The Ordovician Rocks of North West Wigtownshire

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CHAPTER 1 INTRODUCTION

Location of Area

The area lies in south-west Scotland, forming part of the Moors of Galloway, in west Wigtownshire and the extreme south-west of Ayrshire, with boundaries formed by Glen App to the north, the Water of Luce to the east, and a steep scarp running south-south-east from the mouth of Glen App to the village of Dunragit. (Fig. 1)

The area is covered by H.M. Geological Survey's 1" sheets 3 and 7, and by the Ordnance Survey's 6" sheets NX 06, 07, 15, 16, and 17.

In the north and west the area rises steeply, from the deeply cut trough of Glen App and along the western escarpment, whose virtually straight configuration suggests a fault origen. Most of the area is peat covered moorland rolling gently upwards to the hills at the head of Glen App and rising rather more steeply in the extreme south of the area to the bluff of Craig Fell.

Drainage is, westwards, towards Loch Ryan and, in the east, eastwards towards the Water of Luce.

Exposure is excellent for about a mile along the coast in the north where the escarpment forms the shores of Loch Ryan and is usually fairly good along the remainder of the scarp. Fairly good exposure is found on and around Craig Fell but elsewhere on the moors outcrops are confined to occasional stream sections and rounded roches moutonnees.

Account of Previous Research

Nineteenth Century geologists visiting the area were concerned with describing the "monotonous sequence of grits and shales" (Peach and Horne 1899) in the general context of the rest of the Southern Uplands and with an examination of the graptolite-bearing shales which yielded a fairly extensive if poorly preserved Ordovician fauna. In 1839 Moore described some of the graptolites and in 1840 recognised the strata as forming part of a greywacke chain stretching from St.Abbs Head to the Irish Sea. In 1849 Moore published a major description of the rocks, listed graptolite localities, and drew a vertical cross-section across the western end of the Southern Uplands. About this time general papers on south-west Scotland were published by Nicol (1848, 1849), and Harkness (1852). Between 1870 and 1880 Lapworth visited the area to contribute to his papers on the Southern Uplands (1872, 1878). In the area he recognised the Moffat Shales which he thought cropped out "in the cores of anticlines." Specific mention of this area is confined to objective reporting of the highly inclined nature of the beds and listing of fossil localities. In 1899 Peach and Horne published the results of a re-survey of the Southern Uplands in which, for the most part, they accepted Lapworth's findings, adapting them where necessary to fit their own concept of the major structure. Peach and Horne were apparently daunted by the great thicknesses of rocks involved if the steeply dipping succession were unfolded and therefore, no doubt extrapolating from the thick often contorted, shale beds, postulated a highly folded anticlinorial arch as the major structure of the northern part of the Southern Uplands. The present area forms part of this Northern Belt, but specific mention of the area is confined to faunal lists and localities, and a description of the northwards disappearance of black shales so that in the north of the area graptolites are found in thick streaks in "normal" shales. This phenomenon is described as a lateral northwards disappearance of black shales, an interpretation which tacitly assumes that there are few fossiliferous horizons and that these are repeated through the area.

Research in south-west Scotland languished after publication of the Survey Memoir except for brief visits by Kuenen (1953), who interpreted the rocks as a turbidite sequence, and Lindstrom (1958), who detected two periods of stress. Interest was renewed in the late 1950s however and the results of this work are now appearing. In 1956 Walton (1956a) described the rocks to the north of Glen App, in 1961 Kelling re-interpreted the structure and stratigraphy and in 1962 the sedimentary features of the Rhinns of Galloway. Kelling showed that the rocks were a turbidite facies and that the structure in the Rhinns is composed of a series of large complex monoclines rather than an anticlinorium. Gordon (1962) and Rust (1963) described areas in the Silurian rocks of South-west Scotland.

The present area lies to the south of Glen App, to the east of the Rhinns, and to the north of the areas described by Gordon and Rust, and therefore offers opportunities for integrating work over a large area in south-west Scotland.

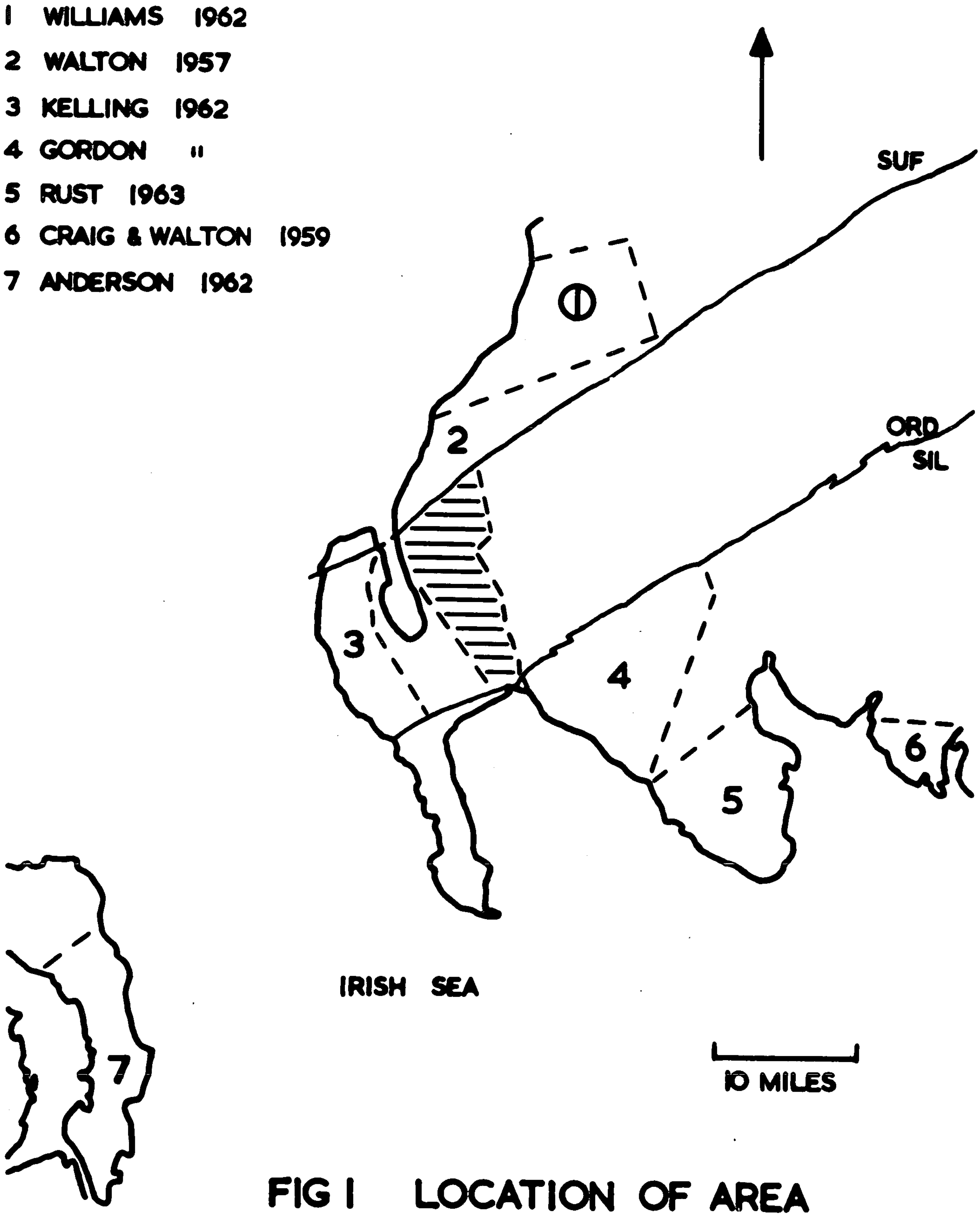


FIG I LOCATION OF AREA

CHAPTER 2 REGIONAL LITHOLOGY

The field study of the area showed that there are three types of greywacke--shale association present. The first is composed of thinly bedded greywackes and shales, with, in addition, fairly frequent thick shale bands. The greywackes are quartsose and mainly fine grained. This type occupies a wide tract in the north of the area and a small patch in the extreme south.

The second type of association consists again of thinly bedded material, but in addition there are frequent interspersals of much thicker greywacke beds. There are very few thick shale bands. The greywackes have a dull appearance due to a low quartz content, and are frequently coarse grained. This type is found in one or two localities to be stratigraphically higher than rocks of the type described above. The second greywacke--shale association occurs in narrow outliers within the main area of outcrop of the first type of association described.

The third type of association consists mainly of very thick beds of greywacke with very little shale. Thinly bedded greywackes are found only occasionally in the succession. There are no thick shale bands. The greywackes are very coarse grained and have a low quartz content. This type forms a broad area in the south.

When these field observations are supplemented by examination of thin sections from the various field types it is found that the different associations have their individual petrological characteristics, confirming the above divisions, and also in some cases allowing further subdivision. The various rock divisions of the area are listed below, followed by descriptions of their individual characteristics.

In stratigraphic order the divisions are:-

Glenwhan Rocks

Boreland Rocks

Cairnerzean Rocks (in part contemporaneous with Boreland Rocks)

Lochryan Rocks, subdivided into
Upper Lochryan Rocks
Lower Lochryan Rocks

The areas of outcrop of the various divisions are shown in Fig. 2.

Palaeontological ages for the various divisions are not obtainable due to the rarity of fossiliferous bands and to the poor state of preservation of fossils when found. Dr. Isles Strachan has kindly examined a representative collection of graptolites from various horizons and states that these show a general Upper Glenkiln--Lower Hartfell age for the rocks.

LOCHRYAN ROCKS

The Lochryan Formation occupies a large part of the area in broad tracts separated by strips of the Cairnerzean Rocks. Exposure for the most part is poor, except along the east side of Loch Ryan, including a short coast section running southwards from Glen App. The two subdivisions of the formation are established by modal analysis, the rocks being indistinguishable in the field.

The typical lithology consists of fairly thin greywacke beds, about 1' thick, interbedded with thin shale bands, 1-3" thick. In addition there are frequent thick shale bands, giving a characteristic high shale content to the formation, the Greywacke:Shale ratio varying between 1·5:1 and 3:1.

The greywackes are usually fine grained, but coarse material is occasionally found in patches on the soles of the greywacke beds. In hand specimen the greywackes are blue-grey to blue in colour, weathering brown or reddish brown. The rocks are quartzose and, especially in the finer grain sizes, very micaceous.

The thin shales are dark grey in colour and are very finely fissile. The parting is, however, frequently absent, the argillaceous interbeds being then more accurately described as massive mudstones. Silty laminations are rare in the thin interbeds but are common in the thick shales where they range from a few millimetres to 1 or 2 centimetres thick.

CAIRNERZEAN ROCKS

The Cairnerzean Rocks can be subdivided into 3 types on modal analysis data, but each type has roughly the same stratigraphic position and the types have the same broad characteristics in the field. The three types are the Cairnerzean Farm type, Claddy House type, and Cairnerzean (North) type.

The typical lithology consists of sequences in which the greywackes are thin-bedded, with greywackes 1-2' thick and shales 2-3" thick, alternating with sequences in which the greywackes are very much thicker, the shales remaining thin. Thick shale bands are uncommon. The thick greywacke beds are often coarse or very coarse grained with impersistent pebble streaks, but the thin greywackes are usually fine grained. In hand specimen the greywackes are pale grey, dull due to a low quartz content, and weather to rusty brown. The shales are similar to the shales of the Lochryan Rocks.

BORELAND ROCKS

South of the moorland of Glenwhan and the Craig Fell there is an area of cultivated ground and pasture, on the low rounded Challoch Hill and Boreland Hill, where exposure is confined to a few small isolated patches. Near East Boreland Farm there are a few exposures in dark grey shale with occasional thin fine grained greywackes, and similar rocks are found near South Boreland Farm, but with more greywacke in the succession, including one 4" band of very coarse greywacke. In the Water of Luce north of the road bridge at Glenluce there is a thick sequence of shales and mudstones, dark blue-grey when fresh but weathering to a rusty yellow. Between the road bridge and the railway bridge to the south there is a short sequence of thinly bedded dark fine grained greywackes mostly about 12" thick with 2-3" shale partings. Upstream these young southwards but to the south quickly change to a north-younging sequence. The rocks dip steeply on either side of this change in younging direction but the actual hinge of the fold is covered by the foundations of the railway viaduct. The steeply faulted junction between these greywackes and the shales to the north is presumably the boundary chosen by H.M. Geological Survey for the Ordovician--Silurian Boundary at this point. The present writer however considers that the greywackes south of the shales should be assigned on petrographic grounds to the Boreland Rocks and that the Ordovician--Silurian Boundary lies to the south, in the unexposed ground between the viaduct and the fossiliferous Silurian rocks at the mouth of the Water of Luce.

The greywackes of this area are dull grey, weathering to a slightly darker colour. In colour, general fine grain-size, and association with a large proportion of lutite they are readily distinguishable from the Glenwhan Rocks immediately to the North. The Greywacke:Shale ratio is not accurately determinable due to insufficient exposures but is of the same order as in the Lochryan Rocks i.e. about 3:1.

GLENWHAN ROCKS

The wide moorland of Glenwhan in the south of the area is occupied by rocks of the Glenwhan Formation, typically exposed as rounded roches moutonnees. Because of the patchy nature of the exposures only the broad lithological features can be seen. The greywackes are found as very thick beds, 10' or more, of a dull grey colour when fresh, weathering to greyish brown. Bed thickness is commonly so great that only very rarely is a bedding surface exposed and determination of the bedding orientation and younging direction is dependent on the occasional thin sequences of thinner bedded material in which greywackes 3-6" thick are interbedded with 1-3" shales. Occasional pale grey or greenish grey shale bands up to 3' thick are found but there are no thick shale bands on the scale of the Lochryan Rocks. An accurate Greywacke:Shale ratio is not determinable but is at least 20:1.

Grain-size of the arenites is coarse to very coarse and pebble streaks are very common. Pebble beds with fragments up to ½" in length often form a whole exposure and one lens of pebble conglomerate 20' long and 3' thick, containing fragments up to 4" long occurs on Craig Fell.

In hand specimen the greywackes have a dull grey lustre with only a few quartz grains visible. In thin section the rocks have a characteristic dusty appearance due to the large content of felspar and basic igneous rock fragments in both of which the felspars are highly altered to a reddish brown alteration product.

CHAPTER 3 PETROGRAPHY of the GREYWACKES

Although there are wide differences in bulk lithology and, as will be seen, in relative composition between the various greywacke types, all the greywackes consist of the same components:- quartz, felspar, ferromagnesian minerals, rock fragments, and a chlorite-sericite matrix. These components are discussed below to indicate how they contribute to the differences between the greywacke types.

MINERALS

Quartz

An essential constituent of the greywackes, quartz occurs as poorly sorted angular to sub-angular grains of low sphericity. All grains contain a large number of small mineral inclusions, often arranged in trains passing across the grains. After the method of Mackie (1896) modified by Keller and Littlefield (1950) the inclusions were classified as Regular (R), Irregular (I), Globular (G), or Acicular (A). Most of the quartz grains contain inclusions belonging to the R, I, or G classes, or mixtures of two or more of these classes. Acicular inclusions are rare. A quantitative examination of 50 quartz grains in each of three thin sections from the Lochryan and Glenwhan Rocks gave the following results:-

	R	I	G	A
No. of quartz grains in which found (%)	58	86	20	16
	50	94	18	12
	34	90	14	22
Mean Lochryan	47	90	17	17
	30	68	70	28
	20	60	80	20
	28	60	90	12
Mean Glenwhan	26	63	80	20

A few quartz grains in each thin section contain much larger mineral inclusions, usually of zircon, epidote, or garnet. These quartz grains usually show little shadow extinction.

A feature of the Lochryan Rocks which is rare in the other types and completely absent from the Glenwhan Rocks is the presence in some quartz grains of growths of stubby anomalous blue chlorite 'vermi.' That this is not an authigenic effect confined to the Lochryan Rocks is shown by some grains in which some of the chlorite crystals form part of the grain boundary. At the boundary this chlorite does not blend into the chlorite of the matrix but has a sharp edge with it. This suggests that the chlorite 'vermi' are a pre-sedimentation phenomenon.

Strain lamellae and shadow extinction are present in all the thin sections examined. In the Lochryan Rocks nearly all of the quartz grains show strain effects but in the Glenwhan Rocks this feature is found in less than a third of the grains. The other greywacke types usually have a high proportion of these grains, though less than the Lochryan Rocks. In all formations the angle between the extinction positions of different parts of a strained grain is usually quite small, less than 20°. According to Potter and Siever (1956), such a small angle indicates an igneous origin for the quartz grains. However Blatt and Christie have recently (1963) suggested that strained quartz is a common constituent of all igneous and metamorphic rocks except acid lavas and is therefore unsuitable as an indicator of provenance.

Felspar

Felspar is a major and in some cases the most common constituent of the greywackes. The species present are quite variable and reflect the felspars present in the rock fragments.

Plagioclase is the common felspar, with a composition in the albite, or in the oligoclase-andesine range. Felspars of both compositions are usually present in a thin section but one composition is usually more common than the other. The common plagioclase types in each rock division are listed below.

Glenwhan		Oligoclase-Andesine	(Max.Ext.Angle 11°)
Boreland		Albitic	(" " " 19°)
Cairnerzean Farm		Oligoclase-Andesine	(" " " 10°)
Claddy House	(a)	Albitic	(" " " 17°)
	(b)	Oligoclase-Andesine	(" " " 15°)
Lochryan	(a)	Albitic	(" " " 21°)
	(b)	Oligoclase-Andesine	(" " " 14°)

The felspar grains are usually irregular or have the form of cleavage flakes, but tabular or lath shaped grains reminiscent in form of the shapes of the felspars in the rock fragments are not uncommon. The greywackes also contain minor amounts of orthoclase and rare grains of microcline and perthite. Except in the Lochryan Rocks the felspars are badly altered to kaolinite and sericite.

Ferromagnesian Minerals

Amphibole and pyroxene are common constituents of the Glenwhan and Cairnerzean greywackes but in the Lochryan and Boreland Rocks they are present only as rare scraps and pseudomorphs. The Glenwhan and Cairnerzean Rocks commonly contain both amphibole and pyroxene as irregular or roughly tabular grains like the phenocrysts in the porphyritic andesite rock fragments found in these greywackes. The pyroxene is generally more common than the amphibole.

The colourless or pale yellow pyroxene has the optical properties of common augite and the amphibole is a pale green - pale yellow - olive green pleochroic hornblende.

The augite and hornblende grains are usually fresh though they do suffer some marginal alteration to chlorite.

Micas

Biotite occurs in very small amount, as well formed laths or as nebulous wisps. The colour is pale red-brown which is pleochroic to pale yellow. The well formed flakes are often seen altering to chlorite or muscovite along the cleavages. Some mantling of other detrital grains suggests that part at least of the biotite is authigenic. However the andesitic rock fragments occasionally contain phenocrysts of a biotite which is identical in colour to the colour of the discrete biotite flakes in the greywackes. Some of the biotite flakes in the greywackes may therefore be detrital.

Muscovite is a common mineral in the greywackes, occurring as long thin or as short stubby laths. The muscovite laths often completely fill the interstices between other detrital grains or mantle other grains. Muscovite is sometimes seen replacing grains or rock fragments at their margins; it is thus probably authigenic.

Chlorite is a common mineral both in the matrix and as discrete grains. Two varieties are found; pale green weakly pleochroic with normal low interference colours, and darker green strongly pleochroic to pale yellow and with anomalous interference colours. The mineral is also found in patches, of various sizes, composed of tiny felted crystals. These probably represent the product of complete replacement of original detrital grains.

Heavy Minerals

Early attempts to examine the heavy mineral content of the greywackes by disaggregation failed as the crushing method did not produce discrete grains, due to the tenacity of the matrix. Thin sections of the greywackes were therefore carefully examined under a high powered microscope to obtain a qualitative estimation of the heavy mineral species present. The occurrences are shown in Table 1. The following differences between rock types were noted.

Apatite is common in all types except the Glenwhan Rocks. In the Lochryan Rocks the apatite is present as small fairly regular grains whereas the other types contain much larger irregular grains. Sphene is common in all the greywacke types except the Boreland Rocks. Tourmaline is common in the Lochryan Rocks, rare in the Glenwhan Rocks and fairly common in the other types. Two varieties of tourmaline are found, one pleochroic colourless to yellow, the other pleochroic olive green to pale yellow. Epidote is fairly common except in the Lochryan Rocks, while Glaucophane is rare or absent except in the Glenwhan Rocks.

Matrix

The detrital grains in the greywackes are relatively poorly sorted with grain-size increasing more or less uniformly above a lower size limit of about 0.01mm. Few grains less than 0.01mm. are visible under a high powered microscope and this grain-size is therefore a convenient boundary between grains and matrix.

The matrix consists of flakes and felted patches of chlorite, sericite, and a dark yellowish-brown mineral, nearly opaque, which is probably a clay mineral. Mica and chlorite flakes have usually grown parallel to the margins of detrital grains, especially if the interstices between grains are very narrow, so that most grains and rock fragments are enclosed in a thin pellicle of matrix material. This pellicle is often seen to replace the detrital grain at the margin.

Opaque Minerals

Pyrite is found as irregular grains, as aggregations of small cubes or spheres, and as a replacement of grains and rock fragments. The curious polar growths of chlorite needles on spheres of pyrite, reported by Kolling (1958) from the Rhinns of Galloway, were also observed in the rocks of this area. Magnetite and hematite are rarely found.

ROCK FRAGMENTS

Rock fragments form a major component of the greywackes. Table 2 shows the rock fragments observed during modal analysis of a large number of thin sections from all formations, illustrating the diversity of rocks present as fragments in the greywackes and also showing the differences between the formations.

Basic Rock Fragments

The Basic igneous rock fraction is high in most of the greywackes, and the type of rock is variable. In the Lochryan and Boreland Rocks the Basic-rock fraction is formed almost entirely of spilitic and keratophyric fragments, with subsidiary amounts of porphyrite. The other greywacke types also contain these Basic-rock fragments but are characterised by containing, in addition, abundant fragments of porphyritic andesite, and minor amounts of other rocks bearing ferromagnesian minerals. In the Glenwhan Rocks andesitic rocks are the dominant rock fragments but in the Cairnerzean Rocks the andesite content is much more variable, and may be subsidiary to the spilite content.

Acid Rock Fragments

The Acid-rock fraction is composed of granitic, quartz porphyry, and acid lava fragments. The distribution of these fragments is fairly constant throughout all the greywackes except that the Boreland Rocks contain a higher proportion of granophyric fragments than the other formations, in which granophyre is rare.

Metamorphic Rock Fragments

The Metamorphic-rock fraction consists mainly of fragments of metamorphic quartzite (see later) and quartz muscovite schist. The other rock types noted in Table 2 are found in small amount, usually only one or two fragments per thin section. The same suite of rock fragments is found in all the formations with the following exceptions. Rock fragments containing glaucophane are found in significant amount only in the Glenwhan Rocks (which also contain detrital glaucophane). Epidotic rocks are rare in the Lochryan and Boreland Rocks, which are also poor in detrital epidote. The Glenwhan and Cairnerzean Rocks do contain epidotic fragments; quartz-epidote fragments in the Glenwhan, and epidosite and quartz-epidote fragments in the Cairnerzean Rocks. In both these formations the epidotic fragments are accompanied in the greywackes by detrital epidote.

Sedimentary Rock Fragments

Greywacke, siltstone and shale, and chert fragments are ubiquitous in the Sedimentary-rock fraction of the greywackes of all formations. Arkose and limestone fragments are very rare. The greywacke fragments fall into two varieties. The first variety of greywacke fragment is very similar in composition to the host rock, containing detrital pyroxene and amphibole if the host greywacke contains these minerals and being without them in sympathy with the host. This suggests that there was some degree of consolidation of the greywacke sediment before it was reworked by the turbidity currents. The second variety of greywacke fragment differs from the first in having a higher proportion of matrix, which is always composed of very fresh pale green chlorite. This variety is thought to have been derived from greywackes forming part of the source area.

Table 1 Occurrences of Heavy Minerals in Thin-section

No. of Thin Sections / %	L		CH		C		B		G	
	No.	%	No.	%	No.	%	No.	%	No.	%
Picotite	21	91	10	77	15	83	10	100	39	95
Garnet	21	91	8	62	16	89	9	90	35	85
Apatite	18	78	12	92	15	83	10	100	9	22
Zircon	23	100	12	92	14	78	9	90	24	59
Sphene	20	87	12	92	16	89	3	30	37	90
Rutile	2	9	4	31	-	-	2	20	8	20
Tourmaline	21	91	9	69	7	39	5	50	-	-
Epidote	5	22	9	69	11	61	-	-	28	68
Glaucophane	3	13	-	-	-	-	-	-	28	68

L--Lochryan Rocks 23 thin-sections

CH--Claddy House Rocks 13 thin-sections

C--Cairnerzean Farm Rocks 18 thin-sections

B--Boreland Rocks 10 thin-sections

G--Glenwhan Rocks 41 thin-sections

Table 2 Occurrences of Rock Fragments in Thin-sections

No. of Thin Sections in/ % which found	L		CH		CF		CN		B		G	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Spilite	37	100	9	100	14	100	3	100	9	90	21	100
Andesite	8	22	9	100	14	100	3	100	2	20	21	100
Diorite	-	-	-	-	2	14	1	33	-	-	8	38
Keratophyre	37	100	6	67	11	79	2	67	7	70	21	100
Porphyrite	24	65	5	56	9	64	3	33	6	60	15	71
Dolerite	-	-	5	56	2	14	-	-	-	-	2	9
Granite	37	100	7	78	14	100	3	33	9	90	21	100
Granophyre	2	5	-	-	3	21	-	-	7	70	-	-
Graphic Granite	9	24	3	33	1	7	-	-	2	20	2	9
Qu. Porph.	35	95	6	67	11	79	1	33	5	50	14	67
Qu. Kerat.	37	100	6	67	6	43	1	33	4	40	12	57
Rhyolite	20	54	3	33	9	64	1	33	8	80	11	52
Glass	27	73	2	22	9	64	1	33	2	20	7	33
Vein Qu.	37	100	9	100	14	100	3	100	9	90	15	71
Greywacke	36	97	6	67	12	86	2	67	4	40	19	90
Shale	30	80	3	33	1	7	2	67	-	-	7	33
Chert	34	92	2	22	12	86	-	-	8	80	15	71
Arkose	18	44	-	-	1	7	-	-	-	-	3	14
Limestone	10	27	-	-	2	14	-	-	1	10	1	5
Cata Clasite	36	97	9	100	6	43	3	100	2	20	12	57
Phyllite	35	95	6	67	7	50	1	33	2	20	2	9
Met. Qu.	37	100	9	100	14	100	3	100	4	40	16	76
Epidosite	4	11	6	67	11	79	3	100	-	-	2	9
Schist:-												
Qu. Musc. Schist	37	100	9	100	14	100	3	100	10	100	16	76
Qu. Gnt. Schist	1	3	-	-	-	-	-	-	1	10	-	-
Graphitic Schist	13	35	5	56	2	14	1	33	-	-	-	-
Qu.Chlor.Schist	20	54	5	56	-	-	2	67	-	-	5	24
Qu + Epidote	3	8	2	22	5	36	2	67	1	10	8	38
Qu. Gnt. Epid.	-	-	-	-	1	7	-	-	-	-	-	-
Qu. Ep. Glauc.	-	-	-	-	-	-	-	-	-	-	1	5
Qu. Glauc.	-	-	-	-	-	-	-	-	-	-	3	14

L - Lochryan Rocks 37 thin-sections

CH - Claddy House Rocks 9 thin-sections

CF - Cairnerzean Farm Rocks 14 thin-sections

CN - Cairnerzean North Rocks 3 thin-sections

B - Boreland Rocks 10 thin sections

G - Glenwhan Rocks 21 thin sections

CHAPTER 4 MODAL ANALYSES

To establish the quantitative mineral composition of the greywacke types present in the area a large number of thin section modal analyses were carried out. Before discussion of the results the general experimental conditions are set out.

Thin sections were analysed on a Swift Automatic Point Counter for eight constituents:- Quartz, Felspar, Basic igneous rock fragments, Acid igneous rock fragments, Metamorphic rock fragments, Ferromagnesian minerals, and Matrix. These constituents had been found to be characteristic of the greywackes by qualitative examination of the thin sections. The essence of the point count method is the degree of rapidity in obtaining the results (see Chayes 1956) but this rapidity induces experimental error by causing misidentifications. The sources of error in the analysis of greywackes are discussed below.

Quartz is defined to include all quartz grains and fragments of vein quartz, i.e. fragments of quartzite in which there are no orientated inclusions, or trains of inclusions passing from one crystal to the next in the fragment. The sources of error are two-fold. Grains of fresh untwinned felspar showing no cleavage, and not in contact with a quartz grain or with Canada Balsam, are not readily distinguishable from quartz and may be counted as quartz. Metamorphic quartzite with a small degree of strain extinction and no orientated inclusions may be confused with vein quartzite.

Felspar includes all low birefringent grains showing alteration, twinning or cleavage, other than ferromagnesian minerals.

Under the Basic rock constituent were counted all spilites, keratophyres, and melanocratic igneous rock fragments, while the Acid rock constituent includes granitic, quartz keratophyre and acid lava fragments, most of which, in these rocks, contain free quartz. Error may arise by the confusion of very leucocratic keratophyre fragments (Basic) and acid lava fragments.

The Metamorphic rock constituent includes all schist, gneiss, and cataclasite fragments and also metamorphic quartzites, which are defined as quartzites in which the grains have sutured margins and either trains of inclusions passing across grain boundaries or micaceous material in the interstices between grains. The absence of inclusion trains or micaceous material from a quartzite of metamorphic origin leads to the fragment being wrongly counted with vein quartzite.

The Ferromagnesian mineral constituent consists of all detrital grains of amphibole and pyroxene.

The Matrix is arbitrarily defined as including all material smaller than 0.1 mm. since the detrital quartz and felspar are not readily distinguishable at this grain-size. In addition all chloritic, micaceous, and clay mineral material, and all heavy mineral grains, opaque minerals, and pseudomorphs, no matter what their grain size, are counted as matrix.

To summarise, the major sources of operator error by misidentifications in these greywackes are the identification of quartz as felspar, metamorphic quartzite as vein quartz, very leucocratic keratophyre as Acid, quartz porphyry as Basic if free quartz is fortuitously absent from the fragment, and very small greywacke fragments as Matrix.

The actual effects of operator errors are discussed in a later chapter.

Preliminary Operations

A major consideration in the present work was to investigate possible sources of inconsistency in the modal analyses and, if possible, to eliminate them. The following operations were therefore carried out before commencement of the definitive analyses.

Grain-size

Modal analysis results depend to some extent on the grain-sizes of the rocks (Kelling 1962). This variable was therefore minimised by choosing, by inspection, thin sections of nearly the same mean grain-size, in practice about 0.3 mm. In addition specimens which were of this mean grain-size but which contained grains very much larger than the other grains in the specimen were not analysed.

