale-green variety. Small flakes of muscovite are of infrequent occurrence and are often associated with decomposing biotite or highly altered plagioclase. A very pale-yellow colour is frequently observed in these flakes.

The large (max. length 2.5 mms.) subhedral prismatic crystals of hornblende are strongly pleochroic in green (X = pale greenish yellow; Y = light olive; Z = grey-green). The mineral is biaxial negative, $2V$ about $65-75^\circ$, with wide extinction angle ($Z \wedge C = 21^\circ$). Simple {100} twins are frequently found and the crystals are often partly altered to biotite, fibrous green chlorite, iron-ores and carbonates.

/Apatite

Apatite is easily the most abundant of the accessory minerals, forming small prismatic crystals, water-clear and with small cross-cracks. Small euhedral crystals of colourless zircon, subhedral magnetites, ilmenite and pyrite in large haematite-coated masses complete the list of minerals in the granites.

Some of the granites have evidently undergone a fair degree of shearing, which has resulted in the peripheral granulation of the quartz and feldspars, the production and partial alignment of small, new flakes of brown biotite (rarely, muscovite) which often occur at the edges of phenocrasts and, in a few instances, the appearance of a crudely foliated, gneissose structure with small, sub-spherical aggregates of radiating feathery and bladed actinolite. Some of these rocks approach biotite-gneiss in appearance while in others there are small, irregular granules and larger patches of clear, pale-green epidote.

Occasional boulders of granophyre have phenocrysts of clear quartz and fresh sodic plagioclase (An 8-14) set in a medium-grained groundmass of quartz and orthoclase, graphically intergrown and with numerous small granular chlorites and larger, aggregated epidotes.

/Microgranitic

Microgranites: quartz-porphyry is the commonest type of fine-grained acid igneous rock. In hand-specimen it is dark grey in colour, when fresh, with numerous phenocrysts (average length 2.5 mms.) of milky-white plagioclase and pale-pink orthoclase with large subhedral crystals of grey quartz and, sometimes, flecks of biotite. Occasional large prisms of dark-green hornblende, up to 5 mms. in length, are also encountered. The rock weathers in colours ranging from roseate white to dirty cream, with a typically smooth surface.

Under the microscope the groundmass is resolved into an equigranular mosaic of quartz and orthoclase of very variable grain-size (0.2-0.7 mms.) with minute flakes of chlorite and tiny granules of magnetite.

The porphyritic quartz is clear and the crystals show the effects of corrosion in marginal embayments, scallopings and narrow channellings. Occasional aggregates of quartz enclose small plagioclase laths while there are narrow spherulitic outgrowths of quartz around a few crystals of feldspar.

The potash feldspar in the phenocrysts is represented almost equally by microperthite (including microcline-microperthite) and by orthoclase. Both occur as large, subhedral plates turbid through kaolinisation and with little or no twinning. In one

/specimen

specimen there is a thin partial rim of sodic plagioclase around a phenocryst of orthoclase. Sodic plagioclase is the dominant feldspar and has the composition of albite (An 8-11). The euhedral tabular crystals are often aggregated and show little zoning. Alteration is usually advanced and the products are kaolin, a great deal of sericite and pale green epidote. Corrosion by the groundmass is often very marked.

The occasional large flakes of brown biotite (X=greyish yellow Z=dusky brown) are often replaced by pleochroic green chlorite which also forms pseudomorphs after dark green hornblende. In a few specimens pale green epidote forms small granular and feather aggregates.

Less common are the quartz-keratophyres which consist of a dull grey groundmass with numerous microphenocrysts of feldspar, and weather to a charcoal-grey colour. Under the microscope they are seen to consist of tabular phenocrysts of slightly kaolinised sodic plagioclase (An 10-15) lying in a very fine-grained felsitic or sub-trachytic groundmass of feldspar with much interstitial quartz. In some cases this matrix has been extensively recrystallised.

The scarce rhyolites have a distinctly vitreous appearance in hand-specimen and are porphyritic, with numerous highly angular,

/"shard-

"shard-like" crystals of clear quartz, and large plates of microperthite and simply twinned sodic plagioclase, all set in a limonite-stained acid glass which shows various degrees of devitrification. Some specimens show good flow-banding and perlitic cracks which are infilled with granular green chlorite.

Rare specimens of graphic microgranite are essentially quartz-porphyrines with a groundmass of graphically intergrown quartz and feldspar.

Diorite: The rare pebbles of this rock-type are usually medium-grained (av. grain-size=1-2 mms.), equigranular, with a dark greenish grey colour weathering to pale cream. They have a characteristic scintillant sheen due to the abundance of prismatic green hornblende which, together with the less conspicuous buff-coloured plagioclase, comprises the bulk of the rock.

The plagioclase usually has the composition of oligoclase (An 12-15) and is highly kaolinised. Occasionally the lath-shaped or tabular grains are zoned from a core of andesine (An 31-33).

Hornblende forms large, subhedral prisms and irregular aggregates and is pleochroic in green (X = pale-green; Y = dark yellowish green; Z = dusky-green). Simple twinning parallel to {10

/is

is common and the $2V$ is about 75° , $\angle AC = 23^\circ$. The hornblende sometimes exhibits poor sub-ophitic relationship to the plagioclase.

Quartz is subordinate in amount and invariably interstitial. It is often crossed by arcuate, limonite-filled cracks. Long bladed crystals of biotite (X=pale yellowish brown; Z=moderate brown), partly altered to weakly pleochroic, pale green chlorite, are often associated with the hornblende.

Dolerite and "Gabbro": In hand-specimen these appear similar to the diorites but are slightly darker in colour, weathering to a dark grey, and with a shiny "felted" surface. They are generally of medium grain-size (about 1 mm.) and are designated gabbros when the average grain-size is in excess of 3 mms., although there is no significant textural difference between the two types. They carry small rods of dark-green hornblende and pale buff-coloured plagioclase. Occasional pebbles are pegmatitic (average grain-size 5-8 mms.).

Under the microscope these rocks are seen to be composed of plagioclase and green hornblende, often ophitically intergrown, with variable but minor amounts of augite, biotite and other accessories.

/The

The average composition of the plagioclase is andesine (An 30-35) but zoned crystals with rims of albite are frequently encountered. The large tabular or lath-like crystals often show very marked alteration, usually to kaolin.

The hornblende is strongly pleochroic in green and exhibits optic properties similar to those of the hornblende in the diorites. It occurs as prisms or as irregular patches and aggregates and is often partly altered to fibrous green chlorite, calcite and, rarely pale-green feathery actinolite. Occasionally there is a core of colourless augite, turbid through incipient alteration and with pale interference-colours, which grades into the hornblende in a manner highly suggestive of the derivation of the latter from the pyroxene. Grains of a brownish hornblende, with $Z\wedge C = 26^{\circ}$, are of infrequent occurrence. Brown biotite is sometimes associated with the hornblende.

Large skeletal crystals of ilmenite and smaller subhedral magnetites are abundant while interstitial quartz occurs in very minor amounts. Apatite is also abundant while prehnite, sphene and epidote are rare.

Spillite: Pebbles of this rock-type are very fine-grained, poorly porphyritic, with very small phenocrysts of clear plagioclase

/set

set in a dark grey groundmass which weathers black. Vesicles, with white or clear infilling material are a common feature of these rocks and such vesicles are often ovoid, with parallel elongation. Frequently the pebbles are highly-jointed - an original feature, apparently, as in the granites.

Microscopically the rocks consist of occasional tabular phenocrysts of albite-oligoclase (An 9-16), unzoned and slightly turbid brown through kaolinisation. These lie in a fine-grained groundmass composed of tiny laths of sodic plagioclase showing diffuse brown alteration, abundant disseminated, granular chlorite and numerous small magnetites. A little clear green epidote also occurs together with interstitial patches and aggregates of clear quartz, presumably of secondary origin. Large subhedral crystals of colourless apatite and brownish zircon are prominent accessory minerals. In occasional specimens a few small granules of colourless pyroxene and green hornblende remain unaltered, in the groundmass.

The plagioclase phenocrysts frequently exhibit "corrosion" by the groundmass along sharply defined cracks or shallow embayments and the small laths of the matrix are occasionally aligned in a crudely trachytic manner. The characteristic textures of the spilite fragments in this and all the other Groups is expressed in

/histogram

histogram form in fig. 23 and explained in more detail in Appendix A (page 17).

Frequent small amygdales are filled with chlorite, quartz and/or calcite. The fibrous chlorite is green, moderately pleochroic, often with fibroradial structure. Quartz may be crystalline or chalcedonic, usually clear or slightly turbid, with undulous extinction. Where best developed the vesicles are rimmed by quartz, followed inwards by chlorite, calcite forming the core.

Andesite: (Plate IX a and b) This occurs as small fragments less than 8 mms. in length, of a red or light-brown colour. In thin-section the andesites consist of a dark or pink glassy matrix in which are set moderately large phenocrysts of plagioclase with or without pyroxene and/or hornblende. The matrix is usually devitrified to some extent and contains tiny microlites of feldspar.

The plagioclase occurs as tabular or squarish subhedral crystals of oligoclase (An 12-20) or are frequently well zoned from a core which approximates to andesine (An 30) to a rim of oligoclase. Large flakes of kaolin and pale-green chlorite are conspicuous, especially in the calcic cores and the crystals occasionally possess diffuse edges through corrosion by the groundmass.

/Pyroxene

Pyroxene forms tabular euhedra up to 0.8 mms. long. It is faintly pleochroic in green and frequently exhibits simple {100} twinning. The optic properties are given below.

	No. of crystals	2V		Z \wedge C	
		Range	Average	Range	Average
Microscopic methods	12	48-53°	56°		
	11	-	-	40-48°	43°
Three-axis Universal Stage	4	56-61°	58°	41-44°	42°

The composition, therefore, is that of normal augite. This augite has almost universally undergone some replacement by pale-green clinochloric chlorite.

Large euhedral prisms of hornblende (up to 1.2 mms. long) display two types of pleochroic scheme. The commonest form is:

X = very pale green; Y = yellow-green; Z = light olive

but gradations occur into a form with green-brown pleochroism.

Both forms appear to have similar optics.

	No. of crystals	2V		Z \wedge C	
		Range	Average	Range	Average
Microscopic methods	12	55-68°	62°		
	12	-	-	21-28°	23°
Universal Stage	6	65-68°	66°	24-29°	26°

/This

This corresponds to a composition similar to that of common hornblende. Simple 100 twins are common and the crystals are sometimes poorly zoned or they may show an irregular patchiness in colour. The mineral alters readily to a pleochroic, rusty brown fibrous iddingsitic material.

Large, euhedral apatites in prisms up to 0.6 mms. long are the only important accessory minerals.

Sedimentary rocks: A complete, gradational series exists among the fragments, from "conglomerates" to mudstone and shale. Such fragments are generally rather angular and are stained red. Occasional small, highly angular chert pebbles are pale-green in colour, sometimes black, rarely jaspery. Earlier observers who remarked on the abundance of red chert in the Corsewell conglomerate have evidently confused this with the far more abundant fragments of red-stained, very fine-grained acid igneous rocks.

Metamorphic rocks: Occasional small boulders and pebbles are amphibolites or, more correctly, hornblende-granulites, and are very dark green in colour. They are fine-grained with a granular, dull matt appearance on a fresh surface. Very occasional porphyroblasts of feldspar attain a length of 1 mm.

/Such

Such rocks consist of a decussate groundmass of plagioclase and green hornblende, with occasional, larger xenocrystic aggregates of hornblende. The small, tabular plagioclase crystals are andesine in composition (An 30-35), slightly zoned to a more sodic rim, and are highly kaolinised. The hornblende is strongly pleochroic in green and is optically equivalent to the amphibole in the dolerite-fragments. Small magnetites are scattered randomly throughout the rock and there is a little interstitial quartz.

Low-grade schists and phyllites, containing mica and chlorite, occur sparingly among the small fragments together with the quartzites and vein-quartz. These fragments will be more fully described in the next sub-section (IIIB).

In their general lithology and in their detailed petrography the rudsaceous rocks of the Corsewall Group are closely comparable with the Finnarts and Glen App conglomerates (Walton, 1956b). The compositional similarities are well illustrated by comparing Walton's fig. 2 with figs. 8 and 9. Moreover the petrography of rock-fragments from the three conglomerates is extremely similar, even in detail.

/There

There is one slight difference, however. Both the Finnarts and Glen App conglomerates contain restricted bands rich in fragments of andesite. Such bands have not been found in the Corsewall Group and it is not clear whether this is a real and original distinction or whether their apparent absence is due to inadequate sampling by the present writer. (Such bands, apparently are not readily identified in the field.)

The conglomerates and boulder-beds of the Corsewall Group, together with the Glen App and Finnarts beds form a distinctive type of deposit which is, however, by no means unique among greywacke-type sediments. Beds with very similar characteristics have been described from several areas, in rocks of various ages.

Pettijohn (1943) in a study of Archean conglomerates in the Canadian Shield region, details many features which are duplicated in the Ordovician conglomerates.

In an account of Upper Cretaceous sandstones (=greywackes) from the Diablo Range, California, Briggs (1953, pp. 422-423; 433 ff.) describes conglomerates with lithological characteristics very similar to those of the Archean and Ordovician beds.

A further point of considerable interest in this connection is the remarkable degree of correspondence in the overall composition of these conglomerates. This is indicated in the following table which gives the percentage composition of the pebbles and boulders in each conglomeratic formation.

/Archean

	<u>Archean</u>	<u>U. Cretaceous</u>	<u>Ordovician</u>
	Pettijohn, 1943	Briggs, 1953	Kelling
Plutonic (Granites)	30	18	29
Acid volcanic, hypabyssal	15)	10)	30)
Basic volcanic, hypabyssal	57 42)	58 48)	59 29)
Sediments	9	13	6
Metamorphics	4	10	5

While no deduction based on only these three examples can be regarded as axiomatic, it seems that there are two major points of resemblance between these conglomerates. There is first of all the uniformity of the lithological characteristics of these beds which may legitimately be adduced as evidence for the similarity of their depositional environment. Secondly there is the correspondence in composition which may be related to parallelism in the tectonic environment prevailing during the deposition of these beds. Whether this parallelism is coincidental or of wider significance can only be determined by comparing the composition of many such beds.

Kirkcolm Group. True rudaceous rocks are rarely found in this Group, but the greywackes are often pebbly and they frequently contain discrete bands of pebbles. However such fragments rarely exceed a few millimetres in size and are usually composed of greenish spilite, chert, fine-grained acid rocks and dark shales.

One band of conglomerate occurs in a sequence of thin-bedded greywackes of the Lower Barren division in the Portslogan coastal section. On its south side this bed is faulted against the northernmost band of black shales in the section, in the cliff about 60 yards south of Cave Ochtree Point.

The bed is about three feet thick and unlaminated, with sharp upper and lower junctions against the greywackes. The material of the conglomerate is ungraded and poorly sorted and consists of numerous sub-rounded boulders, cobbles and pebbles, up to 12 inches in maximum diameter, embedded in a coarse-grained greywacke matrix.

Boulders and pebbles are very assorted as to size but nearly homogeneous in composition. The majority of them, large and small, are composed of coarse-grained greywacke, with only a few, smaller subangular pebbles of amygdaloidal spilite and occasional small chips of greenish chert. Under the microscope the matrix is seen to consist of a poorly sorted greywacke with numerous fragments of chert, some wisps of black shale, angular pieces of amygdaloidal spilite and small fragments of phyllites and schists. Quartz is abundant and there is a little plagioclase and a few detrital flakes of mica. The rock is cut by numerous veins of a brownish carbonate which often carry magnetite and pyrite, and there

/is

is clear evidence of local cataclasis in the granulation of some quartz grains. This conglomerate must be very impersistent since it is lacking from the next exposure of this black shale sequence, some 200 yards to the south.

At Dove Cave, about a quarter of a mile south of the locality described above, in greywackes of the Metamorphic division, there are good exposures on the shore of a peculiar type of conglomerate, designated "honeycomb-rock" (Plate VIIIb).

This comprises a number of thick (5-15 ft. plus), poorly stratified beds of highly quartzose, fairly coarse-grained greywacke which contain very numerous boulders and pebbles (up to 16 inches in diameter) mainly of a greywacke, which is calcareous. The boulders have weathered out preferentially, leaving ovoid hollows. They are generally ovoid in shape and appear to lie lengthwise parallel with the steeply inclined bedding. Most of the greywacke boulders are finer in grain than the matrix, but a few, which are more resistant to weathering, are equally coarse. Besides the greywackes, there are a number of small boulders and streaks or lenses of fissile siltstone and of dark blue mudstone in the conglomerate. Isolated boulders of fine-grained, calcareous greywacke also occur in the beds of massive greywacke with thin siltstone partings which separate the conglomeratic bands. Scour-and-fill and other erosional structures occur at

/the

the base of the coarser bands.

In thin-section the greywacke of the boulders is found to be a quartzose greywacke rich in low-grade metamorphic fragments and very similar to the matrix greywacke. However, the latter is non-calcareous, of coarser grain-size and contains appreciably less detrital mica. The boundary between boulder and matrix is nevertheless rather obscure. There is much evidence of cataclasis in the matrix greywacke, particularly along well-defined shear-zones and the matrix is cut by a number of small veinlets containing a carbonate which is generally colourless, unlike the interstitial carbonate of the boulders which is usually a buff-coloured variety, possibly sideritic in composition.

The difference in grain-size between boulders and matrix, the presence of greywacke boulders in the interbedded greywacke-siltstones and the occurrence in the conglomerates of pebbles of siltstone and mudstone all point to the conclusion that the rudaceous appearance of the rock is not a segregation phenomenon - it was originally conglomeratic.

However the problem of the origin and time of formation of the carbonate still remains. It is not inconceivable that the interstitial carbonate of the boulders is a secondary cement introduced either during consolidation or during the period of stress which produced the cataclastic effects shown in the matrix.

/However

However, several factors militate against this hypothesis.

First the inhomogeneity of the greywacke boulders. Had all the boulders been of similar grain-size it would have been possible to invoke preferential segregation of the carbonate according to grain-size but although many of the calcareous boulders are finer in grain than the matrix, some are as coarse, or even coarser, which appears to rule out any grain-size / segregation relationship. Moreover there are a very few greywacke boulders in the conglomerate which are of similar grain-size to the others yet are non-calcareous

furthermore, the amount of carbonate in the boulder-greywackes is remarkably high. In many cases most of the detrital grains are not in contact. Replacement (of siliceous material) on this scale seems unlikely and it is difficult to envisage any process of secondary interstitial cementation that would expand the greywacke so as to separate the detrital grains without leaving any evidence of this expansive effort in the surrounding matrix-greywacke.

As a consequence of this it is believed that there must have been concomitant deposition of the carbonate cement and the clastic material, eventually producing a calcareous greywacke similar to those now exposed near Kennedy's Pass, Girvan. Subsequently (perhaps pene-contemporaneously, in view of the close petrographic similarity of boulder and matrix greywacke) this calcareous

/greywacke

greywacke was eroded, forming poorly rounded boulders, and deposited, together with pebbles of non-calcareous greywacke, siltstone and mudstone, in a matrix of non-calcareous, coarse-grained greywacke. There may have been a limited amount of mobilisation of the carbonate at a later date, which has obscured the matrix-boulder boundaries.

B. PETROGRAPHY OF THE GREYWACKES

In this thesis the term greywacke is applied to dark well-indurated arenaceous rocks which are usually poorly sorted with much interstitial argillaceous material. In this context the nature of the component grains is not definitive.

Rock-fragments: In every Group rock-fragments tend to be the dominant constituents of the coarse-grained greywackes but are much less abundant in rocks of finer grain. The aggregate suite of fragments present in each Group is fairly wide, comprising igneous (acid, basic and intermediate), metamorphic and sedimentary rock-types. The total of these suites is tabulated below and the relative proportions of the main rock-classes present as fragments in each of the formations are indicated in Tables IV and VII.

/Granite

<u>Igneous</u>	<u>Metamorphic</u>	<u>Sedimentary</u>
Granite, granodiorite	Quartzites	Greywackes
Quartz-porphyrries	Phyllites	Siltstones
Rhyolites	Mica-schists	Shales
Keratophyres	Chlorite-schist	Limestone
Diorites	K Graphite-schist	Cherts
Andesites	K Andalusite-schist	Black shale
Spilites, variolite	Garnet-mica-schist	G Green shale
Dolerite, "Gabbro"	K Garnet-talc-schist	K Arkose
Serpentine	Glaucophane-schist	
Tuffs, acid and basic	P Tremolite-schist	
"Porphyrites"	Cataclasites	
	Gneissose rocks	
	Epidosite	
	Hornblende-granulite	
	P Pyroxene-granulite	
	Hornfelses	

In the list above, rock-types which are prefixed by a letter are confined to the particular Group indicated by the letter; (K stands for Kirkcolm Group, P for Portpatrick and G for Galdenoch).

Many of the rock-types have already been described in the section on the Conglomerates. Those which are peculiar to the sub-rudaceous rocks will now be described.

Serpentine, which occurs in the Corsewall and Portpatrick Groups, forms rounded fragments up to 2 mm. long and consists of a felted or fibrous mass of pale-green serpentinous minerals with acicular tremolite, and relict masses of colourless clinopyroxene and of brown isotropic ?chromite (Plate XIa). In the Corsewall

/rocks

rocks the serpentine is frequently replaced by ochreous iddingsite.

Dolerites are particularly common in the Corsewall rocks but are also found in the Portpatrick (including Galdenoch) greywackes. They normally contain ophitic hornblende which is green in the Corsewall rocks and usually brown in the Portpatrick Group. However, the dolerites in the Portpatrick greywackes often carry clinopyroxene, either fresh or uralitised.

Spilites are particularly common in the rocks of all Groups but are conspicuous in the Kirkcolm rocks where they are virtually the only basic fragment. In this Group, too, variolitic textures are best developed (Plate XIb). Many spilites in the Portpatrick greywackes contain fresh, pale green clinopyroxene, occurring either as phenocrysts or as small granules in the groundmass.

Dioritic fragments are scarce in all Groups but andesites are relatively abundant and are especially characteristic of the Portpatrick Group. In these rocks andesite-fragments may comprise up to 30% of the total fragments and range in size from large (2.5 mm.) to very small (0.05 mm.) (Plate XIIa and XIIb). Several types may be distinguished, depending on the type of porphyritic ferromagnesian mineral(s) occurring with the plagioclase phenocryst. In general these andesites closely resemble those of the Corsewall rocks, previously described, but differ in the following points:

/(1) The

(i) The porphyritic hornblende in the Portpatrick andesites is often dark olive or brown while that of the Corsewall andesites is green. These brown hornblendes are often partly resorbed with a broad, diffuse, rusty-brown reaction rim.

(ii) Very pale green augite occurs in the andesite-fragments from both Groups but intense reddish brown reaction-rims are usually encountered around the augite of the Portpatrick andesites.

(iii) The feldspar of the Portpatrick andesites is invariably very altered, to a much greater degree than the plagioclase of the Corsewall andesites.

(iv) Accessory apatites are large and abundant in andesite-fragments from the Corsewall rocks, but small and rare in the Portpatrick andesites.

Many of the andesites in the Portpatrick Group appear to be tuffaceous or, perhaps, auto-brecciated and the general shape of the fragments is extremely angular (fig. 10) in contrast to the moderately rounded grains of acid igneous rocks. Part of this apparent angularity may be ascribed to "impressing" of the adjacent mineral grains. Similarly, the andesite-fragments in the Corsewall Group are extremely angular (fig. 11) but the occasional pieces of andesite which occur in the Kirkcolm rocks, containing chloritic or biotitic pseudomorphs of hornblende, are much better rounded.

In the rocks of the Kirkcolm and Portpatrick Groups there occur numerous fragments of a rock of rather doubtful affinities, here termed "porphyrite" (Plate XIIIa). It is intermediate in

/character

character between true andesite and quartz-porphyry, consisting of a red-stained microcrystalline groundmass of quartz and feldspar with numerous large tabular phenocrysts of sodic plagioclase which shows complex twinning, and anhedral porphyritic orthoclase. The rock contains pseudomorphs of biotite and possibly hornblende and is rich in accessory apatite.

Of the acid igneous rock-fragments, quartz-porphyry of almost unvarying character, is clearly the most abundant variety. Rhyolitic fragments are often flow-banded and may carry phenocrysts of quartz and albite while the abundant keratophyres and quartz-keratophyres usually show excellent trachytic flow-texture. Granites and granodiorite normally carry microperthite in place of orthoclase and occasionally show granophyric intergrowth.

Pyroclastic rock-fragments are never common and are most abundant in the rocks of the Portpatrick Group. In these rocks the spilitic and andesitic tuffs are fine-grained and much scarcer than the rhyolitic acid tuffs. The latter fragments contain large pieces of quartz embedded in a greenish quartzo-feldspathic ash while the presence of appreciable amounts of argillaceous material and numerous ragged flakes of detrital brown biotite betray the water-laid nature of the tuff.

/The

The Kirkcolm Group in general and the Metamorphic division in particular contain the highest proportion and the greatest variety of metamorphic rock-fragments (Plate XIIIb) but similar fragments occur sparingly in the other Groups.

The metamorphic rock-type of most abundance in the fragments is undoubtedly quartzite. This is often extremely difficult to distinguish from vein-quartz and in fact the name has been restricted to those fragments consisting largely of granoblastic quartz with some pale green chlorite or muscovite growing round the sutured margins of the quartz. Trains of inclusions are often continuous across such margins which is, apparently, a common feature of low-grade metamorphic rocks.

Fragments of quartzo-feldspathic chlorite- and muscovite-schists and phyllites are ubiquitous in their occurrence and are especially common in the Kirkcolm rocks in which, also, there occurs the much rarer graphitic schist, which consists of elongate granular quartz with disseminated long flakes of black opaque material with a metallic lustre in reflected light. Garnetiferous muscovite-schists are common in the Kirkcolm and Portpatrick rocks (Plate XIVa, b) but a much rarer variety, in which the muscovite is replaced by what appears to be talc, forming large feathery aggregates, is confined to the Kirkcolm Group. The few fragments

/of

of andalusite-schist have come from rocks of the Metamorphic division. In these schistose quartz with flakes of chlorite and muscovite show fluxion-structure round porphyroblasts of andalusite which are grey-green, non-pleochroic with crudely rectangular form and prismatic cleavage. The andalusite interdigitates with the groundmass, is riddled with minute quartz inclusions and is slightly altered marginally.

The most interesting of the schistose fragments are the rare glaucophane-schists. These consist of rods and needles of glaucophane, (or a sodic hornblende derivative) with prisms of colourless epidote, set in a fine-grained quartzo-sericitic matrix (Plate XVa). The optics of the glaucophane and its alteration-product are described below, in the section on heavy minerals, but it may be stated here that the glaucophane is abnormal since the extinction angle, γ/C is $10-13^\circ$. Fragments of this rock are very rare but widely distributed throughout each Group.

Fragments of cataclasite are frequently encountered in the rocks of all the formations studied and are conspicuously abundant at some horizons in the Fortpatrick Group. Commonly they are highly shattered and sheared acid igneous rocks (Plate XVb), granites and microgranites in many of which quartzo-feldspathic fragmental detritus "flows" round porphyroclasts of resistant quartz and

/feldspar

feldspar (Plate XVIa). Occasional spilitic and arenaceous sedimentary cataclasites are also found.

Rather rare fragments of gneissose character are found in the rocks of the Kirkcolm and Portpatrick Groups. These are coarse-grained with parallel folia of muscovite, carrying large colourless sieve-garnets, alternating with quartzo-feldspathic layers. Some of the so-called quartzites with elongate quartz grains and parallel rods of chlorite and flakes of muscovite may have been derived from the quartz-rich layers of such gneisses.

Rare fragments, occurring in all the Groups, are considered to be epidiosites. These are composed of granular pale-green epidote and clear quartz with decussate texture, carrying a few small laths of kaolinised plagioclase and very rare composite grains of a green amphibole, probably hornblende (Plate XVIb).

Fragments of hornblende granulite are uncommon and the rock is similar to that found as pebbles in the conglomerates (see p. 73). The few pieces of an interesting pyroxene granulite are confined to the Portpatrick (Basic) Group. This rock comprises a granoblastic mosaic of slightly kaolinised, untwinned plagioclase (R.I. greater than balsam) with tiny granules of colourless pyroxene, greenish epidote and brown rutile scattered evenly throughout the feldspar. This is probably a thermally metamorphosed dolerite.

Of the fragments of sedimentary rocks, the most abundant are members of the greywacke-siltstone suite. In the Portpatrick Group fragments of greywacke and siltstone contain detrital grains of unaltered ferromagnesian minerals and are very similar to the analogous Portpatrick rocks. In the Kirkcolm rocks there are a few pieces of a poorly-sorted, coarse arkosic sandstone which carries plagioclase, microcline and a little argillaceous cement.