Consistency of Identification of Constituents

A group of three thin sections was repeatedly analysed until replicate analyses of each thin section were closely similar. The results are shown in Table 3.

Optimum Number of Points

One of the above thin sections was progressively analysed and the analyses calculated after 875, 1000, 1250, and 1500 points (Table 4). The analyses for 1250 and 1500 points are closely similar to each other and to the later analyses of this thin section in Table 3. A standard of 1500 points was chosen so that there would be a large inertial effect to counteract variations due to slight differences in grain-size between thin sections, and between different parts in the same thin section.

Optimum Magnification

The results in Table 4 were obtained with a microscope magnification of 100 times. To examine the effect of a different magnification this section was analysed with a magnification of 50 times. The result, shown in Table 5 is similar to previous analyses of this thin section.

Definitive Analysis Results

Specimens from the Loch Ryan coast section were collected on a sampling scheme suggested to the writer by Prof. W.C. Krumbein. 20 equally spaced stations were set up along the coastal exposures and at each station two localities were chosen 10' apart. At each locality a specimen was collected if the greywacke was of the correct grain-size. If the locality did not yield a specimen of the required grain-size the nearest greywacke of the correct grain-size was sampled.

The rest of the area was sampled by collecting a specimen at each intersection of a grid with 600 x 600 yard spacings, or at the nearest outcrop to this intersection. Since the grain-size of the rocks is variable only a small proportion of these specimens was suitable for analysis, but the analysed specimens still give a fairly good coverage of the area. In addition the sampling density was increased near formational boundaries, to locate boundaries in poorly exposed ground as accurately as possible.

Lochryan Rocks

The Lochryan Rocks are found in wide stretches in the north and centre of the area. Most of the exposures are concentrated along the short coast section and the escarpment along the shores of Loch Ryan. In the field and in microscopic examination the rocks are homogeneous but the modal analysis results show (Table 6) that they can be sub-divided into Lochryan Upper in the north and the Lochryan Lower in the south, the Lower division having significantly more metamorphic rock fragments than the Upper division (significant at the 1% level).

Cairnerzean Rocks

These rocks occur in several isolated narrow strips. The modal analysis results show that the composition is slightly different in each strip.

Cairnerzean Farm Type

This strip stretching from Craigcaffie to Cairnerzean has two main areas of outcrop, distinguished in Table 7. as Cairnerzean Farm (East) and Cairnerzean Farm (West). An analysis of variance was carried out to determine whether the two samples were samples from the same population and thus establish the lateral homogeneity of the formation. The results in Table 8 show that the differences between the two samples are statistically not significant except in the total quartzose fraction (quartz + acid rocks + metamorphic rocks) in which they differ at the 5% level, the eastern rocks being the more quartzose. To check that this difference is not due to differences in the degree of disaggregation, although the analysis specimens are chosen to be of the same grain size, the total rock fragment fractions in the two samples were compared statistically and found not to be significantly different.

Claddy House Type

The results for this strip are shown in Table 7. Although this group of rocks occupies the same stratigraphic position as the Cairnerzean Farm Rocks, just above the Lochryan Rocks, there are differences in the composition, the Claddy House Rocks showing less quartz and more felspar and basic rock fragments.

Cairnerzean (North) Rocks

The remaining rocks containing ferromagnesian minerals are grouped into this greywacke type. They occur as isolated exposures in the northern part of the area. Table 7 shows a general increase in the content of ferromagnesian minerals and basic rock fragments compared with the Cairnerzean and Claddy House Rocks.

Boreland Rocks

The Boreland Rocks are very poorly exposed and are mostly fine grained. The modal analysis specimens are therefore badly distributed, being collected from the two outcrops of coarse grained material (Table 9). No estimation of lateral variation is possible but thin sections of these rocks do show an incoming of ferromagnesian minerals, in the form of pseudomorphs, towards the top of the division. These rocks therefore pass directly into the overlying Glenwhan Rocks, by a decrease in acid rock fragments and quartz, and an increase in ferromags and basic rock fragments.

Glenwhan Rocks

The analyses for this formation are shown in Table 10. Since the Glenwhan Rocks cover a large area it is important to determine whether or not the analyses form a homogeneous population, in other words whether there is any lateral and/or cross-dip variation in the rocks. To this end the results were divided on a geographical basis into four samples and analysis of variance performed on the constituents individually (Moroney 1958, p.381). No significant variations between the samples were found (Table 11), showing that the formation is a homogeneous rock unit.

Comparison of Modal Analysis Results

To eliminate as far as possible the effects of differing degrees of disaggregation, during weathering and transportation, on the quantitative composition of the greywackes the modal analysis specimens were chosen to have as near the same grain-size as possible. As a check on the assumption that small variations in grain-size do not cause major changes in composition, and are therefore not the causes of the differences between the formational individual analyses, a series of thin sections from various heights above the base in a single greywacke bed were analysed (fig. 4).

Variation in Grain-size

This graph confirms the field observation that changes in grain-size of most of the graded Lochryan greywackes take place near the bottom and near the top of the bed, most of the bed being of one grain-size.

Constituents

Quartz, Felspar, Matrix, and Metamorphic rocks show a net increase in proportion, and the other rock fragments a net decrease in proportion towards the top of the bed. In other words there is a change in composition with grain-size, but this is very slight. When the changes are compared with the variations in proportions found when an analysis operator performs replicate analyses on a single thin section (see below) the within-bed variations are seen to be of the same order as the operator variability. The effect of slight differences in grain-size in causing within-formation variation can therefore be discounted.

Replicate Analyses

The tables of analyses results show some within-formation variability. As shown above this is unlikely to be due to variations in grain-size as the analysis specimens had been chosen to be of the same grain-size. The variability may be due to actual differences in composition between specimens or to operator variances, although great care was taken to maintain consistency of identification. As a measure of the variability the standard deviations of the components analysed were calculated for one formation (Table 12). The Boreland Rocks were chosen for this test as the analyses are quite variable and the composition of this formation is based, of necessity, on only a few analyses, and is therefore not firmly based statistically. One of the definitive thin sections was then selected and analysed at irregular intervals over a fairly long period of time. The calculated means and standard deviations for the replicate analyses of a single thin section (Table 12) are found to be of the same order of magnitude as those for the formational mean analysis, based on several thin sections. In other words the within-thin section variability, due to operator variance, is the same as the between-thin section variability. This result leads to the specific conclusion that the Boreland Rocks are a valid rock-group, despite their variability, and to the more general conclusion that the within-formation variability of modal analyses is a function of operator variance of an operator who is however a consistent analyst since the within-formation variations are small (see Tables 6, 7, 9, 10). Therefore the within-formation variability does not preclude the use of modal analyses to establish formations as homogeneous rock-units.

Comparison of Greywacke Types

The greywacke types described above are compared by amalgamating the analysis components into three groups, (Quartz, Acid rocks, Metamorphic rocks), (Sedimentary rocks, Matrix), (Basic rocks, Felspar, Ferromags), and plotting these groups on a triangular variation diagram, fig. 5.

The diagram shows good mixing of the Lochryan Upper and Lower divisions, in a field completely distinct from that of the Glenwhan Rocks. The area between these two fields is occupied by the rocks of the other greywacke types, which show a progressive northwards change in composition so that the most northerly, Cairnerzean (North) Rocks occupy the same field as the Glenwhan.

The diagram suggests that the Cairnerzean Rocks are kindred to the Boreland Rocks and form a transitional series between the Lochryan and Glenwhan Rocks.

In fig. 6 the composition of the rock fragment fraction of the greywackes is examined in a variation diagram with Basic, Acid, and Metamorphic rocks as apices. Again the Lochryan and Glenwhan Rocks occupy separate fields with the other formations showing a gradation between the two, though less well marked than in fig. 5. In fig. 6 there is a better separation of the Lochryan (Lower) type into a distinct field.

Comparison with Rhinns of Galloway

The mineralogy and petrology of the rocks of the area have enabled the subdivisions of the succession detailed above to be made. It is of interest here to compare these subdivisions with those set up by Kelling in the Rhinns of Galloway (Kelling 1961).

In that part of the Rhinns south of the Glen App Fault Kelling set up three "groups." These are briefly summarised below.

Portpatrick	Basic-clast	Thick bedded greywackes with little shale in succession. Coarse grained felspathic with andesitic frags. and ferromags
	Acid-clast	Thickly bedded but with thick shale bands. Felspathic with acid ig. frags. and ferromags.
Galdenoch		Thin bedded greywackes with frequent much thicker beds. Coarse grained quartzose with andesitic fragments ferromags and large apatites.

Kirkcolm	Upper Barren	Thinly bedded with many shale inclusions. Thick shale bands. Quartzose with spilitic fragments. No ferromags.
	Metaclast	As above but with a higher proportion of metamorphic rock fragments.
	Lower Barren	As Upper Barren but with a few ferromags.

The rock descriptions and modal analyses published by Kelling, together with lateral extrapolations along strike from his map lead to the proposal of the following correlations with the present area.

Glenwhan Rocks	equivalent	to	Portpatrick	Basic-clast
Boreland Rocks	"	"	"	Acid-clast
Cairnerzean Group	"	"	Galdenoch	
Lochryan (Upper) Rocks	"	"	Kirkcolm	Upper Barren
Lochryan (Lower)	"	"	"	Metaclast

The rock types described in this thesis are similar to the descriptions published by Kelling, at times even in finest detail; for example large apatite grains are reported in both Cairnerzean and Galdenoch Rocks. There are however some points of difference. Boreland Rocks are thinly bedded compared with the Portpatrick (Acid-clast). This is parallelled by a reduction in bed thickness of the Lochryan compared with the Kirkcolm Group.

Ferromagnesian minerals are absent from most thin sections of the Boreland Rocks but many specimens, especially those collected near the lowest Glenwhan

Rocks, do contain pseudomorphs. The absence of ferromagnesian minerals compared with the Portpatrick (Acid-clast) may be a further indication of the eastwards impersistence of a distinct formation between the Lochryan--Kirkcolm and the Glenwhan--Portpatrick (Basic-clast). It is shown earlier in this thesis that the Cairnerzean Rocks change in composition northwards, becoming like the Glenwhan Rocks; the distinctive Cairnerzean composition of the type area is lost to the north although the rocks are still stratigraphically just above the Lochryan Rocks. The lack of significant ferromagnesian minerals in the Boreland Rocks and their similarity in composition and lithology to the Lochryan Rocks, suggests that the Boreland Rocks are, like the Cairnerzean Rocks, a passage formation between the Lochryan and the Glenwhan, at much the same stratigraphic level as the Cairnerzean Rocks. (Kelling (1962) equates the Galdenoch and the Portpatrick (Acid-clast)). In this case the Portpatrick (Acid-clast) rocks, a distinct facies in the Rhinns, have changed eastwards, becoming more like the Lochryan Rocks. The stratigraphic picture therefore emerges that in the north of the present area Lochryan Rocks are overlain by rocks similar to the Glenwhan in composition but not in lithology, in the centre of the area Lochryan Rocks are overlain by rocks of a distinctive character and lithology (Cairnerzean Farm type) and in the south of the area Glenwhan Rocks are underlain by rocks identical to the Lochryan in lithology and similar to the Lochryan in composition. These relationships and the corresponding relationships in the Rhinns are illustrated in fig. 7. This figure shows the occurrence of the Portpatrick (Acid-clast)--Galdenoch--Boreland--Cairnerzean rocks between the Lochryan-Kirkcolm and the Glenwhan-Portpatrick (Basic-clast). In the figure this facies is represented as a wedge-shaped body because of the variations discussed above, but this interpretation is very tentative due to the poor exposure precluding very accurate thickness measurements both in the Rhinns and in the present area.

Comparison of Modal Analyses

The mean modal analyses from Kelling (1961) are compared in Table 13 with the means for the corresponding formations east of Loch Ryan. Before proceeding with his own analyses the present writer was fortunate in being able to consult with Dr. Kelling on the identification of the various constituents, an obvious precaution in view of the complex composition of the rocks, discussed above. The analyses of the two operators should then have been directly comparable. However as a measure of the possibility of misidentification of some of the constituents, seven thin sections from the Lochryan (Upper) Rocks were analysed both by Dr. Kelling and the writer. The results are shown in Table 14, with, for comparison, the corresponding mean analysis for the Kirkcolm (Upper Barren) rocks from Kelling 1961. The results showed that the writer's analysis of the seven Lochryan rocks was closer to the analysis of the Kirkcolm (Upper Barren) rocks (Kelling 1961) (i.e. lateral equivalent of the Lochryan Rocks) than was Dr. Kelling's. This suggested that operator variance in the modal analysis of greywackes was a factor which could not be ignored if comparisons between areas were to be made. A more comprehensive trial of the point count modal analysis method was therefore carried out (Table 15). Analysis of variance of the results of this trial, (Table 16) shows that in only two components, Metamorphic and Sedimentary rock fragments, is there no significant difference between the operators. That the lack of correlation between the analysts is due to the inherent possibility of misidentifying component grains and not to any carelessness on the part of the operators is shown in Table 17, which lists the results of calculations of the Rank Correlation Coefficient for the two operators. This table shows that the two operators successfully placed the individual values of each component in the same order of decreasing magnitude. The conclusion is reached that the two operators are able to place components in the same order but the possibilities of misidentifications are great enough for the actual magnitudes to have no significant agreement. The unadjusted point count modal analysis method is therefore not sufficiently accurate for use in regional comparisons between areas of different workers, though, as has been shown earlier, individual workers can be consistent enough for the results to be valid for comparisons inside their own areas.

However the significant ranking correlation between the two operators suggests that a correction factor may be obtained to transform the data to make them comparable. The operator variance results were used to produce graphs (fig. 8) of the results of one operator against the results of the other, for each component. As expected, from the significant rank correlations, the graphs are linearly distributed, with positive correlation. The data for each component were used to calculate the respective correlation coefficients and regression equations; the regression line for y on x is shown on each graph. Each regression line can then be used to transform the present writer's definitive analyses into a form for comparison with the Rhinns' date. (The close correspondence between the writer's initial 7 Lochryan analyses and Kelling's 1961 mean Kirkcolm Upper Barren is thought to have been coincidental, as no other group of analyses shows an unadjusted correspondence with the equivalent Rhinns group.)

Table 18 shows the adjusted mean analyses of the writer's area with ranges in which the adjusted values lie with a 95% confidence level. The range in each case is twice the Standard Error of Estimate computed from the standard deviation and regression coefficient of the respective component in the operator variance analyses. The transformed analyses are compared below with the mean analyses of the corresponding Rhinns formations. The significance of the differences noted in Table 18 is discussed later.

Glenwhan--Portpatrick (Basic-clast)

The components of the mean Portpatrick (Basic-clast) analysis lie within the ranges of the transformed Glenwhan results except for Felspar, Basic, and Sedimentary rock fragments, Felspar being higher and Basic and Sedimentary rock lower in the Portpatrick.

Lochryan (Upper)--Kirkcolm (Upper Barren)

The analyses are comparable except for Basic rocks and Matrix, Matrix being higher and Basic rocks lower in the Kirkcolm.

Lochryan (Lower)--Kirkcolm (Metaclast)

The two mean analyses differ in Quartz, which is higher, and Metamorphic rocks, which are lower in the Kirkcolm (Meta-clast).

Boreland--Portpatrick (Acid-clast)

The mean analyses differ in Felspar and Matrix. If however the average Portpatrick analysis (i.e. Basic-clast + Acid-clast) is used for comparison the only difference with the Boreland is in the Felspar constituent, a further indication of the eastwards loss of a separate distinctive character for the Boreland--Portpatrick (Acid-clast) rocks.

Cairnerzean Rocks

The Cairnerzean Rocks are thought to be the lateral equivalent of the Galdenoch Group of the Rhinns. When the Galdenoch is compared with the corrected values for the various areas of outcrop of the Cairnerzean Rocks, Quartz, Basic rocks and Matrix are found to be different in all four areas, Metamorphic rocks are different in all areas except the Claddy House Rocks, and Sedimentary rocks differ in the Claddy House and Western area of the Cairnerzean Farm rocks. The Galdenoch rocks are higher than the Cairnerzean in Quartz and Matrix, and lower in Basic, Metamorphic, and Sedimentary rocks.

Conclusions

The differences between the present area and the Rhinns are illustrated in fig. 9.

For the most part the results in Table 18 confirm the equivalence of the various formations suggested by the detailed petrography. Any differences may be explained as due to lateral variation between the east and west sides of Loch Ryan, probably caused by the turbidity currents flowing from slightly differing parts of the source area.

The exception to simple comparisons between the two areas are the Cairnerzean Rocks which show no simple relations with the corresponding Galdenoch Group. These disagreements are thought to be further evidence of the non-stable character of the passage rocks between the Lochryan--Kirkcolm and the Glenwhan--Portpatrick (Basic-clast).

Table 3 Consistency of Identification of Specimens during Modal Analysis

		Run 1 %	Run 2 %	Run 3 %	Run 4 %
1W22	Quartz	34.3	27.5	34.8	36.6
	Felspar	4.8	7.9	9.8	10.0
	Basic	10.2	16.0	11.3	11.5
	Acid	2.9	1.5	1.7	1.7
	Met	1.4	0.7	0.4	0.5
	Sed	10.2	7.8	6.4	7.4
	Matrix	36.2	38.6	35.6	32.3
1W51	Quartz	30.3	29.4	30.0	
	Felspar	2.0	4.4	6.0	
	Basic	16.1	17.6	19.8	
	Acid	4.4	5.6	2.6	
	Met	0.3	0.5	1.4	
	Sed	9.3	11.4	10.9	
	Matrix	37.6	31.1	29.3	
3W60	Quartz	30.7	26.2	31.9	
	Felspar	13.9	17.1	21.9	
	Basic	14.9	12.2	9.6	
	Acid	2.6	3.8	3.6	
	Met	3.7	2.4	3.1	
	Sed	2.2	3.3	1.4	
	Matrix	26.7	27.0	19.4	
	Ferromags	5.3	8.0	9.0	

Table 4 Optimum No. of Points for Modal Analysis

1W22

Composition (%) after	876 Points	1008 Points	1259 Points	1519 Points
Quartz	34.8	36.6	35.7	35.0
Felspar	9.8	10.0	11.2	11.3
Basic	11.3	11.5	12.7	13.4
Acid	1.7	1.7	1.7	2.5
Met	0.4	0.5	0.8	0.8
Sed	6.4	7.4	7.5	7.6
Matrix	35.6	32.3	30.4	29.4

Table 5 Effect of Change of Magnification during Modal Analysis

1W22	%
Quartz	37.5
Felspar	10.1
Basic	11.4
Acid	2.8
Met	1.1
Sed	8.7
Matrix	28.1

(Compare results with Table 4)

Table 6 Lochryan Rocks, Modal Analysis Results

Number	3W2	3W4	1W22	9W10a.1	9W10b.2	3W7	3W8	1W56	1W72	1W77	3W14
Quartz	29.8	24.5	31.0	19.8	22.8	35.3	31.0	29.6	23.7	27.9	21.0
Felspar	7.1	15.5	10.9	3.9	5.7	11.0	11.9	10.1	11.7	7.2	7.5
Basic	18.2	12.4	16.4	35.6	21.2	10.2	14.9	6.4	22.0	7.0	17.7
Acid	7.6	8.7	6.4	13.4	21.2	6.5	4.3	9.8	6.0	20.3	12.0
Met	12.3	7.1	6.7	5.3	7.4	5.7	11.9	2.4	6.5	5.2	8.1
Sed	3.0	3.5	2.8	7.5	6.7	3.6	3.2	7.3	2.7	8.5	8.7
Matrix	22.0	28.4	25.8	14.5	14.9	27.7	22.8	34.4	27.4	23.9	27.0
Ferromag	-	-	-	-	-	-	-	-	-	-	-
Total	100.0	100.1	100.0	100.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0

Number	3W15	3W15b	1W81	3W16	1W85	3W11	3W17	3W18	3W20	1W104	9W306
Quartz	22.8	30.6	24.9	30.6	29.3	23.9	38.0	34.3	32.6	15.7	15.7
Felspar	7.4	9.7	3.5	7.1	3.1	11.0	5.0	10.6	9.9	3.5	2.1
Basic	27.7	19.8	14.1	20.0	22.2	24.1	18.9	5.8	6.3	32.1	44.0
Acid	6.4	7.0	13.7	7.9	8.9	7.5	5.5	16.1	13.4	22.8	15.1
Met	12.3	5.5	24.0	10.6	11.6	3.5	11.4	8.2	4.1	6.3	7.9
Sed	8.5	5.5	3.2	4.4	7.1	4.1	6.8	2.3	4.6	14.3	9.7
Matrix	14.9	21.9	16.7	19.5	17.8	25.9	14.5	22.6	29.1	5.3	5.6
Ferromag	-	-	-	-	-	-	-	-	-	-	-
Total	100.0	100.0	100.1	100.1	100.0	100.0	100.1	99.9	100.0	100.0	100.1

Number	9W32	9W31	3W33	3W25	3W26b	3W30	3W35	1W133	Mean
Quartz	26.7	30.6	43.9	32.1	28.9	27.5	31.4	19.2	27.9
Felspar	6.7	6.5	5.9	6.9	7.7	4.8	4.6	3.5	7.5
Basic	25.3	20.2	7.1	20.2	23.9	20.2	19.7	27.6	19.3
Acid	5.0	7.5	9.9	8.5	6.2	3.5	5.0	18.3	10.2
Met	10.5	3.3	11.5	7.3	7.5	7.7	10.1	4.7	8.3
Sed	1.5	5.7	3.8	3.0	3.5	6.8	3.7	10.5	5.7
Matrix	24.3	16.3	17.8	22.0	22.3	29.5	25.6	16.1	21.3
Ferromag	-	-	-	-	-	-	-	-	-
Total	00.0	100.1	99.9	100.0	100.0	100.0	100.1	99.9	

Upper Lochryan (Coast Section)

Number	1W102	4W1	3W83
Quartz	27.0	26.2	35.4
Felspar	6.4	3.5	8.4
Basic	19.5	25.2	17.3
Acid	12.3	12.1	8.5
Met	7.4	10.5	11.8
Sed	4.2	3.7	1.1
Matrix	23.0	18.8	17.5
Ferromag	0.1	-	-
Total	99.9	100.0	100.0

Other Upper Lochryan

Number	3W62	6W27	7W66	9W30a	7W69	3W50	Mean
Quartz	27.5	32.9	30.7	33.3	29.0	34.8	31.9
Felspar	5.5	3.4	8.9	8.5	8.0	7.9	7.2
Basic	24.6	11.9	13.1	12.3	16.9	14.5	15.8
Acid	6.7	8.5	8.7	7.1	6.1	7.5	7.6
Met	9.8	31.6	16.3	15.1	19.1	15.4	17.0
Sed	4.5	1.3	0.5	4.3	3.4	0.5	2.2
Matrix	21.4	10.3	21.8	19.5	17.5	19.5	18.2
Ferromag	-	-	-	-	-	-	-
Total	100.0	99.9	100.0	100.0	100.0	100.1	-

Lower Lochryan

Table 7 Cairnerzean Group, Modal Analysis Results

Cairnerzean Farm East

Number	7W56	7W57	7W58	7W59	7W60	7W65	7W63	7W61	7W62	Mean
Quartz	17.2	10.6	26.1	13.0	13.4	15.9	19.7	13.1	19.2	16.5
Felspar	20.9	10.9	17.6	13.5	11.4	14.8	16.9	7.1	16.9	14.5
Basic	18.6	14.1	13.0	26.3	44.1	23.7	18.6	24.1	20.6	22.6
Acid	7.9	15.9	7.7	6.7	5.9	3.5	4.2	12.7	6.4	7.8
Met	5.2	16.7	15.1	16.9	6.1	12.3	13.0	17.9	4.7	12.0
Sed	1.7	1.5	3.1	1.9	1.8	5.1	1.4	1.9	4.8	2.6
Matrix	12.9	17.7	14.7	10.5	12.4	16.0	20.0	11.3	27.2	15.8
Ferromag	15.5	12.7	2.7	11.3	4.9	8.8	6.3	11.9	0.1	8.2
Total	99.9	100.1	100.0	100.1	100.0	100.1	100.1	100.0	99.9	100.2

Cairnerzean Farm West

Number	3W35b	2W57	3W53	3W54	3W55	3W60	Mean
Quartz	15.2	14.9	17.9	11.9	10.9	14.9	14.3
Felspar	17.8	9.4	11.3	14.9	11.9	18.9	14.0
Basic	23.8	43.4	27.6	33.2	34.6	24.8	31.2
Acid	9.3	9.1	7.5	2.9	0.9	3.6	5.6
Met	9.7	10.9	4.9	4.1	7.5	11.1	8.0
Sed	2.0	2.6	7.3	2.5	2.5	1.5	3.1
Matrix	20.4	7.5	15.4	22.9	19.3	19.9	17.6
Ferromag	1.9	2.3	8.1	7.5	12.5	5.3	6.3
Total	100.1	100.1	100.0	99.9	100.1	100.0	100.1

Claddy House

Section	1W117	2W59	2W60	4W13a	4W13b	4W14	4W15	Mean
Quartz	8.1	8.9	6.9	6.7	4.8	8.5	7.7	7.4
Felspar	19.9	30.7	25.2	20.5	19.7	19.3	11.9	21.0
Basic	23.1	23.9	23.7	25.4	30.1	24.9	39.3	27.2
Acid	1.4	6.0	7.7	7.3	2.4	4.6	6.6	5.1
Met	6.9	5.3	8.6	4.1	5.0	6.8	7.9	6.4
Sed	2.1	2.0	0.9	1.7	2.3	14.8	4.9	4.1
Matrix	28.3	15.9	15.6	19.3	19.3	15.7	13.9	18.3
Ferromag	10.2	7.3	10.9	14.9	16.5	5.5	8.1	10.5
Total	100.0	100.0	100.0	99.9	100.1	100.1	100.3	100.0

Cairnerzean (North)

	7W4	4W2	7W72	8W2	8W5
Quartz	4.7	5.6	4.8	16.7	5.4
Felspar	11.9	11.5	14.2	10.3	18.5
Basic	38.6	35.9	43.8	33.3	37.5
Acid	3.7	1.3	1.6	4.1	2.5
Met	3.1	4.7	7.2	14.1	7.4
Sed	-	0.7	0.9	1.5	4.3
Matrix	22.7	17.4	18.2	18.4	21.5
Ferromag	15.4	22.9	9.3	1.6	2.9
Total	100.1	100.0	100.0	100.0	100.0

Table 8 Statistical Comparisons between Cairnerzean (Farm) East and Cairnerzean (Farm) West

	Total		Between 'A' & 'B'			Within A & B			F	Significance	
	S.S.	D.F.	S.S.	D.F.	Var.	S.S.	D.F.	Var.	Ratio	5%	1%
Q	213	13	11	1	11	202	12	16.8	1.53	N.S.	N.S.
F	222	13	0.21	1	0.21	221.8	12	18.5	90.6	N.S.	N.S.
B	1171	13	33.5	1	33.5	1137.5	12	94.8	2.83	N.S.	N.S.
A	208	13	23.71	1	23.71	184.3	12	15.7	1.54	N.S.	N.S.
M	311	13	87.2	1	87.2	223.9	12	18.7	4.67	N.S.	N.S.
S	39	13	3.25	1	3.25	35.75	12	2.98	1.09	N.S.	N.S.
Mx	251	13	30.86	1	30.86	220.1	12	18.3	1.68	N.S.	N.S.
Fm	259	13	31.9	1	31.9	227.1	12	18.9	1.68	N.S.	N.S.
QAM	1031	13	304	1	304	726.3	12	60.5	5.04	⊕	N.S.
BFFm	837.5	13	105.4	1	105.4	732.1	12	61.0	1.73	N.S.	N.S.
MxS	324	13	51.4	1	51.4	272.6	12	22.7	2.26	N.S.	N.S.

⊕ Significant at 5% level

NS Not significant

Table 9 Boreland Rocks, Modal Analysis Results

	5W2a	5W2b	6W50	6W51	6W53	Mean	S
Quartz	24.4	16.3	18.1	17.5	18.7	19.0	2.8
Felspar	28.6	22.3	19.4	18.7	19.1	21.6	3.8
Masic	13.9	18.1	18.5	14.9	22.2	17.5	8.4
Acid	8.3	3.9	3.5	10.0	18.0	8.7	5.3
Met	1.5	1.9	2.8	1.3	2.0	1.9	0.5
Sed	1.1	0.7	1.1	0.8	2.5	1.2	0.7
Matrix	22.0	36.8	36.8	36.7	17.5	30.0	8.3
Ferromag	-	-	-	-	-	-	
	99.8	100.0	100.2	99.9	100.0	99.9	

Table 10 Glenwhan Rocks, Modal Analysis Results

	NE	NE	NW	NW	NW	NW	NE	NW	SW	SE	NE	SW	SW	SW	SE	SW	SE	SW	SE	NE	SE	
Section	6W21	6W20	3W70	3W87	3W73	3W78	6W10	3W86	3W89	6W11	6W8	3W92b	3W92a	3W93	5W11	3W94	5W9	5W5	8W62	6W13	6W7	Mean
Quartz	3.4	5.0	3.4	2.1	5.9	5.0	1.9	8.5	3.4	3.9	4.7	3.3	5.1	3.9	6.8	5.3	4.2	3.7	8.0	5.3	8.8	4.8
Felspar	6.3	16.5	15.3	15.0	9.1	10.2	11.1	14.1	9.0	18.2	16.2	20.4	17.6	13.9	21.3	16.5	12.4	11.7	11.1	12.4	13.5	13.9
Basic	52.4	46.8	50.2	44.6	46.9	46.9	47.2	33.6	48.1	42.5	47.1	37.7	46.6	49.2	44.6	51.9	56.4	55.4	51.5	45.8	53.7	47.5
Acid	9.2	0.6	4.6	2.4	3.2	7.1	8.7	4.3	10.0	4.3	4.7	3.1	3.2	1.9	3.0	3.1	3.1	3.3	6.1	1.1	2.3	4.3
Met	12.0	0.7	3.5	4.0	1.1	2.1	0.4	6.2	1.3	1.4	1.3	2.7	0.6	0.9	0.9	1.1	0.6	0.7	0.2	2.1	1.8	2.2
Sed	4.7	2.5	1.1	7.6	6.1	11.0	8.9	4.5	0.3	0.5	2.9	1.2	2.4	7.6	1.0	0.1	3.5	6.7	2.7	0.9	1.1	3.8
Matrix	9.9	21.2	18.0	19.4	20.4	13.1	17.8	22.6	20.0	25.4	19.3	23.3	18.9	17.7	17.5	15.9	13.2	13.5	15.5	22.9	13.9	18.1
Ferromag	2.1	6.7	3.8	5.0	7.3	4.6	3.9	6.3	7.9	3.9	3.9	8.3	5.6	3.0	4.9	6.1	6.7	5.1	4.9	9.5	4.9	5.4
Total	100.0	100.0	99.9	100.1	100.0	100.0	99.9	100.1	100.0	100.1	100.1	100.0	100.0	100.1	100.0	100.0	100.1	100.1	100.0	100.0	100.0	100.0

Table 11 Statistical Comparison between four areas of Glenwhan Rocks

	Total		Between Samples			Within Samples			F	Significance	
	S.S.	D.F.	S.S.	D.F.	Var.	S.S.	D.F.	Var.	Ratio	5%	1%
Quartz	65	20	10	3	3.3	55	17	3.26	1.01	N.S.	N.S.
Felspar	303.8	20	30.6	3	10.2	273.2	17	16.1	1.57	N.S.	N.S.
Basic	508.3	20	48.2	3	16.1	460.1	17	27.1	1.69	N.S.	N.S.
Acid	139	20	3	3	1	136	17	8	8	N.S.	N.S.
Met	143.2	20	23.9	3	7.97	119.3	17	7.03	1.13	N.S.	N.S.
Sed	233.8	20	46.9	3	15.6	186.9	17	11	1.42	N.S.	N.S.
Ferromag	85.81	20	2.6	3	0.87	83.2	17	4.9	5.28	N.S.	N.S.
QAM	360.8	20	43.1	3	14.4	317.7	17	18.7	1.3	N.S.	N.S.
BFFm	520	20	152.4	3	50.8	367.6	17	21.6	2.4	N.S.	N.S.

N.S. Not significant

Table 12 Replicate Analyses of a Single Thin Section

	5W2a (Boreland Rocks)							Boreland Definitive Results	
Date	15.1.63	20.2.62	25.10.62	12.2.63	19.2.63	Mean	S	Mean	S
Quartz	18.3	24.4	20.3	19.7	19.5	20.4	2.1	19.0	2.8
Felspar	18.3	28.6	21.4	23.5	16.3	21.6	4.3	21.6	3.8
Basic	32.2	13.9	22.4	22.5	39.0	26.0	8.7	17.5	8.4
Acid	7.2	8.3	8.9	2.5	3.9	6.2	2.5	8.7	5.3
Met	1.5	1.5	2.6	2.0	1.3	1.8	0.5	1.9	0.5
Sed	0.3	1.1	1.6	2.5	1.1	1.3	0.7	1.2	0.7
Matrix	22.3	22.0	22.8	27.4	18.9⊕	22.7	3.1	30.0	8.3

⊕ Inc. 0.5% FeMg

Table 13 Comparison of Formational Mean Modal Analyses

	Glenwhan	Boreland	Cairnerzean (Farm) East	Cairnerzean (Farm) West	Claddy House	Cairnerzean (North)	Upper Lochryan	Lower Lochryan
Q.	4.8	19.0	16.5	14.3	7.4	16.7	27.9	31.9
F.	13.9	21.6	14.5	14.0	21.0	10.3	7.5	7.2
B.	47.5	17.5	22.6	31.2	27.2	33.3	19.3	15.8
A.	4.3	8.7	7.8	5.6	5.1	4.1	10.2	7.6
Met.	2.2	1.9	12.0	8.0	6.4	14.1	8.3	17.0
Sed.	3.8	1.2	2.6	3.1	4.1	1.5	5.7	2.2
Fer.	5.4	-	8.2	6.3	10.5	1.6	-	-
Mat.	18.1	30.0	15.8	17.6	18.3	18.4	21.3	18.2

Rhinns of Galloway

	Portpatrick (Basic-clast)	(Acid-clast)	Galdenoch	Kirkcolm Upper Barren	Kirkcolm Meta-clast
Q.	8.6	19.5	26.2	27.2	37.6
F.	30.9	19.4	9.7	13.3	9.0
B.	29.4	13.1	10.2	9.8	10.0
Acid	5.2	14.7	13.2	10.8	15.5
Met.	0.6	1.5	2.8	5.0	8.0
Sed.	2.3	3.5	1.8	6.7	5.0
Fer.	13.4	3.3	7.8	-	0.8
Mat.	9.3	24.0	28.0	25.5	14.0

Table 14 Comparison of Two Operators on 7 Lochryan Rocks

		7	3	2	5	6	4	1	Mean
GK.	Q.	31.3	24.6	30.4	33.2	29.0	22.0	23.7	27.7
	F.	5.3	6.0	5.4	3.8	8.9	4.9	6.0	5.8
	B.	12.2	17.5	8.4	12.7	11.3	23.9	15.4	14.5
	A.	16.6	26.1	23.4	24.2	21.6	15.1	13.6	20.1
	M.	3.8	2.6	4.3	10.5	7.5	10.7	7.9	6.7
	S.	9.7	11.3	8.7	2.2	7.4	12.3	11.6	9.0
	Mx.	21.1	11.8	18.9	13.4	13.9	9.9	21.4	15.8
	Fm.	-	0.1	0.4	-	0.4	1.2	0.5	0.4
									Mean
WW.	Q.	35.3	27.9	29.6	34.3	32.6	30.6	27.7	31.1
	F.	11.0	7.2	10.1	10.6	9.9	9.7	12.0	10.1
	B.	10.2	7.0	6.4	5.8	6.3	19.8	15.3	10.1
	A.	6.5	20.3	9.8	16.1	13.4	7.0	9.2	11.7
	M.	5.7	5.2	2.4	8.2	4.1	5.5	2.4	4.8
	S.	3.6	8.5	7.3	2.3	4.3	5.5	4.9	5.2
	Mx.	27.7	23.9	34.4	22.6	29.1	21.9	28.5	26.9

c.f. Mean Kub (GK1961)	
Q	27.2
F	13.3
B	9.8
A	10.8
M	5.0
S	6.7
Mx	25.5

GK: Dr. Gilbert Kelling

WW. Present Writer

Table 15 Operator Variance Results

Section	11	28	7	25	3	2	27	23	5	10	24	26	6	4	1	22	9	
Quartz	31.5	30.5	31.3	32.3	24.6	30.4	26.1	25.4	33.2	27.2	20.0	20.8	29.0	22.0	23.7	17.2	13.2	Operator A
Felspar	10.3	10.0	5.3	7.1	6.0	5.4	14.3	5.7	3.8	5.2	7.2	9.0	8.9	4.9	6.0	19.5	13.4	
Basic	12.9	17.1	12.2	10.7	17.5	8.4	13.4	26.3	12.7	15.0	34.6	23.0	11.3	23.9	15.4	22.7	28.2	
Acid	10.2	15.6	16.6	21.2	26.1	23.4	20.3	19.6	24.2	15.4	9.8	15.0	21.6	15.1	13.6	20.3	26.8	
Met.	2.8	3.1	3.8	1.0	2.6	4.3	1.3	5.9	10.5	3.0	1.9	3.5	7.5	10.7	7.9	0.4	3.1	
Sed	8.9	5.3	9.7	8.4	11.3	8.7	5.2	3.8	2.2	12.8	13.2	12.3	7.4	12.3	11.6	2.1	3.4	
Ferromag	0.9	0.2	0	0.1	0.1	0.4	3.3	4.5	0	0.5	6.8	6.8	0.4	1.2	0.5	6.7	5.8	
Matrix	22.6	18.1	21.1	19.1	11.8	18.9	16.2	8.9	13.4	20.9	6.5	9.6	13.9	9.9	21.4	11.3	6.4	
Quartz	35.8	29.9	35.3	35.7	27.9	29.6	30.3	25.6	34.3	21.9	21.9	18.1	32.6	30.6	27.7	19.5	15.4	Operator B
Felspar	10.3	12.7	11.0	11.6	7.2	10.1	19.8	11.5	10.6	8.9	15.9	13.9	9.9	9.7	12.0	8.0	14.0	
Basic	8.9	9.5	10.2	5.1	7.0	6.4	1.3	9.1	5.8	8.9	6.7	17.0	6.3	19.8	15.3	16.2	18.0	
Acid	6.7	18.8	6.5	20.2	20.3	9.8	14.5	22.5	16.1	15.9	11.1	17.2	13.4	7.0	9.2	28.1	29.0	
Met	5.4	4.5	5.7	1.0	5.2	2.4	2.2	3.1	8.2	1.9	1.5	2.5	4.1	5.5	2.4	2.7	1.1	
Sed	4.2	2.9	3.6	6.6	8.5	7.3	4.7	12.5	2.3	9.6	11.5	7.7	4.6	5.5	4.9	5.3	3.9	
Ferromag	-	-	-	0.1	-	-	1.4	2.2	-	-	8.0	3.7	-	-	-	2.7	2.1	
Matrix	28.8	21.7	27.7	19.9	23.9	34.4	25.9	13.5	22.6	35.0	23.5	20.0	29.1	21.9	28.5	20.3	16.5	

Table 16 Statistical Analysis of Operator Variance Data

Const.	Operator B-A Mean Discrepancy	$\hat{\sigma}$	Student's t	Significance	
Q	+ 1.82	3.34	2.24	⊕	
F	+ 3.41	4.66	3.1	⊕ ⊕	
Q + F	+ 5.24	5.23	4.12	⊕ ⊕ ⊕	
B	- 7.88	6.59	4.94	⊕ ⊕ ⊕	
A	- 2.82	5.42	2.14	⊕	(5% level = 2.12)
M	- 0.88	2.71	1.37	N.S.	
S	- 1.77	3.77	1.94	N.S.	
Mx	+ 9.65	4.06	9.8	⊕ ⊕ ⊕	
Total Rx Frags	- 13.2	8.24	6.6	⊕ ⊕ ⊕	

Table 17 Rank Correlation of Operator Variance Data

	R	Student's t	Significance
Q	0.85	6.23	⊕ ⊕ ⊕
F	0.34	1.41	N.S.
B	0.62	3.04	⊕ ⊕
A	0.57	2.68	⊕
M	0.52	2.36	⊕
S	0.53	2.42	⊕
Mx	0.71	3.9	⊕ ⊕

⊕ 5% Level of Significance

⊕ ⊕ 1% Level of Significance

⊕ ⊕ ⊕ 0.1% Level of Significance

N.S. Not Significant

Table 18 Comparison of adjusted N.W. Wigtownshire rocks with corresponding Rhinns formations

	Boreland	Adjusted Boreland	Portpatrick (Acid-clast)		Portpatrick Total	
Q	19.0	18.6 ± 4.8	19.5	Within B range	14.0	Within B range
F	21.6	11.2 ± 6.1	19.4	Outside "	25.1	Outside
B	17.5	23.0 ± 12.2	13.1	Within	21.5	Within
A	8.7	13.7 ± 6.6	14.7	"	10.0	"
M	1.9	3.0 ± 5.2	1.5	"	1.0	"
S	1.2	2.4 ± 1.8	3.5	"	2.9	"
Mx	30.0	18.4 ± 3.8	24.0	Outside	17.9	"

	Cairnerzean Farm East	Adjusted C. Farm East	Cairnerzean Farm West	Adjusted C. Farm West	Cairnerzean North	Adjusted C. North	Claddy House	Adjusted C.H.
Q	16.5	16.7 ± 4.8	14.3	14.7 ± 4.8	16.7	16.8 ± 4.8	7.4	9.3 ± 4.8
F	14.5	9.2 ± 6.1	14.0	9.0 ± 6.1	10.3	8.1 ± 6.1	21.0	11.0 ± 6.1
B	22.6	26.4 ± 12.2	31.2	32.3 ± 12.2	33.3	33.7 ± 12.2	27.2	29.7 ± 12.2
A	7.8	13.2 ± 6.6	5.6	11.7 ± 6.6	4.1	10.6 ± 6.6	5.1	11.2 ± 6.6
M	12.0	12.2 ± 5.2	8.0	8.6 ± 5.2	14.1	14.1 ± 5.2	6.4	7.1 ± 5.2
S	2.6	4.0 ± 1.8	3.1	4.4 ± 1.8	1.5	2.7 ± 1.8	4.1	5.5 ± 1.8
Mx	15.8	8.7 ± 3.8	17.6	9.8 ± 3.8	18.4	10.4 ± 3.8	18.3	10.4 ± 3.8
Fm	8.2	10.6⊕	6.3	9.4⊕	1.6	3.6⊕	10.5	15.8⊕

⊕ By difference

	Galdenoch	c.f. C. Farm East		c.f. C. Farm West		c.f. C. North		c.f. Claddy House	
Q	26.2	Outside C range		Outside C range		Outside C range		Outside C range	
F	9.7	Within	"	Within	"	Within	"	Within	"
B	10.2	Outside	"	Outside	"	Outside	"	Outside	"
A	13.2	Within	"	Within	"	Within	"	Within	"
M	2.8	Outside	"	Outside	"	Outside	"	Within	"
S	1.8	Outside	"	Outside	"	Within	"	Outside	"
Mx	28.0	Outside	"	Outside	"	Outside	"	Outside	"
Fm	7.8								

	Glenwhan	Adjusted Glenwhan	Port. Basic	
Q	4.8	7.2 ± 4.8	8.6	Within G rang
F	13.9	9.0 ± 6.1	30.9	Outside
B	47.5	43.5 ± 12.2	29.4	Just Outside
A	4.3	10.7 ± 6.6	5.2	Within
M	2.2	3.2 ± 5.2	0.6	
S	3.8	5.4 ± 1.8	2.3	Outside
Mx	18.1	10.3 ± 3.8	9.3	Within
Fm	5.4	10.7⊕	13.4	

⊕ By difference

	Lochryan Upper	Adjusted L.U.	Kirkcolm UB	
Q	27.9	25.8 ± 4.8	27.2	Within L rang
F	7.5	7.0 ± 6.1	13.3	
B	19.3	24.2 ± 12.2	9.8	Just Outside
A	10.2	14.8 ± 6.6	10.8	Within
M	8.3	8.8 ± 5.2	5.0	
S	5.7	7.2 ± 1.8	6.7	
Mx	21.3	12.5 ± 3.8	25.5	Outside range

	Lochryan Lower	Adjusted L.L.	Kirkcolm Met	
Q	31.9	29.1 ± 4.8	37.6	Outside L ran
F	7.2	7.0 ± 6.1	9.0	Within
B	15.8	21.8 ± 12.2	10.0	
A	7.6	13.0 ± 6.6	15.5	
M	17.0	16.9 ± 5.2	8.0	Outside range
S	2.2	3.6 ± 1.8	5.0	Within
Mx	18.2	10.3 ± 3.8	14.0	
Fm			0.8	

UPWARDS VARIATIONS IN A SINGLE GRADED UNIT

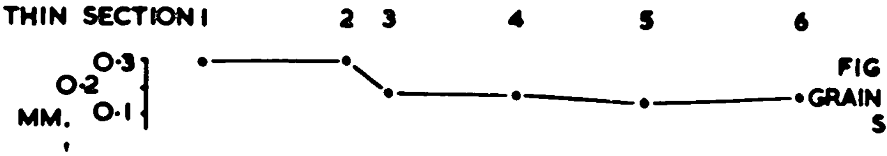
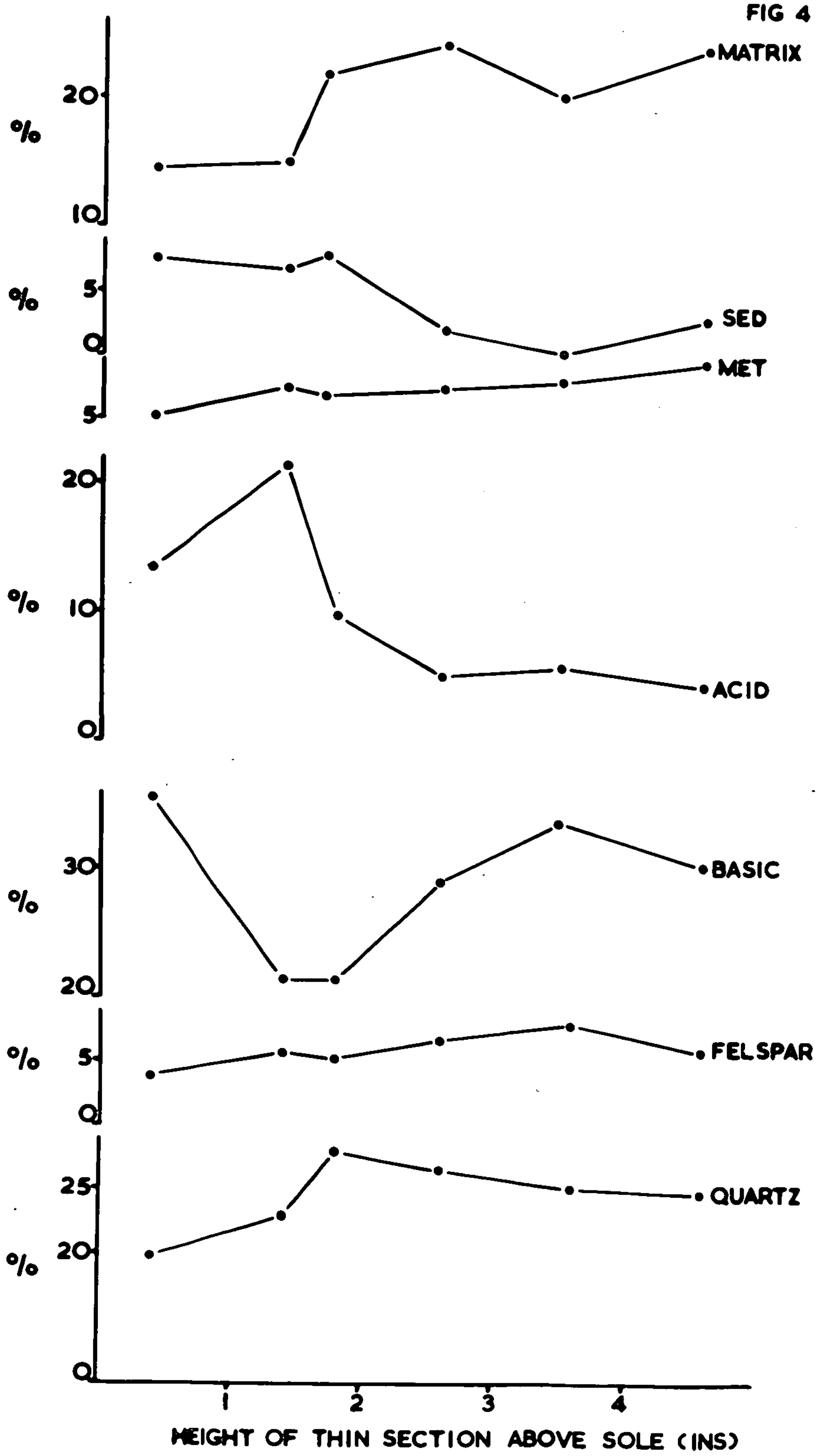


FIG 3

FIG 4



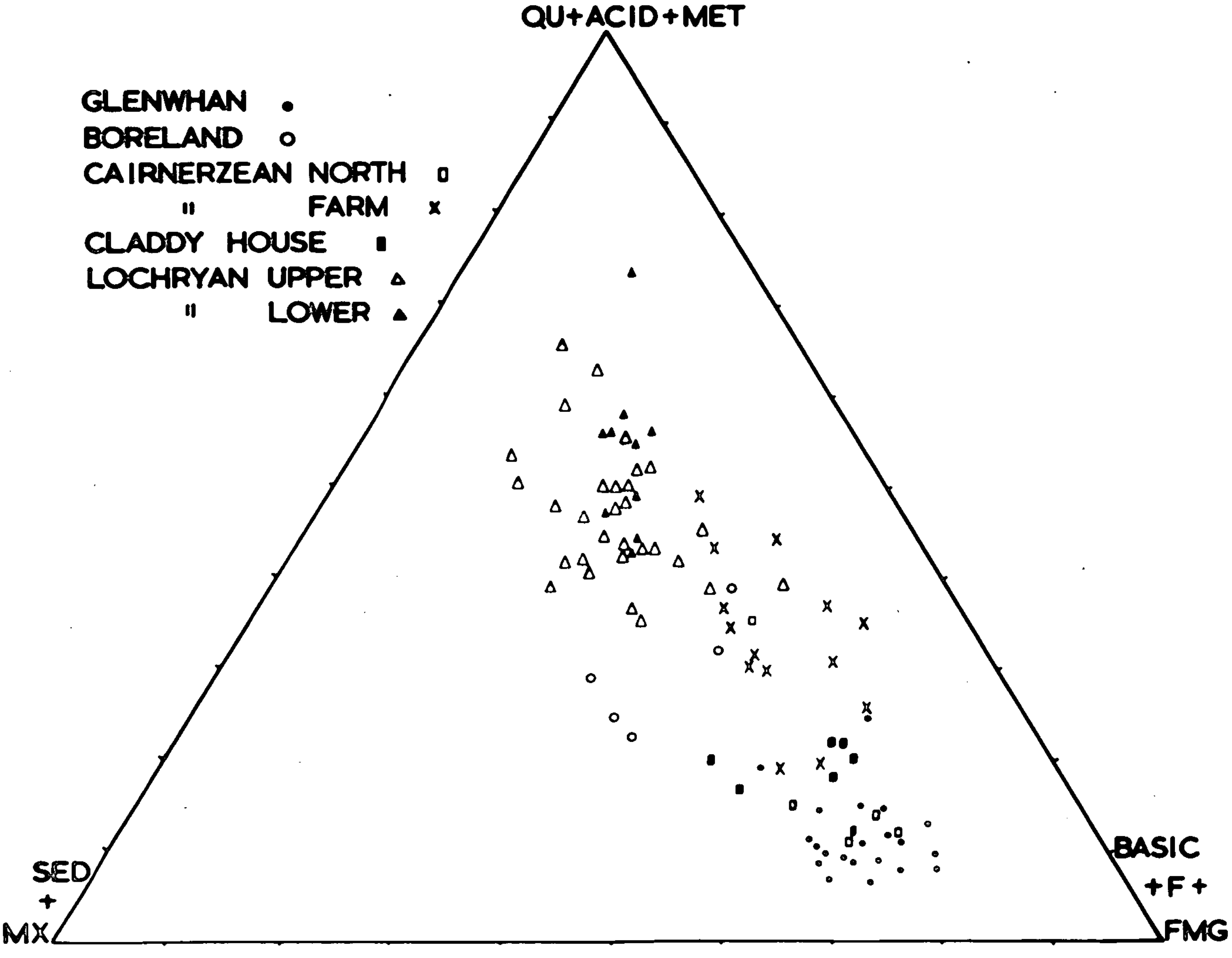
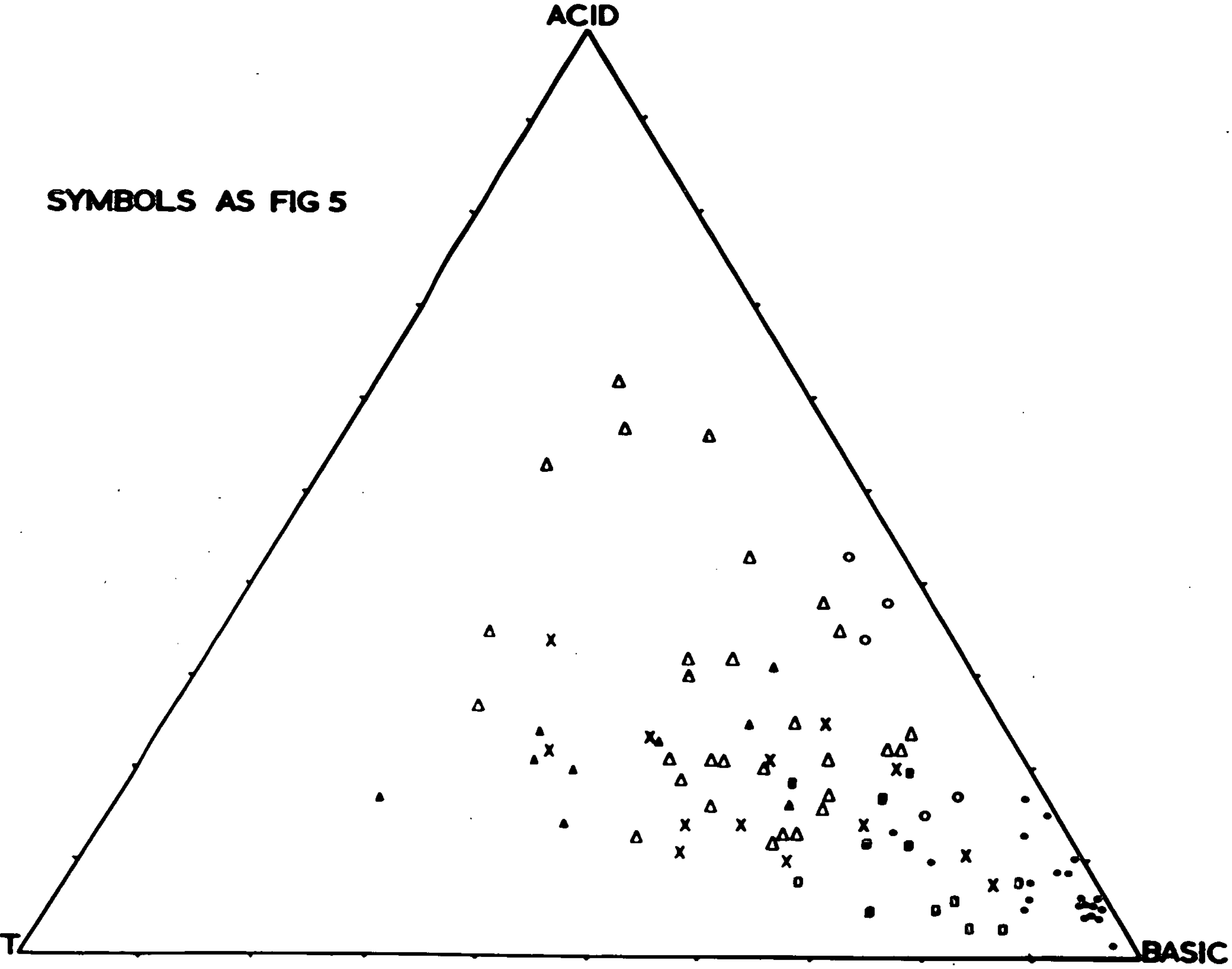