Fragments of chert are of general occurrence but are particularly abundant in the Kirkcolm rocks. These cherts may be colourless, greenish, or various shades of pale brown and often contain pyrite cubes and traces of radiolarian tests. Small ragged and twisted pieces of black shale are a common adjunct of the cherts. Occasional, poorly rounded fragments consist of granular colourless carbonate (probably calcite) which contains occasional small grains of clear detrital quartz and a few rounded magnetites (Plate XVIIa). Such pieces are probably derived from a limestone. As with the andesites, adjacent harder grains and fragments are frequently pressed into the softer fragments of sedimentary rocks.

An interesting feature of these rocks is the frequent association of fragments of fresh and altered rocks in a single thin-section of greywacke. Not only do fragments of different rock-types differ

/widely

widely in the extent of alteration but pieces of the same rock-type may exhibit various degrees of alteration. In this respect the andesite-fragments of the Portpatrick Group are outstanding since they uniformly present a "weathered" aspect due to the highly altered state of the feldspar, even where the ferromagnesian minerals remain fresh. In general, the more basic rock-fragments appear to have suffered most alteration. It seems clear that in every Group the disparity in the degree of alteration of the fragments indicates that the rocks were already altered to a varying degree before incorporation in the greywackes.

Petrographic divisions have been erected within the Groups largely on the basis of the different proportions of various types of rock-fragment. Thus, in the Portpatrick Group Acid and Basic divisions have been recognised, defined by the ratio of acid to basic igneous rock-fragments.

Three divisions are present in the Kirkcolm Group. Two of these, the Lower Barren and the Upper Barren divisions are petrographically similar whereas the greywackes of the intervening Metamorphic division possess distinctive characteristics, notably a high proportion of metamorphic rock-fragments.

Mineral Grains:

/quartz

quartz: Save in the Basic division of the Portpatrick Group, quartz is the most abundant of the detrital mineral grains and is the dominant constituent of the greywackes of finer grain. It occurs as angular or sub-angular grains or, rarely as rounded grains, variable in size from about 3 mm. downwards although in the Basic division the size-range appears to be almost restricted to between 1.5 and 0.5 mm. Many grains are sutured and show undulous extinction and there is a conspicuously high proportion of such grains in the Kirkcolm rocks. A few such grains, in the rock of the Metamorphic division have deformation-lamellae typical of high-grade dynamic metamorphism (Fairbairn, 1949, pp. 13-14). Detrital quartz grains in Corsewall rocks frequently show curved cracks, filled with ochreous limonite.

These grains are usually fairly clear, but with numerous minute inclusions which may be scattered randomly throughout the grain or concentrated into narrow bands, some of which appear to be parallel to crystal faces. However, in the Metamorphic division and to a lesser extent in the rest of the Kirkcolm Group and the Portpatrick Group, many of the quartz grains are conspicuously turbid due to the presence of innumerable, scattered tiny globules and minute indeterminable inclusions. Among these is a colourless mineral which has a refractive index lower than that of quartz, low birefringence, crudely rectangular form, and forms crystals which

/are

are slightly larger than the associated inclusions. This may be some type of clay-mineral.

An examination was undertaken of the inclusions in detrital grains of quartz from rocks of all the formations studied and the inclusions were assigned to the classes of Mackie (1896), modified by Keller and Littlefield (1950), namely:

- (i) Regular (R) - large inclusions of regular rock-forming minerals, in this case mainly chlorite, epidote, biotite and opaque minerals.
- (ii) Irregular (I) - small inclusions of minerals which are usually indeterminable.
- (iii) Globular (G) - gas or fluid bubbles of small or moderate size.
- (iv) Acicular (A) - needle-like crystals of rutile, apatite etc.

Since the object of the examination was to indicate the probable provenance of the quartz in the greywackes of each division and Group it was considered advisable, in order to obtain a reasonable average for the formation, to count only a relatively small number of grains from several thin-sections of rocks representing several horizons and several outcrops in the division. In fact, about 50 grains were counted in each of six thin-sections from each formation, being all the quartz grains present in a number of short random traverses. Some grains contain inclusions of more than one type, in conspicuous amounts, and in such cases the grain was allotted to each of the classes present.

The results of these counts, shown in fig. 12, indicate that in general Irregular inclusions are the most abundant, followed by the Globular variety. An almost uniform proportion of Regular inclusions is maintained in all formations except the Metamorphic and U. Barren divisions of the Kirkcolm Group where there is a marked increase in this class (Plate XIXa). Acicular inclusions are, on the whole, rather uncommon.

Many of the quartz grains have fritted edges due to marginal "corrosion" by the chloritic interstitial material (Plate XIXb). Minute needles of a very pale green chloritic material penetrate from the groundmass into the grains, the needles growing at right angles to the margin of the quartz (fig. 13).

Feldspar: Detrital feldspar is common in all the rocks observed, is a prominent component in the Corsewall and the Portpatrick (Acid) rocks and is the dominant mineral in the Basic division. Plagioclase is almost invariably the most abundant variety, followed by microperthite with minor amounts of pure orthoclase and rare grains of microcline.

In the Portpatrick rocks the plagioclase is of two kinds. These may occur together in the same greywacke but the relative proportions of each are rather different in the two divisions. The first type is relatively fresh, turbid brown with obscure albit

/twinning

twinning and forms large angular and tabular plates. The average composition is sodic, around An 10, and only slightly variable. This form is dominant in the rocks of the Acid division and is believed to be derived from acid igneous rocks. The smaller, broken laths of the second type are normally very altered, so much so that exact determination of the composition is extremely difficult. However it appears that in this case the composition is also sodic, about An 15, but many grains are zoned from a sodic margin to a core approximating to andesine. This variety is particularly abundant in the Basic division and is clearly comparable with the plagioclase of the andesite-fragments, whence, presumably, it has been derived.

In the other Groups large angular and equant grains of turbid brown sodic plagioclase similar to the first type described above, are conspicuous. For example, in the Corsewall Group the plagioclase occurs as tabular grains of moderate size. The composition ranges from An 5 - An 20, the average lying in the albite range, about An 8 (RI < balsam; $2V=80^{\circ}-85^{\circ}$, average of 16 is 81.5° ; sym. extinction angle on albite twins = $2-17^{\circ}$, average of 18 is 13.8°). However, these grains are often zoned from a sodic rim to a highly altered calcic core, ranging up to labradorite in composition. The plagioclase is commonly sericitised and is occasionally altered

/to

to a pale green epidote.

In rocks of all Groups the microperthite occurs as large equant, angular grains which are mottled turbid brown. Locally in the Kirkcolm and Portpatrick (Acid) Groups this potash feldspar may predominate over plagioclase.

Microcline is very rare and occurs as small, water-clear, highly angular grains.

Ferromagnesian minerals: Detrital grains of these minerals, usually fresh, sometimes as pseudomorphs, are abundant constituents of the Corsewall and Portpatrick rocks but are virtually absent from the Kirkcolm Group, apart from tiny scraps of actinolite and glaucophane. Pyroxenes, amphiboles and epidotes are the only species observed and vary from Group to Group in relative aggregate abundance. Thus pyroxene is dominant among the detrital ferromagnesian minerals of the Portpatrick rocks while hornblende is the most abundant species in the Corsewall Group. However, the relative proportions of these species varies even in different greywackes of the same Group.

Pyroxene: A monoclinic form, nearly colourless or weakly pleochroic in pale green in the Corsewall rocks, yellow-green or pale brown in the Portpatrick, is the commonest variety of pyroxene. It occurs in angular prismatic or tabular grains, occasionally in well-rounded grains and shows good prismatic cleavage. These

/grains

grains are always biaxial positive and show simple {100} and polysynthetic {001} twins. Further optic properties are listed below.

	No. of grains	2V Range	2V Average	ZAC Range	ZAC Average	n_{α} Average	n_{γ} Average
Microscopic methods	(45	40-65°	57.3°	33-46°	41.4°	1.682	1.706
	(57						
	(9						
Universal Stage	10	56-62°	59.3°	40-45°	43.5°	-	-

The composition is therefore similar to normal augite.

In the Portpatrick Group there occurs a second variety of detrital pyroxene, similar to that just described but with a uniformly low 2V (20-40°) and low extinction angle ($ZAC = 30-35^{\circ}$).

The normal alteration product of the augite is a pale green chlorite with moderate birefringence but in the Portpatrick Group occasional augites have altered to a peculiar smoky blue chlorite with very low birefringence. Some grains of augite in these Portpatrick rocks, are mantled by a diffuse, poorly pleochroic brown material which also forms a rim round many hornblende grains.

Amphibole: Hornblende, which may be strongly pleochroic in green or in brown or in green and turquoise shades, is the commonest amphibole. Normally, all these varieties may be found in one greywacke but the brown variety is scarce in Corsewall rocks

/and

and dominant in the Portpatrick Group. The grains are usually prismatic or tabular, and angular, showing good prismatic cleavage. Twinning parallel to {100} is common. The mineral is biaxial negative, rarely positive and further optic details are listed below.

	No. of grains	2V Range	2V Average	ZAC Range	ZAC Average	$n\alpha$ Average	$n\gamma$ Average
Microscopic methods	(35 32 6)	55-80°	68°	21-26°	24°	1.662	1.691
Universal Stage	10	58-65°	62°	25-28°	27°		

This hornblende is more resistant to weathering than the augite but is sometimes altered to pale green fibrous actinolite, which also occurs, together with fresh or altered glaucophane, as tiny shreds of detrital origin.

From a comparison with the ferromagnesian minerals in the rock-fragments, it seems probable that most of the detrital augite and hornblende originated in the basic and intermediate rocks, mainly dolerites and spilites in the case of the Corsewall rocks, andesites in the case of the Portpatrick rocks.

Epidote: This is an abundant ferromagnesian constituent of these greywackes and usually occurs as angular prismatic or fairly rounded composite grains which may be colourless, pale limpid

/green

green or turbid brown. Irregular cracks are often conspicuous. Occasional colourless prismatic grains with low birefringence and positive optic sign, probably clinozoisite, are confined to the Portpatrick rocks.

Olivine: Rare serpentinous pseudomorphs of this mineral occur in the Corsewall Group. These are angular and show the characteristic shape and cross-cracks of that mineral (Plate XXa).

Mica: Detrital mica is ubiquitous in these greywackes and attains considerable abundance in the Kirkcolm Group. In this Group large, rather broad "crinkly" flakes of colourless muscovite (sometimes with a faint yellow tinge) are particularly common. Other flakes of colourless mica are broad, rather rounded and carry numerous tiny elongate granules of opaque minerals which are aligned along the cleavage-planes. Muscovite of this type is found in many of the schist-fragments and evidently originated in metamorphic rocks. Some micaceous material with a faint greenish tinge and low birefringence, which occurs in small narrow wisps and stringers and often wraps round detrital grains, may be a clay-mica of detrital origin.

Biotite is the commoner variety of mica in Corsewall rocks and here it is invariably pleochroic in brown:

yellow-brown or pale-brown (Δ) to dark olive or
nigger-brown (Σ).

In the Kirkcolm Group brown and green varieties of biotite are equally abundant while a strongly pleochroic reddish brown type is common in the Portpatrick Group. The short, stubby flakes are often twisted and are frequently "bleached" to a neutral tint. Alteration to a pale green clinochloric mineral is also widespread. An apparently authigenic form of biotite which is found in the Kirkcolm greywackes occurs as small wisps and larger, roughly fusiform flakes. The mineral is weakly pleochroic from colourless to pale brown and is characterised by the presence of innumerable tiny acicular crystals of an indeterminate mineral which are aligned in bands parallel to the length of the flake.

Chlorite: This mineral is found in every Group pseudomorphing the ferromagnesian minerals and detrital flakes are also ubiquitous, but the amount is variable from Group to Group. The Kirkcolm and Corsewall rocks are particularly rich in detrital chlorite, which forms small ragged flakes and sub-angular grains. A yellow-green clinochloric variety is characteristic of the Corsewall greywackes while a dark green penninitic type, with Berlin blue interference-colours, is dominant in the Metamorphic division.

Opaque minerals: Ilmenite, forming leucoxene-coated sub-rounded grains, is the most abundant of the detrital opaque mineral.

/followed

followed by euhedral and spheroidal pyrite which appears to be largely of authigenic origin. Magnetite occurs as occasional angular octahedra, often coated with haematite and also as authigenic euhedra. Leucoxene forms an ubiquitous if inconspicuous stain in the greywackes from all Groups. The reddened greywackes of the Corsewall Group are stained by a mineral which is semi-translucent reddish-brown in transmitted light and variable from ochreous to bright red-brown in reflected light. This material, which is probably limonite, also occurs as minute scales and globules in the argillaceous part of the matrix.

Matrix: Apart from a few rocks in which large "pebbles", (grains greater than 1 mm.) are embedded in a finer groundmass of average grain size 0.2-0.3 mms. (Plate XXb), there is no discrete or separate matrix present in these greywackes: there is simply a more or less uniform gradation in the size of grains and fragments. For convenience, all material with an average grain-size below 0.01 mms. has been assigned to the "matrix". This therefore consists of comminuted mineral grains (largely quartz and feldspar with chips of ferromagnesian minerals) together with a great deal of turbid brown and colourless micaceous and chloritic material much of which is the product of recrystallisation. Turbid brown, finely granular epidote is common in the matrix of the Portpatrick /greywackes

greywackes. Also included in the matrix of the Portpatrick rocks are numerous minute particles of glassy andesite which impart a distinctive "dirty" appearance to the rock in thin-section. There is often a little clear or brownish carbonate present interstitially and in discrete veinlets. This is probably secondary in origin. It is doubtful if, in fact, any primary carbonate exists in these greywackes.

The greywackes are cut by numerous veins, mainly of quartz or of calcite, occasionally containing an opaline material. Prehnite-filled veins are characteristic of the Portpatrick Group. The quartz and calcite veins sometimes carry pyrite and/or magnetite.

Sorting: This is generally poor. It is rather better in the Corsewall greywackes, but the rocks of the Portpatrick (Basic) Group show a very pronounced lack of sorting.

In general, the petrographic character of each division and Group remains virtually unchanged throughout its outcrop. However, there is one exception to this rule. The Acid division of the Portpatrick Group undergoes certain petrographic changes when traced south, beyond Port of Spittal Bay. First, the proportion of fresh ferromagnesian minerals shows a significant decrease which is coupled with an apparent increase in the amount of quartz.

/However

However, because of the intimate quartz-veining of these rocks it is difficult to estimate what proportion of the quartz is detrital. Finally, the proportion of rock-fragments appears to show some decrease in the rocks to the south.

The Kirkcolm rocks show little petrographic variation apart from changes in the relative proportions of quartz rock-fragments and matrix which accompany a southerly decrease in grain-size.

"Pebble"-counts and micrometric-analyses
of the greywackes

In this study most attention has been concentrated on the coarser sediments since these are more amenable to microscopic examination than the fine-grained rocks. It was found that the coarse-grained greywackes from the different Groups and divisions could be distinguished with relative ease by means of their characteristic aspect, whereas the sediments of finer grain were not so readily separable. In order to give a more accurate and quantitative expression of the petrographic differences between formations a number of micrometric analyses have been made of both fine- and coarse-grained greywackes. However, since all the coarse greywackes contain numerous rock-fragments and since the petrographic distinction of the various formations is based largely on the relative proportions of the different rock-types represented

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in the fragments, a large number (78) of counts of the large fragments or "pebbles" (greater than 1 mm.) have been conducted.

Since most of these greywackes lack a distinct matrix, an arbitrary lower size-limit had to be fixed for the pebbles counted in order to achieve a degree of homogeneity in all counts. In any thin-section, therefore, all grains of 1 mm. or over were counted and the relative proportions of each rock-type present (grouped as indicated) expressed as a percentage (to the nearest half of one per cent). In practice, only those thin-sections with more than 70 pebbles were selected, although the average number of pebbles in the tabulated sections is around 100.

To simplify counting and subsequent evaluation of the results, the wide range of rock-types and minerals represented in the pebbles were divided into nine groups as follows.

Large grains of quartz and feldspar are always tolerably common in these greywackes and are sometimes abundant. Consequently it seems necessary to take account of these mineral components in any study of the pebbles. Vein-quartz, distinguished from the quartzite fragments by its lack of oriented inclusions, is added to the lithogenic quartz. In some greywackes, and particularly in those of the Kirkcolm Group, there are numerous large grains of quartz which are sutured, show undulous extinction and possess few

/large

large oriented inclusions, although they are frequently turbid through the abundance of small globular and irregular inclusions. Such grains resemble vein-quartz but the associated assemblage of rock-fragments suggests that this quartz originated in metamorphic rocks.

The Coarse Basic group comprises "gabbros", dolerites, the few dioritic rocks and the rare serpentines. All the albitised basic rocks with average grain-size less than 0.1 mm. are included in the Spillite class. The general assumption of porphyritic texture by the spillitic rocks generally serves to distinguish them from the preceding Group, even where the grain-sizes overlap. Also included in the Spillite group are those glassy igneous rocks, sometimes porphyritic, which contain a high proportion of opaque minerals and are presumably, therefore, of basic composition. Andesite was given a separate heading because it was believed that the presence or absence of this distinctive rock-type was of considerable diagnostic value.

Granitic rocks together with some coarse-grained granophyres constitute the Coarse Acid group while a variety of microgranites fall under the heading of Fine Acid group. The most abundant of these is quartz-porphyry, but graphic microgranite, keratophyres and rhyolites also occur.

/Included

Included in the Metamorphic group are such rocks as the quartzites, low-grade schists and phyllites, cataclasites of several types, garnet-bearing schists and gneissose rocks. All the sedimentary rock-types observed, including the cherts, are included in the ninth group.

For both pebble-counts and micrometric analyses the "average grain-size" was calculated as follows. On a Shand micrometer a number of random traverses were taken across the thin-section and all the grains passing under the cross-wires were registered. The total distance travelled, computed from the micrometer readings was divided by the number of grains and the resultant average intercept used as an indication of grain-size. By repeated experiment it was found that for a greywacke of moderate grain-size a count of 250 grains was sufficient to give results of reasonable consistency. Care was taken to ensure that the traverses chosen were not parallel to the bedding, since grains tend to be aligned in that direction.

There are several obvious deficiencies in this method but the results may be used for limited comparative purposes.

Throughout the succession, pebbles of spilite and of microgranite are almost equally abundant and are clearly the

/most

most abundant rock-types represented in the coarser greywackes (Table IV and Table VII). A notable exception to this rule is the Metamorphic division in which pebbles of these rock-types are much scarcer and fragments of metamorphic origin are dominant. Pebbles of metamorphic rocks are generally more abundant in the Kirkcolm Group and, to a lesser extent, the Galdenoch Group than in either of the two remaining Groups.

Large fragments of quartz are also very common in the Kirkcolm Group and comprise nearly 40% of the pebbles in the Metamorphic greywackes. In the other Groups the average proportion of quartz pebbles remains almost uniform, but is conspicuously low in the Basic division of the Portpatrick Group. An interesting relationship exists between the percentage of quartz pebbles and of Coarse Acid pebbles in these coarse greywackes. Since the grain-size is known to exercise a certain influence on the number of rock-fragments and of quartz grains (fig. 14) it is necessary to divide each percentage by the appropriate grain-size. When the ratios thus calculated are plotted against each other a bilinear scatter is obtained (lines A and B on fig. 15). It is found that most of the points scattered along line B represent rocks with more than 5% of metamorphic pebbles. In the other rocks, represented by points along line A, the percentage of large quartz grains is in direct proportion to the percentage of Coarse Acid (granitic)

/pebbles

pebbles but in those greywackes which are rich in metamorphic fragments this relationship is obscured, or rather weighted by the higher proportion of quartz, much of which is derived from metamorphic, not granitic, sources.

Pebbles of feldspar (mainly plagioclase) are not abundant and appear to be more common in the greywackes which contain numerous granitic fragments - for instance, the Corsewall and Portpatrick (Acid) Groups.

Coarse Basic pebbles are conspicuous in the Corsewall greywackes, uncommon elsewhere, while andesites characterise the Portpatrick Group, especially the Basic division, occur sporadically elsewhere but are lacking in the Metamorphic division of the Kirkcolm Group.

The proportion of granitic pebbles is high in the greywackes of the Corsewall and Portpatrick (Acid) Groups and relatively increased in the Metamorphic division.

The number of large sedimentary fragments shows considerable variation in the individual rocks but by taking the average of a number of pebble-counts it appears that the proportion is relatively constant throughout all the Groups except the Corsewall Group. This uniformity is believed to indicate that these sedimentary fragments are of little value in determining provenance, more
/especially

especially since they consist largely of greywacke-suite rocks and are probably the products of sub-aqueous local erosion.

Two ratios have been used to express differences in the relative proportions of the main rock-types present in the greywackes. The Igneous Index is the ratio obtained by dividing the total of the Coarse and Fine Acid pebbles by the total of the Coarse Basic, Spilite and Andesite pebbles. The Metamorphic Index is the ratio of metamorphic pebbles to total igneous pebbles. Such indices afford a numerical expression of the variation in source-rocks. To define the petrographic properties of a particular series of greywackes, however crudely, it is essential to use both these indices otherwise unjustified comparisons may be made. Thus, both the Metamorphic and the Acid divisions have an Igneous Index of about 2.2 which might invite comparison were it not that the respective Metamorphic indices are completely opposed, namely 0.76 and 0.05.

Reference to the table of averages, Table VII, will show that on this basis the Corsewall and Portpatrick Groups are petrographically similar, and have presumably been derived from sources with similar distribution of acid and basic igneous and metamorphic rocks, even if there is some disparity in the relative proportions of the individual (particularly basic) rock-types. However, the

/two

two divisions of the Portpatrick Group, while maintaining a similar Metamorphic index, differ radically in relative acidity or basicity. The average indices of the Kirkcolm Group indicate its pronounced acid character and its richness in metamorphic pebbles. The petrographic similarity of the Lower and Upper Barren divisions are also clearly demonstrated. The indices of the Galdenoch greywackes indicate that it is intermediate in character between the Kirkcolm Group and the Portpatrick Group but these values cannot be regarded as conclusive since they are averaged from only three specimens.

The results have been expressed in a ternary diagram (fig. 16) in which the three components are the relative percentages of metamorphic, basic igneous and acid igneous pebbles. In this diagram the Corsewall and Portpatrick greywackes are scattered along the Basic-Acid base-line with the Corsewall rocks more or less clustered around the 50% point while the Portpatrick Group has a much wider "spread", enabling separation into the two divisions.

The Kirkcolm Group occupies a wide field extending towards the Metamorphic apex. The rocks of the Metamorphic division are scattered throughout the sector with more than 20% of metamorphic pebbles and possess a nearly constant Basic-Acid ratio. The Lower and Upper Barren divisions, on the other hand, possess a fairly uniform metamorphic percentage but are intermixed. The greywackes

of the Galdenoch Group do not appear to form a distinct field but are evidently intermediate in composition between the Kirkcolm and Portpatrick Groups.

A total of 77 micrometric analyses were carried out on the greywackes: 44 on the coarse-grained rocks and 33 on the fine-grained greywackes (av. grain-size less than 0.25 mms.) The analyses were conducted on a Swift point-counting stage and in each case about 1,000 grains were counted. The number of components was restricted to eight by the apparatus and comprise the following rock-types and minerals: the four types of rock-fragment (basic igneous, acid igneous, metamorphic and sedimentary) detrital quartz, detrital feldspar, detrital ferromagnesian minerals (augite, hornblende, epidote, and including undoubted pseudomorphs) and the matrix, which includes all grains under 0.01 mms. together with detrital chlorite, micas and opaque minerals.

This choice of components is partly arbitrary but it is thought to be that which best enables comparison of the composition of the greywackes studied. It also allows comparison with the pebble-counts.

Only a moderate degree of accuracy can be claimed for these analyses largely because of uncertainty in the identification of

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very small and badly altered grains and also because of the hazy outlines of many grains due to corrosion by the matrix.

The "pebble-content" of all the coarse-grained greywackes selected for micrometric analysis had already been determined, consequently in these rocks only the grains below 1 mm. in diameter were counted, although a note was made of the volume of pebbles present and a ratio was estimated of "matrix" to "pebbles", i.e. grains of less than 1 mm. to grains more than 1 mm. This "volume-proportion" of pebbles is not strictly comparable with the "number-proportion" of the pebble-counts but there seems to be no direct relationship between pebble-size and rock-type so that in this case volume percentage may be regarded as roughly equivalent to number percentage.

Table V gives the results of the micrometric analyses of the coarse-grained greywackes while Table VIII shows the averages of such analyses in all the formations studied. The equivalent results and averages of the analyses of fine-grained greywackes are presented in Table VI and Table IX respectively.

In broad outline these results follow the general pattern of the pebble-counts. Thus quartz, which is usually the dominant component of these lower size-grades, shows a distribution similar to that in the pebbles. The Kirkcolm Group greywackes are rich

/in

in quartz, especially those of the Metamorphic division, although this distinction is lost in the fine-grained rocks. The basic division of the Portpatrick Group is again deficient in quartz but is particularly rich in small grains of feldspar (andesitic plagioclase) and the Corsewall and Portpatrick (Acid) rocks are also highly feldspathic. Detrital ferromagnesian minerals are virtually confined to the Corsewall, Galdenoch and Portpatrick rocks and the proportion ranges from 5-15%, exceptionally 20%.

The rock-fragments can best be dealt with by means of the ratio of acid to basic fragments and the ratio of metamorphic to total igneous fragments; these ratios are respectively equivalent to the Igneous and Metamorphic indices. These indices have been calculated as averages for each formation (Table VIII and Table IX).

In general it may be stated that in the coarse greywackes, compared with the pebble-counts there is a slight but nearly uniform diminution in the value for the Igneous Index, with the exception of the Galdenoch Group which shows a pronounced increase in acidity. The Portpatrick (Basic) greywackes are noteworthy for the high percentage of small basic fragments they contain.

This trend towards basicity is reversed in the fine-grained greywackes where the Igneous Index again rises, due to the increase in the proportion of acid fragments.

On the other hand, the Metamorphic Indices obtained from the micrometric analyses show only a very slight decrease on those calculated from pebble-counts except in the Metamorphic division where there is a very notable decline in the number of metamorphic fragments.

Another ratio of considerable value in these analyses is the Maturity Index. In normal sandstones the quartz-to-feldspar ratio is taken as a measure of maturity since these are the dominant representatives of the stable and unstable minerals, respectively (Pettijohn, 1949, pp. 382-383). However, in the greywackes almost all the other grains except quartz are essentially unstable and therefore the equivalent ratio is quartz-to-other grains (but exclusive of the matrix) (cf. Walton, 1955).

The Maturity Indices of both fine- and coarse-grained greywackes are virtually identical and show considerable variation in different formations (Tables VIII and IX). The index is a measure of the degree of alteration suffered by the material of the greywacke during erosion and transportation and it is clear from the values given that the role of disintegration and alteration in determining the composition of these Ordovician rocks must have been very small. It is apparent that the variations in petrography of these greywackes are more closely related to differences in source-rocks than to variable alteration of the derived material, although the latter factor may have played a larger part in the production

of the Kirkcolm Group greywackes than in the others (cf. Walton, 1955, p. 348).

While the Igneous and Metamorphic Indices vary slightly with grain-size, the relative values for different formations remain remarkably constant and evidently provide a reliable means for expressing petrographic differences. However, such differences can probably best be expressed by means of ternary diagrams, such as figs. 17-19. In these the three components used are: the matrix with sedimentary fragments; detrital quartz with acid and metamorphic fragments; and detrital feldspar with augite, hornblende and basic fragments.

Fig. 17 illustrates the total composition of the coarse-grained greywackes, obtained by amalgamation of pebble-counts with the appropriate micrometric analyses on the basis of the "matrix" - to "pebbles" ratio. It will be seen that the greywackes of the Corsewall Group fall into a roughly triangular field based on the central part of the "Acid-Basic" base-line and with a consistently low proportion of matrix. The Kirkcolm Group have a rather wide distribution with the Metamorphic division well defined but the two Barren divisions are thoroughly intermixed. Greywackes of the Portpatrick Group are confined to a narrow zone which crosses the diagram diagonally. The Galdenoch Group again appears intermediate
/between

between the Kirkcolm (Upper Barren) and the Portpatrick (Acid) Groups.

The composition of the coarse greywackes (less the pebbles) is illustrated by fig. 18. The general distribution is similar to that shown in the preceding fig. 17 but the definition of each formation is not so clear nor so restricted. The composition of the fine-grained greywackes, indicated in fig. 19, is rather more variable than that of the coarser varieties while the distinction between Groups is ill-defined but still appreciable.