FIG 5 DIAGRAM OF MODAL ANALYSIS RESULTS



SYMBOLS AS FIG 5

FIG 6 COMPOSITION OF ROCK FRAGMENT FRACTION

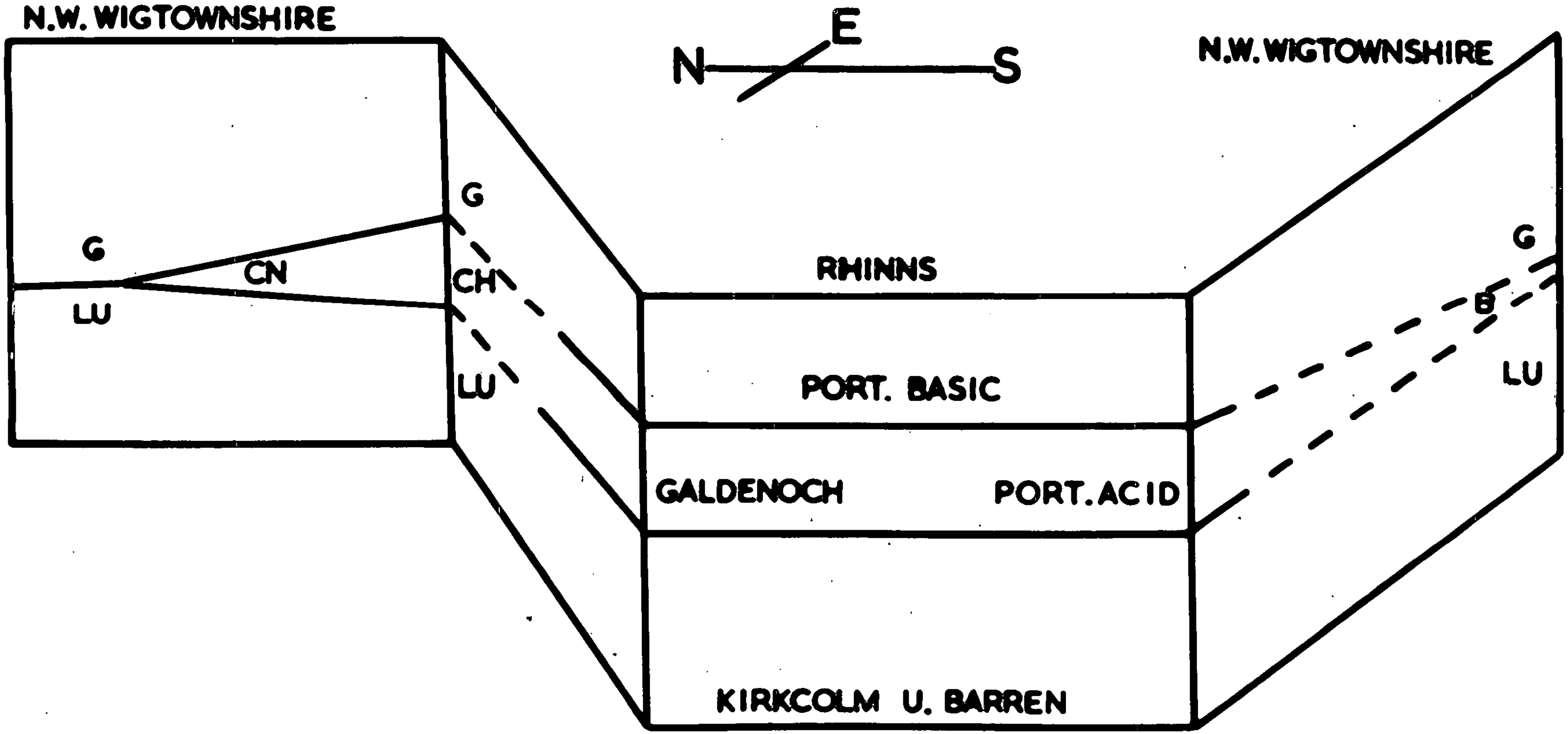


FIG 7 INTER-RELATIONS OF FORMATIONS IN N.W. WIGTOWNSHIRE —RHINNS OF GALLOWAY

FIG 8 GRAPHS FOR COMPARISON OF WELSH AND KELLING MODAL ANALYSES

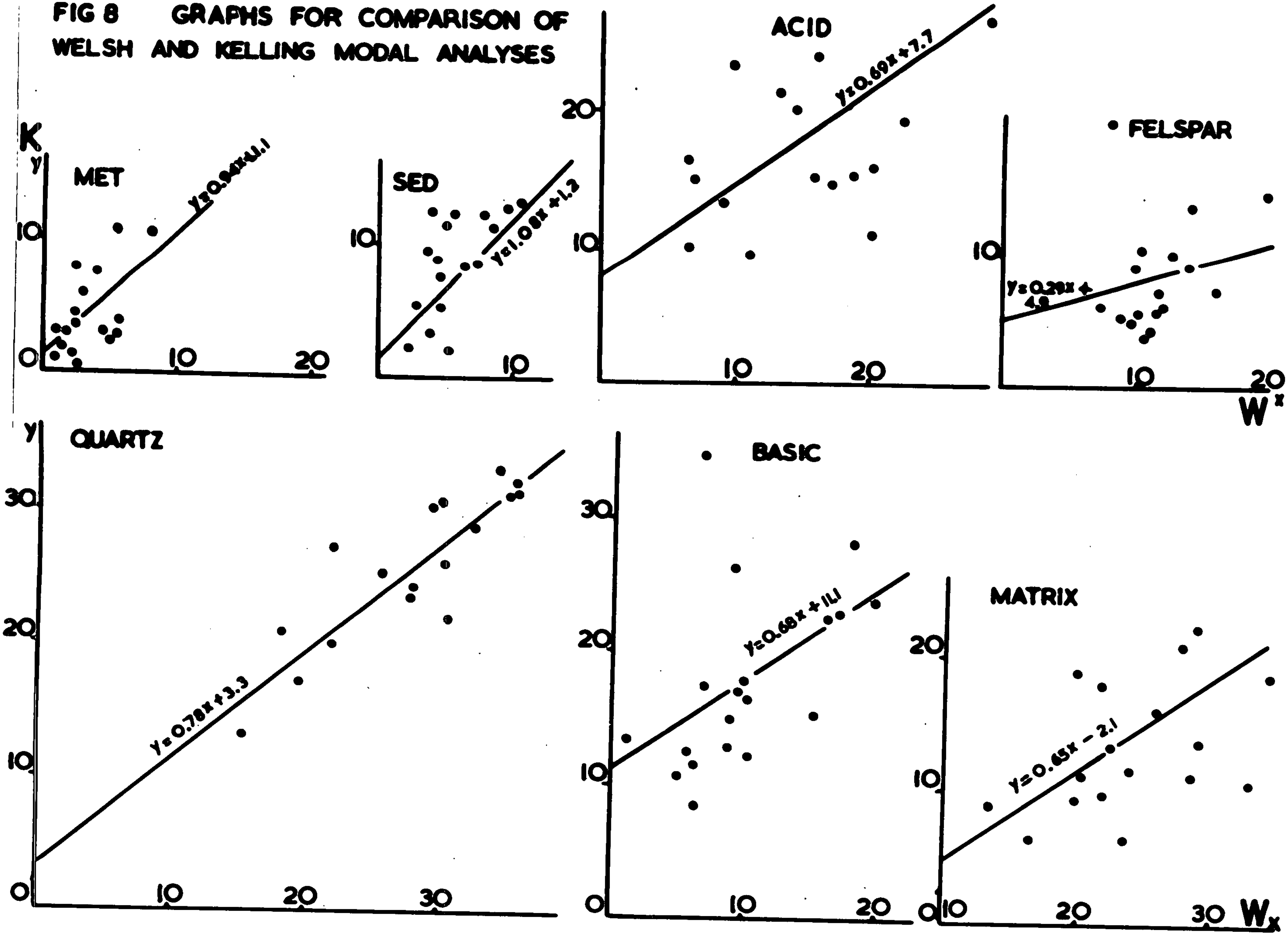
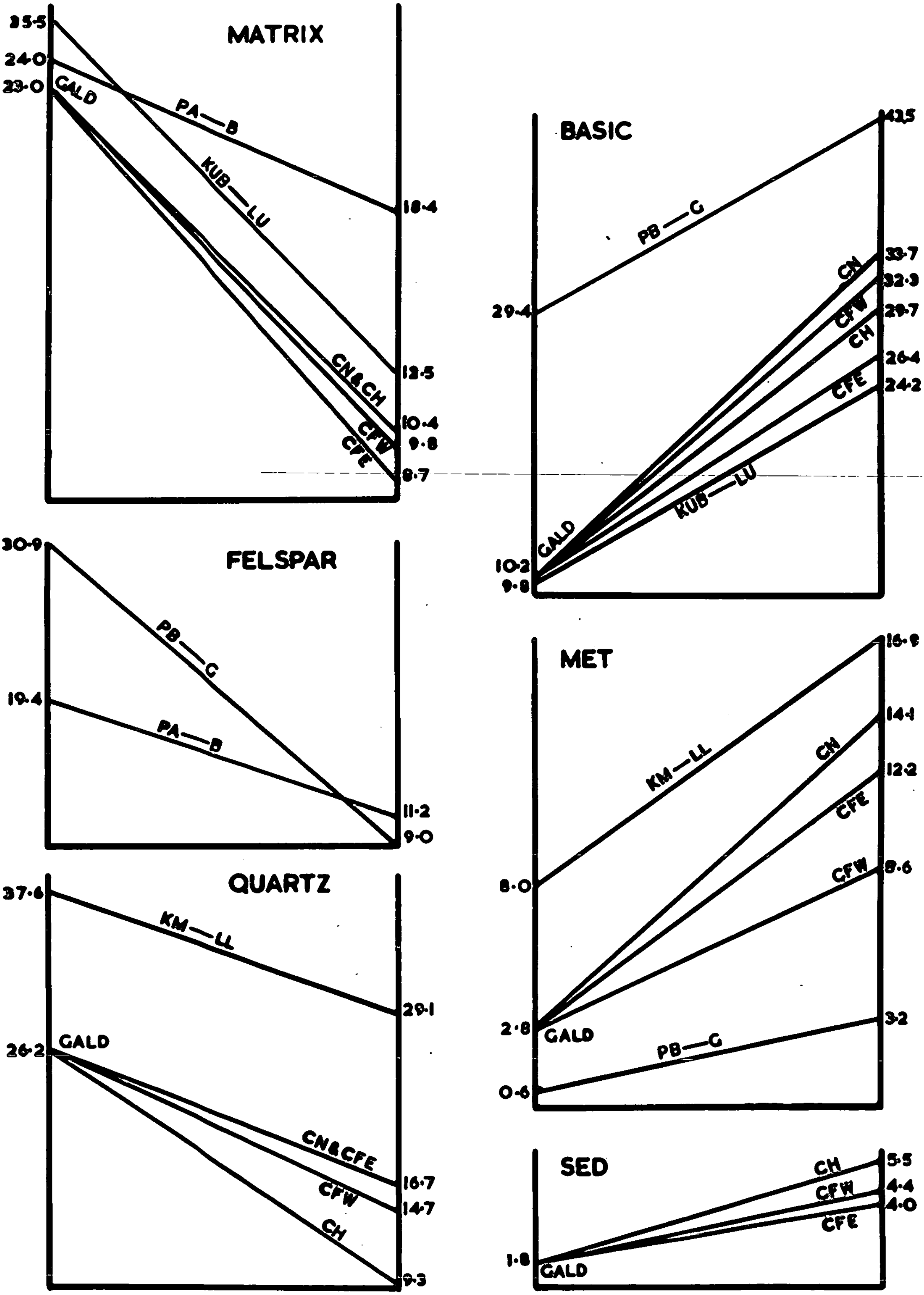


FIG 9 ADJUSTED DIFFERENCES BETWEEN N.W.WIGTOWNSHIRE AND RHINNS



CHAPTER 5 PROVENANCE

The rocks of the area form two distinctive lithological and petrological types, the Lochryan and Glenwhan Rocks, with a passage group, the Cairnerzean--Boreland Rocks, between them, sharing some of the properties of both types. The significant details for an estimation of the source area of the rocks of the area are given below.

Lochryan Rocks

The quartz grains in the Lochryan Rocks show only slight shadow extinction and may thus be igneous in origin (Potter and Siever 1956). This is supported by the types of inclusions in the quartz grains, being mainly of types suggesting an igneous origin with a subsidiary contribution from schistose rocks (Keller and Littlefield 1950). The tourmaline grains have colours indicative of a granite source (Krynine 1946).

The dominant rock fragments in the greywackes are of spilitic-keratophyric type very similar to the spilites in the Ballantrae igneous complex. Acid igneous rocks are much subordinate, consisting of quartz-sodic plagioclase fragments and a few quartz porphyry and rhyolitic fragments.

Metamorphic rock fragments consist mainly of metamorphic quartzite but there is a fairly large content of quartz muscovite schist and phyllite fragments. Higher grade metamorphic fragments are rare and none higher than garnet grade are found. The garnet grains seen in thin section, occasionally quite abundantly, are similar to those found in the garnet-bearing rock fragments.

The source area of the Lochryan Rocks was a mixed acid igneous and fairly low grade metamorphic terrain in which there had been considerable basic igneous volcanic activity. The textural similarity of the basic igneous rock fragments to volcanic rocks of Ordovician age found elsewhere in the Southern Uplands and in Ireland suggests that the volcanic activity in the source area was penecontemporaneous with sedimentation.

The direction of the source area is more problematical. The few current structures in the Lochryan Rocks show a current-flow from the south-east. A remnant of the source area may therefore be the Pre-Cambrian granite and schist mass postulated by Bott (1961) to account for the magnetic and gravity anomalies under the Askrigg Block in West Yorkshire, especially as the anomalies have been traced as far as the Lake District by H.M. Geological Survey (Bullerwell in discussion of Bott 1961). A land mass to the south of the Southern Uplands is also shown by Wills in his Palaeogeographic Atlas (1951).

Kelling (1962) suggests a Dalradian and Highland source together with a Ballantrae type igneous complex as the source of the Kirkcolm rocks. However recent radio-active dating work (Giletti et al. 1961) has shown an absolute age for the Dalradian metamorphism equivalent to Lower or Middle Ordovician. It is unlikely that sufficient unroofing of the Dalradians could have taken place for their metamorphic rocks to be contributors to the Ordovician geosyncline, except along the axis of earliest uplift, which, Dr. W.E. Fraser (pers. comm.) suggests was the Portsoy--Boyndie Syncline belt. This source would involve a distance of transport of at least 200 miles. If a northern source is thus discounted, and the present writer believes that it is since this long transport would take place across an area in which there were topographic "highs" on which shallow water deposition was taking place (e.g. Girvan area, Williams 1962) and which could have a ponding action on the turbidity currents, then the southern source, suggested by the meagre current-flow data of the present area, shed the bulk of the detritus into this part of the geosyncline. This interpretation does not conflict with the more abundant current-flow data from the Rhinns, which show current-flow from the north-east and south-west, as it is now well established that turbidity currents with sources along the margins of a geosyncline could turn to flow parallel to the axis of the trough (Dzulynski, Ksiazkiewicz and Kuenen 1959, Knill 1959). The differences in flow directions between the Rhinns and the present area are probably due to the topographical configuration of the bed of the trough, causing longitudinal currents to curve down the sides of a "low."

Glenwhan Rocks

The quartz grains of the Glenwhan Rocks are nearly all unstrained and the inclusions in the quartzes suggest an igneous source with some contribution from gneissic rocks. Acid igneous and metamorphic rock fragments are the same as in the Lochryan Rocks except for the presence of occasional glaucophane schist fragments. The basic volcanic rocks which were eroded to form a major part of the Lochryan Rocks were replaced by intermediate igneous rocks which were eroded into a flood of andesite fragments, and augite and hornblende grains, the freshness of these minerals suggesting that the andesitic volcanic activity was contemporaneous with sedimentation. The andesites are of a type found elsewhere in the Southern Uplands, for example at Bail Hill-Mains Hill, and andesitic tuffs and lavas of Llandeilo-Caradoc age are abundant in the Lake District. The Glenwhan Rocks are therefore probably the result of deeper erosion into the southern land mass, producing granitic and gneissic detritus, accompanied by andesitic volcanic activity.

Kelling postulates a southern source for the equivalent Portpatrick rocks, in a volcanic island arc, and has data showing that the depositing currents flowed from the south-east or south-west.

The source area for the greywackes of the east side of Lochryan is thought to have been an acid igneous--metamorphic rock land mass whose uplift was accompanied by first basic then intermediate volcanic activity, and whose erosion produced detritus of increasing metamorphic grade.

The presence of a land mass south of the Southern Uplands during the Lower Palaeozoic is a point of some discussion, but is rejected as a major source area by most authors. The evidence of several authors is however capable of interpretation to suggest the presence of this land mass.

Kelling (1962) postulates a northern source for the Kirkcolm and a later southern source for the Portpatrick Group. The equivalent rocks in the present writer's area have been discussed to show that there is a change in composition between the Lochryan (≡ Kirkcolm) and the Glenwhan (≡ Portpatrick Basic-clast) via the Cairnerzean Rocks. This change does not take place by interdigitation of rocks from different source areas but is a change suggestive of progressively deepening erosion of a single source area, accompanied by eruption of first Basic then Intermediate lavas.

Gordon (1962) found axial flow either from north-east or south-west for the currents which deposited Silurian greywackes in Central Wigtownshire. No clear statement of the provenance or location of the source area is given and the provenance of the quartz grains, suggested by their inclusions is misinterpreted. His diagrams (1962, fig. 5, p.127) show that the bulk of the inclusions liesin the I and G classes of Keller and Littlefield which, their tables show, indicate derivation from igneous rocks, and igneous rocks with <u>subsidiary</u> gneissic rocks respectively. It is clearly wrong to state, as Gordon does, that his evidence suggests a metamorphic source for the quartz grains. A more accurate interpretation for the quartz grains in

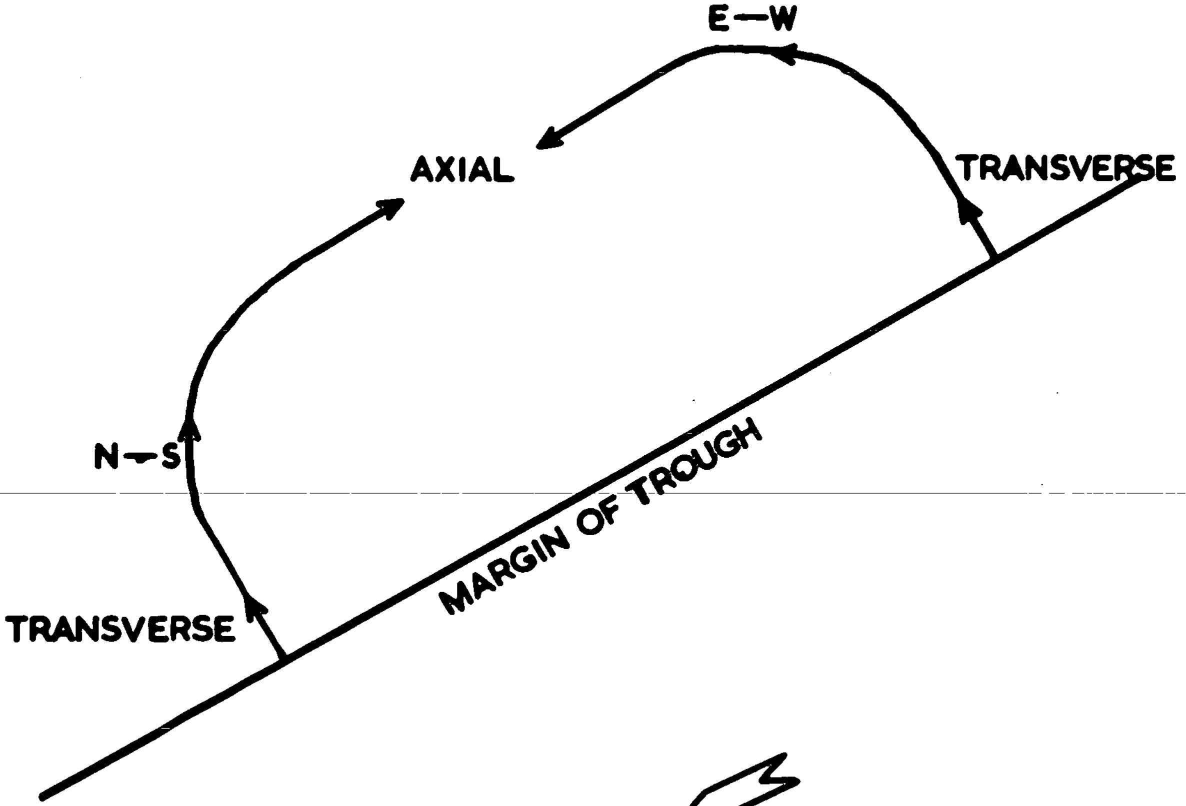
Central Wigtownshire is a provenance in an igneous rock area which includes subsidiary gneissic rocks. The source for the greywackes in Central Wigtownshire is composed of rocks similar to those which composed the Ordovician source area.

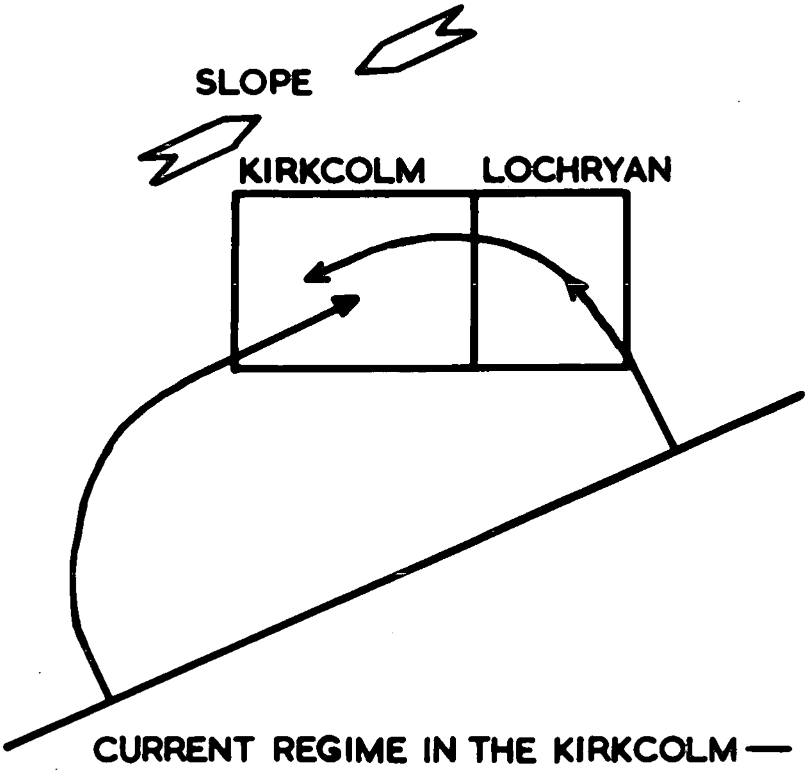
Rust (1963) presents data showing a wide spread in current-flow directions from north through east to south-west, with most of the currents flowing axially. There is no significant flow from the north-west quadrant. These data suggest that the source area lay to the south of South Wigtownshire. See fig. 10.

Craig and Walton (1962) show current-flow diagrams with a dominant flow from the north-east, but there are significant numbers of currents from the south-east and south-west.

The data from all the areas mentioned above can be interpreted as suggesting a southern source area from which turbidity currents, perhaps emanating from submarine canyons, flowed first transversely to the axis of the geosyncline then swung either north-east or south-west to flow along the axis of the trough. The proximity of the site of deposition to the canyon mouth will determine the flow direction of the current at the point. Deposition close to the canyon will show flow directions near to transverse, i.e. approximately from the south-east while distal deposition areas will show axial flow. Fig. 10 shows some possible variations in flow directions. The inset map to this figure illustrates the postulated configuration of the Lochryan--Kirkcolm deposition area, a low point on the trough floor into which currents flowed from different directions from a source area which contained essentially the same rock types all over the area, but in which there were enough local variations to cause the differences in composition reported between the Lochryan and Kirkcolm rocks.

FIG 10 VARIATIONS IN FLOW DIRECTION OF TURBIDITY CURRENTS





CURRENT REGIME IN THE KIRKCOLM — LOCHRYAN DEPOSITION AREA

CHAPTER 6 SEDIMENTARY FEATURES

The greywackes of the area show the sedimentary features usually accepted as typifying a turbidity current deposition, (e.g. Kuenen 1959), though the occurrence of these features varies widely within any particular formation and also between formations.

Graded Bedding

In the Lochryan Rocks grading is a common and characteristic feature. During the stratigraphic measurement of 20 sections along the coast section the sedimentary features of the beds were noted. These are shown in Table 19 which lists the frequency of occurrence in each section. This table shows that simple graded bedding is found in 37-87% (mean 64%) of the greywackes of the coast section. The grading is rarely of the Walton (1956b) type a), perfect grading, but is most commonly of type c), delayed grading, in which the bulk of the bed is one grain-size which coarsens rapidly near the bottom of the bed, and becomes quickly finer at the top, merging into the overlying shale interbed. Repeated grading was much less frequently found on the coast section (0-9%, mean 2%), usually as a streak or lens of coarser material in a finer bed. The more regular repeated grading of Walton's type b) was rarely found. Reversed grading in which the stratigraphic top of a bed is coarser than the bottom was found only once, in a thin siltstone.

The Glenwhan greywackes are much thicker bedded and coarser grained than the Lochryan rocks. They show simple grading only in the thinner bedded greywackes which occur occasionally in the succession. The thicker beds have repeated grading with streaks and lenses of coarse pebbly material distributed throughout the thickness of the bed. One example of the pebbly material infilling a washout has been observed.

Presence of a Parting

A parting in the greywackes is uncommon and is confined to the fine grained tops of the greywackes or to thin fine siltstones. On the Loch Ryan coast section the occurrence is 0-10% (mean 3%), formed by fairly closely spaced planes with a higher proportion of mica than the rest of the rock.

Convolute Bedding

Many of the siltstones which have parting planes show deformations of the partings into low amplitude undulations which are thought to be minor convolution effects as gradations do occur with all stages between shallow undulations and true convolute bedding in which the bedding laminae are deformed into overturned and rolled-up folds. Convolutions are found in 0-11% (mean 5%) of the beds of the Loch Ryan coast section.

Cross Lamination

Cross lamination is very rare in the greywacke beds but is more common in the thin siltstones. On the coast section the frequency of occurrence is 0-8% (mean 2%). The structure is found as very fine foreset laminae of alternating light and dark grey and is therefore visible only on slightly weathered wave-smoothed surfaces.

Due to the lack of unweathered exposures of the Glenwhan Rocks no within-bed structures, other than graded bedding, have been found.

Flute Casts

Very few soles have been found exhibiting flute casts, the only suitable exposures being on the coast section, which has yielded seven examples. This paucity of flute casts is a feature of the rocks, and not due to unsuitable exposures, as there are many examples of smooth greywacke soles along the coast section. The configuration of the flute casts is shown in figs. 11 and 12 and their orientations, after correction for the local dip, in fig. 13. The currents which produced the structures flowed mainly from the south-east.

Longitudinal Fissures and Ribs (Dzulynski and Walton 1963)

Fine parallel striations (fissures) separated by rounded ribs were found on a few greywacke soles. In most cases small cusp-shaped marks were found indicating the sense of the producing current, flowing between 50° and 140°[*] (Fig. 13).

Drag or Groove Casts

One or two small examples of these sole markings have been found, usually with an orientation similar to the flute casts.

Bounce Casts (Dzulynski et al. 1959)

Fig. 14 illustrates a specimen showing bounce casts. These are casts of original hollows, on the muddy sea floor, formed by rock fragments, probably shale fragments produced by contemporaneous erosion, being bounced onto the sea floor by the current, forming small impact hollows. In the specimen the casts are about 1 cm. deep in the centre, becoming shallower towards both ends. Their orientation is parallel to that shown by the flute casts.

Load Moulding

On the shore section the rocks are exposed chiefly as wave-cut platforms or as small cliffs at the back of the beach. Exposures of the soles of beds are therefore not common and estimates of the extent of load moulding must be very tentative. Load moulding is found on the coast section on 0-10%

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[*] All azimuths in this thesis are given as bearings clockwise from True North (0°).

(mean 5%) of the greywacke soles and although this figure will be a minimum there are enough beds exposed with smooth unmarked soles to suggest that these structures are in fact not common.

Since data were available, from the stratigraphic measurement, of the relations of load moulded beds to their neighbours an examination was made of the sedimentary environment of the load structures. Firstly the load structures, chiefly irregular protuberances on the soles, are not related to the grain-size of the bed. Load structures are found on the soles of greywackes which vary in coarseness from pebbly greywackes to fine siltstones. A histogram was made showing the thickness distribution of beds with load structures, using the same class intervals used in the analysis of the stratigraphic measurement results. (See below Table 22) This diagram (Table 20) shows that the modal thickness of load moulded greywackes is different from the modal thickness of all the arenites of the coast section, with a mean bed thickness of 1.94' compared with a mean thickness of 1.42' for all the greywackes of the coast. Statistically however (Chi-square Test of Distribution) the higher mean bed thickness of the load moulded greywackes is not significantly different from the mean bed thickness of all the greywackes.

Recent work has shown that there are several influences which cause the formation of load structures of the knobbly irregular variety discussed here. One influence summarised and advocated by Kelling and Walton (1957) is the presence of surface irregularities on the mud on which the overlying greywacke is dumped by the turbidity current. These irregularities, once buried, are amplified by the differential loading which they cause at the mud--sand interface, with sand pouching down into the irregularities and mud rising concomitantly between the pouches to form flame structures. This theory is supported in the present area by the presence of a small amount of coarse greywacke at the bottom of many of the load structures. It is suggested that irregularities, possibly made by the eroding snout of the turbidity currents or by rock fragments being bounced against the mud surface, were able to trap coarse detritus to a slight extent before being buried by the deposition of the overlying bed.

A second method of production of irregular load structures is illustrated in Dzulynski and Walton (1963). These authors obtained irregular non-directional load structures during experiments with artificially produced turbidity currents, the structures being found after a slow dense current passed over a soft mud surface. These experimental structures were formed only by currents with a narrow range of sizes and strengths and would therefore be found as sole markings on greywackes of a limited range in thicknesses, assuming that the thickness of a greywacke bed is a function of the size and strength of the turbidity current. In the present area however load markings are not confined to a narrow range in bed thicknesses, and a slow current regime could not, therefore, have been the only method of formation of the load structures.

Ten Haaf has suggested that load structures may be formed by differential deposition of sediment initiating later differential compaction. There seems to be no present method for differentiating the structures developed by these various modes of formation.

Sedimentary Structures in the Shales

The thin shale interbeds between the greywackes show finely spaced parting planes but sedimentary structures are otherwise absent. The thick shale bands which characterise the Lochryan Rocks and are found less frequently in the other formations do exhibit some sedimentary features since they commonly contain frequent siltstone ribs, usually 2-12" apart and ½-1" thick. The thin siltstones very frequently are finely cross laminated and have fine load and flame structures on the soles. Current ripple mark is occasionally found.

The Lochryan Rocks are therefore composed of layers in which there is a simple standard succession of sedimentary structures. The bulk of each layer is formed of a poorly graded interval which grades towards the top into a pelitic interval. Between the graded interval and the pelitic interval there may be an interval of parallel lamination but this is relatively uncommon. This simple standard succession contrasts with the Flysch of the Peira-Cava in the Alpes Maritimes in which Bouma (1962) found the following standard succession:-

Pelitic interval
Upper laminated interval
Current rippled interval
Lower laminated interval
Graded interval

This standard succession is fully developed in the thicker greywackes of Peira-Cava but in the thinner greywackes parts of the standard succession are usually absent due to base cut-out and/or truncation of the top. The incomplete layers are explained in terms of distance from the source and interference between several near-contemporaneous turbidity currents. The chief difference between the present area and Peira-Cava lies in the absence of a current rippled interval and the virtual absence of a laminated interval from the layers in Wigtownshire. The difference is probably caused by the different basin configurations in the two areas. The Peira-Cava area was part of an east--west trough into which turbidity currents flowed transversely from the south. The trough however was broken up by a series of north--south submarine ridges into a number of individual cells which were relatively small and in which sedimentation took place independently. The restricted size of these sedimentation cells compared with the large trough in South-west Scotland probably accounts for the more complicated suite of sedimentary structures found in Peira-Cava.

Stratigraphic Measurement of the Coast Section

Stratigraphic measurement of the coast rocks north of Cairnryan was carried out in 20 sections each approximately 275' in thickness. Table 21 shows the thickness of each section and the corresponding values of thickness of greywacke + siltstone, shale + mudstone, greywacke to shale ratio, number of greywacke beds, number of shale beds, and the mean greywacke and shale bed thicknesses.

Histograms were prepared showing the distributions of greywacke and shale thicknesses in each section. These histograms, Tables 22 and 23, suggest a remarkable homogeneity in the succession from one section to the next. This homogeneity may be due to two factors; a long period of sedimentation may have built up a thick mass of more or less similar beds, or a much thinner succession may have been repeated structurally, perhaps several times. A second problem in such a succession which has no obvious marker horizons is whether or not there is any rhythmic or cyclic sedimentation on a scale too large to be visible on the ground to the field worker.

The measurement data have been examined in the light of the following hypothesis (Nederlof 1959). The distribution of greywacke beds greater than a selected thickness was examined statistically to discover whether or not the distribution is random. If the distribution is not random then there must be some form of repetition, either structural repetition of the same beds or repetition of similar beds by rhythmic sedimentation. The distinction between thick greywackes and thin greywackes was set at 4' as the thickness distributions show a fairly smoothly decreasing distribution with increasing bed thickness below 4' while the distributions are more irregular above a thickness of 4'. The null hypothesis was set up that the thick beds are distributed randomly throughout the succession. Data from the greywacke thickness histograms were arranged into 5 groups and the value of χ^2 calculated to be 5.6 with 4 degrees of freedom. This value of χ^2 is not significant at the 5% level. Thus the null hypothesis is accepted that the thick greywackes occur randomly in the succession. Greywackes thinner than 4' thick occur frequently in each section of the stratigraphic measurement, and have a fairly smoothly decreasing distribution with increasing bed thickness, suggesting that the turbidity current formation was controlled by some factor or factors which operated within fairly definite limits. For example, if the turbidity currents are formed by slope deposits being overloaded and beginning to slide (Kuenen and Menard 1952) then turbidity current formation will be quite tightly controlled by the angle of slope and the water content of the sediments. The frequency of occurrence of these thin greywackes in each section is such that any rhythmic sedimentation, which would be controlled by regular variation of the underlying causes of turbidity current formation, would be visible in the field. The random distribution of the thick greywackes shows that neither have they a regular sedimentary occurrence nor are they repeated structurally. The events in the source area which caused the formation of the large turbidity currents, giving thick greywackes, are therefore more intermittent than those producing the thin greywackes, suggesting that the large turbidity currents were perhaps triggered by earthquakes (Bailey 1936) whereas the smaller currents were formed by fairly regular build up of sediment to a point of instability which had only a small margin of variability.

Variation in the proportion of greywacke in a constant thickness of greywackes and shales can take place in three ways; there may be variation in the thickness of a more or less constant number of beds; there may be variation in the number of greywacke beds with the bed thickness remaining more or less constant; or both the number and thickness of the greywacke beds may vary. These alternatives are examined in this area by calculating a series of Correlation Coefficients of the relationships between the amount of greywacke in each section and various parameters.

The variation of mean greywacke bed thickness with the total thickness of greywacke in each section was tested and gave a Correlation Coefficient of -0.21. When this value was tested by Student's 't' to discover the probability of its occurring by chance 't' was found to be 0.913 which is well below the 5% level of significance and is not statistically significant.

The variation of the number of greywacke beds with the total thickness of greywacke in each section gave a Correlation Coefficient of 0.55 and a corresponding Student's 't' of 2.81 which is significant at the 1% level. Since the Correlation Coefficient is positive there is a sympathetic variation of the number of greywacke beds and the total amount of greywacke.

Since the succession is an alternating one, variation in the number of greywacke beds must have a sympathetic variation in the number of shale beds. If therefore variation in the number of greywacke beds is the method of varying the amount of greywacke in each section then there should be an antipathetic relationship between the amount of greywacke and the mean shale thickness. This relationship has a Correlation Coefficient of -0.69 and a Student's 't' of 4.06 which is significant at the 0.1% level.

This evidence strongly suggests that variation in sedimentation in the area is due to variation in the number of turbidity currents arriving in the deposition area. These have already been shown to have a variable size, demonstrated by the variable thickness of the beds.

Radomsky (1958) was able to distinguish between a turbidite portion and a 'normal' shale portion of the shales of the Podhale Flysch, illustrated by the character of the quartz grains found in the shales. In the area of the Lochryan coast section the antipathetic relationship between the mean shale thickness and the amount of greywacke in the succession suggests that turbidity currents played only a small part in contributing shale grade sediment. If the assumption that the thickness of a greywacke bed is an indication of the magnitude of the parent turbidity current is correct and the current contributes a significant amount of shale grade material then thicker greywackes should be followed by thicker shales. Table 24 shows the thickness distributions of shales overlying various thicknesses of greywacke, in two samples drawn from the northern and southern halves of the coast section. The class intervals of the shale thickness distributions were chosen the same as those in the stratigraphic measurement histograms (Table 23) so that direct comparisons could be made. It is seen that the shale thickness distributions for both samples are similar to those of the parent population no matter what the thickness of the underlying greywackes. The turbidity currents which deposited the greywackes contributed little shale grade material to the shale interbeds.

This conclusion is reinforced by a calculation of the Correlation Coefficient for the variation of mean shale thickness and mean greywacke thickness in the coast section, giving a correlation coefficient of 0.16 and a Student's 't' of 0.69, with 18 degrees of freedom, which is not statistically significant.

Environment of Sedimentation

Deposition of the rocks of the area took place in a part of the Caledonian geosyncline bounded to the north by an area of both deep and shallow water deposition (Girvan area, Williams 1962), and to the south by a land mass in which extensive vulcanicity had taken place, probably also in Caledonian times. The southern land mass is thought to have contributed most of the greywacke sediment, mostly fragments of the volcanic rocks and quartz from an acid igneous source. The source area may have been part of the Pre-Cambrian mass found geophysically under the north of England, or may have been an off-shore ridge or 'tectonic land' formed by an early compression of the geosyncline (Kay 1951). Further evidence which tentatively suggests a southern land mass is provided by the presence of a Bouguer anomaly under the Irish Sea (Bott, in press), caused by a thinning of the sedimentary cover, presumably due to a rise in the basement under the Irish Sea.

The basin and shallows area to the north is thought to have trapped most of the detritus from the emerging Highlands (c.f. Gorsline and Emery 1959) so that the background sedimentation in the present area consisted of fine grained silts and muds with sedimentary structures produced by traction currents, indicating no great depth of water (See also Kelling 1961).

Into this quiet possibly quite shallow basin there broke fairly frequent turbidity currents, depositing greywacke sediment. The rocks of the area belong to two facies of greywacke deposition, the early, Lochryan, facies, and the later, Glenwhan, facies with a passage group, Cairnerzean Rocks, between them. The two facies differ in composition, grain-size, mean bed thickness, Greywacke to Shale ration, and sedimentary structures.

Initial deposition in the area, forming the Lochryan Rocks, took place distantly from the source, causing the fine grain and thin bedding of the greywackes (Kuenen and Carrozzi 1953) and the high proportion of lutite in the succession. It has been shown above that greywacke deposition and shale deposition were independent of each other (the discontinuous and continuous sedimentation, respectively cf. Gorstine and Emery 1959). Distance from the source would allow accumulation of a high proportion of lutite in the area as only the stronger turbidity currents would reach the area. (See Bouma 1962) The bedding and grain-size characteristics show that the Lochryan Rocks belong to the Kirkcolm greywacke association set up by Walton (1963). The only difference is in the frequency of sole structures, which, by definition, are abundant in the Kirkcolm association. Exposures of sole structures are by no means abundant along the Loch Ryan coast section, the best exposures in the area, and enough unmarked soles are visible to suggest that sole structures are in fact not common. However this in itself suggests deposition distally from the source. Recent workers (Dzulynski and Walton 1963, Craig and Walton 1962, Hsu 1959, Ten Haaf 1959) have suggested that sole structures occur in zones depending on the decreasing energy of the turbidity current along its course, i.e. on distance from the source. The paucity of flute and groove casts and the presence of irregular load structures and smooth soles are indicative of a low energy, i.e. distal, environment of deposition. Later deposition was closer to the source, causing the thick bedding and much coarser grain size of the Glenwhon Rocks, which from these characteristics are examples of the Portpatrick greywacke association defined by Walton (1963). The alternating thin bedded and thick bedded sequences of the Cairnerzean Rocks formed a passage between these two environments of sedimentation.

Table 19 Frequency of Sedimentary Structures on Coast Section

Stratigraphic Section	No. of Beds in Section	Coarse Beds %	Graded Beds %	Repeated Grading %	Load Structure %	Parting %	Convolutions %	Cross laminations %
1	121	15	47	1	4	9	-	2
2	151	25	37	-	7	5	2	8
3	191	23	45	2	9	3	5	5
4	150	27	64	3	7	3	7	1
5	137	39	77	7	7	2	3	2
6	137	38	69	7	7	2	3	-
7	144	40	64	1	4	1	1	-
8	99	19	60	1	3	6	4	2
9	129	36	67	4	3	10	9	-
10	121	22	78	3	6	2	3	-
11	100	26	72	4	7	3	11	1
12	117	27	87	3	10	1	7	1
13	95	12	82	1	-	2	5	1
14	141	23	75	1	5	2	4	1
15	138	17	59	1	2	2	1	1
16	124	19	64	2	3	2	3	1
17	127	22	65	2	7	-	9	4
18	140	41	69	9	6	-	6	-
19	118	20	54	2	3	3	4	2
20	124	24	49	5	-	3	9	7
Mean		26	64	2	5	3	5	2

Table 20 Thicknesses of Beds showing Load Moulding

-6"	-1'	-1'6"	-2'	-2'6"	-3'	-3'6"	-4'	-4'6"	-5'	-5'6"	-6'	-6'6"	>6'6"
18	38	27	18	12	7	3	2	4	4	2	1	-	2

Total 138

Table 21 Stratigraphic Measurement Data

Stratigraphic
Section

Thickness	1	2	3	4	5	6	7	8	9	10
Total Thickness	276.71'	275.04'	274.33'	275.07'	275.14'	275.99'	278.34'	274.95'	274.90'	250.55'
No. of Beds	187	260	331	268	240	260	278	180	210	227
A Shale + Mu	102.21'	76.43'	69.22'	67.93'	88.64'	99.45'	95.89'	98.42'	64.31'	69.89'
No. of Sh + Mu beds	66	109	140	118	103	123	134	81	81	106
Thus B Gw. + Silt	174.50'	198.61'	205.11'	207.14'	186.50'	176.54'	182.45'	176.53'	210.59'	180.66'
in beds no.	121	151	191	150	137	137	144	99	129	121
Ratio Gw : Sh $\frac{B}{A}$	1.707	2.599	2.963	3.049	2,104	1.775	1.903	1.794	3.275	2.585
Mean Sh + Mu	1.55'	0.70'	0.49'	0.58'	0.86'	0.81'	0.72'	1.22'	0.79'	0.66'
Mean Gw + Silt	1.44'	1.32'	1.07'	1.38'	1.36'	1.29'	1.27'	1.78'	1.63'	1.49'

Grand Total Sh + Mu = 1838.93' Grand Total Gw + Silt 3669.74' ∴ Section = 5509.67'

Stratigraphic
Section

Thickness	11	12	13	14	15	16	17	18	19	20
Total Thickness	291.77'	274.17'	280.39'	278.50'	274.99'	276.55'	274.92'	275.51'	274.54'	276.01'
No. of Beds	201	238	179	268	276	235	234	256	221	216
A Shale + Mu	117.46'	95.38'	120.83'	90.87'	105.08'	90.32'	121.08'	49.12'	120.26'	95.84'
in beds no.	101	121	84	127	138	111	107	116	103	92
Thus B Gw + Silt	174.31'	178.79'	159.56'	187.63'	169.91'	186.23'	153.84'	226.39'	154.28'	180.17'
in beds no.	100	117	95	141	138	124	127	140	118	124
Ratio Gw : Sh $\frac{B}{A}$	1.484	1.875	1.321	2.065	1.617	2.062	1.271	4.61	1.283	1.880
Mean Sh + Mu	1.16'	0.79'	1.44'	0.72'	0.76'	0.81'	1.13'	0.42'	1.17'	1.04'
Mean Gw + Silt	1.74'	1.53'	1.68'	1.33'	1.23'	1.50'	1.21'	1.62'	1.31'	1.45'

Table 22 Greywacke Thickness Histograms

Sec.	< 6"	-1'	-1'6"	-2'	-2'6"	-3'	-3'6"	-4'	-4'6"	-5'	-5'6"	-6'	-6'6"	> 6'6"	Total
1	22	32	22	16	12	7	2	4	1	-	-	-	-	1	119
2	43	44	20	11	12	9	3	6	1	-	-	-	-	2	151
3	80	54	18	14	5	3	3	3	-	4	2	-	2	1	189
4	36	49	20	11	8	8	4	3	4	4	2	-	-	-	149
5	35	32	27	15	9	9	1	2	1	2	-	1	-	1	135
6	43	31	26	12	9	3	2	4	4	1	-	1	-	1	137
7	42	40	27	12	5	7	3	3	-	1	2	1	-	1	144
8	30	14	21	12	3	4	1	3	-	2	2	3	-	4	99
9	26	31	18	20	10	5	3	4	3	1	-	2	2	2	127
10	20	36	31	14	5	7	1	2	4	-	-	-	-	1	121
11	36	18	19	8	5	3	1	1	1	4	1	1	-	2	100
12	24	39	12	7	11	7	6	1	3	2	3	-	1	-	116
13	12	30	13	15	5	6	5	3	2	-	-	3	-	1	95
14	46	39	18	15	6	4	3	3	1	2	4	-	1	1	143
15	43	37	23	9	5	5	7	1	1	1	1	2	-	1	136
16	32	25	21	13	11	6	6	3	2	2	1	1	1	-	124
17	50	30	21	5	10	4	-	2	1	2	1	-	-	2	128
18	40	23	17	25	9	6	5	7	2	-	2	1	1	3	141
19	33	25	24	13	6	7	8	1	2	-	1	-	-	-	120
20	49	20	11	14	9	7	4	2	2	-	-	-	-	4	122
Grand Total	742	649	409	261	155	117	68	58	35	28	22	16	8	28	Beds

Total 2596 Beds

Table 23 Shale Thickness Histograms

Section	<3"	-6"	-9"	-1'	-1'3"	-1'6"	-1'9"	-2'	-2'3"	-2'6"	-2'9"	-3'	-6'	-9'	-12'	-15'	-18'	>18'	Total
1	29	9	7	7	5	1	-	-	1	-	-	-	4	2	1	1	1	-	68
2	49	30	12	4	5	2	-	1	1	1	1	-	-	2	-	1	-	-	109
3	79	32	12	5	5	5	-	2	1	-	-	-	1	-	1	-	-	-	143
4	57	31	13	5	3	2	-	2	-	1	-	-	2	2	-	-	-	-	118
5	41	32	15	7	5	2	-	-	1	-	-	-	-	-	-	1	-	1	105
6	49	27	15	13	6	1	1	4	2	-	1	1	2	-	-	1	-	1	124
7	67	28	15	7	2	1	1	2	-	1	2	2	5	-	-	1	-	-	134
8	42	14	6	5	2	-	-	5	1	2	-	-	3	-	-	-	-	1	81
9	36	20	10	6	1	2	2	-	-	1	1	-	1	-	-	-	-	1	81
10	44	28	15	9	5	3	1	-	-	-	-	-	-	1	-	1	-	-	107
11	40	28	15	9	3	1	-	-	1	-	-	-	-	1	-	-	-	1	99
12	44	33	14	12	3	1	2	3	2	1	-	-	3	1	-	-	1	-	120
13	25	18	11	8	4	3	4	2	3	1	-	1	1	1	1	-	-	1	84
14	47	37	17	6	4	4	4	1	2	-	1	-	3	-	-	1	-	-	127
15	61	22	15	17	1	6	4	2	2	1	1	-	3	2	1	-	-	-	138
16	63	20	10	9	3	1	-	-	-	-	-	-	2	1	1	-	-	1	111
17	53	18	13	8	1	2	-	4	2	-	1	1	1	1	-	-	-	2	107
18	56	27	11	14	5	-	2	-	-	-	1	-	-	-	-	-	-	-	116
19	60	15	9	4	4	3	-	2	-	1	-	-	1	1	-	-	-	2	102
20	48	19	6	4	3	3	1	2	1	-	-	2	-	1	-	-	-	2	92
Totals	990	488	241	159	70	43	22	32	20	10	9	7	32	16	5	7	2	13	2166 Beds

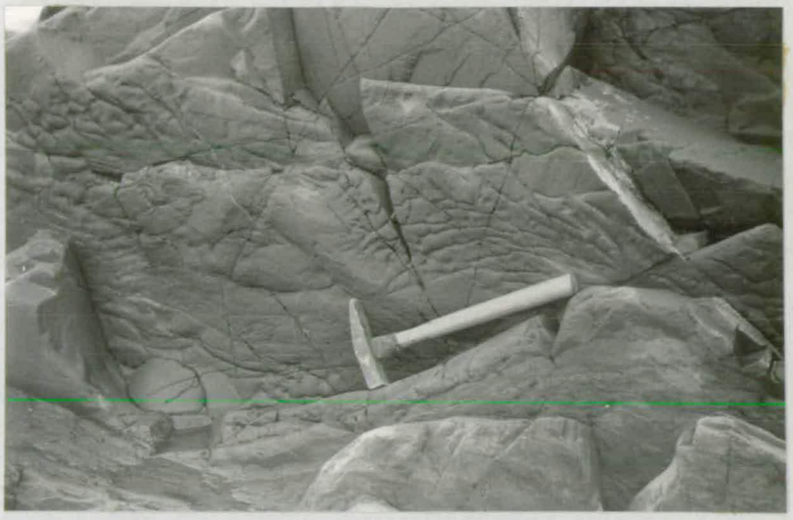
Table 24 Thicknesses of Shales overlying Greywackes

Overlying Shale Thickness

Greywacke Thickness		<3"	-6"	-9"	-1'	-1'3"	-1'6"	-1'9"	-2'	-2'3"	-2'6"	-2'9"	-3'	>3'	Total
<6"	A	82	28	9	5	2	1	-	2	1	2	-	-	3	135
	B	65	34	12	8	7	3	2	-	1	-	-	-	7	139
-1'	A	50	35	17	3	4	4	-	2	2	-	1	-	6	124
	B	58	18	8	8	2	5	3	2	2	1	-	1	5	113
-1'6"	A	37	13	3	5	-	-	-	-	-	-	-	-	2	60
	B	25	15	12	9	2	4	-	-	3	1	1	-	2	74
-2'	A	14	13	5	5	4	1	-	1	-	-	-	-	-	43
	B	18	17	7	3	4	-	-	1	-	-	-	-	-	50
-2'6"	A	4	10	4	3	2	3	-	-	1	-	-	-	1	28
	B	15	2	1	-	2	1	1	-	-	1	-	-	1	24
-3'	A	7	4	5	2	1	-	-	-	-	-	-	-	-	19
	B	8	7	1	2	-	-	1	-	-	-	-	-	-	19
-3'6"	A	4	2	2	-	1	1	-	-	-	-	-	-	1	11
	B	6	2	2	1	-	-	1	-	1	-	-	-	-	13
-4'	A	2	3	1	1	3	-	-	-	-	1	-	-	1	12
	B	3	1	-	-	-	-	-	1	-	-	-	-	2	7
-4'6"	A	2	1	-	-	-	-	-	-	-	-	-	-	-	3
	B	2	1	-	1	-	2	-	-	-	-	-	-	-	6
-5'	A	3	-	-	1	-	1	-	-	-	-	-	-	2	7
	B	1	1	3	-	-	-	-	-	-	-	-	-	-	5
-5'6"	A	1	1	-	-	-	-	-	-	-	-	-	-	-	2
	B	2	-	2	1	1	-	-	-	-	-	-	-	-	6
-6'	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	B	-	-	-	2	-	1	-	-	-	-	-	-	-	3
-6'6"	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	B	1	-	-	-	-	-	-	-	-	-	-	-	-	1
>6'6"	A	3	1	-	-	-	-	-	-	-	-	-	-	-	4
	B	1	1	1	-	-	-	-	-	-	-	-	-	-	3

Sample A - Total 448
Sample B - Total 463

Beds



Figs 11, 12

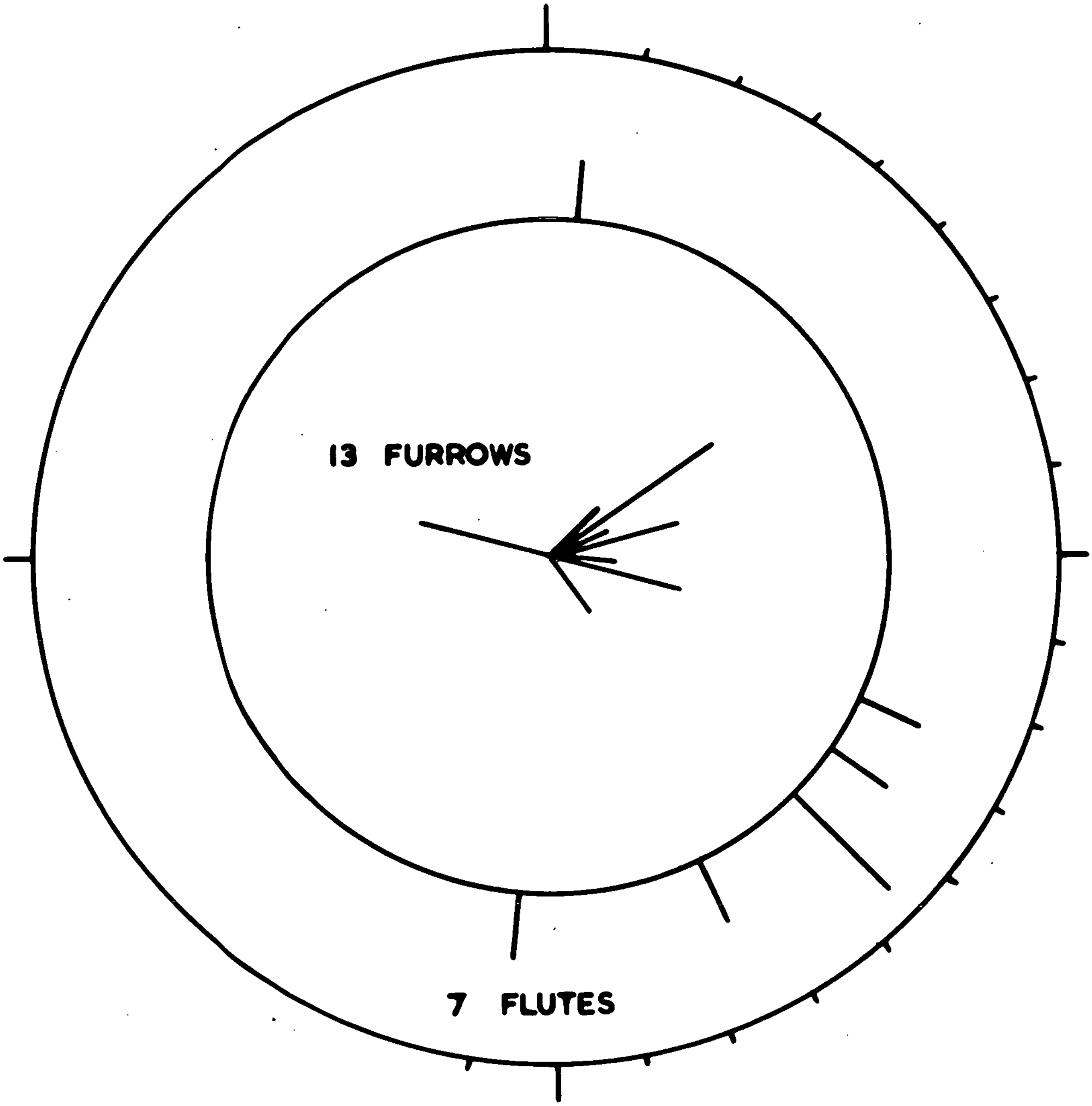


FIG 13 UPPER LOCHRYAN DIRECTIONAL CURRENT STRUCTURE AZIMUTHS

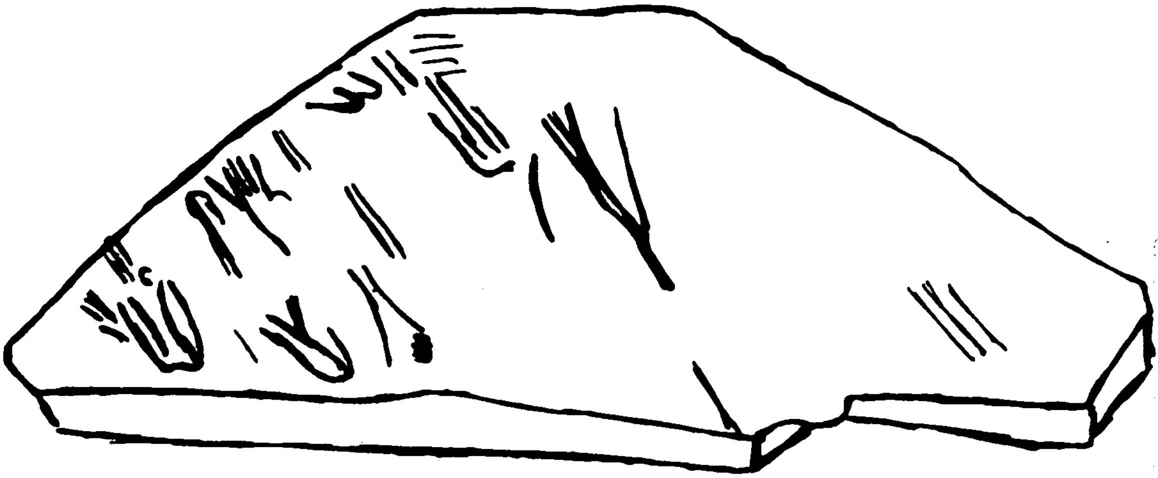


Fig. 14 Specimen showing bounce marks. (drawn from a photograph)

CHAPTER 7 STRUCTURE OF THE AREA

The distribution of the greywacke types, (Chap. 2), is a major aid in elucidating the major structural elements in the area and will, therefore, be described here in fuller detail.

The areas of outcrop of the various greywacke formations are arranged in a series of strips of differing widths, parallel or nearly parallel to the regional caledonoid strike. The rocks found in each strip are described from north to south, and are illustrated in map fig. 2.

The extreme north of the area is occupied by Upper Lochryan Rocks, well exposed along a short coast section and very poorly exposed inland. The rocks dip steeply to the south, but evidence from sedimentary structures, in particular graded bedding and load moulded greywacke soles, shows a consistent way-up to the north. Two of the thick shale bands which are a characteristic feature of the Lochryan Rocks have been mapped along Glen App and are found to be displaced laterally several times by a series of sinistral wrench faults striking roughly north--south. Near Lagafater Lodge in the east of this broad tract of Upper Lochryan Rocks there are several outcrops of rocks of the Cairnerzean Group, which are stratigraphically higher than the Upper Lochryan (see later) and thus require a faulted boundary, downthrowing south.

To the south of this broad strip of Lochryan Rocks there are a few outcrops of Cairnerzean (North) Rocks, forming a narrow strip between Cairnryan and the Water of Luce. Near Cairnryan the Cairnerzean rocks are found above tightly folded Lochryan (Upper) Rocks, providing evidence of the stratigraphical relationship of the two formations. A strike fault, downthrowing to the south, is inferred to explain the juxtaposition of the younger Cairnerzean Rocks with the older Lochryan Rocks to the north, since both formations here have a near vertical dip.

The Cairnerzean (North) Rocks are followed to the south by more north-facing vertical Lochryan (Upper) Rocks, including a thick shale band. The outcrop width between the Cairnerzean (North) Rocks and this thick shale decreases eastwards, suggesting the presence of another fault, as both formations young northwards. There is no evidence for the sense of displacement of this fault, except that a branch of the fault has a sinistral wrench component. This suggests that the fault between the Cairnerzean and Lochryan Rocks had a sinistral wrench component at some stage in its history, but the small-fault data discussed later shows that a sinistral wrench movement on a fault in this orientation was not the first movement on the fault.

The next strip to the south is formed of folded Claddy House Rocks, and, stratigraphically below, folded Upper Lochryan Rocks. Again a major strike fault is inferred to explain the proximity of the folded Claddy House Rocks and the vertical north-facing Lochryan Rocks immediately to the north.

The Claddy House Rocks are in contact to the south with Lower Lochryan Rocks. There is no palaeontological or structural evidence in the area for the stratigraphical position of this division of the Lochryan Rocks but consideration of the composition of the Lower Lochryan Rocks leads to their comparison with the Kirkcolm (Meta-clast) division in the Rhinns of Galloway, which is stratigraphically below the Rhinns equivalentsof the Claddy House and Upper Lochryan Rocks. The boundary between the Claddy House and Lower Lochryan Rocks is therefore a fault. The Lower Lochryan Rocks occupy a wide stretch of ground between the Claddy House Rocks and the Beoch Burn. The rocks are steeply dipping and are often overturned to the north. Minor folding is not significant and way-up is therefore consistently northwards.

The Lower Lochryan Rocks are followed to the south by Cairnerzean Farm Rocks, which also young northwards, suggesting a boundary strike fault downthrowing to the south. Compared with the other areas of Cairnerzean Group Rocks minor folding is not significant and the beds are uniformly overturned to the north, dipping steeply southwards. At the western end of this strip of Cairnerzean Rocks there is a complex area in which small patches of Cairnerzean Farm Rocks are faulted into contact with Upper and Lower Lochryan Rocks, the faulting also causing considerable local variations in the bedding orientations.

The Cairnerzean Farm Rocks are followed to the south by another wide stretch of Lower Lochryan Rocks, the boundary again being a fault. This boundary fault is well exposed in Kilfeddar Gorge, in which the Water of Luce flows along greywackes and shales sheared in the fault plane. Just to the west of the Kilfeddar Gorge the boundary strike fault is displaced by a north-south sinistral wrench fault. This tract of Lochryan Rocks is poorly exposed but shows a west to east variation of strike from 70° to 40°. Overturning is not common, the beds dipping steeply northwards.

Glenwhan Rocks are found to the south, and they also show a west to east swing in strike. Again the stratigraphic position of this formation is determined by comparison with the Rhinns of Galloway, in the absence of palaeontological evidence. In composition the Glenwhan Rocks are equivalent to the Portpatrick (Basic-clast) Rocks which lie westwards along strike in the Rhinns. The Portpatrick (Basic-clast) Rocks lie above the Kirkcolm Group (Lochryan Rocks equivalent) in the Rhinns. The boundary between the Glenwhan and the Lower Lochryan Rocks is therefore a major fault in the present area. Since the west to east swing in strike is found on both sides of the boundary the boundary fault has been modified structurally after its formation.

The most southerly part of the area is a strip of poorly exposed ground covering Boreland Rocks striking 65° and with about 40% of the beds overturned and dipping steeply southwards. There is consistent way-up to the north and in composition the Boreland Rocks grade into the Glenwhan Rocks. The Boreland Rocks are therefore the lateral stratigraphical equivalents of the Portpatrick (Acid-clast) Rocks of the Rhinns of Galloway. Exposure is too poor to determine the extent of minor folding.

Minor Structures

A second major aid in the determination of the major structures of the area is an examination of the minor structures.

The area has been divided, for reference purposes, into a number of sub-areas, shown in fig. 15, corresponding to the main outcrops. The data from the minor structures in these sub-areas are detailed below.

The poles to bedding planes in the area show that the rocks form three broad structural belts. In the north (sub-areas A, B, C, D, figs. 16, 17, 18, 19, 20) there is a broad tract in which the rocks strike between 50° and 60° and dip steeply to the south. Sedimentary structures show that the beds are overturned. Minor folds are not common but their presence in sub-area B causes slight girdling of the poles in figs. 17 and 18 about an axis dipping at a shallow angle towards 60°. The close similarity of the bedding plane orientations in the area is well illustrated in fig. 18 which shows good mixing of the points from two parts of the coast section, and also by comparing this diagram with fig. 17 which shows another sample drawn from the whole coast section, the two figures being identical. (The similarity of the two diagrams also shows the absence of any operator variance with time in the collection of the data as the data for fig. 18 were collected a year after those for fig. 17).

Minor folding in the northern structural belt is confined to small folds in a few thick shale bands and very occasional unbroken fold hinges in greywackes. The axial plunges are recorded in figs. 21 sub-area A, 22, 23 sub-area B. The variability of plunge is quite large, being largest in the small folds in the shales and least in the small folds in the greywackes. In sub-areas A and B the fold axes plunge between 10° and 90° towards 40° to 90°. A few more folds were detected by changes in the younging directions of greywacke sedimentary structures. An indication of the axial trend of these folds was obtained by plotting the stereographic traces of the orientations of greywacke beds of opposite facing directions, the traces intersecting in the fold axis. Fig. 24 shows the intersection (β) points (fold axis poles) obtained by this method in sub-area B. The points are fairly scattered but show the fold axes plunging at a generally small angle, towards 40° to 90°.

Fold style is the same in the small folds in the shales, wave-length 3-12" and in the folds in the greywackes, which are also relatively small with a wave-length usually about 10'. Each fold is a unit composed of a syncline followed quickly by an anticline to the north, the common limb usually being almost horizontal or dipping at a low angle eastwards, see figs. 25 and 26. This fold style is reminiscent of drag fold style and suggests the presence of a major anticlinal axis to the south of sub-area B, (see later).