The variation, illustrated by the Igneous and Metamorphic Index, in the differing proportions of fragmental rock-types with decrease in average grain-size is remarkably constant throughout the various formations and indicates that, in general, basic fragments are relatively more common in the size-grades between 1 mm. and 0.25 mms. whereas acid fragments dominate in the finest grades. There is also a progressive decrease in the relative proportion of metamorphic rock-fragments with decrease in grain-size.

In both coarse and fine-grained greywackes there is an inverse relationship between the proportion of matrix and the grain-size (figs. 20 and 21) but the scatter of points indicates a variable degree of sorting in rocks of similar grain-size.

/The

The conglomeratic greywackes, represented by crosses in fig. 20, appear to contain a uniformly lower proportion of matrix than other, "normal", greywackes of similar average grain-size. This may indicate that the sedimentary history of the conglomerates differs somewhat from that of the associated rocks.

The proportion of rock-fragments also decreases with grain-size in the fine-grained greywackes (fig. 14) and there appears to be a reciprocal increase in the amount of detrital quartz. This relationship, however, is obscured by the petrographic differences between the Groups.

In an account of some Silurian greywackes in Peeblesshire, E. K. Walton (1955), published a number of micrometric analyses. These are comparable, in terms of grain-size, with the greywackes of finer grain from the Rhinns. The composition of the pyroxenous greywackes appears to be rather similar to that of the Portpatrick, or better, the Galdenoch Group while the intermediate and garnetiferous greywackes are closely akin to the Barren and Metamorphic divisions, respectively. However, these Silurian greywackes appear to be slightly richer in quartz and in matrix but poorer in "basic" components than the Ordovician rocks. These relations are borne out by comparing figs. 17-19 with Walton's fig. 2 (p. 342).

The greywackes described by Pettijohn (1943, 1949) and by Briggs (1953) appear to contain more quartz, feldspar and matrix than the normal Southern Upland greywacke and fewer rock-fragments and the maturity indices are correspondingly higher. On the other hand certain Miocene greywackes described by Edwards (1947a) are closely comparable with the rocks of the Portpatrick (Basic) Group. These Tertiary greywackes are highly feldspathic and are extremely rich in basic rock-fragments, especially andesites, but carry only a few detrital grains of quartz. In almost every detail the petrography and lithological characteristics of these Miocene rocks can be matched by the Portpatrick greywackes implying similarity not only of depositional environment but of provenance.

From the fact that greywackes possessing similar textures and occurring in analogous lithological environments may differ widely in mineralogical constitution and from the evidence of the maturity indices, cited above, it appears that differences in composition are largely a reflection of differences in the provenance of the greywacke material. Subsequent changes due to alteration of the material or to deposition in differing sedimentary environments, probably play only a minor part in determining the ultimate composition of the greywacke.

Appendix ATextures of the spilitic fragments

During a study of the "microbreccias" (greywackes) of the North-Helvetic Flysch, Vuagnat (1952) classified the very abundant fragments of "andesitic" (spilitic) facies into eleven groups on the basis of their characteristic texture and on the same basis erected another six classes for the very similar albito-chloritic "diabases". These textural classes are listed below and are illustrated in fig. 22.

Fine hyalopilitic (Hf); coarse hyalopilitic (Hc)
 Fine felsitic (Ff); coarse felsitic (Fc)
 Fine pilotaxitic (Pf); coarse pilotaxitic (Pc)
 Fine fluidal hyalopilitic (HFf); coarse fluidal hyalopilitic (HFc)
 Fine trachytic (Tf); coarse trachytic (Tc)
 Intersertal (I); stellate intersertal (Ic)
 Divergent intersertal (Id); spherulitic fibroradial (SF)
 Spherulitic arborescent (SA); Hieroglyphic (DH)
 Vitrophyric (V)

Of these, all but the two pilotaxitic varieties are duplicated in the spilitic fragments present in the Ordovician greywackes of the Rhinns although the Tc texture is rarely encountered and any occurrences have consequently been added to the Tf class. A further class has been created to contain fragments of spilitic which are glassy, with minute microlites of feldspar and a great deal of disseminated opaque material but which lack phenocrysts. This texture is designated G (for groundmass) since it appears

/very

very similar to the groundmass of the vitrophyric or hyalopilitic classes. However, if the fragments are derived from rocks with these textures the phenocrysts in these rocks are much more widely-spaced than usual.

In the course of microscopic examination of the fragments in the conglomerates and coarse-grained greywackes a note was made of the texture of each spilite fragment observed, the allocation of texture being determined by comparison with Vuagnat's diagrams, reproduced in fig. 22. The total frequency of fragments in each texture-class in all the selected thin-sections was computed for each Group and histograms of these frequencies are given in fig. 23. From this diagram it is apparent that intersertal spilites are by far the most abundant variety with the fluidal hyalopilitic and arborescent spherulitic types lying in second place.

The frequency-variation in the different textural classes from Group to Group is of some interest. Thus, there is a similar distribution of textural types in the Corsewall and Kirkcolm Groups, apart from a slight increase in the SA types in the latter Group. This increase is accentuated in the Goldenoch and Portpatrick Groups which also possess a similar distribution differing from that of the previous two Groups in that the Ic clearly exceeds the Id variety. The distribution in component divisions is not indicated

in this diagram but approximates very closely to the pattern for the Group.

In the absence of any detailed information on the distribution and general frequency of these textures in spilitic lavas, the precise significance of the variation in texture of the fragments cannot be assessed. It may be that among naturally-occurring spilites the intersertal texture is most common or perhaps the illustrated distribution indicates derivation of the fragments from spilites of a specific, perhaps unique type and from a particular locality. In this connection it may be significant that most of the spilitic lavas from the Ballantrae region examined by the writer possessed an intersertal texture.

At any rate it appears that at different times similar but slightly different types of spilite were being supplied (in greater or lesser amounts - see Tables IV and VII) to the greywackes of the Rhinns.

C. PETROGRAPHY OF THE SILTSTONES AND MUDSTONES

Thin beds of lutite intervene between the greywackes and may also form thick, distinct bands. Such beds are normally composed of siltstone rather than mudstone although the proportion of mudstone tends to increase to the south in some formations, such a variation being well illustrated by the Kirkcolm Group (see p. 44).

Under the microscope, siltstones and mudstones from different Groups and divisions are distinguished with great difficulty but there are certain features which remain distinctive. For instance in those Groups where the greywackes carry detrital grains of fresh ferromagnesian minerals, the lutites often contain minute fragments of such minerals; if the arenaceous rocks of a particular formation are rich in grains of feldspar the proportion of detrital feldspar in the siltstones is unusually high. Distinctive heavy mineral grains may also be found in the argillaceous rocks. Thus abundant tiny chips of colourless apatite characterise the siltstones and mudstones of the Corsewall Group.

The microscopic characteristics of these ultra fine-grained rocks are the result of the ultimate development of those trends, already noted, which are related to decreasing grain-size in the greywackes. There appears to be no rigid distinction between the arenaceous beds and the intercalated lutites but rather a gradual

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transition in properties. Thus the lutites contain virtually no rock-fragments (with the exception of the siltstones of the Portpatrick Group which contain many minute particles of glassy andesitic rocks), a consistently high proportion of detrital quartz and much detrital mica, mainly muscovite. The proportion of dark-coloured chloritic-micaceous clayey material is always high and, of course, the amount increases with further decrease in grain-size.

This interstitial cement is usually brown or dark green in colour and is extremely fibrous. It appears to consist of very finely divided greenish chloritic material with substantial amounts of colourless sericite. Both the chlorite and sericite seem to have been recrystallised. Aggregate extinction and crystal elongation of this recrystallised material are characteristic features of many mudstones and shales.

Granules of turbid green epidote, which appear to be secondary in origin, are abundant in some siltstones while tiny globules of reddish brown hydrous iron minerals are also common. These may be evenly scattered throughout the interstitial material or, more usually, occur in thin bands and stringers which are parallel to the bedding. Detrital grains of the opaque minerals are rather uncommon but in many lutites there are numerous tiny acicular

/crystals

crystals of a pale brown mineral, probably authigenic rutile. Pyrite is generally abundant in the argillaceous rocks. As in the greywackes it occurs in the euhedral and spheroidal forms and individual globules are also very common in the chloritic matrix. This pyrite may have been derived by recrystallisation from the amorphous iron sulphide and, from the observed relationships, such a change must have occurred almost simultaneously with, or very slightly later than the recrystallisation of the matrix.

In some siltstones a colourless carbonate is abundant interstitially, taking the place of part of the clay-matrix. While no categorical statement can be made on the basis of the meagre evidence it appears that the carbonate cement is probably primary.

D. PETROGRAPHY OF THE BLACK SHALES AND CHERTS, TUFFS AND "AGGLOMERATES"

True black shales are confined to the region south of Portslogan, although films of black shale up to a millimetre thick and rendered shiny through differential movement are found in the bands of fissile mudstone further north. Normally, the black shales are not interbedded with other rock-types, except thin
/impersistent

impersistent ribs of dark chert. They are usually fissile but may be platy (laminae between 0.5 and 5 mms.) or, occasionally, blocky (laminae between 5-10 mms.). Almost invariably the shales are highly cleaved and cut by innumerable tiny veinlets, mainly of quartz.

Dense black, presumably carbonaceous, material occurs as tiny specks and granules in the argillaceous material but in such profusion that almost all of the underlying textural details are obscured. There are, however, a few sporadic detrital grains of quartz and fairly numerous lenticles and "eyes" elongate roughly parallel to the bedding of clear, very finely-divided chloritic and sericitic material. Pyrite is again very abundant and usually occurs in a globular form, separate and minute, or as long, irregularly narrow granular seams which parallel the lamination. There are also a few much larger cubes.

The cherts are almost always associated with the black shales. Characteristically the bedding of the cherts is highly irregular and lenticular, knobbly, with bands about 1-10 cms. thick separated by thin partings of soft greenish mudstone. Some of the colour differences between the cherts in the Rhinns appear to be due largely to secondary causes since cherts of a grey or a green colour have been observed to pass laterally into the black variety, the

/black

black colouration spreading outwards from joints. Black cherts may also show a lateral transition into the red cherts; in the Crailloch Burn section certain of the black cherts are mottled red in large patches. It is worthy of note that all the fragments of chert found in the greywackes and conglomerates are light-coloured - grey, green, pale red or colourless, but never black.

In thin-section, the cherts are seen to be composed of microcrystalline silica with a variable but usually small proportion of clastic material - usually argillaceous. The number and the degree of preservation of the radiolaria appear to be inversely related to the amount of clay-material present. In some cherts, radiolaria are very numerous and fairly well preserved, their spinose character being conspicuous. In others the tests are of a sporadic occurrence as ill-defined ovoid or spherical bodies.

In the dark cherts the radiolaria have usually escaped the sable colouration of the surrounding silica and are infilled by chalcedonic silica which is more coarsely crystalline than the interstitial silica. Such patches often have a concentric structure, with rather diffuse bands rich in tiny acicular rutiles, epidotes and opaque minerals, alternating with the silica (Plate XXIa). Large irregular patches of secondary magnetite, probably replacing pyrite, and small squarish crystals of greenish

/brown

brown authigenic ?brookite (or epidote??) often occupy the cores of the radiolarian tests. Pyrite and magnetite are also abundant but finely disseminated in the black cherts.

Tuffs and "agglomerates"

The red and green "tuffs" at the south end of Morroch Bay are fissile or thin-bedded and well-jointed. Microscopic examination of these rocks reveals the presence of very substantial amounts of argillaceous material and only a moderate proportion of exceedingly fine igneous detritus, mainly quartz and cloudy feldspar. In fact these rocks are slightly tuffaceous, light-coloured shales and mudstones. Cleavage is often conspicuous and in some cases a false cleavage has been induced by the parallel orientation of the fibres of recrystallised chlorite and sericite.

Tuffaceous bands associated with the black shale sequence in the Portslogan coastal section are distinguishable from the adjacent greywackes only by reason of their more even-grained texture and lighter colour. In thin-section the tuffs are rather well sorted but are petrographically similar to normal greywackes, with much detrital quartz and feldspar. There is little interstitial material and the grains are fairly well rounded. The water-laid character of these rocks is attested by the good stratification, and lamination, and by the occurrence in them of current-bedding and current-ripple-lamination.

The four-foot band of "agglomerate" in this section consists of large pebbles and angular cobbles (up to 6 inches in diameter) of pale green chert, amygdaloidal spilite, black shale and fine-grained greywackes, in order of decreasing abundance, all set in a greenish matrix. This groundmass resolves itself, under the microscope, into a very poorly sorted rock of greywacke type. Large and small sub-angular pieces of green chert which sometimes contain radiolaria are the most conspicuous components but there are also numerous fragments of black or green shale and much rarer small fragments of spilite and of quartzite. Large grains of quartz and feldspar are common and there is a prominent discrete matrix which consists of highly micaceous fine-grained siltstone. Narrow stringers of black shale are of frequent occurrence and usually lie parallel to the bedding.

Despite the agglomeratic appearance in hand-specimen, the petrographic character of this rock throws serious doubt on the assumption that it is of pyroclastic origin. In fact the evidence appears strong that the bed, which is unstratified, lenticular, passing laterally into normal greywackes and siltstones, originated by normal sedimentary processes. It seems likely that there was local addition (possibly by means of slumping) of unsorted coarse clastic detritus, mainly of fine-grained argillaceous and siliceous sediments but with an admixture of igneous and metamorphic rock-fragments, to a bed of unconsolidated micaceous siltstone.

E. THE DEVELOPMENT OF PYRITE IN THE GREYWACKES

Pyrite is of very general occurrence and in some beds it is abundant. Broken and faceted cubes and pyritohedra form an almost negligible proportion of the pyrite grains observed and are evidently of detrital origin occurring in a normal clastic relationship with the adjacent grains. However, most of the pyrite occurs as grains and masses which must be of post-depositional origin since they are clearly transcurrent to the clastic grains and rock-fragments.

Pyrite having this occurrence may be divided into two morphological groups: (i) Euhedral pyrite, (ii) Spheroidal pyrite.

(i) Euhedral pyrite: This is usually found in the form of cubes or pyritohedra, either as single crystals or, more commonly, as aggregates of several crystals, mutually interfering. Euhedral pyrite is never as common as the spheroidal type except in those greywackes which have been subjected to cataclasis (Plate XXIb), but it is often found in the veins of calcite and quartz which traverse many of the greywackes. Occasional, impersistent veinlets of euhedral pyrite are found in some greywackes. This vein-pyrite is often partially replaced by magnetite

/Narrow

Narrow zones of chlorite and chalcedonic silica, similar to those to be described from the spheroidal pyrite, occur around a few euhedral grains while rims of magnetite are fairly common. Many grains have a thin veneer of haematite.

Pyrite of this type is particularly common in some of the more siliceous, fine-grained rock-fragments such as chert, but since the crystals of pyrite are abruptly truncated at the edges of such fragments it is assumed that the formation of pyrite in these probably took place before the erosion of the fragments.

(ii) Spheroidal pyrite: This rather unusual type of pyrite occurs in abundance in some greywackes and takes the form of tiny globules which are usually aggregated together to form a framboidal or berry-like body. This ^{is} commonly ovoid, sometimes spherical, in shape or may be quite irregular. The spheroids may be up to 1.5 mm. in diameter, and the component globules are of the order of 0.01 to 0.03 mm. in diameter. The distribution of these pyritous bodies, spheroidal and euhedral, does not appear to be related to the bedding of the greywacke.

The density of packing of the globules in these spheroids is very variable. Some grains appear homogeneous, revealing little evidence of aggregate structure whereas in others there are

/relatively

relatively wide interstices between the globules. Portions of detrital grains which have been replaced by the pyrite may often be detected in such spaces.

Furthermore, there is considerable variation in the shape of the aggregate, a variation which is related to the density of packing of the globules. When the aggregate is near-homogeneous the shape assumed is ovoid or spherical, occasionally approximating to pyritohedral, but loosely-packed aggregates are usually of very irregular shape (Plate XXIIa). The individual globules also vary in shape but are usually nearly spherical. In some of the loosely packed aggregates the component globules are seen to be pyritohedra or, rarely, cubes. Single globules of pyrite of similar size and shape to those forming the spheroids sometimes occur randomly scattered throughout the matrix of a greywacke and in this case any spheroids present are small and loosely packed, with irregular shape. Most of the aggregates also appear to have originated within the greywacke matrix, although as growth proceeded they would replace and include clastic grains, large and small. Some aggregates are in the form of incomplete spheres and this can best be explained by the relative ease of growth of the pyrite crystals in the matrix compared with the detrital grains (see fig. 24).

In one thin-section there are a number of small spheroids, of very similar aspect to the framboidal pyrite, which are composed

/of

of a translucent substance with moderate relief and low birefringence (possibly cryptocrystalline silica) together with colourless carbonate which appears to be secondary and is also abundant interstitially in the rock. Pyrite, in the form of very tiny irregular granules, appears to be disseminated throughout these bodies. In this case it seems likely that the pyrite has been almost entirely replaced by the other material.

About a third of the total number of pyrite grains observed, euhedral and spheroidal, are accompanied by zones or envelopes of pale green chlorite and/or chalcedonic silica. Moreover a number of the grains have a very thin but nearly continuous rim of magnetite. Frequently the entire zone is composed of chlorite but often silica is also present. Zones composed entirely of silica are of very infrequent occurrence. The maximum area of zone observed in thin-section is only about 10% of the total area of the adjoining pyrite grain.

The zonary chlorite is weakly pleochroic in pale green and gives anomalous blue interference colours. It is often fibrously intergrown with the silica, the length of the fibres being normal to the surface of the pyrite sphere or to the crystal faces, where developed. Where a zone is compounded of silica and chlorite the

/silica

silica often forms the inner part of the zone, next to the pyrite.

These zones are remarkably free from inclusions and usually have a sharp junction with the adjacent rock-material. In all the grains observed the zones, if present, never form a continuous envelope but only partially surround the pyrite. A striking feature of this partial envelope is that it often exhibits a polar arrangement (figs. 25a and b), the zones commonly being concentrated at the antipodal points of an ovoid or a spherical grain. It may be that the apparent lack of zones in many grains is due to the random nature of the section which has failed to cut the true poles of the spheroid. The occasional grains with a unipolar zone may also be accounted for in this way. The orientation of all the "polar planes" of the pyrite grains in one thin-section seems to be sub-parallel but may show deviations of up to 30° . This polar plane apparently does not coincide with the bedding and may make a considerable angle with it. It has not yet been found possible to relate the orientation of this plane to any structural or lithological direction.

The chloritic zone is lacking where the pyritous body is in contact with a siliceous grain, while magnetite rims are usually present only where the silica zone is absent. On a few spheres outgrowths of pyrite post-date the formation of a magnetite rim

/but

but are themselves rimmed by magnetite. Such outgrowths also appear to antedate the formation of the surrounding zones (fig. 25a).

Authigenic pyrite of euhedral type has been described by Woodland (1938) from mudstones of the Harlech Grit Series in Merionethshire. With a few significant exceptions, Woodland's descriptions of the zones of chlorite and silice and the magnetite rims agree with those given here. A further zone, of siderite, found in the mudstones has not been observed in the Ordovician greywackes.

Spheroidal masses of pyrite have been found by many workers (cf. Proc. Geol. Soc. London, No. 1550, 1957, and Pettijohn, 1949, p. 116), mainly in fine-grained sedimentary rocks such as clays and shales. However, few details of their morphology have been given.

In the present case it appears that part of the euhedral pyrite has been introduced by veins although many euhedral grains occur in unveined rocks and presumably could not have been produced by this method. It is probably significant that euhedral pyrite is best developed and most abundant in rocks which have suffered an exceptionally high degree of dynamic metamorphism as, for

/instance

instance, in fault-planes (Newhouse, 1927, p. 81). In this instance it would appear that any pyrite present in the rock, possibly disseminated throughout the matrix as the amorphous disulphide, has been aggregated and recrystallised with a euhedral habit.

From the available evidence it seems a reasonable inference that the framboidal structures have been produced by aggregate growth of numerous tiny pyritohedra, growth proceeding radially from a centre which was usually situated in the chloritic matrix of the greywacke. The degree of perfection in the shape of the aggregate and the density of packing would appear to be related primarily to the ease of growth of the pyrite crystals.

Love (1957) concluded that spherical and irregular pyritous bodies occurring in some Lower Carboniferous shales and limestones in the Midland Valley of Scotland are syngenetic. He proposed that the pyrite replaced the shell-material of tiny organisms which themselves produced, during their life cycle, the hydrogen sulphide necessary for the reductive processes.

While many of the spheroids described here have strong morphological affinities with organic bodies, the clear transection of detrital grains, the irregularity in shape and the variation in density of packing all indicate a post-depositional rather than a
/syngenetic

syngenetic origin. Further proof for the relatively late date of formation is afforded by the fact that in several cases spheroidal bodies of pyrite cut through calcite veinlets (fig. 24), although in other cases the carbonate has partially replaced the pyrite and thus appears to be of later date. Further, in one instance the recrystallised sericitic-chloritic material of the greywacke matrix has been partly domed up and partly broken through by the growth of a pyrite spheroid.

The original source of the ferrous sulphide is not known. It may have been present in the argillaceous matrix of the greywacke, or perhaps introduced during the early stages of diagenesis, in a finely disseminated state. Whatever its origin, the indications are that when crystallisation was initiated the disseminated amorphous sulphide migrated towards certain foci and commenced to crystallise out as tiny pyritohedral crystals which progressively replaced the detrital material. Spheroidal aggregates of such crystals grew by accretion in the radial manner described earlier. Crystallisation did not commence until the rock had been consolidated, at least in part, and it seems probable that the crystallisation was induced by the pressure of superincumbent rocks.

The mode of formation of the zones surrounding pyrite crystals in the greywackes remains obscure. Woodland interpreted these as

/spaces

spaces produced by the contraction consequent upon the formation of crystalline pyrite from the amorphous iron sulphide, such spaces being simultaneously filled with chlorite, silica or siderite. The sequence of the zones and the nature of the infilling materials was accounted for partly by the composition of the circulating solutions and governed by the presence or absence of carbonic acid.

While this explanation may account for the presence of zones round some of the euhedral grains, it cannot be applied to the case of the spheroids because in all cases the volume of the zone is very much less than the theoretical volume required which is half of that of the pyrite body itself. Moreover there are many spherical and euhedral bodies which do not possess surrounding zones so that there appears to be no direct genetic connection between zone and pyrite crystal.

It is clear that the zones were formed after consolidation and compaction of the rock, else the adjacent detrital material would have infilled the original spaces now occupied by such zones. The characteristically ovoid shape of the grains, the polarity of the zones and the approximate parallelism of the polar-planes all point to an external cause. It is therefore tentatively suggested that the formation of the zones is a metamorphic phenomenon of local significance.

On this view the pyritous bodies, originally spherical where fully developed, have been subjected to directional pressure, and have yielded by slight elongation, presumably normal to the stress-direction, while silice and chlorite which may have been dissolved from the adjacent matrix, crystallised out in the relatively low-pressure areas at the poles of the now-ovoid body.

F. HEAVY MINERAL GRAINS

Procedure: About 20 gms. of the specimen of greywacke were broken off and pounded (not crushed) to release the discrete grains from the matrix. The resulting greywacke-sand was then sieved, the fractions passing through the 30 mesh (0.0197 ins.) being retained.

The heavy detrital mineral grains were separated from the light fraction in a separating-funnel, using bromoform (S.G. 2.9). Since most of the heavy residues contained a high proportion of detrital iron-ores, a magnet was passed over the dried separations, removing the magnetite. Passing the mineral grains through a Frantz isodynamic separator, at 0.1 amps. with 10° side-slope, ensured the removal of most of the ilmenite from the heavy residues.

In some of the greywackes of the Corsewall Group, secondary iron-staining (limonitic) made it necessary to boil the sieved

/greywacke-

greywacke-sand in dilute oxalic acid (0.1N). This effectively removed most of the iron-staining, without affecting any of the other constituent minerals, except, perhaps, the apatite, which acquired a rather pitted surface, due to slight corrosion. For microscopic examination, the grains were mounted in refractive-index oils.

Description of Grains: Some 18 mineral species occur in the heavy residues (fig. 26), of which three are opaque minerals.

Garnet. There are two principal varieties of this species (i.e. pink and colourless) with a few grains of an intermediate colour and a few with a yellowish tinge. Grains of garnet occur in all but two of the separations.

Pink garnet (which is probably almandine) generally occurs in large angular or subangular grains, up to 1.5 mm. in diameter, approximating to dodecahedral shape and showing conspicuously uneven fracture. Poor {110} cleavage is often developed while oscillatory combination of the dodecahedron {110} and trapezohedron {211} produces step-like faces. The colour ranges from a faint rose tinge to a strong reddish-orange. The surface of these grains is often slightly etched. Inclusions are not common and are randomly distributed throughout the grains, although occasional

/grains

grains are cored by large euhedral grains of rutile or ilmenite. Strong cross-cracks, filled by red limonite (?) are characteristic of this variety. They are usually irregular in orientation, but are sometimes arranged radially. Occasional grains of pink garnet exhibit anomalous, very low birefringence.

Grains of colourless garnet are generally smaller, with a maximum diameter of 0.8 mm. In rocks north of the Southern Upland Fault they are euhedral dodecahedra, broken or whole, but to the south, they commonly occur as angular platy fragments or tabular grains, showing sub-conchoidal fracture, or as rounded dodecahedra. Tiny grains of the opaque numerals form the bulk of the very numerous inclusions which are sometimes arranged in concentric or spiral rings. Sieve-structure is characteristic of, but not restricted to, colourless garnets from rocks rich in fragments of metamorphic rocks. Strong cross-cracks are rarely encountered in this variety, although tiny, irregular, anastomosing fractures, with associated slight limonitic staining, are occasionally observed.

The yellow garnets, which range from pale lemon to honey in colour, occur only in rocks of the Portpatrick Group. The grains are normally subhedral, rounded dodecahedra, slightly fractured and with few inclusions. Conspicuous cross-cracks are common and it seems likely that this is but a sub-variety of pink garnet.

/Alteration

Alteration of the garnets to a pale green chlorite and an iron mineraloid, or to magnetite may be observed in some thin-sections of greywackes.

Zircon. Occurs in every separation. Two varieties of this mineral were also found (cf. Walton, 1955, p. 335). The first comprises those grains with a length-width ratio in excess of 1.5 and which carry inclusions. Such grains are usually colourless but may be pink, pale brown, or even pale mauve with very faint pleochroism. The length is very variable up to a maximum of 0.2 mm. The smaller grains are usually colourless and of euhedral form. Typical developments are the prisms $\{100\}$ and $\{110\}$, with the pyramids $\{111\}$, and sometimes $\{311\}$, while the $\{001\}$ pinacoid occurs but rarely. Larger grains are usually well-rounded but often retain traces of the original crystal faces. Poor cleavage, which is normally prismatic, but may, rarely, be pyramidal, is often developed, while irregular cracks, parallel to $\{001\}$, also occur. Limonite-filled radial cracks, are of infrequent occurrence in the larger grains. Inclusions are very common and consist of (in order of abundance) zircon (colourless), apatite, rutile, opaques, small cavities and brookite. Acicular inclusions are often oriented parallel to the c-axis and the grains are sometimes cored by a large crystal of an opaque mineral. Zonal growth is

/common

common in both large and small grains. Very occasionally, grains of this type exhibit optical anomalies. They give a biaxial positive interference figure, with $2V=10-15^{\circ}$ and with abnormally low birefringence. Other grains show "undulous extinction".

The second variety, which is very much less common in these separations than the first, consists of grains of zircon with a length-width ratio of less than 1.5 and with few inclusions, or none, and generally a purple colour. The shade ranges from pale mauve to clear, strong purple, with some brownish tints, due to iron-staining. The length of the grains is rather greater than in the first variety; the average is about 0.15 mm., the maximum about 0.4 mm. However, the shape is almost invariably ovoid or nearly spherical, the grains being exceedingly well-rounded. The surface of the grains is frequently "frosted" or shows shallow scallopings. No zonal growth has been observed in these grains, nor prismatic cleavage. The very scarce inclusions are apatite, cavities or opaques. Undulous extinction is exhibited by occasional grains.

Alteration of the zircons has not been observed, but they often possess a thin, patchy coating of yellow limonite.

apatite. Small, colourless or very pale blue transparent grains of this mineral are found in 27 separations out of the total of 36. The average length of the grains is 0.36 mm., average
/width

width 0.24 mm. and the average mean R.I. is 1.642. These grains are generally angular and platy or tabular; occasionally they occur as hexagonal prisms with rounded terminations, and especially in the rocks south of the Southern Uplands fault, as small ovoid grains. Forms observed include $\{10\bar{1}0\}$, $\{10\bar{1}1\}$ and very rarely $\{0001\}$. Fair $\{0001\}$ cleavage is sometimes encountered, while frequently the surface is minutely pitted, giving a "frosted" appearance - this may be due to solution by the oxalic acid. Inclusions are not common and usually show random distribution. Only one example of strong zoning has been observed.

While most grains of apatite are uniaxial negative, very rare grains give biaxial interference figures, $2V=10-15^\circ$ and in this case the fast ray makes an angle of $3-6^\circ$ with the c-axis. A thin, patchy coating of yellow limonite is frequently observed and, when alteration is advanced, this limonite extends in vermicular fashion into the centre of the grain.

Tourmaline. This species occurs in all but three of the residues. There are two varieties, distinctive both in colour and form. The most abundant type is brown, intensely pleochroic from honey (ϵ) to nigger (ω) and with characteristic blotchy colouration. The grains are generally euhedral, prismatic, with occasional development of pyramidal faces $\{10\bar{1}1\}$. Irregular
/basal

basal partings are sometimes found and these may define one termination of a grain. Frequently, indistinct striations parallel to the c-axis, with iron-ores aligned along these lines, are observed. Inclusions, randomly oriented, are common in these grains.

Very rare grains are pleochroic in green, from pale green (ξ) to greenish turquoise (ω). They are similar in form to the brown variety and sometimes exhibit brownish tinges so that they are evidently referable to this variety.

The second type is weakly pleochroic from translucent Prussian blue to indigo. In form, the grains are usually angular or broken, with sub-conchoidal fracture. Pseudo-hexagonal plates defined by the basal parting and non-pleochroic, are rare. Inclusions are not common and no regular striations have been observed.

Both varieties are uniaxial negative, $n_{\xi}=1.67$, $n_{\omega}=1.63$.

Rutile. Another common species. Again there are two varieties, almost equally abundant. The first is pleochroic from light golden-yellow to deep amber and transparent. Grains are usually small (average length 0.1 mm.; average width 0.03 mm.), prismatic or acicular, rarely tabular. The terminations are usually rounded, but $\{100\}$, $\{110\}$ prisms and $\{111\}$ pyramids have
/been

been observed. Prismatic {100} cleavage is common while striations parallel to {101} (presumably due to polysynthetic twinning) occur infrequently. Genuiculate twins have been observed but they are rare. Grains of yellow rutile are sometimes rendered semi-opaque through the presence of minute, disseminated alteration products.

Slightly larger grains (average length 0.2 mm.) are "foxy-red" in colour, pleochroic from light red-brown to dark crimson and often semi-opaque because of total internal reflection. These grains may be prismatic, with rounded ends, and occasionally show development of the basal pinacoid, but more commonly they are angular, platy or tabular, showing marked sub-conchoidal fracture. The prismatic cleavage and striations parallel to {101} are fairly common in this variety also. Inclusions are rare in both varieties.

Epidote. This is normally slightly pleochroic from clear yellow-green to pale grass-green. The grains are of medium size (average diameter, 0.3 mm.) and irregularly angular in form, although occasional grains are angular prismatic, and {001} cleavage flakes are common. Good {100} cleavage is frequently developed, together with numerous irregular cross-cracks. The surface of a few grains appears to have been etched into a series of minute shallow pits. The grains are invariably biaxial negative, $2V$ about $70-80^\circ$, with average R.I.=1.74.

/There

There are a few small flakes which display all the characteristic properties of epidote but are colourless and exhibit anomalous blue interference-colours. These are regarded as being zoisite in composition.

Fyroxene. (See thin-section descriptions). Besides augite, which is of frequent occurrence among the heavy minerals, grains of a rather unusual form of pyroxene were found in one residue. The grains are large (average length 1-3 mm.), tabular and angular and are evidently defined by cleavage. These flakes are light coffee-brown in colour and non-pleochroic. There is little trace of cleavage on the face of the flakes, but the saw-tooth form of the edges indicates two cleavages, at about 90° . The extinction angle of the fast ray, measured from straight edges, is 30° - 42° and the interference figure may appear uniaxial or biaxial positive, with $2V=10^{\circ}$. The mean R.I. is 1.701 and the birefringence is fairly strong. A pyroxene of the composition of pigeonite is strongly indicated.

Hornblende. See thin-section descriptions.

Glaucophane. Grains of this mineral occur in five separation and in an additional fifteen thin-sections. The mineral occurs principally as $\{110\}$ cleavage flakes, the average length being about 0.2 mm. Two inter-grading types are recognised. The first

is pleochroic from colourless (X), to lavender blue (Y), to mid-violet (Z), and the optic plane is normal to $\{010\}$ with $Y\wedge c=14^\circ$. The second has the pleochroic scheme: pale green (X), dark violet (Y), ultramarine (Z), with the optic plane parallel to $\{010\}$ and $2\wedge c=12^\circ-15^\circ$. The first type has very marked dispersion, $r < v$. The first type is biaxial negative, $2V$ about $40-55^\circ$, while the second is biaxial positive or negative, $2V$ variable between 10° and 40° . In the first type, $n_\alpha=1.62$, $n_\beta=1.63$, $n_\gamma=1.63$ but the R.I.s. of the second type are slightly higher. There is usually one marked cleavage, with poor parting normal to it. Inclusions are few.

The first variety is evidently similar to that described by Walton (1956) from the Glen App and Finnarts conglomerates, and to that which occurs in an exposure of glaucophane-schists, near Lendalfoot. This variety is believed, in the course of alteration to grade into the second type, which is probably a variety of hornblende (cf. Winchell, p. 441).

Picotite, (Spinel). Another common species. It is non-pleochroic, colour variable from light coffee-brown to dark red-brown; translucent in thin-section but opaque in grains and invariably isotropic. Sub-vitreous to sub-metallic in lustre. It generally occurs as small, highly angular, fractured platy

/grains

grains, but occasional broken octahedra have been observed. There is no good cleavage developed, but only irregular, impersistent narrow cracks. Inclusions are extremely rare.

Brookite. The infrequent grains of this mineral are pale greenish-brown in colour, non-pleochroic. In form, they are generally euhedral and very small (average width = 0.04 mm.), tabular parallel to {001} and with good prismatic {100}, {110}, and pyremidal {011} faces developed. They often occur as aggregates of several euhedra. No good cleavage has been noted, but tiny, impersistent cracks, parallel to {100} have been observed. Inclusions are very rare, but occasional grains are cored by ilmenite(?). The grains frequently possess a thin veneer of leucoxene.

Very minor amounts of rounded tabular anatase and acutely ragged, brown sphene have also been encountered in some heavy mineral separations.

Of the opaque minerals, ilmenite is the most abundant, although in some cases it is not easy to distinguish from magnetite. It occurs chiefly in the form of large, slightly rounded or angular wedge-shaped or tabular grains and, occasionally, as small, rounded rhombohedral plates. The colour of the mineral is reflected

/light

light is a purplish blue, and the lustre is dull metallic. The grains often possess a thin sheath of leucoxene and their surface is usually rough and pitted.

Next in abundance is pyrite, of which there are two varieties^{*}. The first, or euhedral, type is particularly common in rocks of the Portpatrick Group. Grains of this variety are of moderate size (average diameter, 0.15 mm.) and show dodecahedral, pyritohedral, striated cubic, and occasionally octahedral faces. Striations, parallel to {100} and {210} are commonly present. These euhedral grains are often aggregated together forming platy or botryoidal masses. The second, spheroidal, variety consists of medium-size aggregates (average diameter, 0.2-0.25 mm.) apparently consisting of numerous tiny globules of pyrite. These aggregates are usually spherical bodies, but are often irregular and ragged in shape. Grains of both types may occur in the same separation and have often acquired a thin veneer of bright red haematite (cf. Woodland, 1938, p. 451).

Magnetite. This mineral, which is common in the separations, occurs as irregular, highly fractured grains, often with minute facets developed on some faces, or as larger rounded octahedra. Some patchy alteration to limonite may be observed.

/Finally

(*See, also, thin-section descriptions.)

Finally, there is one interesting mineral which does not occur in the separations but is present in at least three thin-sections. This mineral is believed to be staurolite. It occurs as small (0.03-0.05 mm.) broken prismatic grains, with saw-tooth edges and one grain possessed a pyramidal termination. The pleochroism is distinctive, from colourless (faster ray) to strong yellow-brown, and in several grains there is a marked marginal zone pleochroic from colourless to dark brown. The refractive index is high, between 1.7 and 1.75, while prismatic cleavage is poorly developed. The mineral is length-slow, biaxial, of doubtful sign and optic axial angle, but the optic axes emerge in the {001} - {010} zone. Maximum birefringence gives first-order red colours, and the extinction is nearly or exactly parallel to prism-edges. An intriguing point is that not one grain of this mineral contains any inclusions.

Discussion: From the accompanying lists (Table X) it will be seen that there is no clear-cut differentiation of heavy mineral suites according to stratigraphic horizon. The minerals comprising the rather meagre aggregate suite occur in each of the several stratigraphic groups. However, some limited observations can be made on the distribution and relative abundance of the various minerals and their varieties.

/(1) While

(i) While zircon is an ubiquitous species in these rocks, it is rather less common in the Corsewall and Portpatrick Groups, principally because purple zircon is rare in these rocks.

(ii) Garnet appears to be a rare species in rocks of the Corsewall Group.

(iii) Apatite is abundant in the Corsewall and Galdenoch Groups common in the Portpatrick, and rare in the Kirkcolm rocks.

(iv) Hornblende, pyroxene and epidote are conspicuously abundant in the Corsewall, Portpatrick and Galdenoch Groups.

(v) Tourmaline, and particularly the brown variety, is rarely encountered in the Portpatrick Group.

(vi) Rutile and tourmaline appear to be particularly abundant in rocks of the Upper Barren division of the Kirkcolm Group (20-24 in Table X).

More generally, the separations appear to be typical of the rather restricted suite commonly found in greywackes. Perhaps the most striking feature of the Rhinns suite is the remarkable prevalence of apatite, usually regarded as a very unstable mineral. Of considerable interest, too, is the ubiquity of zircon and garnet and the spasmodic abundance of hornblende, augite and epidote. The unconfirmed but probably correct identification of the enigmatic mineral described above as staurolite means that this is the first

/recorded

recorded occurrence of the mineral in greywackes from the Southern Uplands. Picotite, the brown spinel, though not so common as in some Silurian greywackes (see below) is still widely distributed and is a highly characteristic constituent of these Ordovician rocks.

Before proceeding to a discussion of this suite in the light of comparable separations it is necessary to discuss here two important factors. In the first place it is possible that, despite the precautions taken in the dis-aggregation of the rocks some of the minerals present in the separations may have been released from rock-fragments, accidentally crushed. However, examination of the thin-sections reveals that each of the heavy minerals may occur free in the greywackes. The net result of breaking-up the rock-fragments, therefore, would be to augment the number of those heavy minerals (such as hornblende, augite, epidote and apatite) which occur in abundance in the fragments, at the expense of those which normally occur as discrete grains in the greywackes. This virtually rules out any attempt at an accurate quantitative analysis of the separations, but does not materially affect either the type of qualitative study attempted above nor the determination of the ultimate source of the minerals.

/Secondly

Secondly, several of the minerals in the suite are clearly authigenic. Such, for instance, is the origin of the brookite, most of the pyrite, and some of the magnetite and epidote.

Mackie, in a preliminary report to the British Association (Mackie, 1929) described the heavy minerals separated from a large number of Silurian greywackes collected along the strike from Peebles to Ballantrae, in the Rhinns, and at Glenluce.

Statistically, out of 61 separations:

34	contained	augite
22	"	hornblende
14	"	enstatite
52	"	zircon (of which 32 had <u>purple zircon</u>)
38	"	garnet
19	"	sphene
38	"	"melanite"
5	"	glaucophane
21	"	epidote
23	"	apatite
16	"	tourmaline
18	"	rutile
7	"	pyrite
11	"	chlorite
2	"	anatase

and 1 each contained brookite, magnetite, dolomite, fluor and hypersthene.

Mackie appended a note in which it was stated that the brown mineral he had identified as "melanite" was not, in fact that mineral. (It is highly probable that this mineral is that which the present writer has identified as picotite.)

/Mackie

Mackie was impressed first by the abundance of augite, and melanite, both of which are uncommon as heavy minerals, and also by the remarkable freshness of the minerals, which he attributed to "the relative impermeability of the Silurian rocks". He drew attention to the absence from the suite of monazite and the high-grade metamorphic minerals - kyanite, staurolite, sillimanite and andalusite.

In a hitherto unpublished study of the petrology of the Queensberry Grits of the Moffat area, T. H. Wilson describes the heavy minerals which he separated from 54 specimens of greywacke. The list of minerals he determined is given below:

Zircon (colourless and purple), tourmaline (brown, green and blue), rutile (foxy-red and yellow), garnet (colourless, pale pink and, rarely, yellow), augite, hornblende, enstatite, hypersthene, epidote, chlorite, sphene, apatite, anatase, fluorspar, mica, "chromite", magnetite, pyrite.

Wilson gave fairly detailed descriptions of these minerals and inferred from the suite and also from the rock-fragments the possible nature of the source-area of the greywackes. (Discussion of his ideas will be deferred to the section on provenance.) This list of minerals corresponds very closely with Mackie's findings.

/In

In general and in detail these minerals are very similar to those found in the Ordovician rocks of the Rhinns. Even varietal differences are similar (e.g., the brown, green and blue varieties of tourmaline), while the form of the different types of mineral grains is also remarkably alike. The principal differences are that Wilson records enstatite hypersthene and fluorspar, which are not present in the suite from the Ordovician rocks of the Rhinns while glaucophane, brookite and ilmenite, present in the Rhinns, appear to be absent from the Queensberry Grits.

More recently, E. K. Walton, in a published study of greywacke in Peeblesshire (Walton, 1955), records the heavy minerals found in some 18 specimens of greywacke. A list of these minerals is again appended:

Augite, hornblende, garnet (pink to colourless), epidote, zoisite, zircon (two types; (i) grains with length/breadth ratio of 2 or 3, pink or colourless, (ii) grains with few or no inclusions well-rounded, purple or faintly pink), tourmaline (brown), rutile, picotite, spatite and sphene, pyrite, magnetite and leucoxene-coated ilmenite. The form and relative abundance of each of these minerals was indicated, together with the nature of the inclusions.

This suite differs slightly from those found in the Queensberry grits and the Ordovician rocks in being even more restricted.

/However,

However, there are some points of resemblance, particularly if the form of the different species is considered. An interesting point is the abundance of pyrite in the Peeblesshire rocks, where it exceeds ilmenite, which is, of course, the dominant opaque mineral in the Rhinns.

G. DIAGENESIS AND METAMORPHISM OF THE GREYWACKES

No specific investigation of the post-depositional changes in the greywackes has been undertaken in the present study but certain features were noted during the systematic examination of the rocks.

Strictly speaking, no distinction is possible between the processes of diagenesis and metamorphism (Pettijohn, 1949, p. 476) but for convenience it is proposed to separate under the title of metamorphism those changes which are believed to have occurred after consolidation of the greywackes.

Diagenesis: The material of the greywackes can have undergone little change in the period between deposition and compaction. The presence in abundance of many minerals, such as augite and hornblende, which would have decomposed readily in the presence of oxygen or chemically active solutions suggests that there was in fact little chemical interchange between the unconsolidated greywacke and the surrounding medium.

/The

The burial and subsequent compaction of the greywacke material was presumably accompanied by physical and chemical re-organisation of some of the constituent grains. Pore-spaces would be readily eliminated through infilling by the argillaceous fraction and any connate water expelled. Reconstitution of the interstitial material of clay-grade to sericite and the clay-micas probably occurred at this period, perhaps as a result of the pressure of a great pile of superincumbent sediments. The production of the authigenic minerals including pyrite, brookite, some epidote and magnetite may be spread over a long period but most of them are of later date than the recrystallisation of the clay-matrix and, in the case of the pyrite, partly later than some of the calcite-veining.

Few of the greywackes possess a true mineral cement. In almost every case the grains are bound together by an interstitial argillaceous "paste". The high degree of cohesion of these greywackes may be partly due to impregnation of the matrix by silica as a result of slight metamorphism, but this is probably assisted by the extreme angularity of the component grains which interlock readily, in the manner of the pieces forming a jig-saw puzzle. Such an interlocking texture possesses great rigidity since to break the rock it is necessary to rupture the grains.

/Another

Another, less apparent factor is the residual electrostatic charges on the clay particles which may be mutually opposing and thus provide a binding-effect which is individually negligible but significant in aggregate.

Occasional greywackes are rich in interstitial carbonate which is sometimes colourless, resembling calcite (one R.I. below, another above balsam) but more often it is pale brown and gives a positive reaction for iron and may therefore be siderite. The carbonate is evidently secondary for it is usually confined to very restricted zones, up to 10 mms. in width, which do not lie parallel with the bedding. Moreover carbonate of similar type occurs in veins cutting the rocks and, in a few favourable thin-sections, the interstitial carbonate has been observed to emanate from such veins.

Metamorphism: At different places and in differing degrees the Ordovician greywackes of the Rhinns display the effects of two types of metamorphism - dynamic and thermal.

The most spectacular effects of dynamic metamorphism are seen in the greywackes near major movement-planes, although true mylonites have not been observed. The fine-grained greywackes adjacent to the Southern Uplands Fault, for instance, are thoroughly

/cataclastic

cataclastic in texture and in some cases a type of "mortar-structure" is developed, many of the originally highly angular grains becoming rounded in the process. Concomitant with the cataclasis there appears to be introduction of carbonate which now occurs interstitially. Large cubiform crystals of pyrite have grown in the rock and replace the matrix, including carbonate, and detrital grains (Plate XXIb). Near smaller movement-planes cataclastic veinlets of variable width from 1 mm. upwards are often found. These consist of a brownish isotropic matrix of pulverised material, sometimes carrying carbonate, in which are embedded shattered detrital grains (Plate XXIIb).

Certain of the greywackes, and particularly those associated with the black shale bands exhibit rather a different form of cataclasis. In these an "eyed" or flaser-structure is developed (Harker, 1950, p. 167) probably as a result of differential movement between greywacke and shale. A sub-opaque, grimy brown, micaceous matrix, partly recrystallised, flows round long, narrow lenticles of detrital quartz which often shows undulous extinction.

In the strongly folded region south of Port of Spittal Bay, the tectonic deformation of the rocks is much more severe than elsewhere and as a consequence the greywackes are generally somewhat shattered. In some cases there is very slight peripheral

/granulation

granulation of the detrital grains of quartz while the chloritic and micaceous material of the matrix is often recrystallised into long stringers which may envelope entire grains (Plate XXIIIa). Associated with the shattering is quartz, introduced in veins which are themselves often affected by the deformation. This quartz is so intimately mingled with the grains that it is virtually impossible to estimate what proportion of the quartz is detrital and what is introduced. Some of the finer greywackes appear to possess a certain, very crude schistosity due to the alignment of the recrystallised micas and chlorite.

Thermal effects have been observed in greywackes adjacent to dykes and sills and, on a much larger scale, in the rocks around the Cairngarroch porphyrite mass and its apophyses. Here the greywackes have been thoroughly baked and rendered splintery. The hornfelsic nature of these rocks is fully confirmed under the microscope (Plate XXIIIb). The margins of many of the detrital grains are fuzzy and some grains are recrystallised. The detrital feldspar is uniformly turbid while the clay matrix has been transformed into a yellow-brown fibrous material resembling biotite. Colourless granules of epidote are common in this matrix and appear to be a further product of the metamorphism.

H. PROVENANCE OF FRAGMENTS AND GRAINS

The majority of the boulders and fragments in the rocks of the Corsewall Group were derived from an area consisting largely of igneous rocks. Spilite lavas possessing textural and mineralogical properties similar to those of the spilite fragments in the greywackes are found in situ in the Ballantrae district. Acid volcanic rocks such as the keratophyres and quartz-porphyrines do not occur in this area but are recognised as normal associates of the spilites in the geosynclinal volcanic suite. Moreover such rocks are found in Tweeddale (Ritchie and Eckford, 1931) and the presence of ?Arenig volcanic rocks in the Highland Border Series may be regarded as evidence for the former presence of such rocks over a very wide area of mid-Scotland. The fragments of quartz-porphyry and keratophyre, then, were probably derived from a westward extension of this volcanic terrain, now completely eroded or lying below sea-level. The source of the andesitic fragments is probably to be sought in this vanished volcanic platform. Andesitic tuffs and lavas, probably of Arenig and Glenkiln age, now exposed at Bail Hill, Sanquhar and Mains Hill, Ballantrae, bear close comparison with the fragments. They contain phenocrysts of brown and greenish-brown hornblende and yellowish augite, with abundant apatite, and are texturally similar to the fragments.

Of the intrusive rocks the serpentines, dolerites and "gabbros" can be matched with similar rocks in the Ballantrae igneous complex where there are also small exposures of dioritic rocks of an aspect similar to that of the dioritic fragments. Some of the albitic granites are comparable with Ballantrae rocks such as the Byne Hill mass, but the majority of the coarse acid fragments are granodiorites carrying microperthite and a little microcline and cannot be matched locally. Some of these granites have been described as Lewisoid (Tyrrell and Begg, 1933, p. 67) but, while sometimes sheared, they are not gneissose. Moreover, they contain only traces of microcline, unlike the normal Lewison orthogneisses or granites (Phemister, 1948, pp. 10-12). It is possible that the fragments were obtained from an eo-Caledonian intrusion.

Most of the scarce fragments of metamorphic rocks found in the Corsewall greywackes may be assigned to the low-grade thermal and dynamic metamorphism associated with the Ballantrae igneous complex. Hornblende-schists and granulites are extensively exposed around Littleton Hill and elsewhere (Beveridge, 1950) while schists comparable in all respects with the epidote-glaucophene rock fragments occur in situ near Lendalfoot (Balsillie, 1937, pp. 30-32, and cf. Walton, 1956b, p. 142) and in
/agglomerates

agglomerates near Pinbain (Bailey and McCallien, 1957, pp. 47-48). The occasional fragments of chert, black shale and greywacke suggest that a small area of older Ordovician sediments was also exposed in the parent land-mass.

The rock-fragments in the Kirkcolm greywackes indicate an extension of the contributing source-area. Thus, while an igneous complex similar to the Corsewall source-area still supplied some material to the Kirkcolm rocks, an increasing proportion of the detritus was derived from a region composed largely of metamorphic rocks. From this metamorphic complex came the fragments of phyllites, schists, epidiosites and gneisses. The presence of fragments with garnet and andalusite is evidence that fairly high-grade metamorphic rocks were exposed.

Most of the sedimentary rock-fragments, including black shale and chert which are locally abundant, may be ascribed to penecontemporaneous erosion but the occasional pieces of arkose are reminiscent of the Torridonian (cf. Walton, 1955, p. 354) confirming the probable Highland source of much of the Kirkcolm material.

Throughout the deposition of the Lower Barren and Metamorphic divisions this metamorphic region became an increasingly important contributor of detritus but the petrography of the Upper Barren

/division

division indicates a reversion to conditions of provenance roughly similar to those prevailing during Lower Barren times. This reversion could have been achieved by renewed uplift and rejuvenescence of the igneous source-area but in this case the greywackes of this upper division should be appreciably coarser. The change in current-direction in the Upper Barren rocks probably indicates an alteration in the drainage system, resulting in the derivation of these rocks from an easterly extension of the Ballantrae igneous complex.

The Portpatrick Group was derived from a very different source-area. Andesite fragments are ubiquitous and become increasingly abundant throughout the Group. These andesites differ slightly from the Bail Hill-Mains Hill rocks and from the fragments in Corsewall rocks (p. 83). Presumably, therefore, they were supplied by a different source. It is likely that the andesitic fragments were eroded from tuffs rather than solid lavas since it seems improbable that weathering of the latter could proceed with sufficient rapidity to release fresh grains of augite and hornblende. Moreover the greywackes cannot be considered in situ tuffs because of the variable weathered state of the andesite fragments and their association with numerous rounded fragments of other rock-types and minerals (Edwards, 1947a, p. 141)

/Nevertheless

Nevertheless, the extreme angularity of the andesitic fragments (fig. 10) indicates a short transport-distance.

Spilitic fragments are also common in Portpatrick rocks and differ from the Ballantrae rocks in that the pyroxene is pale green in colour, not the more common pale brown of the Arenig spilites. The remaining rock-fragments are similar to those found in the other Groups but the proportion of rhyolitic lavas and tuffs is unusually high.

From these facts and bearing in mind the stratigraphic evidence it appears that the Portpatrick rocks were derived from a dominantly volcanic area, probably an island arc. This area must have been folded and elevated prior to U. Glenkiln times and initially acid igneous and metamorphic rocks were exposed extensively, with lesser amounts of spilite and andesite. This terrain supplied the material of the Acid division. Later, there must have been increasingly frequent eruptions of basic^{*}, and to a much smaller extent, acid volcanics, which supplied the material forming the rocks of the Basic division.

/Most

* Periodic vulcanism is invoked to account for the relative freshness of the andesites and ferro-magnesian minerals throughout a great thickness of sediments. The detritus supplied to the greywackes from a single volcanic episode would become increasingly weathered in course of time.

Most of the mineral grains may be assigned to the disintegration of one or other of the rock-types present. Quartz is of particular interest as an indicator mineral, of rather restricted value.

From the work of Mackie, of Keller and Littlefield and the results indicated in fig. 12, it is possible to estimate the relative importance of the rock-types contributing quartz to the greywackes of each formation. It appears that igneous rocks were the source for most of the quartz in the Corsewall rocks and only little was derived from schistose metamorphic rocks. The quartz in the Galdenoch and Portpatrick greywackes seems to have originated mainly in the igneous rocks but substantial amounts were probably contributed by gneissose rocks.

Greywackes of the Lower Barren division contain a great deal of quartz of igneous origin, but a major portion has also been contributed by the metamorphic rocks. In the Metamorphic division the greater part of the quartz is derived from metamorphic sources, schists and gneisses, while the role of igneous quartz is correspondingly decreased. A rather similar distribution is found in the Upper Barren division in which, however, the majority of the quartz grains are of igneous derivation.

Of the heavy minerals, most of the zircons are well-formed and for these a granitic source is indicated, nor can a primary igneous origin be discounted for the rounded colourless zircons since Mackie (1928, p. 26) noted the occurrence of rounded and ovoid zircons in many granites. Some of the very well rounded purple zircons which characterise the Kirkcolm rocks may have been derived from sedimentary rocks but the association with metamorphic rock fragments suggests that at least a proportion of these purple zircons were derived from a Highland metamorphic terrain, probably of Lewisian type (cf. Mackie, 1923).

The pink garnet is believed to have come from igneous rocks since it is generally euhedral, never shows sieve-structure, and is the only variety observed in the rock-fragments; moreover Mackie (1928, p. 28) noted that the garnet occurring in granites is usually pink. This variety is most abundant in the Corsewall, Galdenoch and Portpatrick rocks whereas the colourless and sieve-garnets, of metamorphic origin, are dominant in the Kirkcolm Group.

Apatite is the characteristic heavy mineral of the Corsewall rocks and is probably derived from igneous rocks similar to those of the Ballantree complex where it is an abundant accessory. Significantly it is much less common in the Portpatrick Group, despite the high proportion of igneous rock-fragments there.

/Mackie

Mackie (1928, p. 10) has noted that angular blue tourmaline is specially common in pegmatites and it is possible that the source-rocks of the Kirkcolm Group, which contains a high proportion of this mineral, included pegmatites.

The grains of picotite could have been derived from any body of ultrabasic rocks, but the abundance of this mineral in the Ballantrae serpentines (cf. Bailey and McCallien, 1957, p.41) may be adduced as evidence for the local derivation of the detrital picotite in the greywackes.

The presence of staurolite in Kirkcolm rocks is of great interest since it records the highest grade of metamorphic rocks exposed at this period.

The general immaturity of the sediments and the presence of many minerals highly susceptible to weathering, together with the great thickness of sediments deposited in a comparatively short time all point to a source-area undergoing rapid erosion in which mechanical weathering was dominant.

See Table XIV for a summary of conclusions regarding provenance.

IV. SEDIMENTARY STRUCTURES

A. NON-DIRECTIONAL STRUCTURES

Graded bedding: Most of the described types of graded-bedding (Kuenen, 1953b; Ksiaskiewicz, 1952; Walton, 1956a) have been observed but, apart from the Kirkcolm greywackes, grading is seldom well-developed. Even in the Kirkcolm Group, few examples of perfect grading (Kuenen, 1953b, fig. 1A) are known.