The central structural belt includes sub-areas E--K, L, and N. The regional bedding orientation is shown by figs. 27 to 32 for sub-areas E, F, G, H, J, and K. These show a regional strike of 70°, and a north to south decrease in the amount overturning.

The regional strike pattern is disturbed in sub-areas I and N where there is much complicated faulting, and in sub-area L where there is a swing in strike from the regional strike of 70°, shown by sub-area K to the west (fig. 32) to a strike of 40° (fig. 33). Sub-areas L and K include both Lower Lochryan and Glenwhan Rocks, and the boundary fault between them. This west to east swing in strike of the boundary therefore suggests that the boundary fault between the two formations has been affected by a later structural episode. The general north younging pattern of the central structural belt is also affected in several narrow strips in which there is a large amount of minor folding. In style this minor folding is usually tight with steeply dipping limbs. However in sub-area F in which a series of folds are exposed in a burn section the folding in the lowest part of the burn is of an open style with low amplitude, fig. 28. This diagram shows a low axial plunge towards 70° with a near vertical axial plane. Further uphill the folds become tighter until in the highest part of the burn the beds dip steeply towards each other. This suggests that the minor folding is concentric in style, but unfaulted fold hinges are too few and too poorly exposed to examine the style at first hand.

Fig. 34 illustrates the strike variations in sub-areas N and I, showing the large proportion of beds in these sub-areas which have a north--south strike. Overturning is not common.

Fig. 35 shows β-intersections for sub-area E scattered along a vertical great circle with a 65° azimuth. The number of points is unfortunately too few to determine whether this form of distribution has any structural significance. For sub-area F, fig. 36, the fold axes plunge at a low angle towards 50° to 80°. A stereogram of an axial plane cleavage well developed in a quarry in sub-area F, fig. 37, has the poles to the cleavage planes well concentrated with a maximum corresponding to an axial plane with 70° azimuth and a steep dip to the north.

The complications in sub-areas I and N are further illustrated in fig. 38. The β -points in this diagram have a scattered distribution but are divisible into three sets, two of which plunge at a low or moderate angle towards 10° to 50° or 220° to 250°, and a third set which has steep or near vertical plunges. This sub-area is complicated by faulting and it is thought that the folds with a shallow axial dip have been rotated from an original regional 60 - 70° trend to their present orientation by the action of these faults. The association of steeply plunging folds with shear faulting has been reported elsewhere in the Southern Uplands by Kelling (1961), Gordon (1962), and Rust (1963), and satisfactorily explains the steep folds in sub-areas I and N.

The southern structural belt (sub-areas M, P, Q, and R), is a region of fairly intense minor folding shown by changes in facing direction and attitude of the beds. Overturning of the beds which are steeply dipping with a regional strike of 60° to 65° is uncommon. The northern part of the belt is the only part of the whole area in which there is a wide stretch of rocks which young southwards, see cross-section fig. 50. The rocks in this belt are best exposed on Craig Fell (sub-area M). Fig. 39 illustrates the bedding configuration in this sub-area, the rocks being folded with steep north-facing and rather shallower south-facing limbs. Girdling of the poles shows a regional shallow fold axis plunge towards 60°. The rest of the belt is more poorly exposed with the beds dipping steeply to north and south, figs. 40, 41, 42. No unbroken fold hinges are exposed so fold orientations are derived from bedding intersection diagrams. Figs. 43 and 44 show β -points indicating fold axis plunges towards 30° to 70°, at a low to moderate angle in sub-areas P and Q, and at a moderate to steep angle in sub-area M. Additional evidence from sub-area M is provided by fig. 45 which shows the plunge of cleavage--bedding intersections steeply towards 40° to 70°, and fig. 46 which shows the attitudes of the axial plane cleavage. In fig. 46 there are two clusters of poles to cleavage planes, with the larger number of planes dipping south and a small number near vertical dipping north.

Summary

The data for the various sub-areas is summarised in Table 25.

Only meagre data are available from the individual sub-areas but they do suggest that there is a fairly wide range of fold-axial trends. The data are examined further in fig. 47 in which all the axial trends observed in the sub-areas, or inferred by β -diagrams are plotted. When contoured, fig. 48 the data are seen to be grouped into several maxima which are listed below.

i) Plunging at 10° towards 50°
ii) " " 30-50° towards 65°
iii) Horizontal along 75°
iv) Plunging 20° towards 10°
v) Vertical and near vertical

Maxima i), ii), and v) are arranged in near girdle fashion but it is not thought that this is a true girdle caused by later folding of an original set of low plunging fold axes but that the distribution is caused by the fortuitous occurrence in the area of two axial trends 50° and 75°, which are closely aligned and which interfered with each other, and a set of vertical axes associated with wrench faulting. Maximum iv) is formed by only a few folds, from sub-areas I and N where faulting is thought to have rearranged the orientation of blocks of the country rock.

The main stress directions which produced folding in the area were probably aligned along 140° and 165° corresponding to the 50° and 75° axial trends.

Major Fold Structure

The distribution of formations and the small fold data enable a major fold model to be constructed to explain the consistent north-younging attitude of the beds and the restriction of small folding to fairly narrow strips in the area.

The major folding of the area produced beds which dip steeply, northwards or, overturned, southwards, with a strike varying between 50° and 70°. Two folds styles are seen, one with tightly folded near parallel limbs, the other formed of small anticline--syncline units in which steeply dipping north-facing limbs are separated by a short limb with a fairly low angle of dip. Folds of the second style are quite rare, being found only in sub-area B, but this restricted distribution may be due to imperfect exposure. The few unfaulted examples have axial plunges towards 50° to 60° and are thought to be associated with the 140° principal stress.

The minor folds plunge eastwards at variable angles but the variation in plunge is not due to successive tilts to the east as faults with a low angle of hade show no preference for a dip to the west and fault planes with vertical slickensides, shown later to be early structures, intersect in a horizontal line, fig. 49. It is therefore more likely that the folds formed with their present axial plunge. Anderson (1962) explained the regional eastwards tilt of the Ards Peninsula in Northern Ireland as a result of the intrusion of the Newry igneous rocks. However the regional tilt of fold axes is a wide spread phenomenon in the western Southern Uplands and is probably due to a fundamental cause of which the Newry intrusions are another manifestation. In any case Anderson himself considers that the tilting was contemporaneous with the folding.

Following a principle well established in metamorphic structural geology (e.g. Weiss and MacIntyre 1957) the configuration of the minor folds in the shales and of the few unfaulted fold hinges in the greywackes is used to deduce the configuration of the major folds, that is a major fold style composed of anticline--syncline units in which steeply dipping north-facing limbs are separated by a shallow dipping limb. The shallow limb is much crumpled by small folds which do not however seem to cause much change in stratigraphic level. Effectively therefore it is the plane joining the crest lines of the minor folds, i.e. the faltenspiegel of Craig and Walton (1959) which defines the horizontal attitude of the middle limb of the anticline--syncline units. The structure of the area is formed of four of these major fold units, illustrated in fig. 50.

The northern fold unit, Unit 1, is formed of the rocks between Glen App and Cairnryan. The Cairnerzean (North) Rocks in the Glen Burn lie in the synclinal core of the unit, most of which is therefore formed of the north limb of the anticline. The second major fold unit, Unit 2, lies between Cairnryan and the Beoch Burn. The Claddy House Rocks are the anticlinal hinge, most of the unit therefore being formed of the south limb of the synclinal part of the unit. Unit 3 lies between the Beoch Burn and the Lochryan--Glenwhan boundary. The Cairnerzean Rocks in the type locality are mostly unaffected by minor folding, and, facing north, thus lie on the southern limb of the unit. In Unit 4, which is formed of the Glenwhan and Boreland Rocks, the anticline--syncline configuration is best illustrated, only part of the anticline's northern limb being faulted out. The boundaries between the fold units are major strike faults which have had a complex movement history, (see later). The net result of their movement however is a downthrow to the south.

Faulting

The area has been much affected by faulting, not only on a large scale producing the major strike faults, but also on a small scale in which displacements are of the order of a few feet or a few inches. The multiplicity of the small faulting is best seen along the well exposed coast section. Due to the thin bedded nature of the Lochryan greywackes and shales of the coast section the displacement of many of the small faults can be determined by matching the beds on each side of the fault and by tectonic curvature of the beds into the fault plane.

Wrench Faults

The poles of 214 sinistral and 163 dextral wrench faults are shown in figs. 51 and 52 respectively. In both diagrams there is a wide scatter of points which has been examined by preparing histograms of the azimuths of the faults, fig. 53. The strikes of the faults are seen to form broad fan-shaped distributions, about a north--south azimuth for the sinistrals and an east--west azimuth for the dextrals. Separate histograms were drawn for those wrench faults with a hade less than 10°, figs. 54 and 55, and show that these faults have a bimodal distribution of their azimuths, with the sinistrals having modes along $15-195^{\circ}$ and $175-355^{\circ}$ with a subsidiary mode along $155-335^{\circ}$, and the dextrals having modes along $65-245^{\circ}$ and $115-295^{\circ}$. If the 175° sinistrals are considered to be the complements of the 115° dextral faults then application of the stress theory (Anderson 1951) produces a maximum principal stress along

145-325° and a value of 30° for ϕ, the angle of internal friction. This angle of ϕ is close to the mean value of 33° derived from a few pairs of complementary wrench faults in the field. The other wrench fault modes, using a value of ϕ of 30° give maximum principal stresses along 165-345° and 125-305° for the other sinistral modes, and 95-275° for the remaining dextral mode.

Normal Faults

The orientations of 40 normal faults are shown in fig. 56. Again there is a wide spread in their distribution. Separation of those faults with a dip greater than 60° enables Anderson's (1951) method to be applied, assuming a ϕ angle of 30°. Fig. 57 shows a bimodal distribution of their azimuths with modes along 35-215° and 55-235°, corresponding to minimum principal stresses along 125-305° and 145-325° respectively.

Thrusts

Fig. 58 shows the orientations of 115 faults with a reverse displacement. From these data fig. 59 was prepared showing the azimuths of those faults with a dip less than 30°, i.e. thrusts which can be analysed by Anderson's method. The distribution is again bimodal with modes along 25-205° and 50-230°, corresponding to maximum principal stresses along 115-295° and 140-320° respectively.

Williams (1959) and Kelling (1961) following McKinstry (1953) consider polymodal wrench fault distributions to be due to azimuthal swings of a single principal stress, producing second and third order shears. Examination of the data from the present area however shows that the wrench fault principal stresses often produced thrusts, and folds. It is therefore considered that each principal stress was a discrete event in the area, especially as there are also normal faults in the correct orientation for generation on release of each stress, although direct evidence for the age of the normal faults is meagre.

The following stress periods have affected the area:-

145-225° producing folds, thrusts, wrenches, and possibly
followed by a tensional phase producing normal faults
165-345° producing folds, and wrench faults
125-305° producing thrusts, wrench faults, and possibly
followed by a tensional phase with normal faulting
95-275° producing wrench faults

Evidence for the age relationships of these stress periods is meagre in the present area. Sinistral wrenches generated by the 145° principal stress are seen to be displaced by sinistral wrenches generated by the 165° principal stress, and a porphyrite dyke filling a tension fracture associated with the 145° principal stress is seen displaced by a sinistral wrench generated by the 165° stress. One fold hinge faulted by a thrust generated by the 125° principal stress is exposed on the coast section. A more satisfactory fault chronology will be suggested later by analogy with other areas.

Oblique Slip Faults

Few faults in the area have slickenside evidence for an oblique slip displacement. The data are therefore amalgamated from widely scattered exposures, mainly quarries in structural sub-areas A, K, and M. The poles to the oblique slip faults are shown in fig. 60, which shows that most of the oblique slip faults have hades greater than 10°. Each of these faults was analysed by the method detailed in Williams (1959), which enables an oblique slip fault to be classified as a wrench-normal or wrench-reverse hybrid, gives the orientation of the principal stress axes, and gives the value of ϕ for each fault. Comparison of the analysis results with the slip where known for a few faults showed, however, that the method did not consistently classify some of the faults, giving a wrench-normal displacement for some and a wrench-reverse for others whereas the field evidence in each case suggested a reverse displacement. Williams (1959) believes that such discrepancies do not invalidate the method, which analyses but one phase of movement on the fault, the movement which produced the slickensides. In other words the discrepancies are evidence of reactivation of faults under a later period of stress. However if a later stress system is producing renewed movement on earlier faults oblique slickensides may be generated even though the stress system is not itself oblique (e.g. fig. 61). Williams attempted to assess the extent of reactivation in the Girvan area by an examination of the ø values obtained from small faults. A similar study of the present area is tabulated below, along with the corresponding results from Girvan.

ø	0-9	10-19	20-9	30-9	40-9	50-9	60-9	70-9	80-9	Wigtownshire	
%	10	14	12	15	13	17	8	7	4	110 faults	Mean ø = 40°
										Girvan	
%	11	14	9	22	16	13	10	5	0	100 faults	Mean ø = 35°

The distributions of ø values are very similar, the difference in mean values probably being due to the Girvan area's having a more varied lithology than the present area. Only a relatively small proportion of the values lies in the 30-40° range which has been suggested by various authors (McKinstry 1953, Hafner 1951) as a good average value for ø. Most of the values lie outside this range and are explained by Williams (1959) in terms of existing fault planes reacting to further periods of stress, the low values of ϕ being obtained from reactivated faults near the theoretical planes of shear of a frictionless material, and the high angles from faults near the new $\sigma_1 - \sigma_2$ plane. If however reactivation is rife in an area it must be assumed that a proportion of the oblique slickensides were generated by reactivation and not by oblique stress systems. Since this proportion can not be estimated and since, in the present area, the absence of marker horizons precludes the recognition of individual reactivated faults, except in one small area, the application of William's technique is not valid.

Further evidence of reactivation is obtained in the field in sub-areas I and N, in which the structure is extremely complicated due to the close proximity of several large faults, both wrench and strike faults. Fig. 62 shows a large scale sketch map of the area with the sense of movement and interaction of the faults illustrated.

The faults in these sub-areas belong to two sets, two major strike faults forming the northern and southern boundaries, and several wrench faults, sinistrals trending about 15°, and a dextral trending about 135°.

The age of the strike faults is not directly determinable in the field but from their orientation and stratigraphic effect they are thought to be early near vertical dip-slip structures produced by the 145° principal stress. The sinistrals and dextral are nearly complementary, generated by a 180° principal stress, and displace the strike faults. Reactivation is shown by displacement of the sinistrals themselves by the strike faults, possibly due to reactivation during the 95° principal stress as the strike faults are in the correct orientation for a dextral reaction to this stress, which is elsewhere manifested as small dextral wrenches. Reactivation is also shown by a downthrow component on the wrenches and by different senses of this downthrow on different faults and different parts of the same fault, fig. 62.

The history of faulting shown by this small area is therefore thought to be:-

i) Production of major strike faults by 145° principal stress

ii) Wrench faulting produced by 180° principal stress

iii) Reactivation of strike faults under 95° principal stress, causing displacement of ii). Release of the 95° principal stress is a possible source of the downthrow components found in ii) which are in approximately the correct orientation for normal reaction to the release of this stress, but the age of the downthrow movement is not determinable.

Comparison with Other Areas

The main stresses affecting the present area are listed in Table 26. The major structure detailed above is formed of large anticline-syncline units modified by strike faults to produce the present distribution of formations. This explanation of the structure is completely different from that put forward by Peach and Horne (S.U.M. 1899). Although no direct reference is made to the area except for the description of fossil localities, the cross-sections drawn across the Northern Belt make it clear that they considered the rocks to be repeatedly folded into a series of anticlines involving only a small thickness (2500') of rocks. The modern technique of using the sedimentary structures of the greywackes to determine their way-up shows, however, that even the well exposed coast section contains few fold hinges and few reversals from a general north-younging direction. The thicknesses of rocks are therefore greater than Peach and Horne believed (fig. 2).

A major structure of anticline--syncline units has been proposed elsewhere in the Southern Uplands by more recent workers (Craig and Walton 1959, Rust 1963) including, of particular interest, Kelling (1961) for the Rhinns of Galloway. The present area lies along strike from the Rhinns and has been found to have similar lithology and stratigraphy. It is therefore not surprising that the two areas should have the same general structure though they differ in detail, in particular in the greater influence of strike faulting in the present writer's area.

Anderson (1962) was severely critical of Kelling's structural history, on the grounds of insufficient data in the Rhinns. Anderson criticised Kelling's proposal of a discrete stress period for each of the Caledonian folds in the Rhinns, preferring to explain the folds in the Ards Peninsula, and the folds in the Rhinns, in terms of one main compressional phase in which azimuthal swings of the maximum principal stress were caused by local lithological variations. However it is shown below that these "local" variations in the Caledonian principal stress directions are in fact extremely widespread. The present writer also interprets the Caledonian stress directions as discrete events since each is manifested by a varied suite of structures and some of the stresses are followed by a tensional phase. This interpretation is also open to criticism for lack of evidence, due to poor exposure, but it is regarded as more than coincidence that two relatively small samples (Rhinns and the present area) should indicate the same periods of stress, even though Kelling and the present writer differ slightly in the interpretation of the structural history of their areas.

The various stress periods affecting the Loch Ryan area are listed in Table 26. There is meagre evidence for the relative ages of the various stresses and nearby areas have therefore been used to see if there is any widespread regional stress pattern into which the Loch Ryan area can be fitted by analogy. These areas are:-

Girvan area	(Williams 1959)
Rhinns of Galloway	(Kelling 1961, Lindstrom 1958)
Central Wigtownshire	(Gordon 1962)
South Wigtownshire	(Rust 1963)
Ards Peninsula N.I.	(Anderson 1962),

and their location is shown in fig. 1. Data on the trends of the structural elements have been extracted from the respective texts and from figures, Table 27. To illustrate the differing interpretations of the data the authors' own structural histories are included. There are two schools in the interpretation of the data. Williams, Kelling, Anderson, and Gordon interpret the Caledonian movements as composing an early folding--thrusting phase followed by a later wrench fault phase, the polymodal distributions of the wrench fault azimuths being due to second and third order swings in the maximum principal stress direction, after McKinstry 1953.

Rust on the other hand interprets each individual stress direction as a discrete event since the presence of several dyke generations, Caledonian and Tertiary, in South Wigtownshire, enables fault sequences to be established. As previously stated the present writer favours this interpretation, and believes that the stress patterns in all the areas so far studied in South-west Scotland can be interpreted in this way. Williams states (1959, p.661) that "the stress field giving rise to the more important Main wrench faults showed the same tendency for azimuthal swings of the principal stress axes as were found for the axes in the folding and thrusting." It is regarded as an unnecessary complication to postulate the repetition of the same swings, especially as the data in Table 27 shows the polymodal fault and fold patterns to have a very wide areal distribution.

Sequence of Events in North-West Wigtownshire

Table 26 shows that the stress patterns found in the present area have a widespread occurrence in South-west Scotland. It is therefore thought valid to amplify the structural history in the present area by analogy with the other, areas, in which exposures are better.

I. The earliest structures found in the area were produced by a 145-155° principal stress forming folds plunging at a shallow angle towards 55°, and more steeply towards 65°, thrusting and wrench faulting. The folding phases established the major folds of the area by throwing the rocks into a series of anticline--syncline units. This stress period was probably followed by a tensional phase in which there was normal faulting and dyke intrusion.

This maximum principal stress is clearly equivalent to the early 145° stress direction which produced major folding and wrench faulting in South Wigtownshire and is found producing structures in all the other areas except the Ards, where it was not detected. See Table 27.

II. Following the tensional phase of I there was renewed folding and sinistral wrench faulting with a 165° . From their azimuths the major strike faults were probably established during this stress phase.

A 165-170° maximum principal stress produced folding in the Rhinns, Ards, and Girvan areas, where the respective authors regard it as the major folding stress, and wrench faulting in all areas except South Wigtownshire.

III. The position in the stress sequence of a maximum principal stress along 115-125°, manifested by thrusts, sinistral wrenches, and, on release, normal faults is dubious, except for the evidence of one exposure in which a thrust produced by this stress is seen displacing an early fold hinge. A maximum principal stress in this orientation produced thrusts and dextral wrenches in the Rhinns and on, release, normal faults, and generated sinistral wrenches in Central Wigtownshire, but neither of the respective authors attaches any significance to it. The closest reference to such a stress is the 110° which formed the Ardwell folds in the Girvan area, the last Caledonian folds according to Williams. This stress may also be equivalent to, but on a different orientation from, Rust's F4 (folds and thrusts with 135° σ_1) but Rust dates his F4 as Hercynian. It is thought that the 115-125° σ_1 in the present area is, in fact, equivalent to the Ardwell fold stress, and is not represented in South Wigtownshire.

IV. The final stress manifested in the area was a 95° maximum principal stress which produced dextral wrench faults, and dextral wrench reactivation of the major strike faults. This stress is closely analogous to Rust's F6 (reactivating faults) and also produced structures in the other areas except the Rhinns. This phase was illustrated by Blyth (1949) who ascribed the shearing in the porphyrite dykes of Galloway to an east-west compression.

Conclusion

The present area in South-west Scotland fills a gap between the other areas in which work has been completed. The preceeding paragraphs and Table 27 illustrate that the structural features of all the areas belong to a very wide stress pattern in which the major principal stresses have a ubiquitous occurrence and a well defined history.

The position of the area also completes a cross-section across South-west Scotland from Girvan to Burrow Head. This is shown in fig. 63 and should be compared with the cross-section in Lapworth (1878, 1882) and Peach and Horne (1899).

Table 25 Summary of Minor Fold Data

Sub-area	Reg. Strike	Overturning	Folding: Axial Plunge	Remarks
A	50°	Dominant	10° - 90° towards 60° - 90°	Small anticline - syncline units in shales
B	60°	Dominant	1. 0-40° towards 50° - 65°	Unbroken anticline - syncline units in greywackes
			2. 0 - 60° towards 40° - 90°	Inferred by β-diagrams
			3. 35° - 55° towards 55° - 75°	Unbroken anticline - syncline units in shales
C	60°	Dominant		
D	50°	Dominant		
E	70°	50% of readings	1. 40° - 50° towards 60° - 70°	Inferred by β-diagrams
			2. 10° towards 240° - 250°	
			3. Vertical	
F	70°	None	1. 0 - 20° towards 50° - 80°	Inferred by β-diagrams
			2. Low angle towards 70°	From poles to axial plane cleavage
G	70°	50% of readings		
H	70°	50% of readings		
J	65°	Dominant		
I	60° variable	Not significant	1. 10° towards 30° - 50°	Inferred by β-diagrams
			2. 0 - 70° towards 220° - 250°	
			3. Vertical	

Table 25 (Contd.)

Sub-area	Reg. Strike	Overturning	Folding: Axial Plunge	Remarks
N	0-70°. Very variable	Not significant	1. 20° towards 0 - 10° 2. Vertical	Inferred by β -diagram
K	70°	30% of readings		
L	40°	Not significant		
M	60°	Not significant	15° - 85° towards 40° - 80°	Inferred by β - diagram and cleavage - bedding intersections
P	60°	Not significant	30° towards 60°	From π diagram
Q	65°	Not significant	Hor. towards 65°	From π diagram
R	60°	40% of readings		

Table 26 Summary of Stress Data

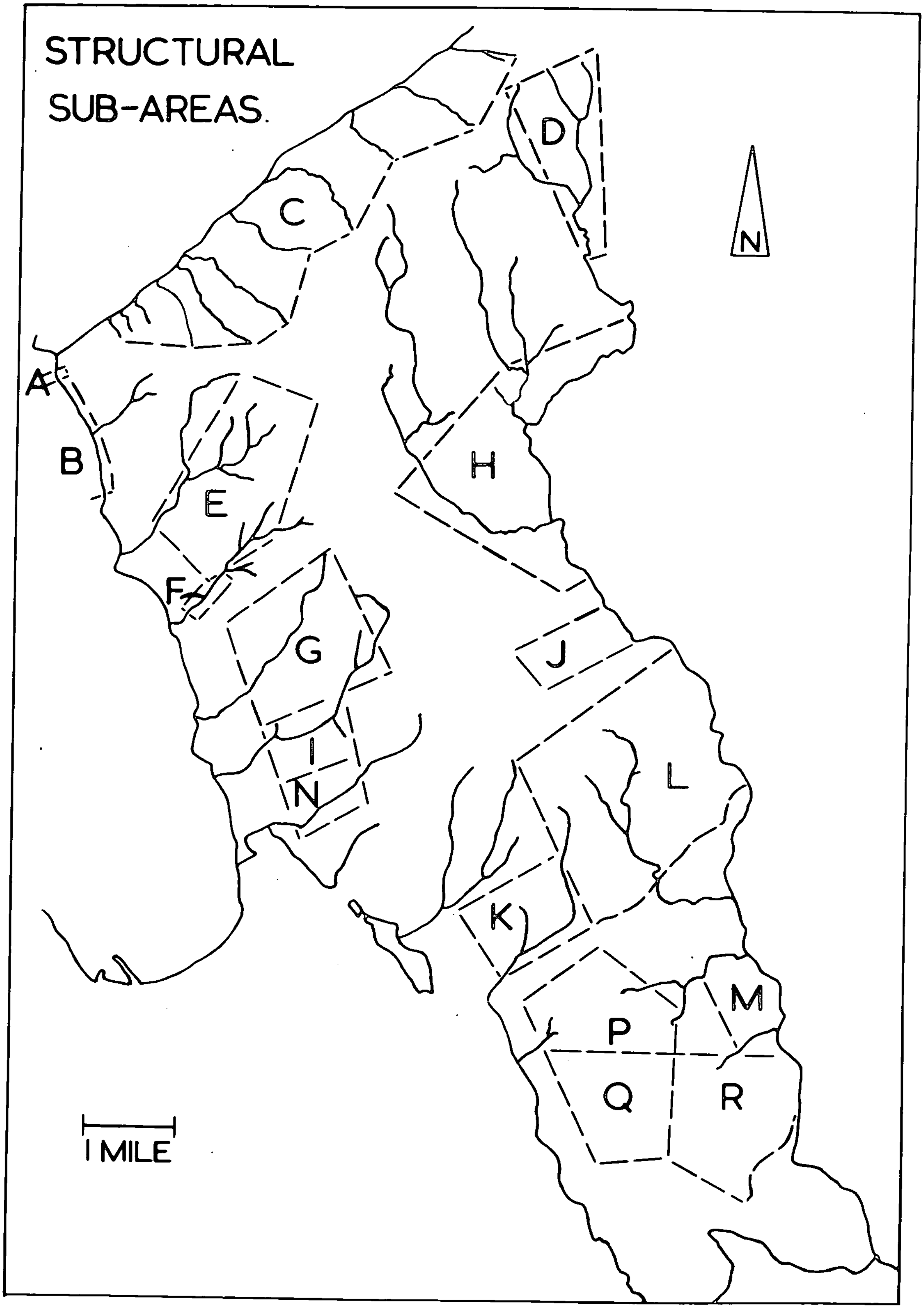
Azimuth of σ_1	Structure
140° - 145°	Folds on 50° axis Wrench Faults (Sin. 175, Dex. 115°) Thrusts along 50° Normals along 55°
165° - 170°	Folds on 75° - 80° axis Sinistral wrench faults along 195°
115 - 125°	Sinistral wrench faults Normal faults along 35° Thrusts along 25°
90 - 95°	Dextral wrench faults along 65° Reactivation of Strike faults

Table 27 Summary of Regional Stress Data in S.W. Scotland

	Rhinns of Galloway Lindstrom 1958	Girvan Williams 1957	Rhinns Kelling 1961
Fold Trends	47°	54° 67° 79° 137°	65 75 100
Fold σ_1	137°	144° 157° 169° 47°	145 165 190
Thrust Trends	75°		65-75 95 135
Thrust σ_1	165°	130-160° 180° 25° 60° 95°	155-165 185 45
Sinistral Trends		Wrench Fault σ_1	175, 190-200, 25-35, 55
Sinistral σ_1		140-170 50° 70° 100°	145, 160-170, 175-185, 25
Dextral Trends			130, 155, 175, 90
Dextral σ_1			160, 185, 25, 120
Normal Trends			75, 40, 30, 165, 105
Normal σ_3		172-197, 140-158, 105-285	165, 130, 120, 75, 15°
History of Events (From Text)	1. Folds σ_1 137°	1. Folds $\overset{\sigma_1}{150 - 170}$	1. Folds 145 σ_1
	2. Thrusts σ_1 165°	2. Thrusts 145°	2. Folds & Wrenches 165 σ_1
		3. Folds 110°	3. Normals $\overset{\sigma_1-\sigma_2}{75}$ $\overset{\sigma_3}{165}$
		4. "x Folds" 45°	4. Folds 190 σ_1
		5. Wrench 160°	
		7. 1st Normal $\overset{\sigma_1-\sigma_2}{80\text{-}107}$ $\overset{\sigma_3}{170\text{-}197}$	
		8. 2nd " 50-68 140-158	
		9. 3rd " 15° 105	

Table 27 (Contd.)