Multiple-grading is the commonest variant, particularly in the coarse-grained greywackes and is well displayed in the greywackes of the Portpatrick Group at the north end of Morroch Bay. This type of grading generally occurs in fairly thick beds (up to 8-10 ft.) which are composed of a number of graded units. These may be of any thickness from a few inches to several feet and are sometimes truncated upwards by a sloping erosion-surface (fig. 27). Frequently the units show interrupted grading, the upper fine-grained portion being absent. A few multiple-graded beds show a gradual upward diminution in grain-size, i.e. the average grain-size of each graded unit decreases upward.

Delayed grading is often developed. The graded bed is usually coarse at the base, medium-grained and ungraded throughout the greater part of its thickness then grades rapidly into siltstone

/within

within the uppermost few inches (Walton, 1956a, fig. 1c). A less common type is medium-grained and ungraded from the base, grading rapidly at the top into a fine-grained portion. In many graded greywackes which apparently lack a basal coarse-grained portion, careful search often reveals the presence of a very thin and impersistent layer of coarse material occupying original depressions in the underlying bed.

Interrupted grading, which involves the absence of the upper, fine-grained part of the bed, is common at some horizons in the Kirkcolm Group.

Inverted grading (Plate XXIVa) is rarely recognised and is probably scarce. It usually occurs in thick, multiple-graded beds and is more common, or conspicuous, in the pebble-bands within thick greywackes.

Probably the most characteristic type of grading in these rocks is the rather unusual form in which the basal few inches are medium-grained, ungraded, and are followed by a coarse layer which grades slowly upwards. This is similar to Ksiaskiewicz's pen-symmetrical grading (1952, fig. 2e).

Laminated bedding: Many beds of greywacke are laminated. The laminae are generally quite thin (0.2-2 inches, on average) and are discernible by reason of differences in colour and/or

/grain-

grain-size. Alternating laminae may consist of coarser, usually light-coloured, material and darker fine-grained greywacke or silt. Even in fairly coarse greywackes there may be thin laminae of dark silt or clay. These layers are usually completely parallel and are seldom of equal thickness, one grade - either coarse or fine - usually predominating over the other.

Lamination is most frequently observed in the fine-grained upper portion of graded beds and may comprise more than half of such beds. At the top current- and convolute-bedding are often developed.

On the other hand, some beds of greywacke are laminated throughout; the laminae tend to be rather impersistent laterally. Occasional beds, laminated throughout, show a gradual decrease in grain-size upwards (cf. Ksiaskiewicz, 1952, fig. 3a).

Many of the mudstones and siltstones are finely banded or laminated, the layering normally being attributable to the interposition of highly argillaceous filaments in material of coarser grain. Such rocks often exhibit intricate folding and faulting on a microscopic scale. In many instances the plications appear to be penecontemporaneous with deposition since the upper limit of the contorted band is usually an unfolded erosion-surface.

/Scour-fill

Scour-fill and erosional structures: Many beds of greywacke are irregular at the base with evidence of local erosion, whereas the tops are usually regular, merging imperceptibly into shale or siltstone. The basal irregularities range from minor depressions to large scoured-out hollows several inches in depth. They are best developed where a greywacke of moderate grain-size lies on a mudstone or shale. In some cases tongue-like wedges of the greywacke have forced apart the laminae of the underlying lutite band and in section these wedges may appear as isolated lenses.

These scour-fill structures and larger "wash-out" structures are common in the Corsewall rocks, especially at the base of the conglomeratic bands (fig. 28 and Plate XXIVb) and, to a lesser extent, in the Portpatrick greywackes. The infilling greywacke is only rarely current-bedded.

The coarsest material of the greywacke is often found in these hollows. Basal pebbly layers appear to have filled in the irregularities first of all then to have spread evenly so that the upper surface of such layers is approximately horizontal (fig. 29). Likewise, the infilling greywacke may be laminated, the laminae being parallel to those in the upper part of the bed.

Scour-fill and associated erosional structures also occur within beds of greywacke but are often difficult to detect, except

/where

where the underlying greywacke is laminated. Such structures are most conspicuous at the base of the intrastratal pebble-bands which are a characteristic feature of the Portpatrick rocks. An interesting related feature of these beds is the occurrence of mound-like piles of pebbles which have accumulated above certain of the scour-fill hollows (fig. 30). These serve to emphasize that truncated laminae are the only reliable indication of an erosive structure.

Evidence of erosion is also frequently found in the laminated siltstones and mudstones. In this instance the coarser infilling material is generally current-bedded.

Slumping: Demonstrable occurrences of intraformational slumping are comparatively rare in the Rhinns. There are several horizons where beds of greywacke consist of a melange of twisted and rotated blocks but many such beds are referable to some tectonic dislocation. Where it has been noted, the slumping has been confined to a single, rather thick bed of greywacke. Such a bed is usually banded or laminated and this reveals the internal folding which in most cases is relatively minor. However, in some beds the bands of greywacke are completely disrupted and twisted into "balled-up" forms (fig. 31). There is often some degree of internal thrusting and the convolutions are usually

/beheaded

beheaded by the overlying, undisturbed, bed.

Where determinable, the axes of these internal folds are of very irregular orientation and appear to bear no obvious relationship to the local current-direction. Some slumped beds may be followed along the strike for several scores of yards and are observed to thicken and thin in a very irregular manner. There appears to be little doubt that such beds have moved while unconsolidated, possibly through gravity-sliding, and have yielded by plastic deformation.

B. DIRECTIONAL STRUCTURES

(1) Upper-surface structures.

See appended paper "Ripple-mark in the Rhinns of Galloway".

RIPPLE-MARK IN THE RHINNS OF GALLOWAY

By

GILBERT KELLING

(to be published in Trans. Edin.
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 - (a) General
 - (b) Transverse ripple-mark
 - (c) Complex ripple-mark
 - (d) Longitudinal ripple-mark
- III. CONCLUSIONS

Abstract

In a typical greywacke-siltstone lithology of Ordovician age, ripple-marks of several types were encountered. Besides typical asymmetrical current-ripple-marks, complex and interference-ripple-marks occur. Other ripple-like structures were longitudinal with respect to the current-direction and it is demonstrated that these are best regarded as true ripple-forms.

The morphology, internal structure and lithological settings of these ripple-marks are described and inferences are drawn as to their mode of origin and the role of current-action in the formation of the sediments which contain them.

I. INTRODUCTION

Ripple-mark¹ is seldom mentioned in descriptions of rocks of the greywacke facies and their typical sedimentary features. Indeed, it has been stated in several general papers that the rarity of ripple-mark in these rocks is one of the characteristics of the greywacke suite (vide Bailey, 1930, Pettijohn, 1943). However, Kuenen (1953a) noted that ripple-mark, usually observed in sectional view, sometimes occurs in the siltstone fraction at the top of beds of graded greywacke. He described them as small-scale asymmetrical, current-formed ripples and, in a later paper (1953b), commented on their abundance and their use as indicators of current-direction.

Walton (1955) in an account of Silurian greywackes in Peeblesshire, gave a brief description of ripple-marks exposed in plan and, in 1956, described ripple-marks seen in section.

Ripple-mark is abundant in the greywacke-suite rocks of Ordovician age in the Rhinns of Galloway and the various forms present are described in this paper.

Ripple-marks were most frequently seen in sectional view but may also be seen in plan on numerous bedding-planes. In confirmation of Kuenen's observations, it was found that ripple-mark

/commonly

¹Throughout this paper the use of the singular ("ripple-mark") denotes the general form, whereas the plural ("ripple-marks") refers to specific examples of the form (cf. Kindle and Bucher in Twenhofel, 1932).

commonly occurs at the top of graded greywackes, but it was also observed within virtually ungraded greywackes and also, though in rather different forms, in the inter-bedded siltstones and mudstones.

Moreover, load-casts found on the base of some beds of greywacke were morphologically very similar to ripple-marks of various types (Kelling and Walton, 1957) and must be included in any description of these structures.

II. DESCRIPTION OF RIPPLE-MARKS

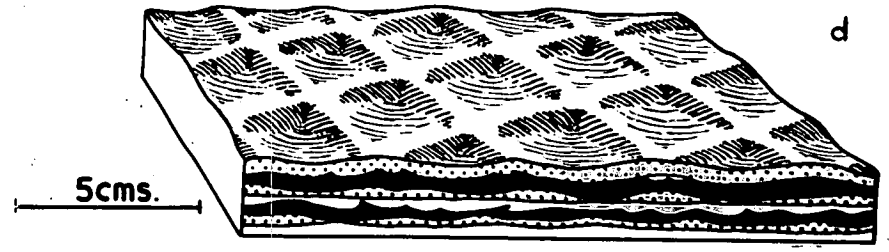
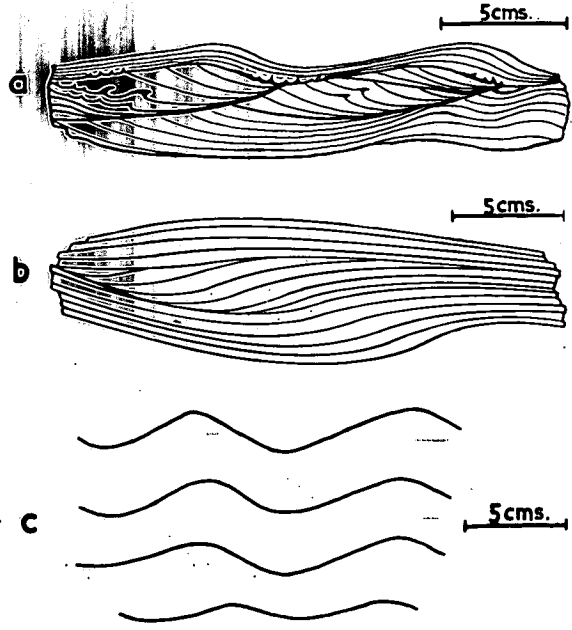
(a) General. In the following account, only those ripple-marks exposed in plan on bedding-planes have been considered. Those observed only in section are neglected because of the difficulty of determining their precise orientation.

Ripple-marks were assigned to one of the three groups (transverse, complex, longitudinal) according to their orientation relative to the local current-trend, which was independently determined from other oriented sedimentary structures, preferably current-bedding, but also flute-casts and groove-casts. It was found that ripple-marks in each of these groups had a distinctive morphology which, in the absence of other more reliable evidence, can often be used to determine current-direction.

(b) Transverse ripple-mark. This was the most abundant type of ripple-mark encountered. Compared with the other forms, transverse ripple-marks are of relatively large dimensions, the

/wave-length

Fig. 1



wave-length ranging from 2.5 to 26 cms. with an amplitude of from 0.5 to 4.0 cms. (in undeformed ripples) and an average ripple-index of 7.5.

Generally, they are asymmetrical, with the typical profile of a current-ripple (fig. 1), and frequently crest and trough are equally rounded. However, some examples have nearly symmetrical profiles and some have fairly sharp crests, with wide, shallow troughs.

In plan, transverse ripple-marks are sometimes continuous, parallel ridges extending for many feet across an exposure with no original break. Such ridges often bifurcate rather irregularly, with short "cross-bars". However, most of the ripples observed were discontinuous in plan (Plate Ia), sometimes even tending towards linguoid. In discontinuous ripples, the ridges are interrupted at irregular, short intervals by slight embayments, which generally encroach from the adjacent trough into the steep or lee-side of an asymmetrical ripple, producing a sigmoid pattern. Such a pattern may result from turbulence in the current which formed the ripples (McKee, 1954, p. 60).

Transverse ripple-mark generally occurs in the silty top of graded greywacke beds, but in the Rhinns it is found in other positions also (cf. Walton, 1956, p. 265). For example, the ripple-marks found in a small quarry on Craigoch Moor and at the locality north of Lady Bay occur in two-foot bands of coarse-

/grained

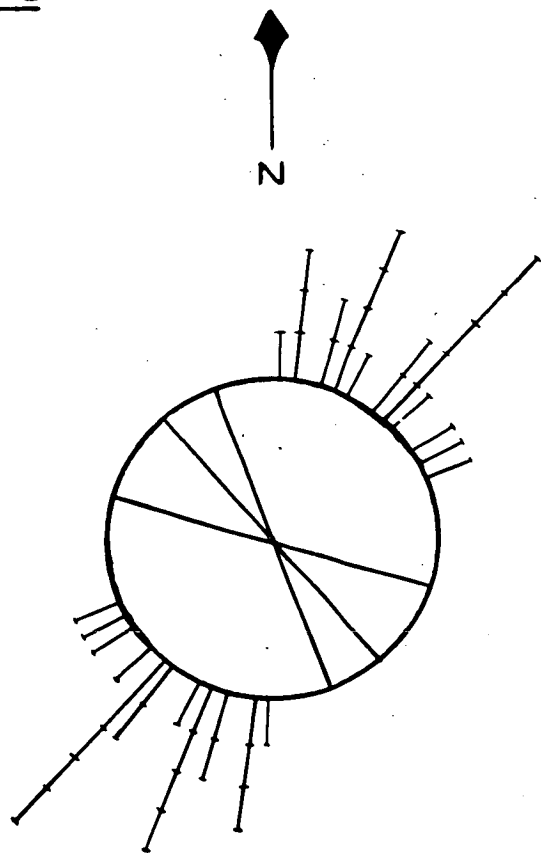
grained, well-laminated siltstone, sandwiched between thick beds of ungraded pebbly greywacke. At Port Logan, transverse ripple-marks are found in the fine-grained top portions of poorly-graded laminated greywackes. Similar ripples also occur in the fissile siltstones interbedded with the greywackes; sometimes the whole bed of siltstone, up to a foot thick, may be ripple-marked, or else only part of it is marked in this way.

In general, the transverse ripple-marks found in siltstones differ from those found in greywackes in possessing a small amplitude and a larger ripple-index.

The ripple-ridges generally trend at about right angles to the local current-direction, but may show deviations of up to 20° - 30° from this orientation. Moreover, although the crests are commonly fairly straight, they sometimes have a sinuous trend, which also produces deviations of up to 25° from the rectilinear position (cf. Kuenen and Sanders, 1956, p. 666).

At Port Logan, several bedding-planes carrying transverse ripple-marks are exposed, and while the orientation of the ripples on one surface remains fairly constant, the trend is very variable from one bed to another. Within the fifty feet or so of sediments examined, the maximum variation is about 50° . Strong groove-casts at the base of some of the ripple-marked greywacke beds show a similar variation, indicating that the diversity of trend of the ripples is a reflection of changes in the current-direction (fig. 2

Fig. 2



In common with the other forms, but in a rather more spectacular manner, transverse ripple-marks often exhibit signs of penecontemporaneous deformation in the accentuation of troughs and crests and the over-steepening of component laminae. This may result in the production of rows of isolated elliptical hollows, occupying the original troughs. This early stage is well illustrated by the ripple-marks found in greywackes at the mouth of the Geldenoch Burn. As deformation continues these hollows coalesce and become deepened, while the crests become constricted and steepened. The final product of prolonged or intense deformation is a ripple-form exaggerated in the vertical sense, with wide bulbous troughs and narrow pointed crests. This form is found, as casts, on the base of beds of coarse-grained greywacke which are in contact with a ripple-marked siltstone layer.

From this, and other evidence (Kelling and Walton, 1957), it seems highly probable that the basic cause of this type of deformation is unequal loading of a layer of unconsolidated silt or mud, with surface irregularities (e.g. ripple-marks) by a layer of coarser and denser material (the greywacke), with induced diapiric flowage of the less dense silt into the crests and concomitant flowage of the greywacke into the troughs. Consequently, the structures are termed transverse-ripple load-casts.

Calculation of the ripple-index for undoubted transverse-ripple load-casts gives an average value of between 2 and 3, compared with a mean value of 7.5 for the normal transverse ripple-marks.

Except in the case of load-casts, the internal structure of this type of ripple-mark is normally well-preserved and readily examined. In general, these ripples consist of a series of current-laminated units superimposed one above the other and separated by minor planes of erosion. Individual laminae may vary in thickness from about 1 to 6 mm. and such variations may occur in one ripple-unit.

Examination of a specimen such as that illustrated (fig. 1a and 1b) reveals the mode of formation of these ripples. It is evident that, like normal current-ripples, more deposition has occurred over the crest or on the lee-side of it, producing thickening of the laminae at these points. In the specimen illustrated, the laminae consist of layers of coarse and fine-grained siltstone, separated by thin films of dark mudstone. There is no appreciable general change in grain-size across the depth of the specimen (2 inches) although coarser layers occur irregularly, mainly in the upper part, and these tend to slope more steeply than the others.

An interesting feature of this specimen (fig. 1a) is the presence of numerous tiny flame-structures, projecting upwards from some of the thicker films of mudstone. The superjacent laminations pass virtually undisturbed across the flame-structures confirming the view that deformation was almost simultaneous with deposition of the overlying coarser material, occurring before tractive forces could produce the lamination.

(c) Complex ripple-mark. Under this heading are included interference ripple-patterns of all types. To the best of the author's knowledge, ripple-mark of this type has not hitherto been recorded from rocks of the greywacke facies, although Walton reported that the crests of asymmetrical current ripple-marks in the Linton region of Peeblesshire were "partly broken by interference" (Walton, 1955, p. 331).

Load-casts with a typical interference-pattern were first found in greywackes south of Binks, near Lawick (Kelling and Walton 1957, Plate 1b) and shortly afterwards true interference ripple-marks were discovered by the present writer at the High Barbeth locality. Since then, further examples have been found in the Rhinns, but apparently this form of ripple is of relatively rare occurrence in the greywackes.

Complex ripple-marks occurring in the Rhinns may be divided into two principal types:

- (i) Compound ripple-mark, produced through modification of a pre-existing set of transverse ripples by a superimposed series of current-ripples, the latter presumably belonging to another, later phase of current-action.
- (ii) True interference ripple-mark, formed during a single phase of current-action and by one complex current (see below).

There is considerable variety in the form assumed by the compound ripple-marks. The examples at Port Logan display several stages in the modification mentioned in (i) above and here the

/superimposed

superimposed current-ripples appear to have been grafted on to the stone-sides of the earlier forms. Later stages show some broadening of the first ripple-crests, producing a very crude cellular pattern. In most cases the trend of the superimposed or later ripples is at about 90° to that of the earlier pattern. Similar modification may be seen at Lady Rue, north of Lady Bay.

True interference or cross-ripple marks were best observed at High Harborth. Here, on the top surfaces of beds of poorly graded greywacke and exhibiting considerable variety of form and dimension such ripple-marks are common. On some bedding-planes they are the only form of ripple-mark, while on others they lie in the troughs of large current-ripples.

In both cases the pattern consists of roughly rectangular cells formed by the intersection of two sets of ridges at about right angles to each other. However, where interference ripple-marks occur along the width of the cells and the height of the ridges are considerably greater than in the equivalent form associated with transverse ripple-marks. Interference-ripples of the latter type often display the characteristic "Stapel's nest" appearance (Mindle, 1917, p. 35).

The crests of some of the larger interference ripple-marks appear to pass into symmetrical transverse ripple-crests of small scale (cf. Mindle, 1917, Plate XIII), and in this case such crests are oblique to the trend of nearby large current-ripples.

Generally, both sets of interfering ridges are equally developed and are nearly symmetrical or slightly asymmetrical in profile. The crests of the larger interference ripple-marks are usually rounded, while those of the smaller "trapezoid" variety are often angular.

In all the examples observed at High Lerbeth, whether large or small-scale, the orientation of the two principal sets of ridges remains remarkably constant at around 135° - 150° and 50° - 70° respectively. The current-direction (from 20°) inferred from the orientation of the transverse ripple-marks, bisects the two trends given above.

Examination of the internal structure of these ripple-marks from High Lerbeth throws some light on the problem of their origin. Unlike the other complex forms, described above, which contain numerous cross-cutting laminae and erosion-surfaces, the true interference ripple-marks reveal no trace of erosion, except at the surface of the bedding-plane. The crests, apparently, have been created by thickening of successive individual laminae (composed of coarse-grained siltstone) and this is the case even at the junction of two crests (fig. 3).

It is clear from this that these are strictly depositional structures and there can be no time-lag between the formation of the two sets of ripple-marks, as there is in the other complex forms previously described.

/rurtner

Further evidence for this simultaneous origin is evinced by the similar degree of development of both sets of ridges and the constancy of their orientation. It appears unlikely that a later, interfering current would maintain a constant direction and intensity equivalent in each case of that of the current forming the initial ripples. It may be that these ripples are, in effect, the resultants of one current acted upon in an oscillatory manner by external forces, as yet unknown, which remained constant throughout the duration of current-flow.

Kindle and Bucher (in Twenhofel, 1932) maintained that interference-ripples were formed either by the resolution of ordinary waves into two sets of interfering oscillations, or by sharp changes in wind-direction which form wave ripple-mark at an angle to the original trend.

The examples described above probably belong to the first group, but it seems improbable that they were formed by normal wave action. They rather appear to be the products of one complex current and are closely related to transverse ripple-marks, into which they sometimes merge.

However, the nature of the forces producing break-up and oscillation in this current cannot, as yet, be determined. The presence of "tadpoles' nests" in the troughs of large current-ripple-marks suggest that configuration of the bottom may play a leading role in this process, but this alone cannot explain all the associated features.

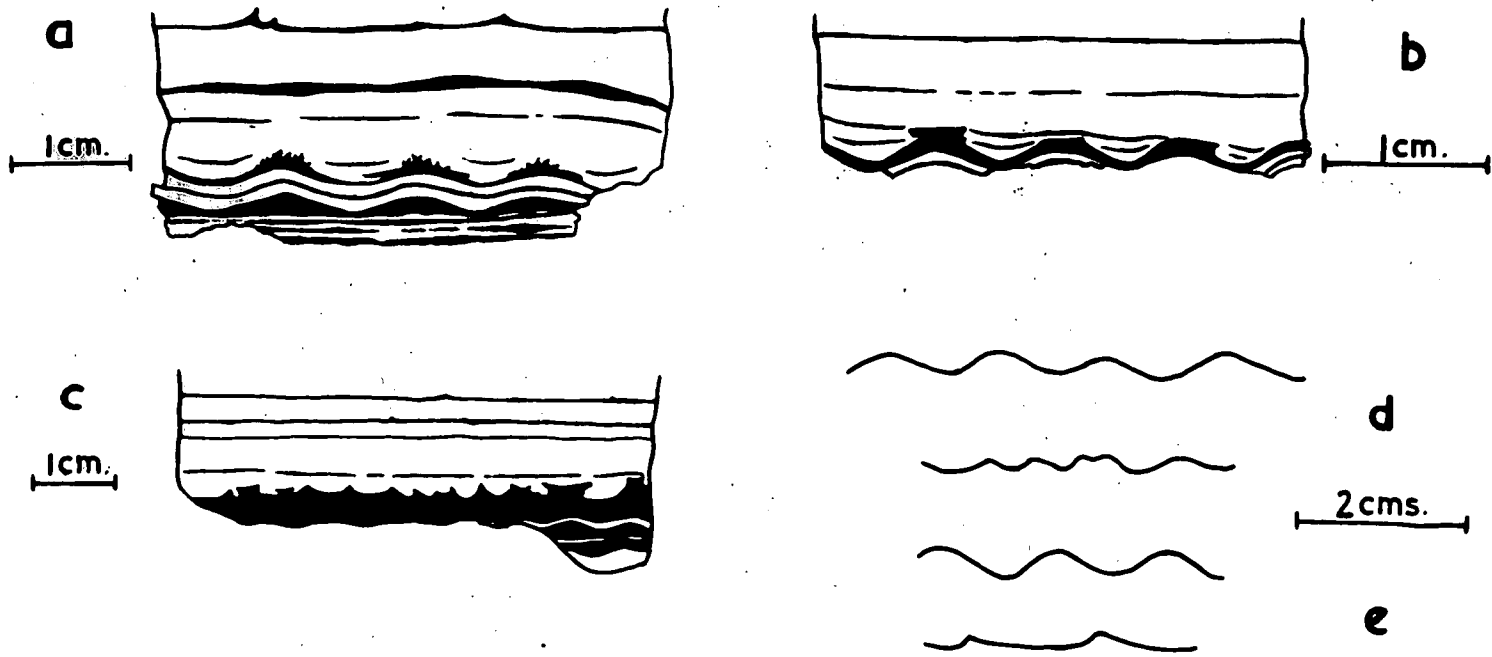


Fig. 3

(d) Longitudinal ripple-mark. Van Straaten (1951) first discovered ripple-marks of this type on tidal flats of the Dutch Waddenzee, where they usually occur in mud, sometimes in sand. He noted the remarkable straightness and parallelism of their crests, the equal rounding of crest and trough, their wave-length of 15-60 mm. and ripple-index of 10-12. It was suggested that they were the products of erosion rather than of deposition, and that they resulted from the interplay of wind-waves and a constant current, in shallow water.

Two years later van Straaten (1953) supplemented his previous observations and introduced a new type, designated "longitudinal wave-current-ripples". The material forming the crests of these ripples, it was thought, accumulated by the oscillation produced by wave-action on pre-existing transverse current-ripples.

All the examples of longitudinal ripple-like structures observed in the Rhinns are of relatively small dimensions, the wave-length ranging up to about 2.5 cms., exceptionally to 5 cms., the amplitude between 0.25 and 1.25 cms. Many conspicuous examples occur as casts, frequently load-casts, on the soles of greywacke beds, but the "originals" or counterparts were also found occasionally, and from these it was usually possible to obtain some idea of the genetic process.

There are two main types of these structures, each with its characteristic morphology. In the first type the profile is

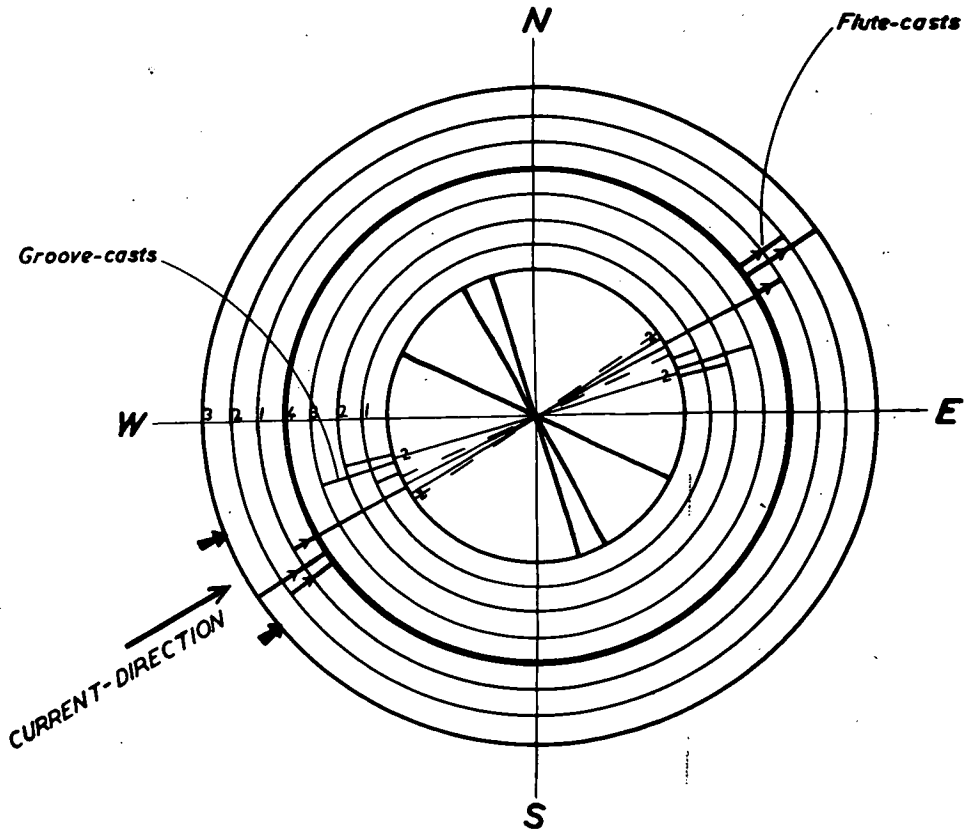
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sigmoidal, crests and troughs being equally rounded (fig. 3 a) and usually symmetrical. Occasionally the crest is actually wider than the trough (fig. 3d). In the other form, the profile is regular, with narrow, angular ridges separated by much wider, relatively flat troughs (fig. 3e). The crests of this type are usually symmetrical; occasionally they are slightly asymmetrical.

In plan, ridges of both types are regularly spaced, often slightly sinuous (Kelling and Walton, 1957, Plate 1c), but always parallel. Structures of the first, or "corrugated" type rarely show branching, whereas the ridges of the second, or "mud-ridge" type frequently bifurcate and always, as Kuenen pointed out, the confluences point downstream. Both types have been observed to pass into and out of a crude cellular pattern of ridges, resembling interference ripple-mark.