	Ards Anderson 1962		Central Wigtownshire Gordon 1962	South Wigtownshire Rust 1963
Folds	70°	$\underbrace{15 \quad 130}_{\text{Assoc. with Wrenches}}$	65	45 55 95 115 180
Folds σ_1	160	70°	155	135 145 185 25 90
Thrusts				110 45
Thrusts σ_1				20° 135
Sinistrals	195		15° 25° 155°	185°
Sin. σ_1	165		165° 180° 125°	145
Dextrals	125		135 155 10 65	110
Dex. σ_1	165		165 180 40 95	145°
Normals				
Normal σ_1				
History of Events	1. Folds 2. Wrench Kinks 3. Faults	σ_1 160° 70° 160°	σ_1 1. Folds & Thrusts 155° 2. Wrenches 165° 3. " 175°	σ_1 1. Folds 135 & Thrusts 2. " 145 & Wrenches 3. " 185 4. " 135 & Thrusts 5. " 25° 6. Reactivation of Faults 90° σ_1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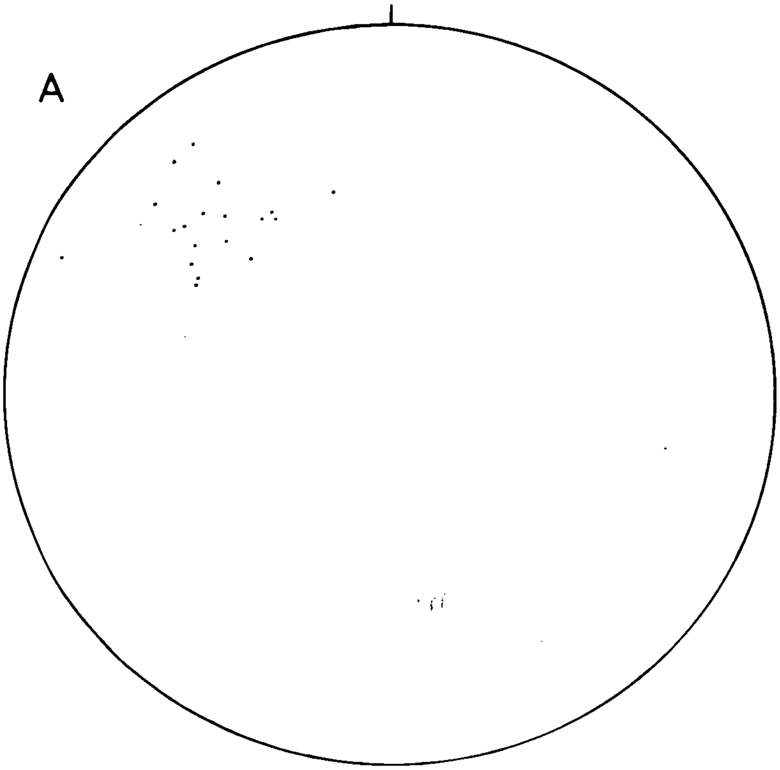
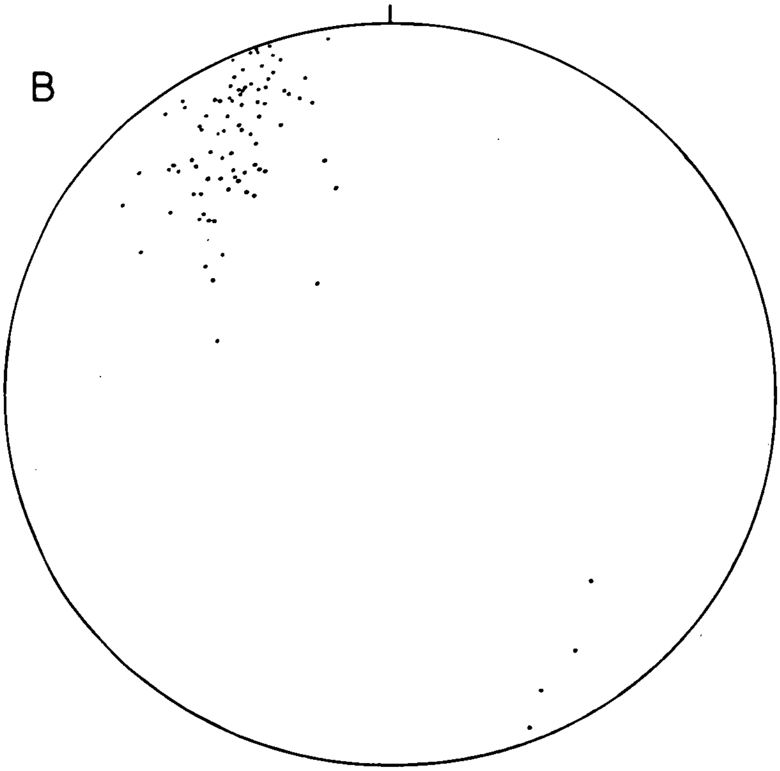
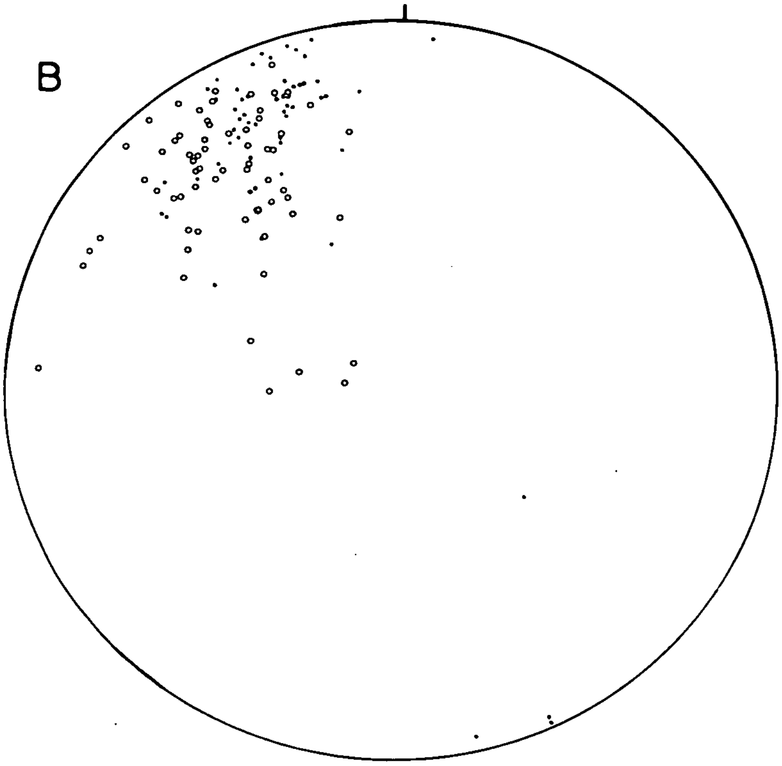
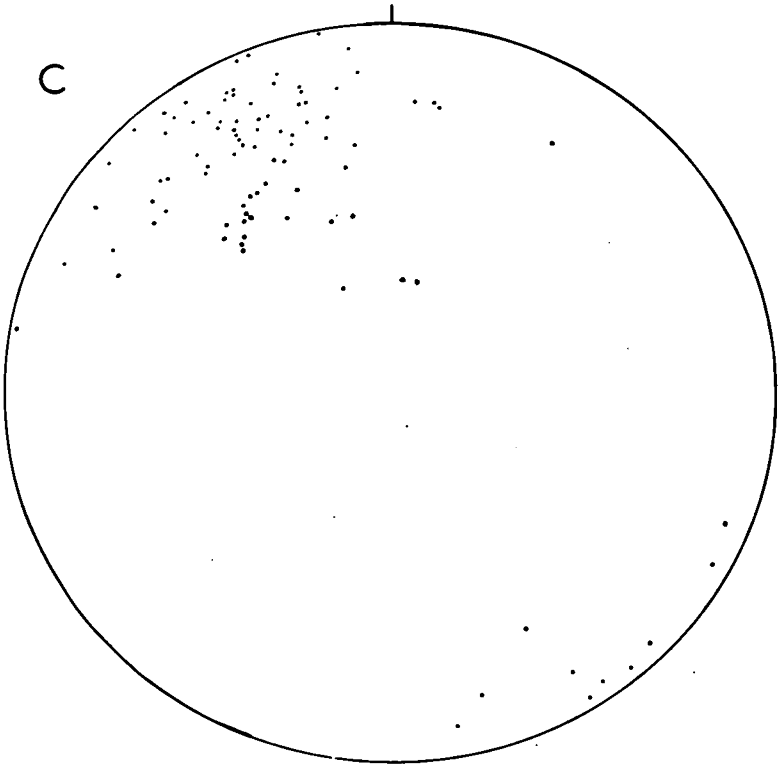




Above Fig. 16   19 poles to bedding planes

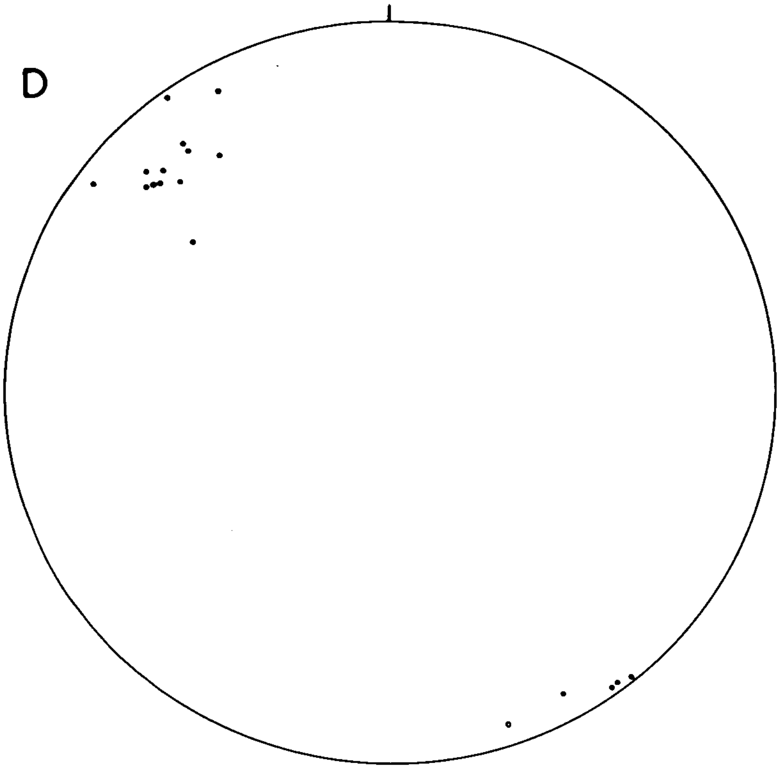
Below Fig. 17   88 "   "   "   "

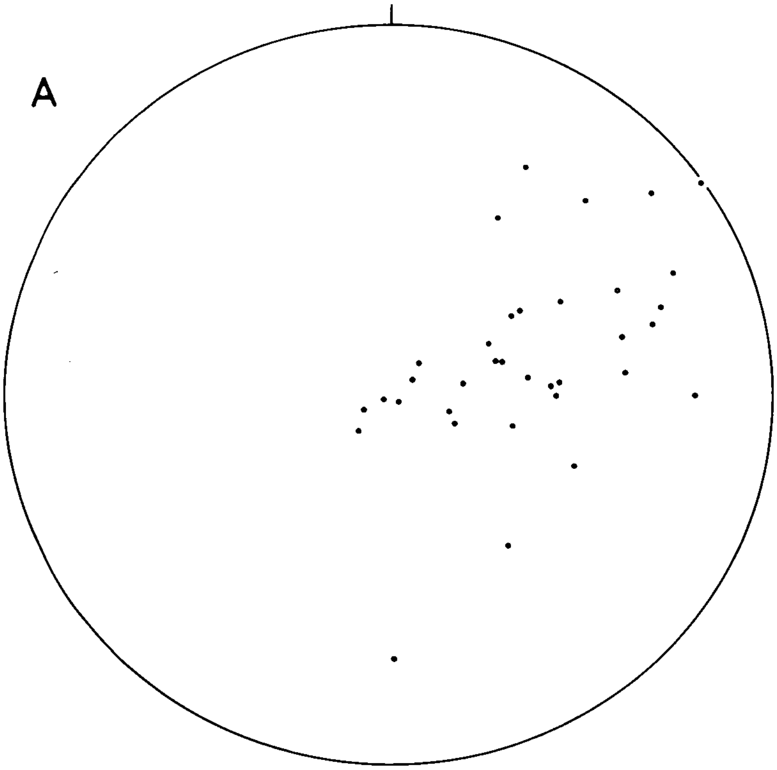




Above Fig. 18 Poles to bedding. Southern sample (Points) 57 poles.
Northern sample (Circles) 51 poles

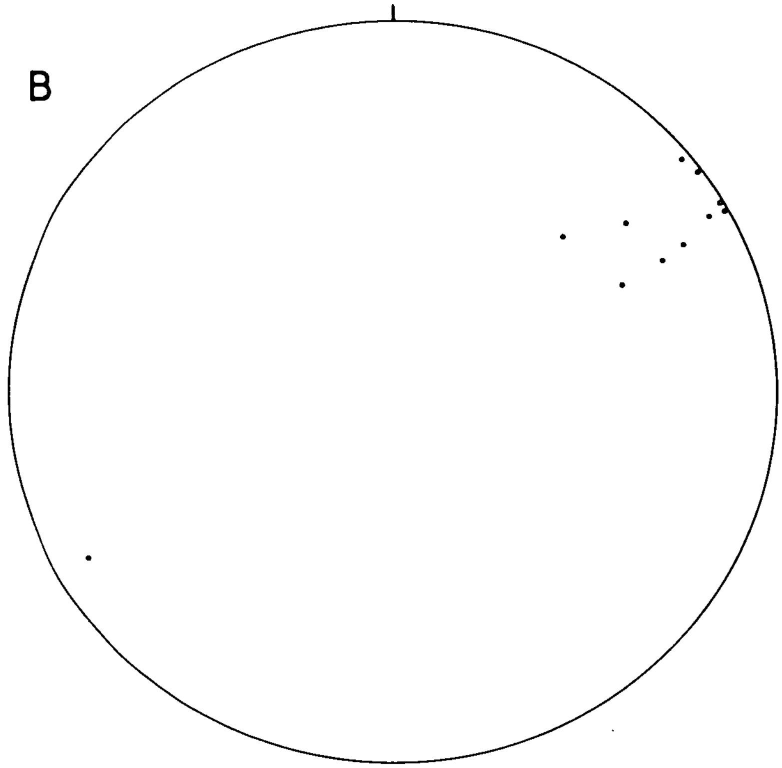
Below Fig. 19 92 poles to bedding

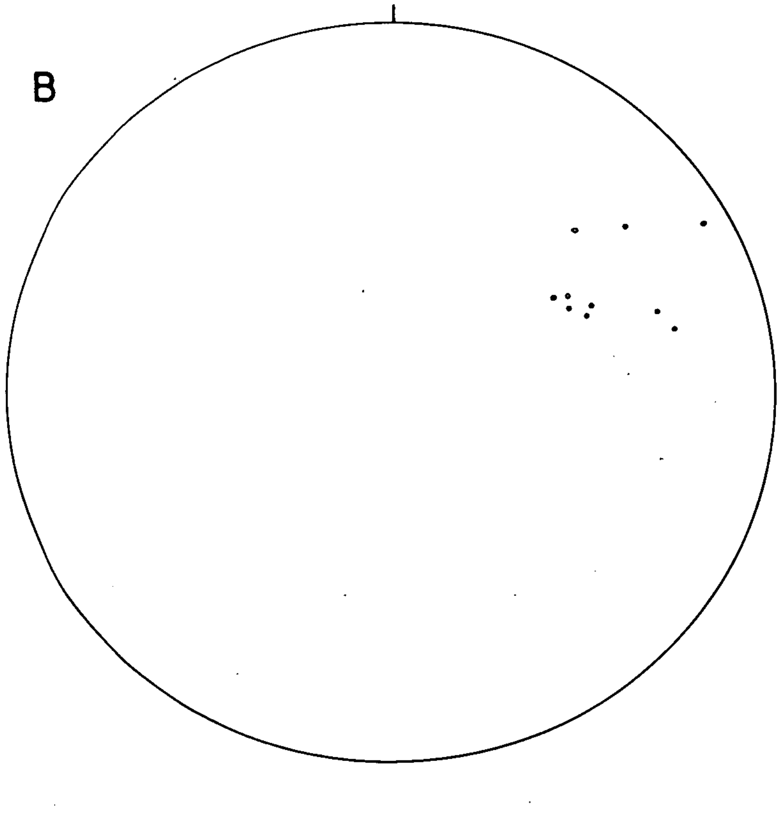




Above Fig. 20 18 poles to bedding

Below Fig. 21 35 axial plunges of small folds in shale





Above Fig. 22 11 fold axis plunges

Below Fig. 23 10 axial plunges of small folds in shale

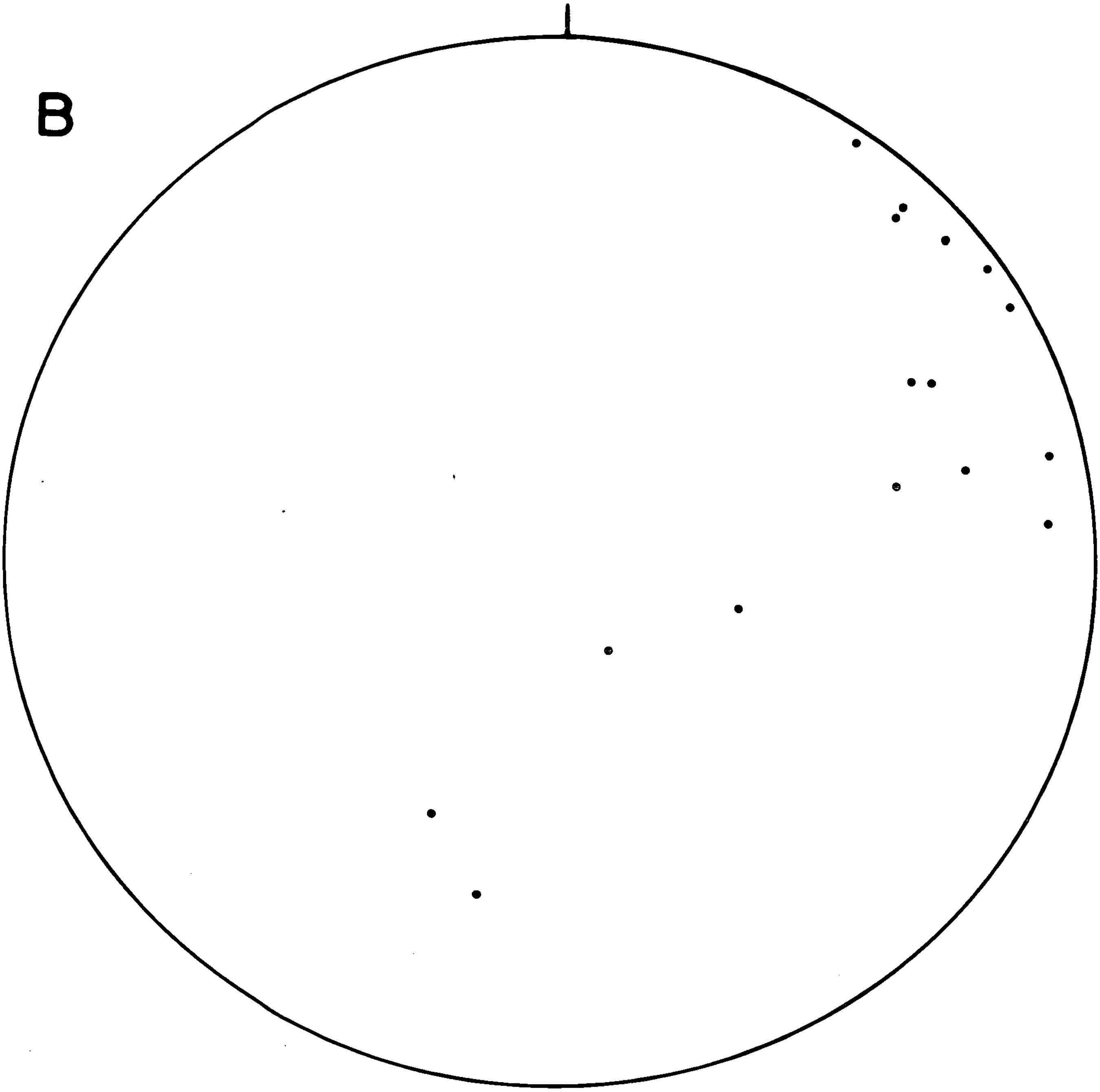
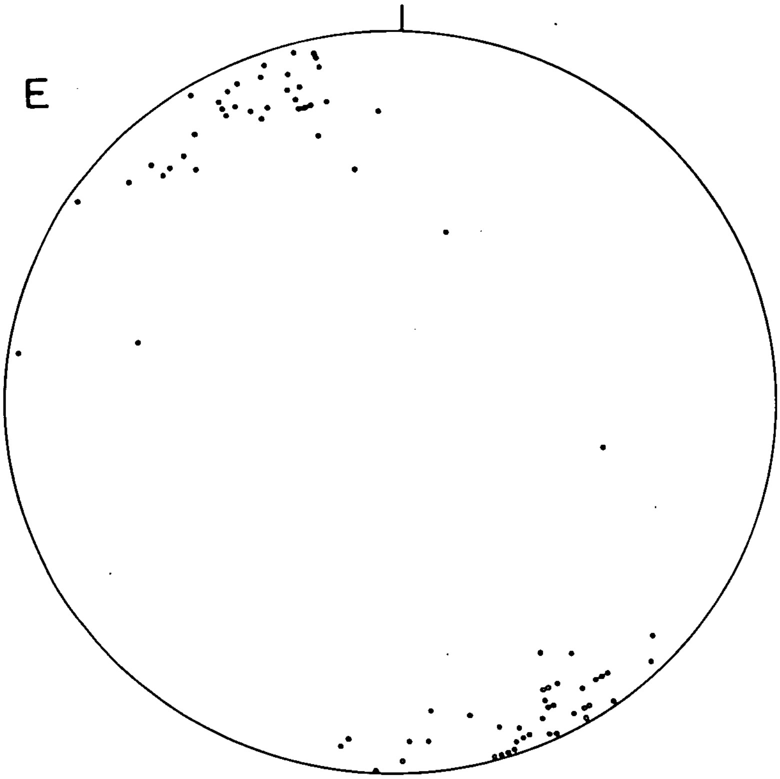
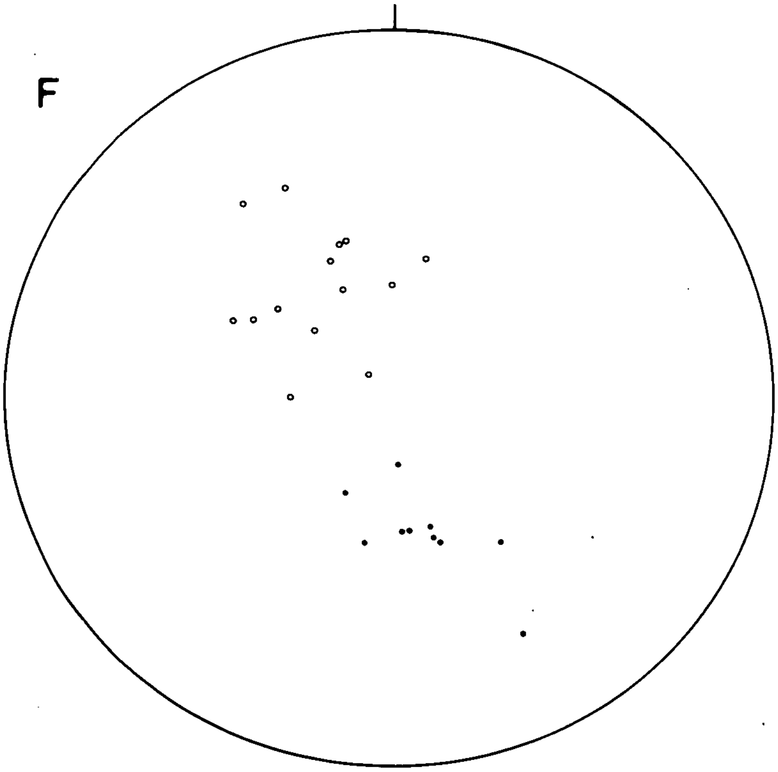


Fig. 24   16 bedding intersections

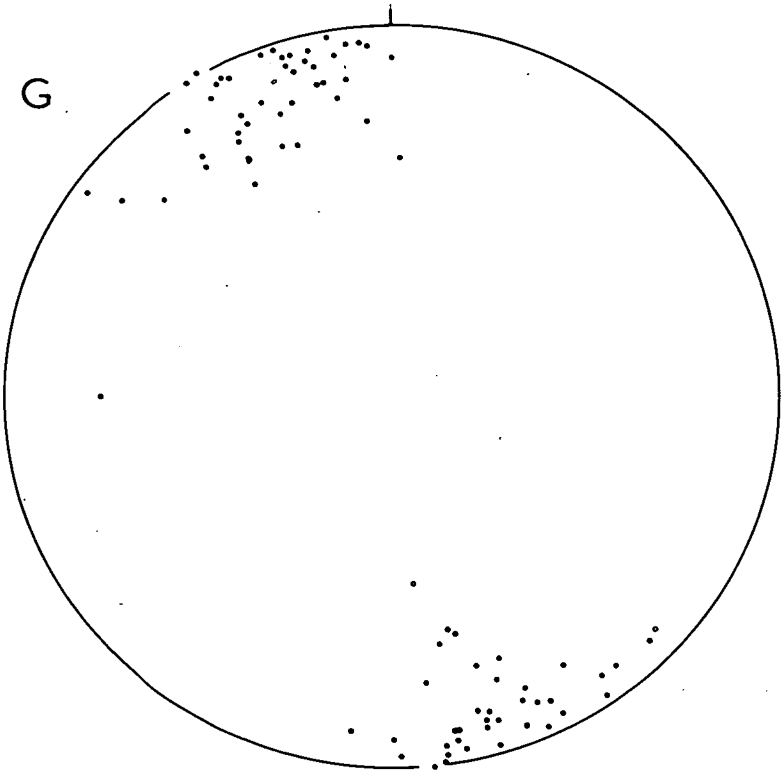
Figs 25, 26.

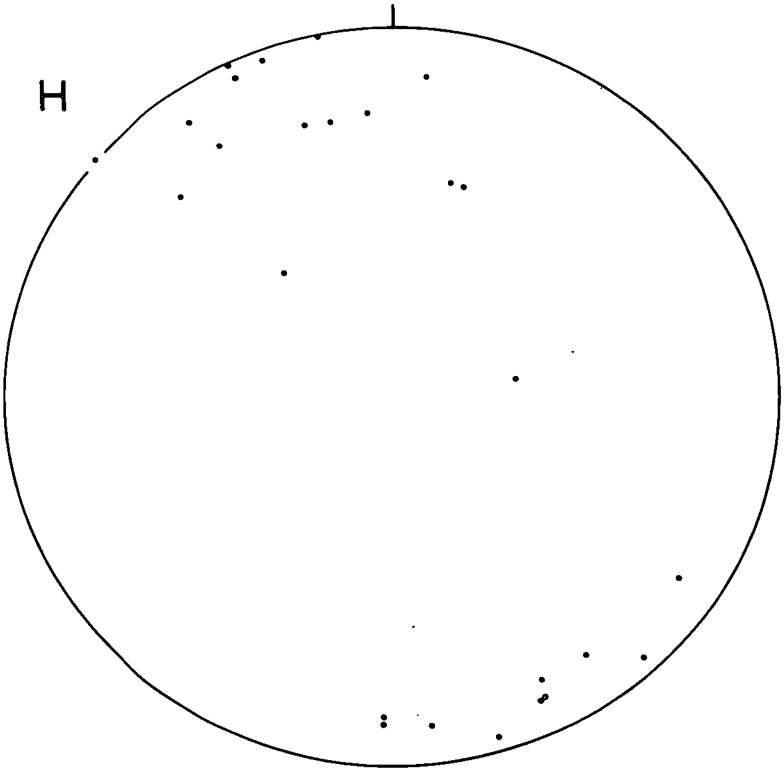




Above Fig. 27 78 poles to bedding

Below Fig. 28 24 poles to bedding (points young north, circles young south)





Above Fig. 29 84 poles to bedding

Below Fig. 30 26 " " "

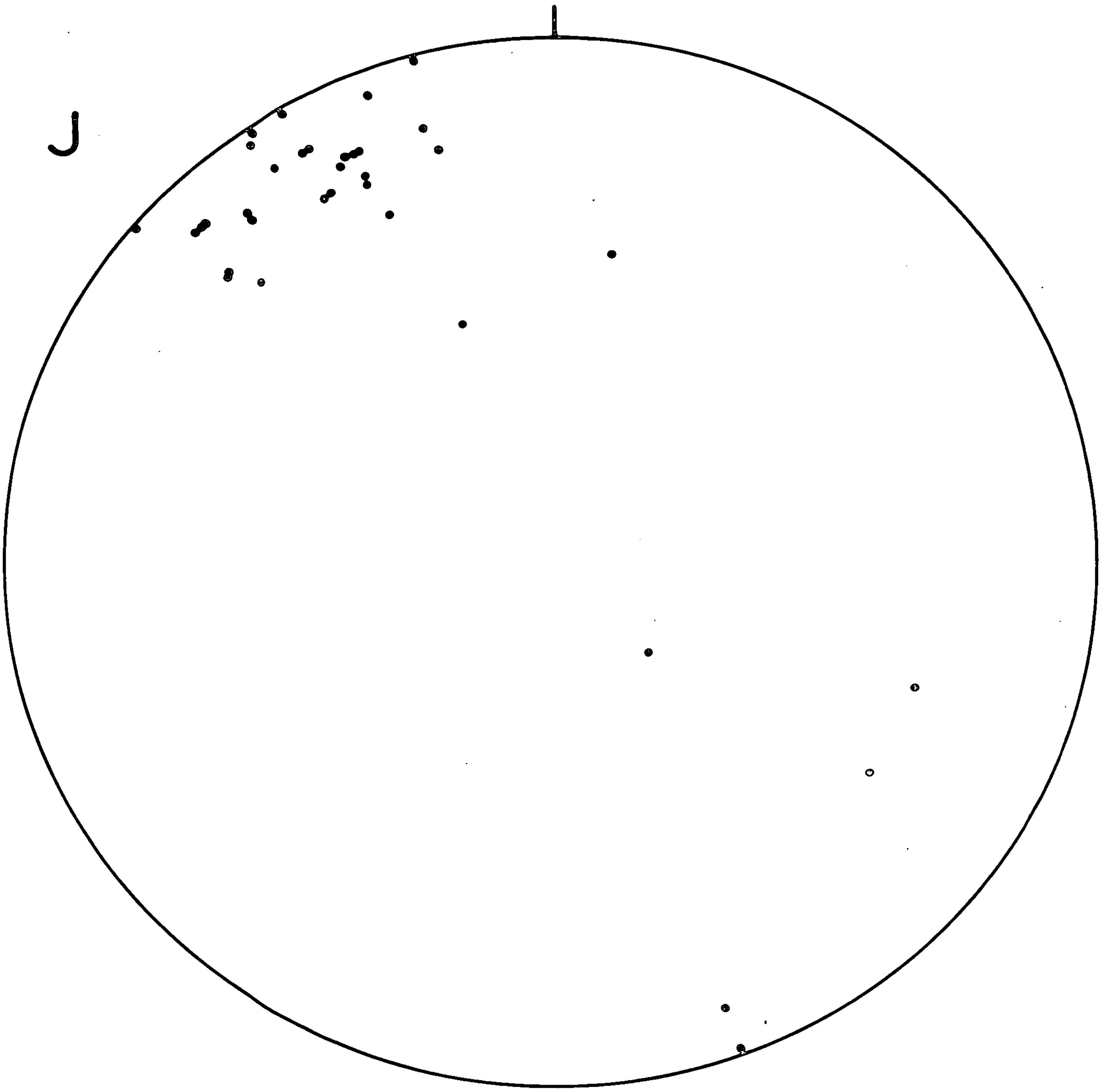
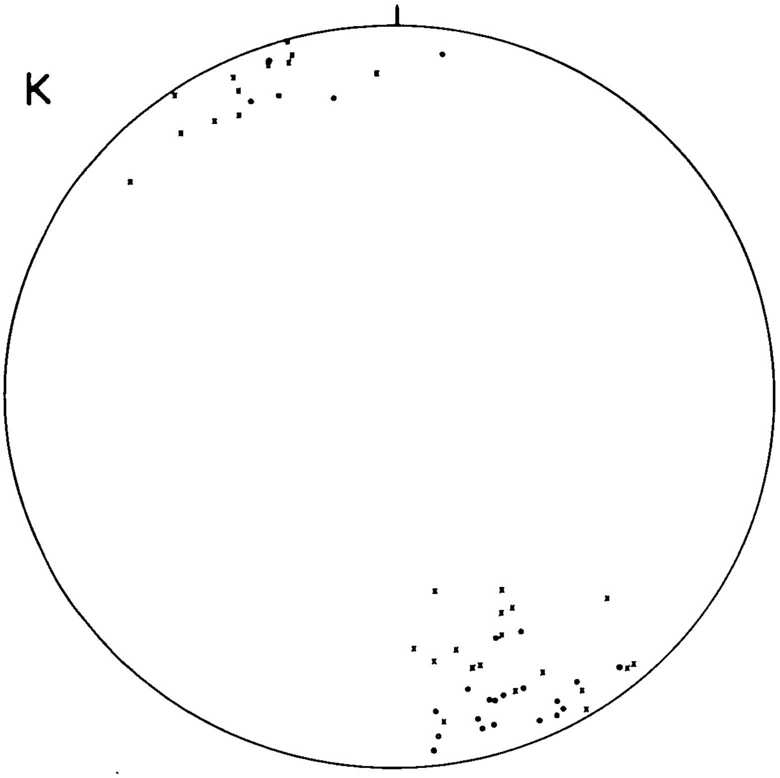
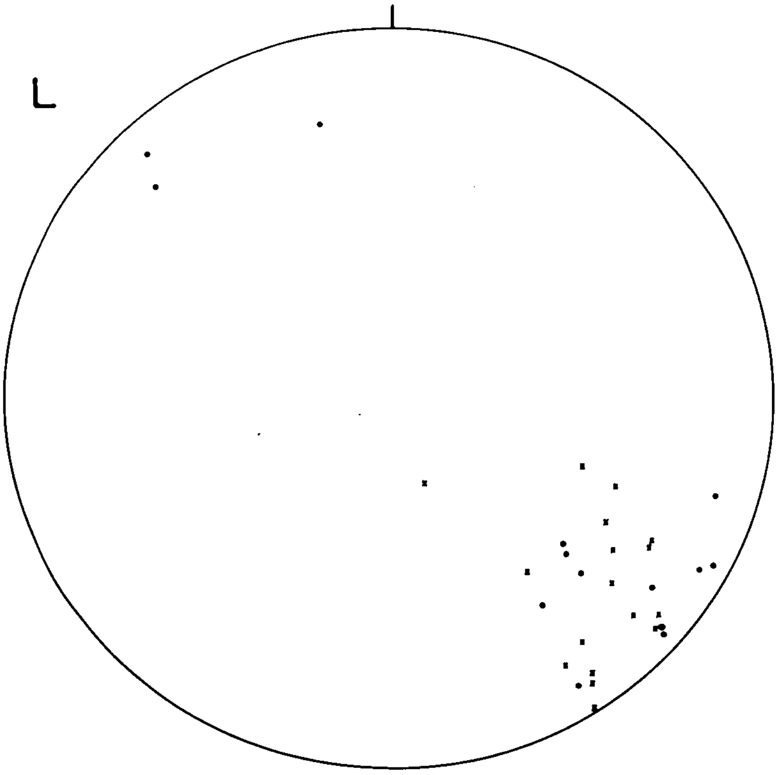