On some surfaces carrying "mud-ridge" structures, there is a chevron-pattern of tiny hollows which splay outwards from either side of each mud-ridge, the chevrons "vee-ing" upstream as determined from nearby independent evidence of current-direction. Each of the hollows is about 5-6 mm. long, and has the shape of a very elongate tear-drop, the maximum width of about 1 mm. being attained at the distal end. Most of these hollows end in a tiny ovate pit, often deeper at one end - the down-current end. Such minute "pock-markings" also occur profusely in the troughs between the mud-ridges, and occasionally some of these pits contain grains

Fig. 4



of sand. It is evident that such pock-markings are the result of deposition of sand-grains from a sand-laden current running over a surface of mud, chevrons being formed where the grains grooved the sides of mud-ridges.

The ridges of these presumed longitudinal ripple-marks are always parallel to the local current-direction, with minor local deviations. Where both varieties occur at the same locality, they are always nearly parallel to each other.

This structure apparently is formed in fine-grained sediments. And generally, it is visible only where a greywacke lies on top of such a sediment and subsequent deformation has produced load-casts. The mud-ridge type appears to form only in poorly-laminated mudstone, whereas the corrugated type usually occurs in well-laminated fine-grained siltstones.

Several instructive examples have been found, which show the internal structure of these ripples. Most of these are of the corrugated type, since the mud-ridges seldom show details of their internal morphology.

The internal structure of the corrugated type is illustrated by one of the figured examples (fig. 3a) which represents both the ripple-marked siltstone and the overlying coarse-grained siltstone. The ripple-marks appear to have originated as regular undulations in the alternating laminae of fine-grained siltstone and mudstone forming the base of the specimen. These undulations appear to

originate in a thin, irregular layer of mudstone. Erosion, which must have preceded deposition of the coarse siltstone, has removed some mudstone from the troughs of the ripple-marks. Laminae of the siltstone infilling the troughs are slightly down-arched.

From this typical example it seems clear that the corrugated type of longitudinal structure is largely of depositional origin. The evidence of slight erosion and of the down-arched laminae precludes any possibility of a compaction-deformation or tectonic origin. Moreover, many of the laminae of the ripples are covered with numerous flakes of mica and this must be regarded as further evidence of depositional origin, since the siltstones are quite unmetamorphosed.

In some cases, the troughs of the original undulations may have been partly filled by homogeneous mud, traces of which remain only on the crests of the ripples, having been eroded from the troughs (fig. 3b).

The close affinity between longitudinal and transverse ripple-mark was noted by van Straaten (1951, p. 53 and fig. 4) and has also been observed by the author on the modern beach in Knock Bay on the Rhinns. G. Y. Craig and E. K. Walton (personal communication) have furnished the writer with two interesting examples of this inter-relation.

The first occurred on the modern beach near Carsethorn, Kirkcudbright, where longitudinal ripples were observed in patches of fine-grained sand. These ripples had a mean amplitude of about

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0.3 cms. and a wave-length of 2-2.5 cms. They were symmetrical or slightly asymmetrical, with rounded or slightly pointed crests, which occasionally bifurcated. On the margins they were broken and passed into transverse current-ripples which had wave-length of 7.5 cms. and amplitude of 1.5 cms.

The second example was observed on the base of a greywacke bed in Fauldbog Bay, Borgue, Kirkcudbrightshire. Here, rather poorly-developed load-casts of longitudinal ripple-marks occur on the same surface as load-casts of transverse ripple-marks, the trends of the two sets of ripples being mutually perpendicular.

It seems appropriate to discuss here the distinction between longitudinal structures of the type described above and other structures, such as grooves, flutes, their casts and load-casts, which also occur on greywacke soles and are cut into the underlying fine-grained sediments.

The fundamental difference, of course, lies in the respective origins of the two types of structure. Ripple-mark owes its origin, whether depositional or erosional, to the flow of water over a bottom of unindurated sediment, whereas grooves and flutes are thought to be formed by the erosive action of a sand-laden current over a bottom of fine-grained sediment. However, this distinction is true only of the more extreme forms of either process. Some structures may be produced by a combination of both processes, the sediment moving partly by saltation and partly by suspension.

In the field these longitudinal structures are readily distinguished from grooves and groove-casts, for the grooves are large, widely-spaced and of irregular depth, whereas the ripple-like structures are small, regularly and closely-spaced and of uniform height. However, some confusion may arise between elongated flute-casts and casts of the longitudinal structures, since they may appear rather similar, externally. Here the concept of time of formation is valuable.

As indicated above, flutes are believed to be cut into soft fine-grained sediment through the erosive action of a turbulent current carrying greywacke material which is later deposited. But ripple-marks, by definition, are created by water-flow and, if they occur in the mudstones and siltstones immediately underlying a greywacke, must have been formed at some time prior to the advent of the current which deposited the greywacke material.

Such ripple-marks may be modified by erosion and buried under the greywacke but provided some trace of the original internal structure remains, as it does in the case of the corrugated longitudinal structures, the time-relations are clear - the structure was formed before the advent of the currents which deposited the greywacke - and there can be no confusion with flutes and flute-casts.

The mud-ridges, however, pose a real problem. There is no evidence of their true internal structure and, even if there were, if they are erosive in origin, they will be morphologically similar

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to elongated flutes and flute-casts. In such a case the time-factor is all important. Were these ridges formed before, during or after the erosive phase of the current which deposited the overlying coarse material?

Kuenen (1957) suggested, tentatively, that a pattern which greatly resembles the mud-ridges of the Rhinns was formed through scouring of a muddy bottom by a turbidity-current, with exaggeration of the remaining ridges of mud by subsequent load-casting. This would imply that formation of the ridges was during the erosive phase of the current. However, such an origin seems unlikely. Kuenen admits that it is the ridges, not the troughs (or original scour-pattern) which are dendritic and bifurcate - a very improbable situation if scouring was the chief factor.

Again, if the scouring were of the type normally associated with the structures which are obviously erosive in origin, such as the flutes, one would expect the scoured-out hollows to commence at one point and splay outwards in a down-stream direction, in which case the confluences of the ridges so formed should point upstream. In fact, the confluences of the mud-ridges point downstream. Moreover, the regular spacing of the ridges, their constant height, the near-planar nature of the troughs together with their great width in comparison with that of the ridges, all militate against this hypothesis of scouring.

/Again

Again, the presence of the pock-markings is evidence that the mud-ridges did not form after the erosive phase (although, as Kuenen suggests, there may well be exaggeration of the structures by load-cast deformation), and in fact this strongly indicates that they antedate the scouring action of the current. It is highly probable that the ridges were formed before scouring began, since they have been furrowed by sand grains in the process described above. While this evidence is not entirely unequivocal, it is considered to be strong prima facie evidence for the early formation of these ridges. This being so, it is submitted that such structures as these, together with the corrugated longitudinal structures are best designated longitudinal ripple-marks.

Kopstein (1954) in the course of work in the Harlech Dome of N. Wales found ripple-like structures, parallel to the current-direction, occurring in fine-grained sediments, which he described as "pseudo-ripples" of tectonic origin. In several respects the description of these ripples is highly reminiscent of the "corrugated" type of longitudinal ripple-mark, from the Rhinns.

Describing convolute lamination from the Appenines ten Haaf (1956) noted ripple-marks showing longitudinal patterns. These had been formed, not by foresetting as in transverse-current-ripples, but by a continuous undulating lamination.

Kuenen and Sanders (1956) described indistinct ripple-marks, the long axes of which were parallel to the current. They

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suggested that these ripples might be analogous to longitudinal sand-dunes, since their internal structure indicated transport parallel to the long axis. The partly depositional origin of such ripples was thought to render them distinct from the longitudinal ripples of van Straaten which are thought to be products of erosion alone.

In a recent synoptic paper Kuenen (1957) mentioned and figured (his fig. 22) a curious pattern consisting of a number of sub-parallel confluent deep furrows on the sole of a greywacke, such furrows being the counterparts of ridges which must have been formed in the mudstone on which the greywacke lies. Such ridges apparently trend parallel to the current.

Sujkowski (1957) in an account of the Carpathian Flysch describes a form of ripple-mark "in which each lamina is bent into a wavy pattern, like a sheet of corrugated iron. All the laminae remain strictly parallel throughout the thickness of the bed". He claimed that the whole layer had the appearance of a single unit, deposited in one body of moving water.

From the foregoing summary it will be seen that ripple-like forms, with longitudinal trend, and occurring in greywacke-type rocks, have been observed by a number of writers. Hitherto, however their significance appears to have escaped the notice of most observers. These forms are evidently of two types. First, the longitudinal structures formed by continuous undulating laminations

(ten Haaf, Sujkowski, Kuenen and Sanders). Second, the mud-ridges of Kuenen (1957). Such a conclusion accords with the evidence presented above.

Mention must be made of some structures bearing a superficial resemblance to the mud-ridge type of longitudinal ripple-mark, but which are very probably of tectonic origin. These take the form of small ridges of mudstone, narrow and very straight, or the equivalent casts in overlying greywackes. They occur only in regions where the fine-grained beds show marked cleavage or strong jointing, and their orientation is almost always parallel to that of the trace of the cleavage or jointing on the bedding-planes.

Careful examination of these "pseudo-ripples" often reveals small cracks, sometimes quartz-filled, extending downwards from the ridges into the underlying mudstone. Moreover, the usual adjuncts of normal mud-ridges are always absent from these structures - chevrons, pock-markings, evidence of erosion. Their trend is generally at variance with the local current-direction. Consideration of all the evidence strongly indicates that these "pseudo-ripples" are formed tectonically.

III. CONCLUSIONS

The transverse ripple-marks present little difficulty as regard origin. They originated through the action of a unidirectional
/current-

current-flow which in many cases must have been persistent throughout a fairly long period of time - sufficiently long, at least, to form several generations of ripple-marks up to a maximum thickness of 20-30 cms.

The frequent occurrence of this type of ripple-mark in the siltstone fraction at the top of beds of graded greywacke has been cited as evidence for the creation of the ripples by the same current which transported the material of the greywacke, and this study has done nothing either to reinforce or to rebut this conclusion. However, it appears that current-activity was not confined to periods of greywacke deposition, since transverse and other ripple-marks also occur in the fine-grained sediments interbedded with the greywackes.

That the currents forming the transverse ripples were not exactly uniform in direction or intensity is attested by the variable orientation and discontinuous nature of any one set of ripple-marks. The more discontinuous forms, approaching linguoid shape, bear strong affinity with the "current-mark" of Kindle (1917) or the "cusp-ripples" of McKee (1954) which, as the latter showed, probably resulted from "irregular and fluctuating streams".

Further evidence for fluctuation in current-strength and direction is furnished by the complex type of ripple-mark in which an earlier set of ripple-marks is modified by a second, later set, which has an entirely different orientation.

On the other hand, true interference ripple-mark, as indicated earlier, must have originated in quite a different way and affords evidence of wave-like oscillations in the currents which produced it.

The rippling characteristics of mud and fine-grained silt would not permit the formation of normal ripple-marks and so longitudinal forms resulted from current-action in this type of sediment. The precise mode of origin of longitudinal ripple-marks remains obscure, but it is possible that the "corrugated" type is but a modification of the "mud-ridges", being produced by the deposition of successive thin layers of siltstone, each of which undulates in conformity with the underlying laminae and with the shape of the surface with mud-ridges. The mud-ridges themselves may be the products of erosive agencies.

The depth of water in which these ripple-marks were formed remains doubtful. Interference ripples have hitherto been regarded as indicative of very shallow water (Kindle, 1917, p. 34 and Kindle and Bucher in Twenhofel, 1932, p. 658), while longitudinal ripple-marks have only been observed on modern tidal flats. On the other hand, Menard (1952) reports oscillation-ripples from the ocean bottom at great depths.

The present study has shown that ripple-marks of several types may occur in sediments of the greywacke suite and that from an examination of their form much can be learnt about the nature of

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PLATE I



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the currents which produced them. It is hoped that in future studies of these rocks more attention may be devoted to ripple-mark

DESCRIPTION of TEXT-FIGURES and PLATE

- Fig. 1: (a) and (b) Cross-sections of asymmetrical transverse ripple-mark to show mode of formation.
- (c) Typical profiles of transverse ripple-mark in the Rhinns of Galloway.
- (d) Cross-section and stylised plan-view of a specimen of interference ripple-mark from High Barbeth.
(See p. 182) Vertical scale x 2.

NOTE. In diagrams of cross-sections of ripple-mark, mudstone is indicated in solid black, fine-grained siltstone in white, and coarse-grained siltstone in stippled ornament. This ornamentation grossly exaggerates the slight differences between the bands.

- Fig. 2: Diagram illustrating variation in trend of a series of transverse ripple-marks from a thin succession of rocks, near Port Logan. Ripples are indicated outside the circle, groove-casts indicated within it (see p. 178).

- Fig. 3: (a)-(c) Composite cross-sections of specimens of the corrugated type of longitudinal ripple-mark.
(a) Slocknamarrow Inlet; (b) Juniper Face;
(c) Black Stot.
Vertical scale slightly exaggerated.
- (d) Profiles of corrugated longitudinal ripple-mark.
- (e) Profiles of mud-ridge longitudinal ripple-mark.

- Fig. 4: Current-rose diagram, Slocknamarrow Inlet. Ripple-mark indicated within centre circle; heavy black lines denote transverse ripple-marks, thin continuous

/lines

lines denote corrugated longitudinal ripple-marks, thin dashed lines denote mud-ridge longitudinal ripple-marks. Numbers on some lines refer to the number of occurrences, if greater than one.

Groove-casts are indicated in intermediate circles, flute-casts in outer circles and current-stratification around the outside circle. The number of occurrences of each structure is given by the number of circles crossed. Readings within 5° sectors are aggregated. (cf. Crowell, 1955).

PLATE I: Types of ripple-mark from the Rhinns of Galloway -

- (a) Discontinuous, near-linguoid current-ripple-mark in siltstone, Craigoch Moor, Portpatrick. (Scale is 9 ins. long.)
- (b) Specimen of true interference-ripple-mark, with rectangular cells, from High Barbeth (x 1/5).
- (c) Specimen of corrugated-type longitudinal ripple-mark, from Slocknemorrow Inlet (x 1/6).

(11) Under-surface structures:

Groove-casts: These are straight, sub-parallel ridges of considerable length. Depth and width are roughly proportional and remain constant along the length of the ridge but are variable in different specimens, from 0.1-3 and 0.2-6 inches respectively (Plate XXVIa). Very small groove-casts, however, tend to be rather impersistent and closely spaced whereas larger groove-casts are more widely spaced and often carry smaller parallel ridges and striations. The ends of such grooves have rarely been observed. The termination is not abrupt but slopes gradually until the groove merges into the bedding-plane.

In the Rhinns most of the deeper grooves are not found at a greywacke-shale contact but rather at the junction of a coarse greywacke and an immediately underlying fine-grained greywacke. Presumably this is related to the greater cohesiveness and consequent resistance to erosion of the clay compared with the granularity of the arenaceous beds (Hjulstrom, 1939, fig. 1).

Cross-sections through groove-casts usually show slight asymmetry (Plate XXXIa) and closely resemble certain scour-fill structures in their erosive characteristics. However, no lamination or current-bedding has been observed within these structures, although there is often an accumulation of coarse-grained material at the base of the hollows.

/Groove-

Groove-casts with a conspicuous "herringbone" pattern in plan have also been observed in the Rhinns (Kuenen, 1957, Plate 2B and C). No adequate explanation has yet been offered for this type of grooving.

On most under-surfaces the groove-casts are virtually parallel and are longitudinal with respect to the local current-direction (obtained from independent sources), but they do not indicate the current-sense. Occasionally, two sets of groove-casts with regularly divergent trends are found. It appears that one of these sets consistently cuts the other and is therefore the later structure (cf. Walton, 1955, Plate IB). Groove-casts are seldom associated with flute-casts or other under-surface structures, but where there is such an association the cross-cutting relationships indicate the priority of the grooves.

Groove-casts were first described by Hall (1843) who attributed their formation to the erosive effects of oceanic currents carrying coarse material. Clarke (1918) submitted that they were formed by the movement of current-borne pack ice on beach deposits.

Kuenen (1957a) recognises two types of groove-cast. The first, termed slide-marks, he explains as the grooves or scratches produced by subaqueous sliding or slumping. These may occur in

/or

or under shales as well as greywackes. The second and commoner type he named drag-marks. Kuenen follows Rich (1950), who modified Shrock's suggestion, assigning these groovings to the dragging of stones or shells, probably attached to algae over a bottom-surface of relatively unindurated silt or mud, the propellant force being turbidity-current.

It is clear that these structures are the casts, in the overlying greywacke, of grooves gouged out of the underlying finer-grained band. Recently Dzulinsky and Radomski (1955) claim to have observed groove-casts with a piece of shale lying at the termination and have concluded that these marks are formed by the propulsion of angular pieces of recently deposited mud over the soft bottom during turbidity current action. However Kuenen (1957, p. 252) rejects this explanation, claiming that the examples they illustrate are of slump or slide-marks. He also points out (loc. cit.) that a soft chunk of mudstone would soon become rounded by abrasion and would then produce a rounded furrow instead of the angular hollows, with striations, which characterize groove-casts. Moreover, he adds, shale-fragments are very seldom found at the base of greywacke beds, although they occur, often in profusion, in the higher levels. It certainly appears that the grooves are much too regular in depth and width to be created in this manner.

The dragging of algal anchor-stones also seems rather an unlikely explanation, particularly for Lower Palaeozoic or earlier rocks. It is difficult to envisage the finely-sculptured striations being formed by this means. Moreover, to the writer's knowledge there is no recorded instance of a large pebble lying at the end of a groove-cast. Rucklin (1938, fig. 10) produced very similar groovings in mud by means of a moderately fast sand-laden current and this mechanism is probably the most significant means of producing grooves.

Grooving action is typical of several types of sediment-laden media moving according to the laws of fluid dynamics. Thus striations and grooves of very similar aspect are produced (on solid rock) by glacier-ice, by landslides and snowslides and even by nuees ardentes. The prerequisite for such furrowing appears to be high density of the scouring medium. The size of the striations is more or less related to the size of the abrading particles but large glacial grooves are known to have been produced by fortuitous enlargement of single striations and it is possible that the large groove-casts described above have arisen in similar fashion, the accessory striations within such grooves being the traces of small enlarging particles. In this way grooving may be assigned to the action of pebbles no larger than

/those

those actually observed in the greywackes (up to 1-2 cms. diameter without recourse to large cobbles which are as yet undetected in these beds.

Flute-casts: (Crowell, 1955). These are nacelle-like structures occurring on many greywacke soles. They range in size from small elongate weals, difficult to distinguish from small groove-casts, to large bulbous projections several feet long and wide (Plate XXVib). An intermediate form is about 2-6 inches long and is typically pear-shaped (cf. Kuenen, 1953b, Plate B 2). The depth of the flutings is generally about one-third of their width but some are much deeper. Almost invariably one end is rounded and deep whereas the other end gradually slopes up to meet the bedding-plane, simultaneously flaring outwards. The greatest depth usually occurs just behind the deep or beaked end so that the lengthwise profile is asymmetrical whereas the cross-section is generally symmetrical. The steep end occasionally has an overhanging lip, usually attributable to load-cast deformation.

Many flute-casts have a corkscrew or spiral form (Plate XXVIIa) while others are twisted towards the deeper end (Plate XXVib). In the corkscrew types observed the spirality is more commonly sinistral than dextral, while the twisting of the other type is apparently random. However, on one surface one sense of spirality or direction of twisting usually predominates.

/The

The surface of these structures is normally quite smooth but there is sometimes an inconspicuous near-horizontal ridging around the steep end which might be considered the external manifestation of a horizontal lamination within the flute-cast. Kuenen (1957, p. 241) has suggested that these fluted steps are the result of slight differential erosion of a laminated mud or silt. However, this was not confirmed in the few cases where observation of the internal structure of such casts was possible.

Flute-casts may occur on the same surface as other sole markings but are generally found alone. They may be isolated (Plate XXVIIb) or in close contact (Plate XXVIb), scattered randomly or arranged in rows which may be parallel (Plate XXVIIa) or oblique to the length of the casts. Usually, all the flute-casts on one bedding-plane are of similar shape and dimensions.

The length of these structures is generally parallel to the local current-direction, with the steep end upcurrent. Occasionally there are forked or conjugate flutings (Plate XXVIIIa, X), only one of which is parallel to the regular trend of the structures and to the current-direction.

Some of the smaller flutings are very elongate and compressed (Plate XXXa) whereas another type is similar to the large flute-casts but is horse-shoe shaped, i.e. the centre of the cast is

/not

not bulbous but inverted, domed upwards (Plate XXVIb, X, and cf. Rucklin, 1938, hufeisen-wulste).

Lamination, but not current-bedding, has occasionally been observed within the infilling greywacke of the flute-casts and coarser grains are often found at the deep upcurrent end. Lamination in the underlying lutite band is often truncated against the flute-casts (Plate XXVIIIb) affording clear evidence of the erosive, gouged-out nature of the flutings.

Rucklin (1938) described this form of structure from under-surfaces of beds in the Muschelkalk. He recognised a series from short, simple flutings (einfache zapfen-wulste), through corkscrew forms (korkzieher zapfen) to large, flattened shapes (flachzapfen). He claimed that these structures could be produced through the action of a sand-laden current running over soft mud. The twisted and spiral forms he attributed to vortices, a conclusion to which Kuenen (1957, p. 240) gives tacit consent.

Maxson and Campbell (1935) have described and illustrated examples of fluting from limestone in the bed of the Colorado river. They ascribed the formation of these structures to the action of a turbulent, rapid, silt-laden stream, the immediate cause of the flutings being small vortices with horizontal axes (see 1935, fig. 4). Occasional corkscrew forms are created by vertical vortices and occur on sloping surfaces.

A similar mode of origin is proposed for the flutings in these ancient mudstones and siltstones, although the process would presumably be very much more rapid in view of the relative incoherence of the uncompactd lutite. Maxson and Campbell also noted that longitudinal grooves were formed where the stream-velocity was high and the bottom relatively smooth. It may be that fluting and grooving are both directly related to the stream-velocity. Longitudinal furrowing apparently occurs in the high-speed phase of current-action, at velocities partly dependant on the amount of material carried in suspension and on the grain-size of the material over which the current is passing, which governs the friction at the sediment-water interface. With decreasing stream-velocity turbulent effects become apparent and local vortices are formed, producing flutings and perhaps destroying, or at any rate, partly concealing earlier grooves. However, under special conditions, the flow may remain relatively smooth till the velocity is lower than the minimum critical velocity for the formation of flutes.

In this connection the apparently consistent priority of the grooves becomes important. The question also arises of the contemporaneity of under-surface markings - grooves and flutings - and the deposition of the overlying greywacke. Dzulinsky and

/Radomski

Radomski (1955) submitted that sole-markings may be created by a bottom-hugging current then left uncovered until a later, non-erosive current deposited the infilling material. On this hypothesis two or more sets of structures, possibly with divergent trends, could be formed by successive erosive currents prior to the deposition of the greywacke.

Kuenen maintains that the nature of turbidity currents opposes the suggestion of separate cutting and later filling by some other agent. He evidently ascribes multiple sets of groove-casts to different phases of the same short period of erosive action during one turbidity current which, with decrease in velocity deposited its load to fill in the excavated grooves and flutings.

It is difficult to envisage the formation of multiple, divergent sets of structures in the manner and within the short period of time postulated by Kuenen, and without the formation of structures with intermediate trends, although multiple point-sources (submarine canyons) for the turbidity-current have been postulated by Crowell (1955) to explain similar phenomena. However, it is equally difficult to see why, if there was a time-gap between formation of these structures and their infilling, there was no apparent flowage of the plastic mud and silt into the depressions, nor why there was no deposition of lutite in the

/hollows

hollows during the intervening period. At present, therefore, the question of the contemporaneity of structure formation and infilling remains unanswered.

A bottom-structure of very rare occurrence in the Rhinns (Plate XXIXa) closely resembles the "cabbage-leaf markings" described by Kuenen, pp. 255-256). Where less extremely developed the bifurcating markings tend to be linear parallel to the current and are reminiscent of the small elongate flute-casts.

Load-casts: See appended paper:

"Load-cast Structures: Their Relationship to Upper-Surface Structures and their Mode of Formation."

Load-cast Structures : Their Relationship to Upper-Surface Structures and their Mode of Formation

By G. KELLING AND E. K. WALTON

(PLATE XVII)

ABSTRACT

The form and distribution of load-casts suggests a genetic connection with structures previously formed on the upper surface of the underlying bed. On analogy with salt-dome development, the growth of load-casts and associated flame-structures is attributed to the density contrast between upper and lower bands and differential loading caused by the projections and depressions formed by the upper-surface features. This hypothesis is the basis of a new classification of load-cast structures.

INTRODUCTION

STRUCTURES occurring on the under-surfaces of many greywackes and sandstones have received considerable attention in recent years and some confusion has arisen concerning their classification (see Prentice, 1956, and Kuenen and Prentice, 1957).

Of frequent occurrence among these structures are those known as load-casts (Kuenen, 1953, Flow casts, Shrock, 1948, p. 156), and these consist of sandy, coarse-grained material forming bulbous pockets which project downwards into the underlying shale. Following Shrock, the formation of load-casts has been generally ascribed to unequal loading of a soft mud by coarser-grained, overlying material. Kuenen (1957) has treated some aspects of this process and in the present paper an attempt is made to carry the analysis a step further.

In addition, curved, pointed tongues of shale, as seen in vertical sections, penetrating into overlying beds of greywacke, have been described as "antidunes" (Lamont, 1938), and "flame-structures" (Walton, 1956a). Lamont was influenced by the work of Taylor (1935 and 1936), impressed by the regular spacing of the structures and their resemblance to antidunes (Gilbert, 1914), but Prentice (1956) and Walton (1956a) doubted this mode of formation. Kuenen and Menard (1952) produced flame-structures experimentally and ascribed their formation to "(1) drag exerted by the turbidity current on the watery clay film of its bed, (2) local settling and squeezing caused by the rapid accumulation of overburden on the highly mobile foundation".

During investigations of the Lower Palaeozoic rocks in the Southern Uplands of Scotland, the authors have been impressed by the fact that load-cast structures constantly exhibit forms which can be correlated with those of upper-surface structures, and by the coincidence of flame-structures and load-casts. This correlation has been

alluded to previously only for individual occurrences. Fuchs (1895) commented on the resemblance of certain mudflow structures, on the lower surfaces of Flysch sandstones, to ripple-marking, but he maintained that there was no genetic connection, and Bucher (1919) suggested that they might be called pseudo-ripples. Lately, Crowell (1955) has noted that "there may be transitions between load-casts and flute-casts" while Kuenen (1957) accounts for some load-casts by the deformation of pre-existing drag-marks and flute-casts. We wish to emphasize that the correlation between previously formed upper-surface structures, load-casts, and flame-structures is a general one. Furthermore, recognition of this leads directly to an explanation of the origin of load-cast structures and clarifies the problem of nomenclature and classification.

UPPER-SURFACE STRUCTURES	TABLE 1	
	UNDEFORMED	UNDER-SURFACE STRUCTURES DEFORMED
		(Flow-casts, Shrock, 1948 Load-casts, Kuenen, 1953)
<i>Group I.</i>		
A. <i>Grooves</i> (Drag-marks, Kuenen and Sander, 1956)	<i>Groove-casts</i> (Shrock, 1948)	<i>Groove-load-casts</i> (in part, torose load-casts, Crowell, 1955) (in part, Korkzieher Zapfen, Rücklin, 1938)
B. <i>Flutes</i> (Flow-markings, Rich,	<i>Flute-casts</i> (in part the flute-casts of Crowell, 1955) (Flachzapfen and in part Einfache Zapfen-wulste, Rücklin, 1938)	<i>Flute-load-casts</i> (Load-casts and in part flute-casts and torose load-casts, Crowell, 1955) (Flow-rolls, Rich, 1950) (Lobate rill-marks, Clarke, 1918) (Einfache Zapfen-wulste in part and Korkzieher-Zapfen in part, Rücklin, 1938)
<i>Group II.</i>		
A. <i>Transverse Ripple-marks</i>	<i>T-Ripple-casts</i>	<i>T-Ripple-load-casts</i> (? Flow-casts, Prentice, 1956)
B. <i>Longitudinal Ripple-marks</i>	<i>L-Ripple-casts</i>	<i>L-Ripple-load-casts</i>
C. <i>Interference Ripple-marks</i>	<i>I-Ripple-casts</i>	<i>I-Ripple-load-cast</i>

CLASSIFICATION

Table 1 summarizes our conclusions and includes the synonyms which, in the light of the relationships discussed below, in our view now become unnecessary. The table does not attempt to cover all the structures described from under surfaces, but only those where load-casts and flame-structures are known to be involved.

In the ensuing discussion it should be noted that the upper surface features referred to now occur *below* the under-surface structures. In order to avoid possible confusion we have used upper-surface consistently throughout in relation to the underlying fine-grained bed, and under-surface features relate to the overlying coarser-grained bed.

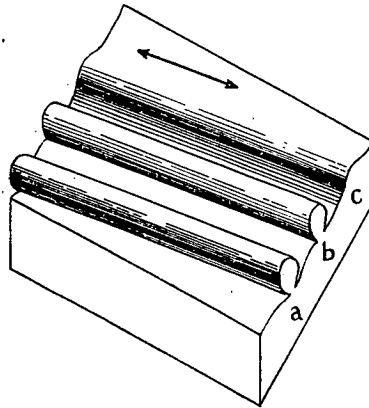
THE FORM OF LOAD-CASTS

Group I.

Load-casts often of large size, elongate; either linear and con-

tinuous, or lobate, discontinuous; usually irregularly spaced; associated flame-structures well-developed.

A. *Groove-load-casts*.—These load-casts are characteristically long and often remarkably straight. They vary in size up to about 1 ft. across and about 9 in. deep. Their similarity to groove-casts is clear and convincing. Text-fig. 1 is a composite diagram illustrating their form as it is often seen in inverted sequences in the Southern Uplands. In this diagram, (a) represents an extreme form of groove-load-cast, with marked indentations and long, slender flame-structures; (b) is an intermediate, and more common form, showing less pronounced indentation and short, stubby flame-structures; while (c) represents



TEXT-FIG. 1.—Groove-casts (c) and groove-load-casts (a) and (b). The structures are parallel with the current which, as the arrow indicates, may be from left or right. Bed inverted.

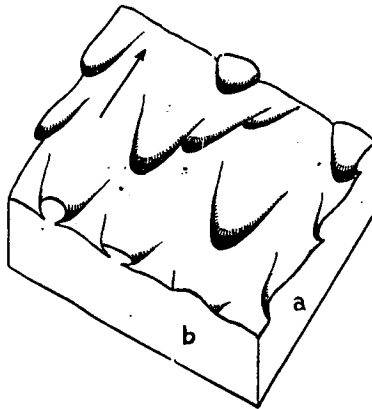
an undeformed groove-cast. Examples have been described from the Silurian rocks of Peeblesshire (Walton, 1955, pl. iA). They are also common in the Ordovician rocks of the Rhinns of Galloway and the Wenlock rocks on the west side of Kirkcudbright Bay.

B. *Flute-load-casts*.—One of the best examples of this type has been illustrated by Pringle and Eckford (1945, pl. ii). The structures have the typical tear-drop shape, with one end deep and bulbous and they become wider and more shallow at the other, the down-stream end. Flute-load-casts show considerable variation in size and shape, with the largest reaching up to 10–12 in. long, 8–10 in. wide, and up to 2–3 in. deep at the “nose”.

Similar structures have been described simply as load-casts by Crowell (1955). The form and distribution of these deformation-structures is such as to leave little doubt of their close relationship

with those similar structures which show no deformation, such as the flow-markings of Rich (1950) and Kuenen (1953*a*) and the flute-casts of Crowell (1955) and Prentice (1956). Indeed, Kuenen (1953*b*, pl. B2) illustrates one surface from the Rhinns of Galloway which shows both undeformed flute-casts and deformed flute-load-casts.

Text-fig. 2 is a diagrammatic representation of these structures showing various degrees of deformation and illustrating in plan and section the forms which may be developed. Undeformed flute-casts are represented at (*a*) and (*b*), all the other structures illustrated being deformed to some extent. The deformation is indicated by the indented form and the occurrence of large flame-structures, which can be seen in both longitudinal and transverse views.



TEXT-FIG. 2.—Flute-casts (*a*) and (*b*) and flute-load-casts. Structures inverted, current from bottom left.

The torose load-casts of Crowell (1955) are of two types. One is similar in shape to the structures above and may be simply a flute-load-cast with the deeper end down-stream. The other type is longer and may have a composite or spiral form. Now, Kuenen (1953) noted groove-casts of similar form so that this second type is one of our Group IA—the groove-load-casts. Rücklin (1938) described short, spiral forms (Korkzieher Zapfen) which we regard as flute-load-casts.

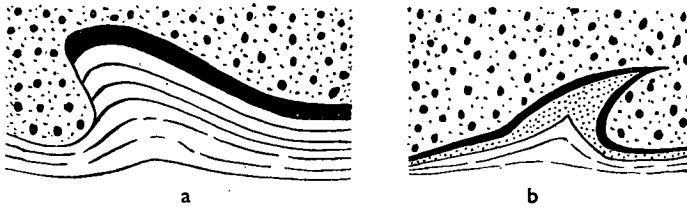
The large flame-structures associated with the flute- and groove-load-casts often provide evidence of the action of both erosion (of the underlying laminae) and of later deformation (of both coarse and fine-grained beds). Text-fig. 3 shows a clear example from the Ordovician rocks of Morroch Bay in the Rhinns of Galloway. The structures illustrated by Walton (1956*b*, fig. 8) show distinctly the squeezing upwards of the fine-grained bands.

Group II.

Load-casts with a regular pattern in plan; deformation often slight, and flame-structures small.

A. *Transverse Ripple-load-casts* (Pl. XVII, fig. 1).—Asymmetrical ripple-marks are a common feature on the siltstones at the top of greywacke beds, but few examples of the corresponding load-casts have been described (see below). One example, where strong indentation is developed, is exposed at Jameson Point, in the Ordovician rocks of the Rhinns of Galloway (Pl. XVII, fig. 1). These structures have a wavelength of 2-3 in., comparable with that of the normal transverse ripple-marks; they anastomose in a similar manner, and the current-direction as determined from associated cross-lamination, is normal to the length of the load-casts.

Prentice (1956) describes as "flow-casts" structures which are developed at right-angles to the prevailing current. This also suggests



TEXT-FIG. 3.—Flame-structures, Ordovician rocks, Morroch Bay, Rhinns of Galloway.

(a) Erosion has preceded deformation, slight thickening later.

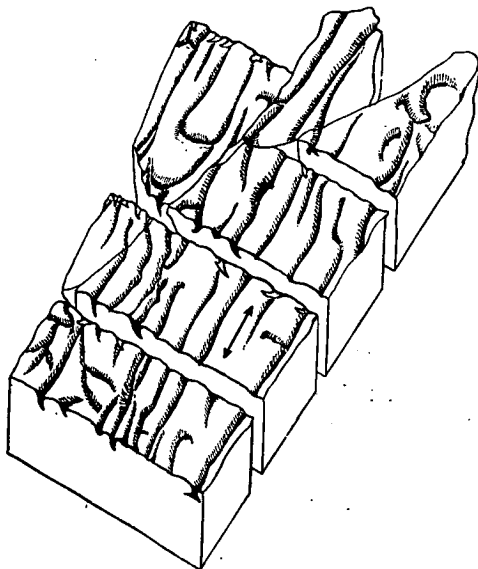
(b) Pronounced thickening of the laminae during the growth of the structure.

The height of the structures is 2.5 cm.

deformation from a surface with transverse ripple-marks. It is our opinion that the use of the term "flow-cast" is undesirable where the structures show a connection with upper surface features. Flowage, as well as downwards-sagging, may have played a small part in the formation of any of the structures described here. Where there has been a great deal of movement resulting in the complete loss of any initial pattern, then "flow-cast" may be applicable, but otherwise the use of a separate term obscures the genetic relationship between the load-cast and the original structure.

B. *Longitudinal Ripple-load-casts* (Pl. XVII, fig. 2).—Structures on many greywackes, siltstones, and mudstones in the Rhinns of Galloway appear to be longitudinal ripple-marks. Details supporting this conclusion are to be given elsewhere (Kelling, in preparation). Of direct interest to the present study is the fact that in many cases flame-structures are developed and it is evident that slight load-casting has taken place.

Text-fig. 4 is based on a specimen from the Hawick rocks, near Binks, Roxburghshire. It shows the under surface with casts of longitudinal ripple-marks while a series of sections reveals flame-



TEXT-FIG. 4.—Longitudinal ripple-load-casts based on a specimen from Binks, near Hawick.

Lower surface shows ripple pattern. Sections show flame-structures, asymmetrical, pointing either to the right or left, and symmetrical. At the top left is a symmetrical flame structure, one limb of which has been turned back on itself. Structures parallel with the current.

Specimen is 30 cm. long. The flame structures have been exaggerated slightly; they average 3 mm. in length.

structures developed in the crests. It will be noted that symmetrical and asymmetrical flame-structures occur and the latter may be directed in different directions even along the same crest.

C. Interference Ripple-load-casts.—An example of this type is illustrated in Pl. XVII, fig. 3, which is also taken from the Hawick rocks, near Binks. The pattern suggests original interference ripple-marks and the section view shows small flame-structures. It is possible that the "flow-cast" illustrated by Shrock (1948, fig. 117) was also developed by deformation of original interference ripple-marking.

THE FORMATION OF LOAD-CASTS

As indicated earlier, the formation of load-casts has been ascribed to unequal loading. The observed form of these structures and their

relationship to upper-surface features leads inevitably to the conclusion that their formation is the result of loading rendered unequal by the presence of original irregularities on the upper-surfaces of underlying fine-grained beds.

In this we may profitably draw an analogy with the development of salt-domes, and particularly germane to this discussion is a series of experiments carried out by Parker and McDowell (1955) who used scale models to investigate the initiation and growth of salt-domes.

Their results show that when a heavier layer immediately overlies a lighter layer then any original upward projection of the lower stratum into the upper tends to produce a state of unstable equilibrium. The weight of the relatively heavy upper layer is less over the upward projections from the lower layer than it is over the intervening parts of the lower stratum. If this difference is sufficiently great then the downward pressure of the upper layer causes the underlying lighter stratum to flow towards the projections which, in consequence, grow upwards in diapir fashion.

Now, in the case of load-casting we have similar conditions in that the lower muddy layer, mainly due to its higher water content, has a lower density than the overlying sandy layer. Figures given recently by Hamilton and Menard (1956) show the probable density contrasts (e.g. coarse sand — 2.08, sand-silt-clay — 1.44), but variations would occur due to differences in the grain-size, composition, and, in the case of the underlying layer, in the amount of compaction. Moreover, if the surface of the muddy layer was characterized by ripple-marks, grooves, or flutes these would provide original irregularities, of the nature of projections and depressions, on the upper surface of this layer. By analogy with Parker and McDowell's experiments it can be inferred that, after the accumulation of a sufficient thickness of the overlying sediment, there would be flowage of the muddy sediment towards relatively elevated crests and concomitant movement of the sandy material into the depressions.

In this way flame-structures would inevitably be developed from the upward-flowing mud, and load-casts would grow by sinking and slight lateral movement of the coarse-grained overburden in the original depressions. One puzzling feature of flame-structures is their pointed nature in contrast to the rounded tops of salt-domes. Load-casts associated with grooves and flutes often attained a considerable size because of the initially large dimensions of these depressions, whereas those associated with ripple-marks generally exhibit a smaller amount of growth, related to the lesser dimensions of the ripple-ridges. Transverse and interference ripple-load-casts are, apparently, rather rare and this may be due to the slightly different densities of the sediments in which they were formed.

Parker and McDowell found that growth of the domes was stopped most effectively by increasing the thickness of the overburden and this may well have been the determining factor in the cessation of growth in the load-cast structures.

Experiments with sand and mud layers have been begun in the Grant Institute of Geology in an effort to establish the relative importance of the various factors involved in the growth of flame- and load-cast structure.

DIRECTIONS OF THE FLAME-STRUCTURES

Reference has been made to the tendency for flame-structure to be pointed obliquely upwards constantly in one direction. This suggested to Lamont (1938) an origin as antidunes, while Kuenen and Menard (1952) and Kuenen and Prentice (1957) suggested that the drag involved during deposition from a turbidity current would tend to pull over the shale projections.

The examples described above invalidate the antidune hypothesis. It has been shown that when the structures seen in section are examined in plan, they show only rarely the regular crests transverse to the current, and, moreover, regular spacing if present is readily explicable on the basis of their derivation from ripple-crests. These criticisms apply to the interpretation of flame structures as the antidunes of Gilbert (1914). Dr. Lamont kindly showed us the manuscript of his current paper in this journal and it appears that he uses the term "antidune" in a different sense. Some flame-structures have been formed in the way he suggests, by concomitant scouring and filling (see Walton, 1956*a*, fig. 7). Recently Dr. D. A. Bassett and one of us, have found such examples of scour and fill in the Cambrian Hell's Mouth grits in North Wales. However, the majority are connected with "load-casting".

It would appear, also, that though current-drag may be a contributory factor, it is not the only one. This is particularly the case where flame-structures are developed from longitudinal ripples (Text-fig. 4). Here the current is parallel to the flame-crests. Further, the flame-structures do not always fall in the same direction and, finally, symmetrical, as well as asymmetrical structures occur (Walton, 1956*a*, fig. 4).

It seems probable that the main factor producing the inclination of flame-structures is the subsequent compaction of the coarse-grained bed. Adjustments during such compaction would probably not be exactly vertical, and, in addition, any slight initial slope would tend to favour a more or less regular asymmetry in the flame-structure.

ACKNOWLEDGMENTS

We wish to express our gratitude to Dr. D. L. Reynolds for drawing

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EXPLANATION OF PLATE XVII

- FIG. 1.—Transverse ripple-load-casts on the base of an Ordovician greywacke bed, Jameson Point, near Kirkcolm, Rhinns of Galloway. Length of scale, 6 inches.
- FIG. 2.—Longitudinal ripple-load-casts, on the base of a thin bed of greywacke; Ordovician, old quarry near Cairndonald, Rhinns of Galloway. Coin (diameter $1\frac{1}{4}$ inches) gives scale.
- FIG. 3.—Interference ripple-load-casts, at the base of fine-grained Silurian greywacke. Specimen from Binks, near Hawick.



FIG. 1.



FIG. 2.

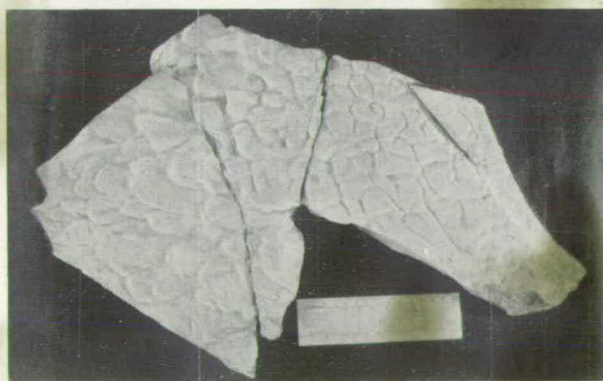


FIG. 3.

RIPPLE-LOAD-CASTS

The linear structures - groove- and flute-casts, load-casts and ripple-marks do not appear to be distributed evenly throughout the succession but rather they occur in restricted areas. Thus several scores, or even hundreds of feet of greywackes may contain only a few bedding-planes with these structures yet within the next fifty feet or so almost every bedding-plane may exhibit some form of linear structure.

Organic Markings: Trails and burrows are occasionally encountered on greywacke soles. These are generally small and cylindrical, meandering and irregular. In most cases they are filled by the greywacke and pass up from the mudstone or siltstone into the greywacke but in several instances they are filled with argillaceous material and meander along the base of the greywacke then pass down into the lutite. The former type is evidently pre-depositional while the other forms are probably "entrapment burrows".

(iii) Intrastratal structures:

Current-bedding: The true current-bedding found in most of the greywackes is small scale and is best developed in the upper, fine-grained part of graded beds. Occasionally it occurs at the base of beds of greywacke and entire units of siltstone, up to 6 inches thick may be current-bedded throughout.

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The foreset laminae of current-bedded units are usually convex downwards but post-depositional deformation has often caused oversteepening and convolution of such laminae. Large-scale current-bedding, in multiple units each up to a foot or more thick, is sometimes encountered in the coarse greywackes and the conglomeratic bands of the Conglomeratic division (fig. 27) and it is noticeable that in these the laminae are very seldom distorted.

Current-bedding has been used extensively in the present study to determine or confirm the sense of current-movement. Since the measurement of current-direction from current-bedding in the field is attended with very considerable manipulative difficulties and consequent inaccuracy, oriented specimens were taken and treated in the manner described by Crowell (1955, p. 1362). The azimuth and dip of the trace of the same foreset current-lamination on two or more non-parallel sliced planes of known orientation are plotted on a stereogram. The great circle on which all these points lie represents the trace of the lamination in question and, for convenience, the pole to this plane is taken. It is found that the laminations, even in one current-bedded unit, may show considerable variation in attitude (fig. 32). It is therefore necessary to measure a large number of planes in order to obtain even a moderately accurate estimate of the current-trend. The

/current-

current-direction used is an average one; it is that line which divides the points into two equal sectors. This line almost always coincides with the steepest laminae.

Convolute-bedding: Detailed descriptions and discussions of this phenomenon have been published by Migliorini (1950), Kuenen (1953a and 1953b) and ten Haaf (1956). Convolute-bedding commonly occurs in the fine-grained greywackes and in the finely laminated siltstones and mudstones. In detail it much resembles slumping with intricate contortions and local attenuation or thickening of the banding. The internal folds vary from gently symmetrical to diapiric and overturned, recumbent folds are often developed (Plate XXIXb). There appears to be a rough correlation between increasing intensity of contortion and decreasing grain-size. Similarly the amplitude and wave-length of the convolutions are generally greater in the greywackes than in the siltstones.

In contrast to slumping, convolute-bedding shows a gradual diminution in the intensity of plication both upwards and downwards in a single bed, sometimes resulting in the appearance of parallel, conformable laminae at the top of the convoluted unit. In other cases, however, the upper boundary is erosional. Moreover the lamination in a single bed may be contorted and attenuated but is very seldom ruptured or faulted. The constant thickness of

/convoluted

convoluted beds is also in marked contrast to the irregularity associated with slumping.

As both Kuenen (1953b) and ten Haaf (1956) have noted, constricted anticlinal forms are common in the contorted beds. In the Rhinns of Galloway, however, the lutites are characterised by extremely irregular isoclinal folds.

The relation of these structures to the current-direction is rather obscure. Kuenen (1953b) found that in the Silurian rocks of Wales the axes of the convolutions are usually normal to the current while ten Haaf (1956), in the macigno of north Italy, could find little evidence of a general trend in these structures, such elongation as there is being parallel to the current. Kuenen found that the folds, where systematically overturned, heel over in a downstream direction. In the Ordovician rocks of the Rhinns of Galloway the convolutions are generally very irregular, with short, indeterminate crests and only in the coarser beds is there any conspicuously regular trend or strike of the folds. Where this can be measured it is sometimes roughly normal to the local current-direction but is more often oblique, and is very rarely parallel to the current. The direction of overturning is also quite inconsistent. Frequently the direction of overturning may become reversed as a convoluted bed is followed for some

/distance

distance along the strike, although the direction remains constant if the overturning is very pronounced. Generally, however, it has been found unsafe to attempt inference of the current-sense from structures of this kind.

The formation of convolute-bedding has been ascribed to various causes. Rich (1950) postulated horizontal mass movement or sliding after the deposition of the overlying bed to produce the crumplings. Kuenen (1953b) refuted this by describing cases where the internal morphology of the structure proved that the convolutions were at least initiated during deposition of the bed. Migliorini (1950) offered the explanation that the folding resulted from the expulsion of water from the lower part of the compacting bed and the concentration of the rising water at certain points, dragging up the higher laminations. However the voids created by the ultimate expulsion of the gathered waters could only be partially filled by the minute quantities of suspended sediment present in the upwelling water which should, moreover, form a banding with an arrangement distinct from the distorted laminae. Such voids or transcurrent laminae are not observed, however.

Kuenen has suggested that convolutions are due to hydroplastic deformation of a growing asymmetrical ripple-form through the slight inequalities of pressure on crest and trough created by simple flow

/of

of water over these features. The ripple-like form of many of the observed convolutions together with the common occurrence of truncated laminae, since folded, in such bands lead the writer to conclude that, in the greywackes, some process similar to that envisaged by Kuenen must have occurred to produce these contortions. Whether the convolutions of the very fine-grained bands are produced in an analogous fashion is not at all clear, since differences in grain-size and hydrodynamic properties could conceivably produce the observed differences in size and intensity of contortion.

(iv) Analysis of current-directions:

A systematic examination of the directional current-structures in the Ordovician rocks of the Rhinns was undertaken in order to obtain some information on their derivation. The pitch of linear structures such as groove- and flute-casts and ripple-marks, was measured in the field and, by rotation about the strike, after allowing for the local plunge, the original trend of the structure was found and the current-direction inferred from this. The actual sense of the current was given, where possible, by current-bedding and, where this was lacking, by flute-casts, or transverse ripple-mark. The ubiquitous ripple-lamination was used on very few occasions and with some caution, owing to the reservations

/attached

attached to the use of this structure (cf. Kopstein, 1954, pp. 47-50). In many instances the linear structures give a more consistent, accurate and easily obtainable bearing than that afforded by current-bedding.

The well marked propensity of the linear structures to occur in abundance in restricted areas enabled the setting up of "stations". These are localities at which all the directional structures within a restricted vertical thickness of sediments - in this case defined at 100 feet - have been measured. Only one measurement or observation of the trend of each type of structure present was recorded from one bedding-plane except where a structure exhibits two or more regular but divergent trends, in which case each trend is recorded as a separate observation.

A total of 25 stations have been created in the area, representing 394 observations. There are 16 "major stations" with ten or more observations; and 9 "minor stations" with from five to ten observations each. The distribution of the stations and observations in each formation studied is indicated in the following table:

/No.

	<u>No. of Stations</u>	<u>No. of Observations</u>
Corsewall Group	1	11
Kirkcolm Group		
L. Barren div.	5	127
Metamorphic div.	7	121
U. Barren div.	7	68
Galdenoch Group	1	8
Portpatrick Group		
Acid div.	2	33
Basic div.	2	25

The rocks of the Kirkcolm Group clearly contain proportionately many more directional (and particularly linear) structures than the rocks of the other Groups. This suggests that relative abundance or paucity in such structures is related to the type of lithology which is itself governed by a particular depositional environment. This aspect of the problem of deposition is discussed in more detail in later pages.

The orientation of all the structures at any one station is expressed by means of composite diagrams such as figs. 33 and 34. Commonly all the structures at one station have a very similar trend and imply the same current-sense. In a few cases it is necessary to assume the presence of two divergent current-directions. Occasionally evidence of the sense is absent or conflicting and only the trend can be given. The current-direction used is that

/"average"

"average" direction which divides the indicated structures into two numerically equal groups.

Besides stations there are many localities at which only a few observations (1-5) could be recorded. Twenty such localities, comprising 63 observations are included in this study and the current-direction inferred at each locality is indicated on the appropriate map.

The maps (figs. 35-37) show that while the current-direction within one station may remain reasonably constant there is great variation, in some cases amounting to a reversal, in the current-directions obtained from different stations, even within the same division. This variability is in striking contrast to the very uniform and consistent directions obtained in recent studies on the rocks of other geosynclinal areas such as the Harlech Dome (Kopstein, 1954), Denbighshire (Cummins, 1957), Germany (Kuenen and Sanders, 1956), Poland (Ksieskiewicz, 1956) and Italy (ten Haaf, 1957), but is in accordance with the observations of Kuenen (1953b and 1957b).

It may be suggested that this variation is due to intense tectonic deformation of the region studied but while this may produce minor variations it cannot produce apparent reversals of current-flow, unless the fold-plunge is nearly vertical. Moreover the local fold-axis has been determined at almost every station and the plunge is invariably quite low.

The few current-directions in the Corsewall Group indicate a general derivation from the north (fig. 35) confirming the conclusions based on provenance of the rock-fragments in the greywackes.

Within the Kirkcolm Group as a whole and also within each division the current-directions show great variability. In the absence of marker-bands within each division it is impossible to tell whether the differing current-directions have been obtained from slightly different horizons in the division or whether rocks at the same stratigraphic level, deposited simultaneously, may show several different directions of derivation.

In the Lower Barren division (fig. 35) the current-sense appears mainly to oscillate between NE and SW (Table XI), with relatively minor contributions from the SE.

The variable current-directions in the lower part of the succeeding Metamorphic division (fig. 36) afford evidence for the persistence of the unstable conditions which characterised the previous period. Strong southerly currents seem to have been more common in the southern part of the outcrop. However, in the northern outcrops the currents almost uniformly appear to have flowed from the north-east.

The current-directions in the Upper Barren division are almost
/entirely

entirely from north-east or east-north-east, indicating comparative stability of the depositing currents.

Rather scanty evidence in the Galdenoch and Portpatrick Groups discloses further considerable variation in current-direction but with a conspicuous southerly component (fig. 37). The Galdenoch and Portpatrick (Acid) rocks appear to have been derived from between south-west and south-east while southerly and easterly sources have contributed to the Portpatrick (Basic) rocks.

C. SPHERICITY AND ROUNDNESS

Sphericity-values were calculated for 154 pebbles and cobbles and 71 boulders of different rock-types from eight localities in the Corsewall (Conglomeratic) Group. The lack of necessary apparatus prevented calculation of the roundness. In determining sphericity the method employed was that of Krumbein (1941) involving measurement of the three principal diameters of each pebble or boulder. The Wadell sphericity (Wadell, 1932) was calculated for 61 pebbles and the values thus obtained were found to be consistently slightly lower than those given by the intercept method, (the means are 0.75 and 0.77 respectively).

Mean sphericity of the pebbles is 0.76, compared with 0.77 for the boulders (standard deviation of 0.09 and 0.11 respectively)

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The values for individual rock-types in the pebble-fraction are indicated in fig. 38 and those for the boulders are closely comparable. Pebbles of granite and microgranite possess the highest sphericities and have clear modes, contrasting with the wide spread of the values for spilites and dolerites.

The volume of each pebble was plotted against the intercept sphericity (fig. 39) in order to ascertain whether, within the limits of the study, sphericity is a function of pebble-size. The random scatter of points in fig. 39 clearly shows that there is no correlation between these two variables, and this lack of correlation is still maintained if each component rock-type is treated separately.

Walton (1956a) determined sphericity and roundness of pebbles and cobbles in the Finnarts and Glen App conglomerates. There, the average mean sphericity is 0.705 (S.D. 0.08), significantly less than the value for Corsewall pebbles. Since Walton used the Wadell method, procedural differences may account for part of the discrepancy and incomplete sampling is probably another contributory factor. However there probably remains a real, though small, original difference between these areas. Individual rock-types in the Finnarts-Glen App rocks also appear to have somewhat lower values (cf. fig. 38 with Walton's fig. 2) although

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the general distribution is strikingly similar to that of the Corsewall pebbles.

Adequate disaggregation of the rocks proving impossible, a thin-section study was undertaken of the sphericity and roundness of quartz grains and spilite fragments in the greywackes of each formation studied. Quartz was chosen because of its uniform abundance, ease of identification and probable polygenetic character. For essentially similar reasons spilite was chosen to represent the rock-fragments. Microgranite is the only other rock type fulfilling the listed requirements but it is believed that spilite is probably more susceptible to induced changes in shape and roundness.

A total of about 200 quartz grains and 100 spilite fragments were counted from each formation. In the Kirkcolm Group each of the principal outcrops of each division was treated as a separate sampling-unit, where possible, in an attempt to discover whether there is any significant lateral variation in sphericity and roundness. In each sampling-unit the total was composed of all the grains between 0.5 and 1.5 mms., encountered in a series of random traverses across each of four or five thin-sections chosen at random.

/Roundness

Roundness and sphericity were both obtained by comparison of the grain-outline with the standard silhouette - charts of Krumbein (1941) and Rittenhouse (1943).

In order to ascertain the degree of reproducibility of the results achieved by this method, one month after the actual investigation was complete further counts were made on seven randomly selected thin-sections using (i) the same traverses, and (ii) a new set of traverses. Differences between the mean sphericity for each sampling-unit (200 or 100 grains) on a straight recount varied between 3 and 7%, average 5%, while using new traverses the differences were between 2 and 6.5%, average 3.7%. Similar differences were obtained from the roundness values.

It may be inferred from this that in this method day-to-day variation is of greater significance than sampling bias. However, since the original counts were carried through without a large break and since some degree of practice is necessary in this comparison method - a practice which was lacking in the recounts - it is believed that the results achieved are fairly reliable for the present purpose. It seems, however, that these results can only be used as relative values for comparison with others obtained by similar means, and that is sufficient for the present purpose although it would clearly be desirable if absolute values could be calculated.

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These results are expressed in Table XII and XIII. Treating sphericity first, the values for both quartz and spilite remain relatively uniform throughout all the formations studied. Differences in sphericity of the units within the Kirkcolm Group are not statistically significant^{*}, nor is the total mean for this Group significantly different from that of the Galdenoch or Portpatrick Groups. On the other hand, the mean sphericity of the quartz and spilite fragments in the Corsewall Group is significantly lower than that of the other Groups.

Similar general relationships hold for the roundness values. Again the means for Kirkcolm, Galdenoch and Portpatrick Groups are virtually identical while that of the Corsewall Group is considerably lower. The large standard deviations of the mean roundness values are indicative of the wide mixture of rounded and angular grains in these rocks.

Several points of interest arise from these results. It is believed that sphericity depends largely on initial shape and is little modified by abrasion. Since information is lacking on

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^{*}Using the Standard Error of differences between the means

$$(S.E.D = \sqrt{\frac{\sigma_1^2}{N} + \frac{\sigma_2^2}{N}})$$

the sphericities of rock and mineral fragments from different source-rocks it is not clear whether identity of sphericity in different samples of the same rock-type or mineral, such as obtains in the present study, is determined by similarity of source or of sedimentary history. However, it appears likely that quartz derived from equigranular rocks such as granites, microgranites and thermal quartzites should possess higher initial sphericity values than the quartz obtained from gneissose and schistose rocks. If this is correct then the sphericity values for the Metamorphic division are anomalous since it contains much quartz of the latter type (see fig. 12) but has a mean sphericity similar to that of the other formations. Now, besides source-differences there is another major factor in determining the sphericity of a sample of sedimented grains - that is the sorting history. According to Pettijohn (1948, p. 420) grains of similar shape tend to settle simultaneously, provided density and grain-size are not too contrasted. Where the grains are transported in suspension, the more spherical grains will settle out before those of lower sphericity the reverse process operating during transport by traction. It may be argued that in the present case this environmental factor has predominated, obscuring the relatively small source-differences. On this theory, Kirkcolm and Portpatrick rocks were deposited under comparable conditions (in terms of /location

location, transport-medium and current-velocity) whereas the depositional environment of the Corsewall rocks was quite different. This, of course, is borne out by the respective lithological characteristics.

Quartz of metamorphic origin, which is more abundant in the Kirkcolm-Portpatrick rocks than in the Corsewall Group, has been observed to possess slightly higher average roundness and this compositional factor may account for part of the disparity in roundness-values between these Groups. However, the depositional factor is probably significant in this case also, since there is known to be a rather good correlation between shape and roundness (Pettijohn, 1949, p. 422). This correlation will also assist in accounting for the higher roundness of the spilite fragments in Kirkcolm-Portpatrick rocks.

A point of further interest in this connection is that judging from the relative sphericity and roundness values, which give only a very imperfect picture, the rocks of the Corsewall Group are less mature than those of the Kirkcolm and Portpatrick Groups, thus partly corroborating the petrographic evidence.

D. CONDITIONS OF DEPOSITION

It has long been recognised that greywackes represent a unique type of sedimentation typical of geosynclinal areas. These rocks are clearly the products of very rapid and intense denudation of an associated folded region of considerable elevation. That transport and deposition were equally rapid may be inferred from the fresh state of susceptible minerals, the general angularity of the grains and the mixed, unsorted nature of the deposit. While this much is undisputed, some doubt exists as to the nature of the transporting (or depositing) medium and the location of the site of deposition.

Various theories have been evolved to account for the typical features of a normal greywacke sequence. The importance of flocculation of the quasi-colloidal clay material concurrently with normal settling of the coarser grains was stressed by Woodland (1938), following Boswell (1930) and was supported by Pettijohn (1943). Bailey (1930) ascribed the main feature of greywackes - graded bedding and poor sorting - to deposition from a cloud of sediment thrown into suspension by "sea-quakes" in the unstable region bordering the top of the continental slope.

This concept has been modified and expanded by Kuenen and others into a theory of turbidity current deposition. These

/currents

currents have been observed and inferred on several occasions and have been produced experimentally. This explanation successfully negotiates an objection presented to Bailey's "sea-quake" theory, that in deposition from suspension large grains would settle out far more quickly than smaller grains and mud so that sorting at each level in the bed so-formed should be very good whereas, in the graded greywackes, it is poor. The interbedded lutites, on the Kuenen hypothesis, are regarded as the products of very slow pelagic sedimentation.

This turbidity-current hypothesis has been widely applied by various workers to greywackes of all ages. Kuenen and Natland (1951) showed that the rocks of the Ventura Basin were of deep-water origin and Kuenen and Carozzi (1953, p. 365) stressed the similar features of the greywackes and modern deep-sea sands presumably deposited from turbidity currents. However, in the same paper it was pointed out that effectively the only limitation of depth so far as normal greywackes are concerned is that they must be deposited below the depth of re-working by waves and tidal currents. Since wave-base is at very variable depths in different bodies of water it is probable that sediments of this type may be deposited in relatively shallow water (cf. George, 1957, p. 287).

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The lithology of both divisions in the Corsewall Group is unique in the formations studied. In the Flaggy division the virtual absence of grading in the greywackes, the flaggy, even-bedded character of the rocks together with the high proportion of lutite and the abundance of hydroplastic deformation features serve to place this group in the "clino" group of Rich (1951), a term which involves no depth connotation.

During the deposition of these rocks, relatively quiet conditions evidently prevailed, with a steady and not insignificant supply of clay and silt and occasional influxes of coarser clastic material, the sedimentary structures in which indicate a concomitant increase in current action. The rather poor sorting of the coarser rocks implies lack of re-working which may be construed as evidence for deposition in an area below wave-base. Taken in conjunction with the evidence of the succeeding division the evidence suggests that this flaggy division was laid down on the gently sloping front of a large immature delta, in an area between the estuaries of the main distributaries.

The rapid passage into the succeeding Conglomeratic division marks the advent of a somewhat contrasted type of sedimentation. The depositional regime in which these rocks were formed was evidently dominated by strong currents.

It has been indicated already (p. 74) that the Corsewall conglomerates are closely similar to the Glen App - Finnarts and the Archean beds described by Walton and Pettijohn respectively. These authors have suggested that the conglomerates are piedmont deposits, formed on broad flood-plains subject to occasional marine incursions. Davies and Platt (1933) considered that similar conglomerates occurring in an Ordovician-Silurian greywacke sequence, were formed in a shallow-water marine environment. On the other hand Kuenen (1953b) concluded that certain Ordovician conglomerates in the Girven succession are slide-conglomerates, formed by the wholesale sliding of unconsolidated mud and silt, loaded with pebbles and boulders, into deep waters.

The lithology of the conglomeratic bands in the Corsewall Group suggests that they form an integral part of a normal sequence rather than catastrophic interludes in that sequence. The small proportion of muddy matrix (on average, less than 10%) is insufficient to enable such a mass to move as a mud-flow. Moreover the main lithological features of the boulder-beds (see p. 40) do not lend support to the slide-conglomerate hypothesis. The lamination, current-bedding and well-developed banding of the coarser beds and the numerous current-formed structures in the silty interbeds strongly suggests that the conglomeratic bands are the products of fairly strong, localised current-action resulting

erosion and maximum deposition in certain restricted locations, apparently linear (fig. 40) and probably of the nature of river-channels. Between the periods of maximum current-activity there was steady and fairly rapid deposition of greywacke and siltstone over a wide area. The conditions listed above are probably best fulfilled in the flood-plain environment of a large immature delta building southwards. It is conceivable that the Corsewall, Finnarts and Glen App conglomerates represent the sites of the main distributaries of such an Ordovician delta.

If such is the depositional environment of these beds, little reliance can be placed on the current-directions obtained from them, since these would be expected to show considerable local fluctuations related only in the broadest sense to the regional slope. However the limited evidence available, together with the petrographic considerations, indicates a general northerly source.

Lithologically the Kirkcolm rocks are quite distinct from those of the Corsewall Group and accordingly it seems reasonable to infer that the conditions of deposition were also rather different. The dominant lithology is a sequence consisting of greywackes which are often graded and contain numerous directional current-formed structures. Intervening between the greywackes are siltstones with occasional mudstones which betray signs of

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moderate current-activity in ripple-marking, current-bedding and small scour-structures. Long intervals of relatively quiet deposition are indicated by the occasional thick bands of siltstone while periods of increased competency in the currents responsible for the deposition of the greywackes are disclosed by the frequent pebble-bands.

The greywackes themselves evidently represent periods of maximum current-strength. The frequent occurrence of linear scour-structures at the base of these beds and of ripple-mark and small-scale current-bedding at the top are in direct contrast to the Corsewall rocks where the scour-structures are usually non-directional and the current-bedding on a large scale. These structures indicate that the Kirkcolm greywackes were deposited from fairly powerful episodic currents. However, the poor sorting of the greywackes is evidence that there was little current-winning after deposition, which clearly must have been rapid.

Pettijohn (1943, pp. 948-949) quoted the abundance of pyrite and graphite in the Archean greywackes as an indication of their marine origin. Similar features in the Kirkcolm and Portpatrick rocks, together with their intimate association with graptolitic shales and the occasional occurrence of graptolites within the greywackes, are considered by the present writer to be strong

/evidence

evidence for the marine origin of these rocks.

The turbidity current hypothesis probably is the most satisfactory explanation yet offered for the integrated features of a greywacke sequence, but in the case of the Kirkcolm and Portpatrick rocks there are several features which are difficult to reconcile with this mode of deposition.

First of all, the interbedded sediments are very seldom fine-grained mudstones or shales; more often they are silty and show evidence of current-action and sorting. Furthermore they are not petrographically distinct from the associated greywackes but in fact exhibit close affinities with them (p. 120). Crowell (1955, pp. 1368-1370) also recognised these features and explained them as resulting from the deposition of muddy material "by small, slow and dilute turbidity currents which may have originated frequently in comparison to the more powerful ones responsible for the sandstone beds". However, in the present case the regular intergradations of silt and mud are indicative of relatively constant rather than spasmodic supply of sediment. Edwards (1947a) noted the close petrographic similarity of some Miocene greywackes and their muddy interbeds and claimed that muddy and silty material was being continuously added to the area of deposition (1947, p. 141).

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The prevalence of lamination in the greywackes, often throughout the entire bed, is evidence that traction (not suspension) often played a large part in their formation, local variations in current direction and competency producing interbedded layers of different grain-size.

It is believed, therefore, that the area of deposition of the Kirkcolm rocks was subject to continuous sedimentation of silt and mud and to slight but persistent current-action, able to move by traction and to some extent to sort materials of silt-grade. The greywackes probably represent temporary and fairly rapid accessions of coarse material brought to this environment by dense, sediment-laden currents. It is possible that these turbidity currents were initiated by the dense flood-waters of a river-system stemming from the bordering highland area.

The petrographic evidence suggests a northerly source for the Kirkcolm sediments whereas the current-directions are variable, mainly alternating between NE and SW (see p.229). From all other indications such a direction is parallel to the Ordovician shoreline represented in part by the Girvan deposits.

Kuenen (1957b) has pointed out that many basins, and especially geosynclines, have derived their sedimentary filling longitudinally from one end. However, in the present case the provenance of the

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sediments, the rapid alternation and general irregularity of the currents all militate against such an explanation.

It appears more feasible that the features cited above are indicative of relatively local sources, probably deltas, feeding sediment towards the south-east into a broad basin. This had a general, if slight, slope to the south thus accounting for the general decrease in thickness in this direction and trended NE-SW, possibly as a reflection of post-Arenig folding. Sediment-laden currents, flowing south-east, were diverted into this depression and the directional-structures in the greywackes deposited from such currents naturally indicate only the local directions of transport which would therefore be from NE or from SW depending on the actual location of the river-mouth. The occasional currents with NW sense evidently flowed directly from the adjacent coastline, down the landward slope of the basin.

Such conditions appear to have been sustained throughout the entire area during the deposition of the L. Barren division. However, during the deposition of the later Kirkcolm rocks, while the fluctuating current-directions in the southern outcrops still record the influence of the basin, in the northern outcrops the structures indicate that the currents became increasingly uniform in sense, flowing mainly from the NE. This may be explained by

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the building-out of sediment from the delta-sources lying to the north-east. By the gradual acquisition of sediment a relatively smooth south-west facing slope was established over the north-east part of the basin and accordingly currents flowed directly down this. However, on reaching the more distant parts of the basin, represented by the southern outcrops, such currents would be subject to interference from currents flowing from other sources lying north and west of the present area and the observed fluctuations in current-directions would result.

During the deposition of the Corsewall and Kirkcolm greywackes black graptolitic shales and cherts were accumulating in the southern part of the basin. The association of black shale and chert has often been cited as evidence of a deep-water environment (Hinde, Peach and Horne, 1899; Lapworth, 1889; Steinmann in Bailey, 1936) but other workers (Grabau and O'Connell, 1917; Jones, 1938; King, 1923; Twenhofel, 1932) have adduced evidence for their accumulation in shallow water conditions.

It appears that the primary requisites for the formation of black shales and radiolarian cherts are similar - quiet, poorly aerated waters; virtually no deposition of terrigenous material; lack of benthonic life. It is generally conceded that most black graptolitic shales and associated radiolarian cherts are marine.

/Given

Given such conditions, regardless of depth of water and other factors, these sediments will be formed. While the possible depth at which such conditions may be found in the open ocean is very great, in virtually land-locked basins protected from the open sea by bars, poor bottom-circulation might occur at relatively small depths.

It is envisaged that the black shales accumulated on the landward-facing gentle slope of a submarine ridge or sea-mount, trending parallel with the Ordovician shore-line and effectively separating the relatively shallow, semi-stagnant geosynclinal basin from the open ocean to the south and south-west. Such an environment would fulfil the requirements listed above (cf. fig. 10 in Fleming and Revelle, 1939). Occasional pauses in clastic sedimentation permitted the formation of black shales in areas nearer land, thus producing the interbedding of greywackes and graphitic shales.

The conditions prevailing during deposition of the Portpatrick Galdenoch rocks are believed to have been roughly comparable to those envisaged for the Kirkcolm Group. However the volcanic arc source-area - which may have been a rising, sub-aerial portion of the submarine ridge postulated above - appears to have lain to the west and south-west and was fairly near, judging from the relative

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coarseness of the greywackes and the thickness of the bedding.

Interbedding of Portpatrick (Acid) greywackes with thick bands of graptolitic (L. Hartfell?) blue-black shale in Morroch Bay indicates that initially the greywacke sedimentation was infrequent and restricted in amount. The limited extent of greywacke deposition in the lowermost part of the Group is revealed by the presence of Middle Hartfell (*O. quadrimucronatus*) shales at Porteyew and possibly at Colfin. However, the later Portpatrick rocks evidently spread far over the area.

From the lithological and petrographic nature of the Galdenoch rocks it is possible that, at least during the early stages of Portpatrick sedimentation, there was simultaneous contribution of Kirkcolm-type sediments from the northern source-area, although this probably did not affect the southern part of the region (around Portpatrick).

The current-pattern for this Group, particularly in the Basic division, is far from clear but apparently represents conditions of great variability.

See Table XIV for a summary of conclusions regarding provenance and mode of deposition.

V. STRUCTURE

A. GENERAL ACCOUNT

The concept advocated here of the structure of the Ordovician rocks in the Rhinns of Galloway differs widely from the currently accepted interpretation of Peach and Horne (see pp. 12 and 29). These workers considered that the rocks of this part of the Southern Uplands were plicated into a series of isoclinal folds, the crenulations on a major anticlinorium. By this means apparently enormous thicknesses could be greatly reduced and the frequent fossiliferous bands ascribed to repetition of a single horizon. Faulting was thought to be of very secondary importance.

It has been demonstrated earlier (pp. 27 and 29), in specific instances, that from the direction of upward sequence the postulate isoclinal folds cannot of themselves account for the observed facts. Moreover, few of the folds observed are isoclines. The evaluation of structure based upon the criteria mentioned above and expressed in fig. 41 is much less uniform in general pattern than that envisaged by Peach and Horne and the role of faulting and especially thrusting is apparently much greater than previously considered.

The main structural elements of this area are a number of north-facing major monoclinial antiforms usually bounded by faults

/and

and thrusts, and with complex subsidiary folding on the shallow southern limbs. There are also two broad belts in which the folding is at once more regular and more intense (fig. 42).

The first of these comprises all the rocks occurring to the north of the Southern Uplands Fault. On the west coast these are seen to be folded into a monoclinial antiform of which the vertical northern limb and gently flexured south limb are exposed. Eastwards, along the strike, the general dip of this rearward limb appears to increase considerably due to the gentle easterly plunge of the moncline. On the west coast the hinge of this fold is faulted and approaching the fault-plexus of the Southern Uplands Fault in Dally Bay there is a marked increase in the degree of minor folding on the south limb. The Southern Uplands Fault itself is slightly oblique to the trend of this monoclinial structure but partly occupies the hinge of another major monocline involving rocks of the Kirkcolm Group and forming the second structural unit.

This unit extends from Dally Bay to Galdenoch and eastwards across the peninsula. Beds on the north limb of the monocline are merely uptilted but those on the south limb are heavily folded and faulted. At Portobello the hinge of the major fold is again faulted while there is a general gentle plunge to the ENE.

The third structural segment occupies the belt stretching

/east

east from the coastal section of Galdenoch to Killantringan Bay. The northern part of this unit consists of gently folded beds of Galdenoch, U. Barren and Metamorphic greywackes but south of Cave Ochtree Point the rocks include L. Barren and Metamorphic greywackes and are highly contorted and faulted. This increased deformation may be related partly to the increase in the proportion of lutite in the succession and also to the proximity to the Killantringan thrust-zone which abruptly truncates this unit at its south end. The major folds involved in this unit all plunge at low angles to the ENE.

South of this complex area there is a fourth structural unit - the Portpatrick monocline - lying between the Killantringan thrust-zone and a fault at the south end of Morroch Bay. The massive greywackes of the Portpatrick (Acid) Group on the south limb of this structure are corrugated into a number of large, relatively tight folds which pass into gentle undulations in the area immediately north of Morroch Bay.

The area of intense deformation between Morroch Bay and the Portayew thrust-zone constitutes the fifth tectonic sector. Beyond the Port of Spittal anticline the coastal exposures consist of Portpatrick (Acid) greywackes intensely contorted and fractured; there is also a pronounced lineation caused by the intersection

/of

of cleavage and bedding-plane and this gives rise to very typical "crenulation" of the shales (Plate XXXIIa). It is probable that, in spite of the extreme complexity of structure, there is little change in tectonic level in this area.

B. DETAILS OF STRUCTURAL FEATURES

Folds

The main fold-styles observed are sketched in fig. 43. Most of the folds observed or inferred from structural profile-sections are asymmetrical structures of type (b) with small isoclinal drag-folds developed incompetently in the interbedded shales (Plates XXXIIb and XXXIIIa).

Symmetrical folds of type (a) are found only in regions relatively remote from the major tectonic boundaries and generally form in thin-bedded sequences (Plates XXXIIIb and XXXIVa). There are numerous large isoclinal folds of type (c) in the highly disturbed region north of Portayew but elsewhere folds of this type are virtually unknown. On the other hand, small isoclinal folds of type (d) are very common in the thicker shale-bands and become very angular in such bands. Such small folds are frequently sheared along the axial plane.

The flexural folds illustrated as type (e) are characteristic

/of

of the vertical northern limbs of the monoclinial structures while type (f) box-folds are infrequently encountered in the massive greywackes.

From the composite stereogram (fig. 44) it may be seen that most of the fold-axes plunge to between NE and ENE, with subsidiary maxima plunging gently to E and to WSW and steeply to ENE. This last group consists of a number of small drag-folds within the disturbed zones of the Salt Pans Bay thrust and the Portpatrick wrench fault. Otherwise differences in fold-trend do not appear to be related to locality. The axial planes of asymmetrical and overturned folds are mainly inclined to the south except in the region of Portayew where this dip is reversed. Conspicuously disharmonic folding often occurs in areas where the folded beds contain a high proportion of shales (Plate XXXIVb).

Fracture cleavage is sometimes developed in the fine-grained beds and appears to be restricted to certain areas. It is conspicuous in the area north of Portayew where it is clearly parallel to the axial planes of the adjacent folds. Elsewhere the relationship is not so clear and in a few instances the cleavage appears to be slightly warped about a roughly N-S axis.

Faults

Faulting is of considerable importance in the structure of this region. Several major dislocations produce effects of

/considerable

considerable stratigraphic significance while there are numerous smaller faults of local importance.

Major faults:

(1) Southern Uplands fault. From the stratigraphic evidence this fault appears to downthrow to the south, the probable throw being about 3-4000 feet. The attitude of the "fault-plane" is obscure since there is no single clear-cut plane of movement but rather a wide shear-zone. In Dally Bay however, within the shatter-belt there are numerous slickensided master-joints which dip steeply south on an ENE strike and it therefore seems probable that the Southern Uplands Fault fades in a similar direction. Both here and in Lady Bay there are a number of small tangential feather-faults associated with the major fracture. An interesting point here is that most of the slickensides on the joints and faults are nearly horizontal.

(ii) Killantringan thrust. The zone of shattering associated with this dislocation is 600 yards wide in Killantringan Bay and is presumably related to the shallow inclination of the main thrust-plane. A number of minor thrusts in the shatter-belt dip to the north at moderately high angles. Evidence for the eastwards continuation of this thrust is obtained from the fact that the Portpatrick (Basic) northern boundary cuts across the /regional

regional strike-direction. Moreover there is a wide belt of highly shattered and quartz-veined rocks all along this boundary in which low-angle joints with vertically pitching slickensides are conspicuous.

(iii) Portpatrick wrench-fault. This fracture, which trends NW-SE, has displaced the Acid-Basic boundary by nearly two-thirds of a mile in a dextral sense and has resulted in intense shattering, which in places has completely obscured all sedimentary structures, along the shore for a distance of half a mile north of Portpatrick harbour. Quartz-lined joints trending parallel to the postulated fault dip at 30° to the NE and carry numerous stepped horizontal slickensides indicating dextral movement (cf. Hills, 1953, fig. 87).

(iv) Portayew thrust. The zone of intense shattering at Garryharry, south of Portayew, has already been described together with the stratigraphic evidence for the presence of a major fracture at this locality. The indicated northerly hade is deduced from the attitude of several associated minor thrusts and the occurrence of several large slickensided joints which dip to the north.

As indicated in a previous section (p157) the rocks involved in each of these major movement-planes exhibit highly cataclastic textures.

Minor faults:

Subordinate dislocations are frequently observed in these rocks but it is often impossible to calculate the exact amount of throw although it is generally possible to tell the direction of displacement by means of slickensides, hade of the fault-planes and the behaviour of beds adjacent to the fracture.

The frequency of faults of different type, with observed throws believed to be in excess of 20 ft., is indicated below.

Normal	Wrench			Thrust	Unknown
	S.	D.	?		
29	10	5	8	18	5

Total: 75

S Sinistral; D Dextral; ? Uncertain

Normal faults usually possess near-vertical fault-planes but in a restricted area between Galdenoch and Salt Pans Bay there are a number of unusual normal faults which dip south at 30-40° and are coincident in orientation with local joint-planes. There is generally little shattering associated with normal faults. The trend is very irregular but there is a poor maximum at WNW-ESE.

Wrench-faults are the commonest type of dislocation in the area north of the Southern Uplands fault but are of infrequent
/occurrence

occurrence elsewhere. There is often pronounced shattering in the vicinity of such faults. From the meagre data available it seems that sinistral faults predominate and are generally oriented about $N30^{\circ}E$. The hade of these faults is usually near-vertical.

Thrust-faults, a category which includes the few high-angle reverse faults, are often conspicuous in areas of intense folding (Plate XXXVa). The attitude of the thrust-planes is greatly variable but the angle is generally between $30-50^{\circ}$. In the northern part of this region the inclination of the thrusts is dominantly southward whereas south of Portslogan the thrust-planes slope to the north. The usual trend of the south-sloping thrusts is $N55^{\circ}E$ while that of the north-sloping planes is $N75^{\circ}E$. The thrust-planes with southerly inclination are generally parallel to the axial planes of nearby folds; this is true of the northward-sloping thrusts only in the Portayew area.

Small thrusts are very common in heavily folded shale bands and even the larger fractures seem to occur preferentially near such bands. In many cases the shales appear to have "lubricated" the movement, becoming corrugated into a series of drag-folds in the process.

Evidence of the date of the faulting is forthcoming from two exposures. At Slouchneglasson, a few hundred yards north of the

/mouth

mouth of the Galdenoch Burn, a low-angle normal fault has displaced a porphyrite dyke 30 feet to the south. Two parallel thrusts occur at Dunanrea Bay, 1000 yards north of Portayew, each dipping north at 30-40°. A thick band of shales with greywackes has been caught between the two planes and has evidently been moved south about 40 ft. by the upper thrust. A vertical porphyrite dyke which passes through the shales and the upper thrust is cut off at the lower thrust and has been moved at least 10 ft. Adjacent to the thrust this dyke is highly brecciated. There is thus evidence that at least some of the faulting is later than the period of dyke-formation which is usually regarded as of Lower Old Red Sandstone age.

VI. SUMMARY OF CONCLUSIONS

Detailed conclusions are offered at the end of each section. The general conclusions are given here.

First, it has proved possible to erect a stratigraphic succession within the coarse clastic rocks with the aid of the few fossiliferous bands and by using sedimentary structures to determine the upward sequence. By these means the intercalation of several bands of black shale within the greywacke sequence has been detected as far north as Portslogan. Relatively rapid lateral variations in thickness and lithology have been found within several formations, amounting to a general southward attenuation and increase in the proportion of shale in the rocks of Glenkiln age. In view of these lithological variations, the petrographic properties of the greywackes have proved to be of considerable correlative value. The interbedded shales indicate that all the rocks examined may be assigned to the Glenkiln horizon, with the exception of the uppermost formation, the Portpatrick Group, which is probably of Hartfell age. The calculated maximum thickness of these Ordovician rocks is about 6,600 feet.

Comparison with similar rocks of different ages and locations has enabled the conclusion to be drawn that variations in the
/composition

composition of the greywackes are more closely related to differences in source-rocks than to subsequent selective alteration of the derived material.

Descriptions have been given of the various sedimentary structures found in the rocks examined. Graded-bedding is not abundant save in the rocks of the Kirkcolm Group while lamination is relatively common. Erosional structures, such as scour-fill hollows, are particularly well developed in the Corsewall rocks. Under-surface structures are common and are believed to be the products either of different phases of the erosive action of fairly high-speed sediment-laden currents (groove-casts and flute-casts), or of penecontemporaneous deformation of pre-existing surface irregularities due to rapid deposition of greywacke on an undulating surface of unindurated mud or silt (load-casts). Ripple-mark is also abundant and evidence has been presented to show that besides transverse ripples, interference and longitudinal forms occur.

Analysis of the current-directions obtained from these structures reveals a highly complex current-pattern. However, the Corsewall and Kirkcolm rocks were evidently derived from northerly sources while the rocks of the Portpatrick-Galdenoch Group came mainly from the south or west.

/Conclusions

Conclusions regarding the provenance and mode of deposition of these rocks are summarised in Table XIV. It may be stated here that the Corsewall rocks were derived from a local dominantly igneous area, petrographically similar to the Ballentrae complex. The source of the Kirkcolm rocks lay in an igneo-metamorphic terrain while the Portpatrick rocks are the products of a volcanic island arc with some acid plutonic and metamorphic rocks exposed. Rocks of the Corsewall Group were deposited on a large south-building delta while those of the Kirkcolm and Portpatrick-Galdenoch Groups were formed in a broad basin, bounded to the south by a submarine ridge near which black shales steadily accumulated. There was continuous moderate current-action and deposition of silt and mud in this basin, with occasional turbidity currents depositing the coarser rocks.

Structurally, the area consists of a number of large monoclines with vertical but otherwise unfolded northern limbs and complexly folded south limbs. These monoclines are interrupted, at intervals, by areas with more intense folding. Most of the folds major and minor, plunge at low angles to the ENE. A number of large and small thrusts, many of them directed south, have been observed and inferred. The Southern Uplands Fault is believed to be a normal fault, which hades to the south in this area. A

/large

large dextral wrench-fault is postulated, running NW through Portpatrick and a large south-directed thrust occurs at the erstwhile-mapped Silurian boundary near Portayew. In general the role of faulting is believed to be considerable.

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