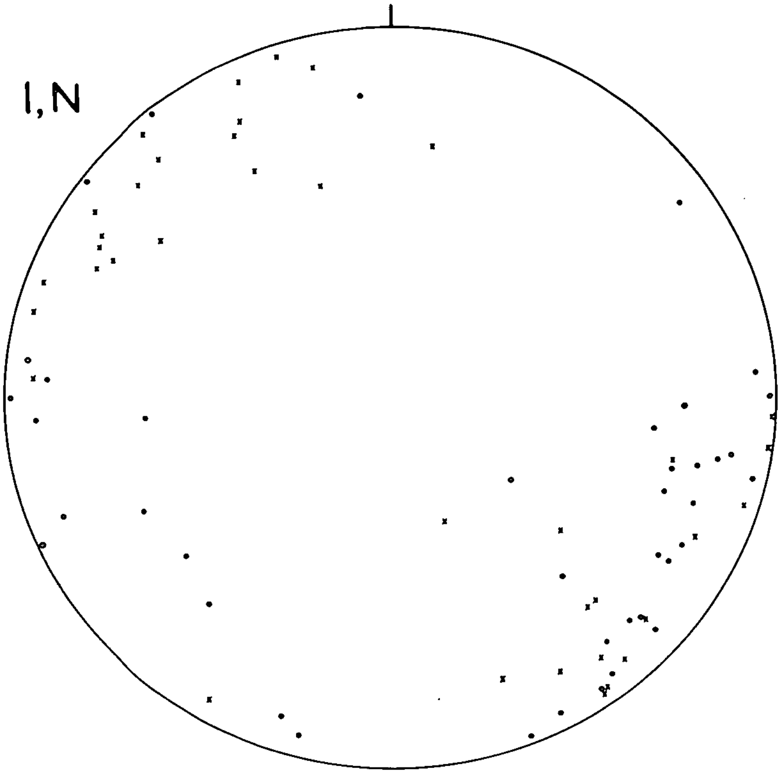
Fig. 31 35 poles to bedding planes

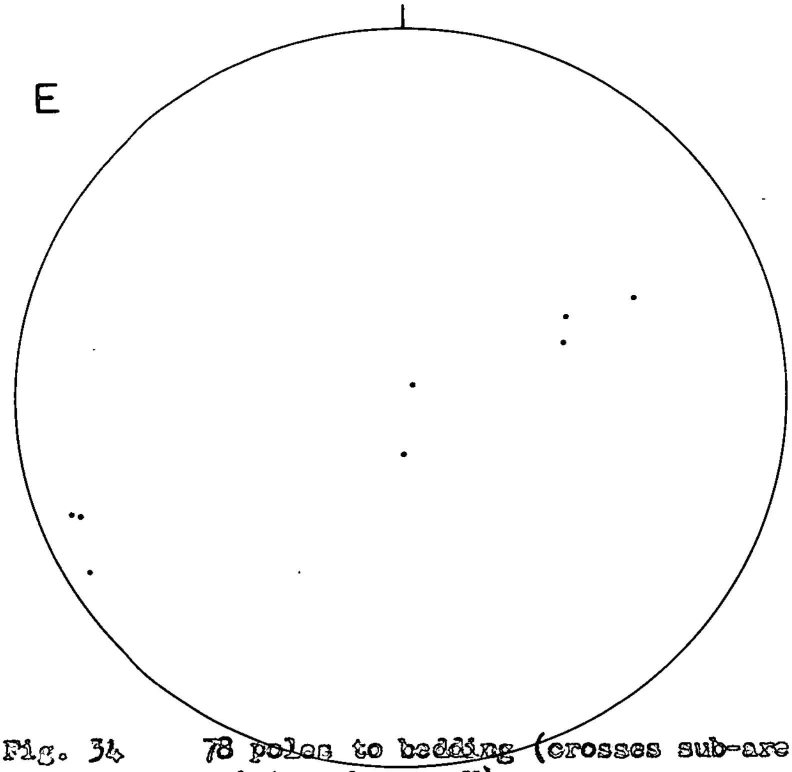




Above Fig. 32 54 poles to bedding (points Lochryan, crosses Glenwhan Rocks)

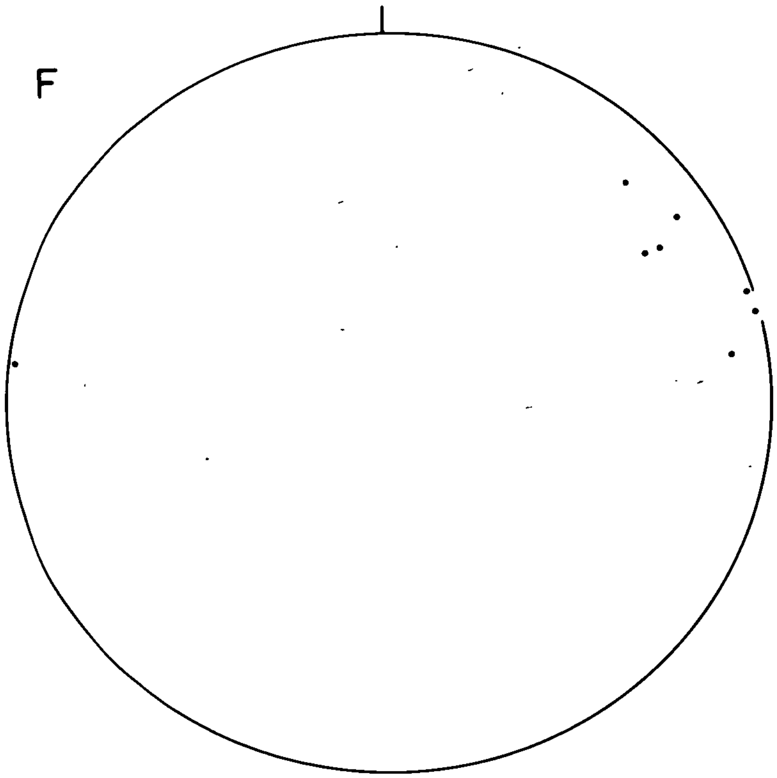
Below Fig. 33 31 poles to bedding (symbols as above)

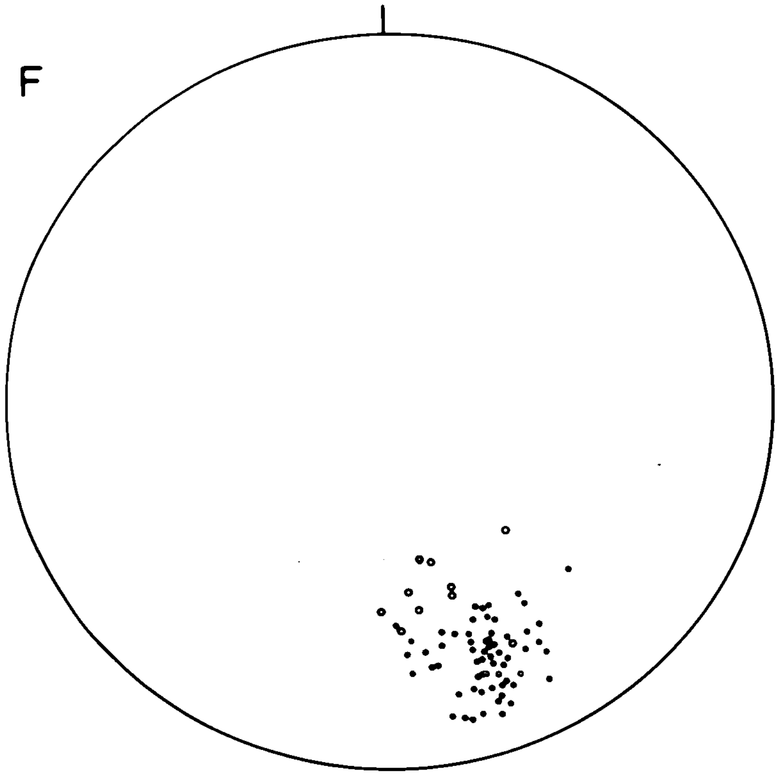




Above Fig. 34 78 poles to bedding (crosses sub-area I points sub-area N)

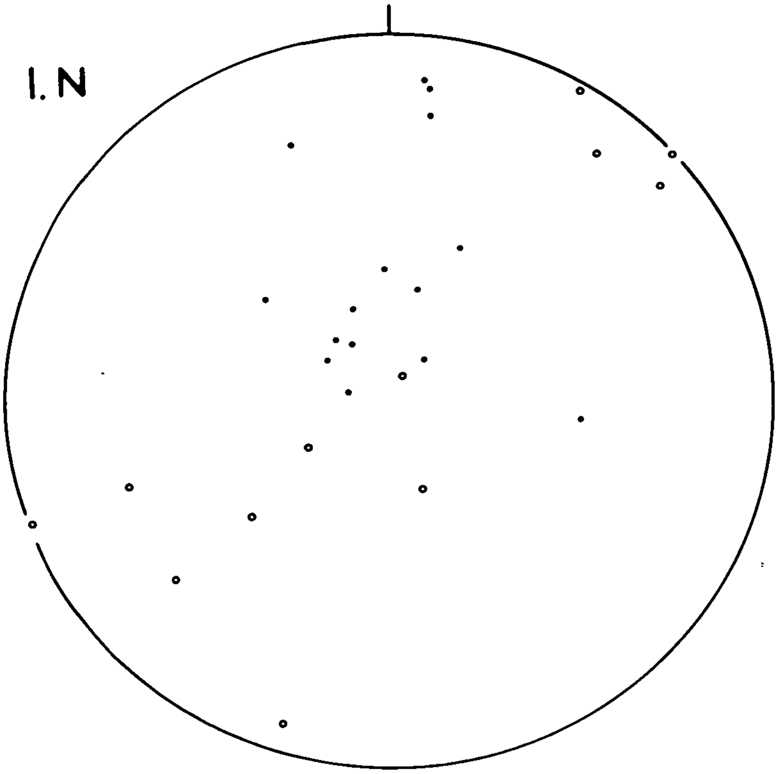
Below Fig. 35 8 bedding intersections

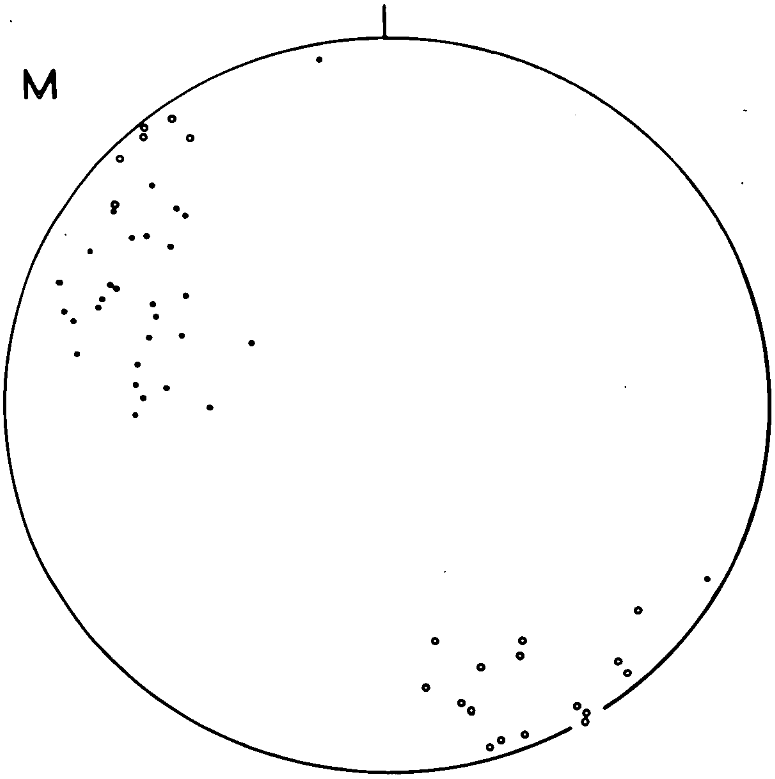




Above Fig. 36 7 bedding intersections

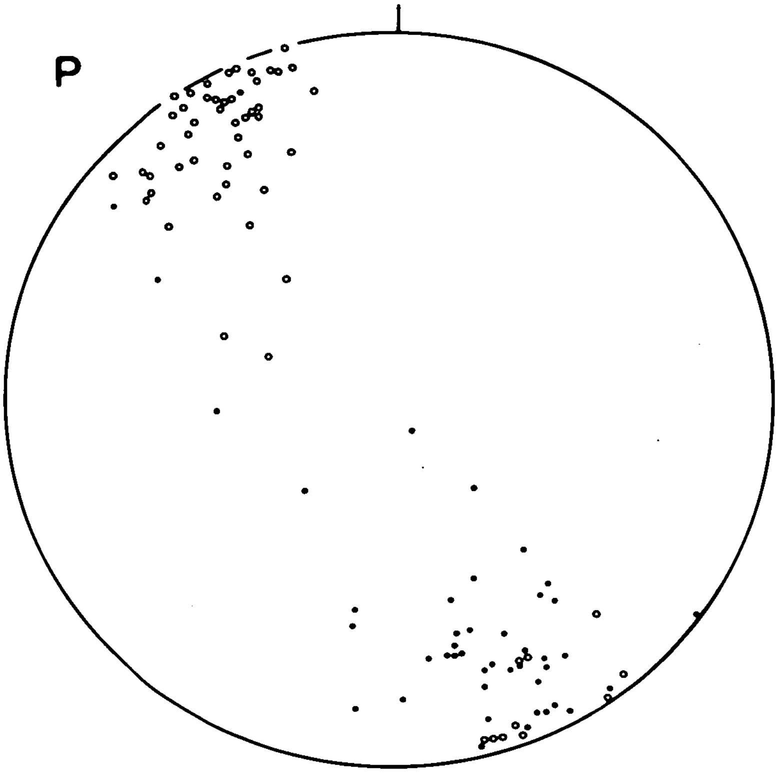
Below Fig. 37 61 poles to axial plane cleavages
(points: circles, bedding)

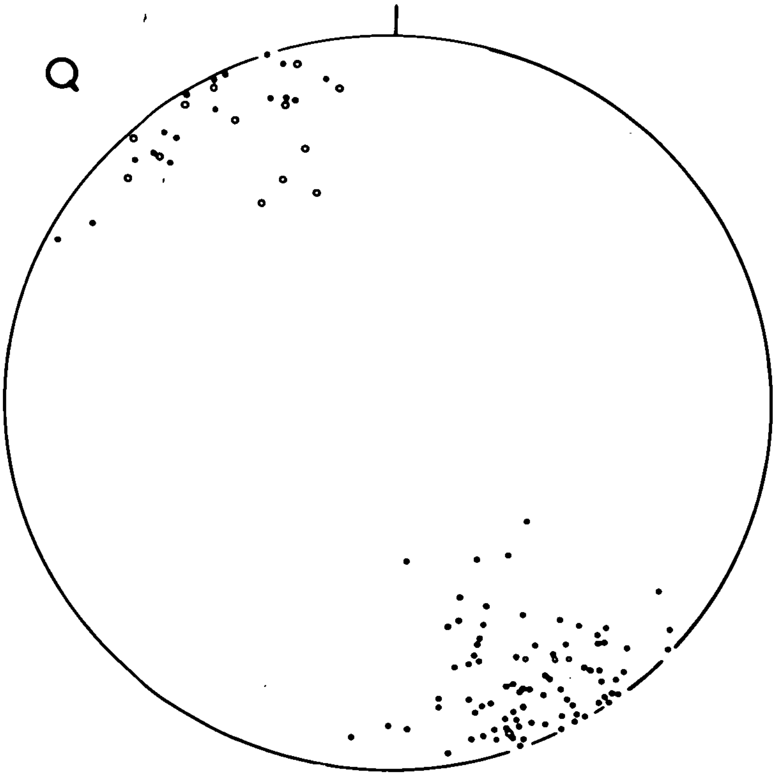




Above Fig. 38 27 bedding intersections (points sub-area N, circles sub-area I)

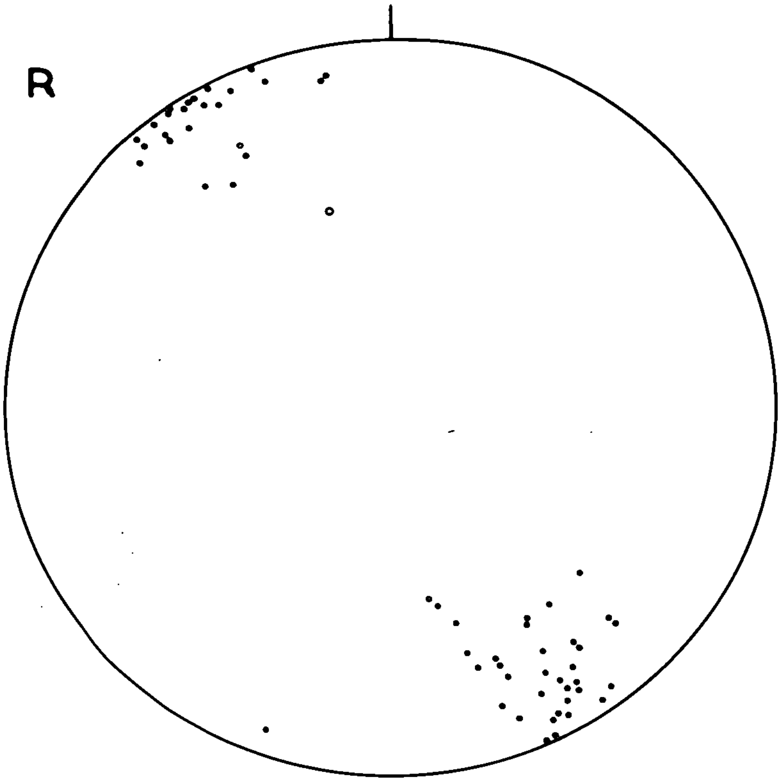
Below Fig. 39 52 poles to bedding (points young south, circles young north)

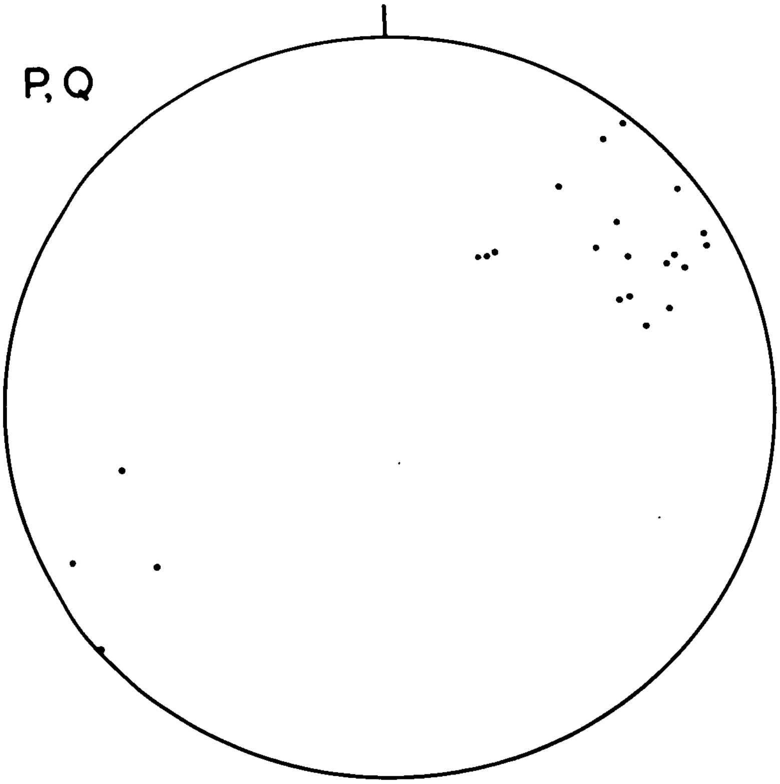




Above Fig. 40 — 100 poles to bedding (points young north, circles young south)

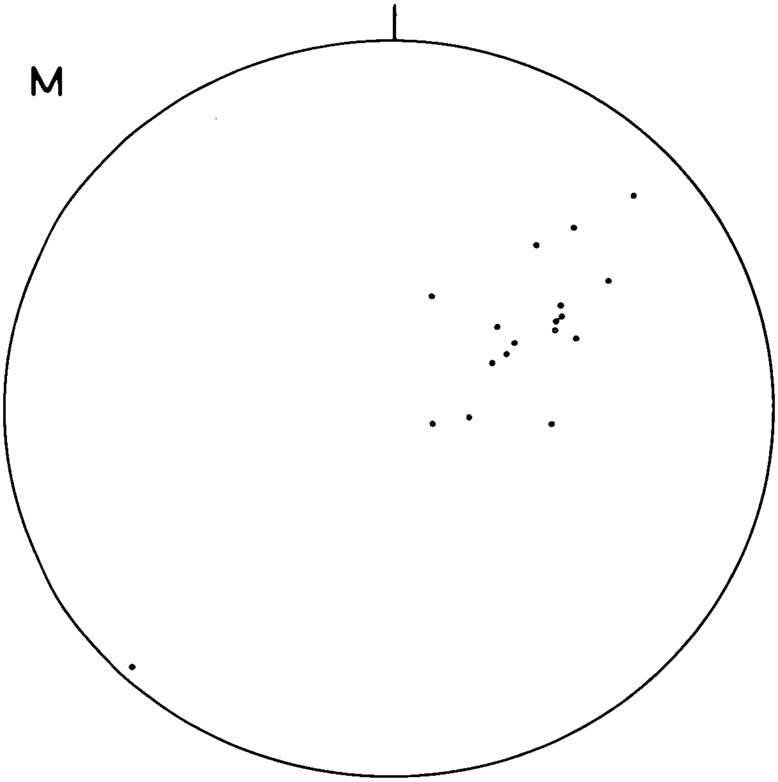
Below Fig. 41 — 115 poles to bedding (symbols as above)

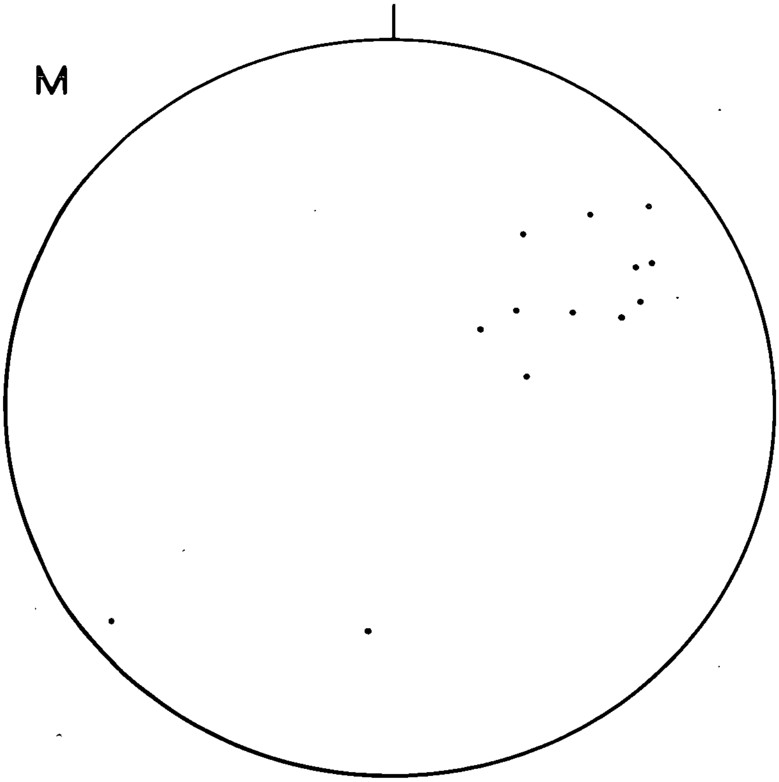




Above Fig. 42	60 poles to bedding (symbols as fig. 40)

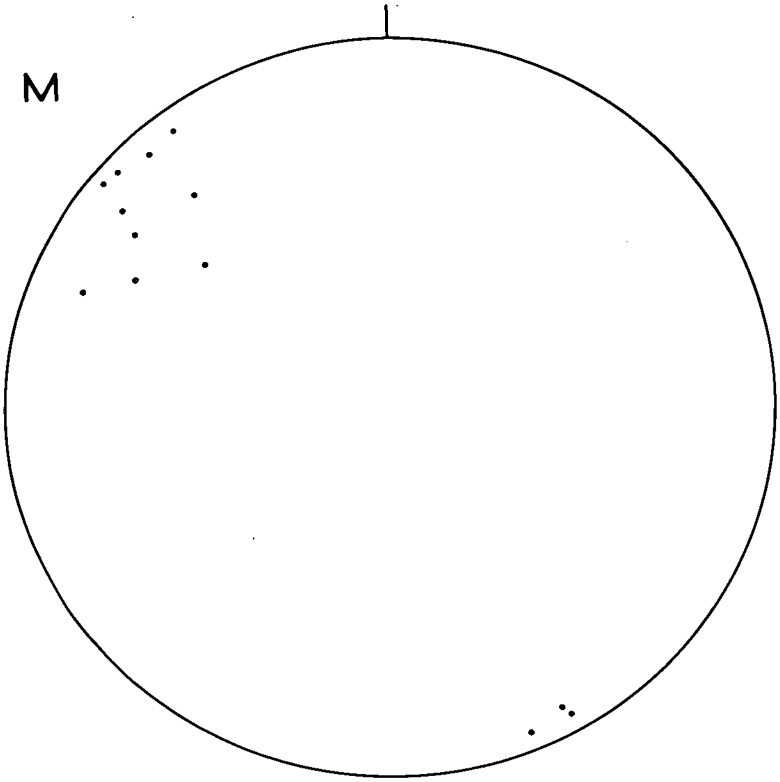
Below Fig. 43	23 bedding intersections

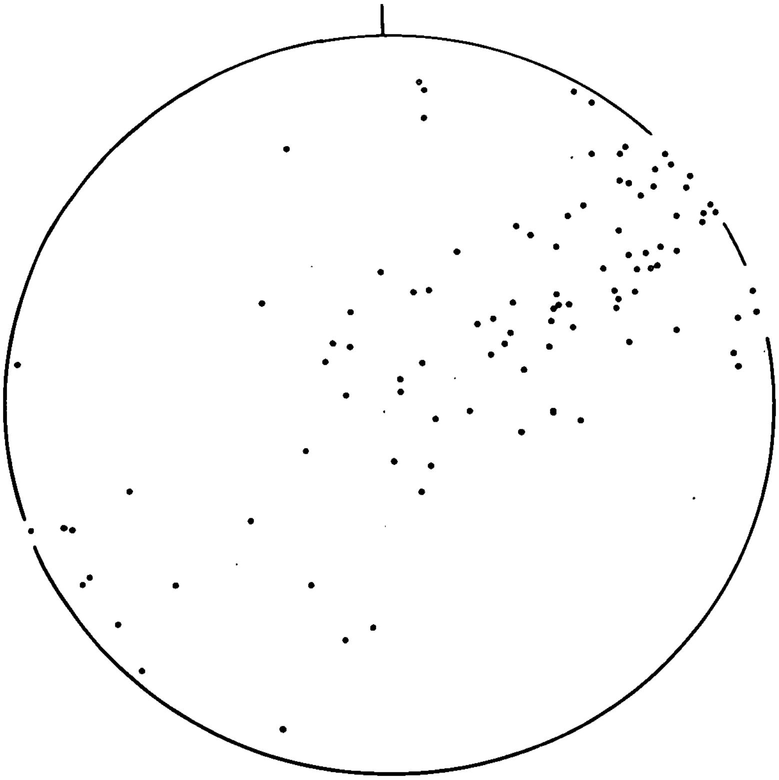




Above Fig. 44   18 bedding intersections

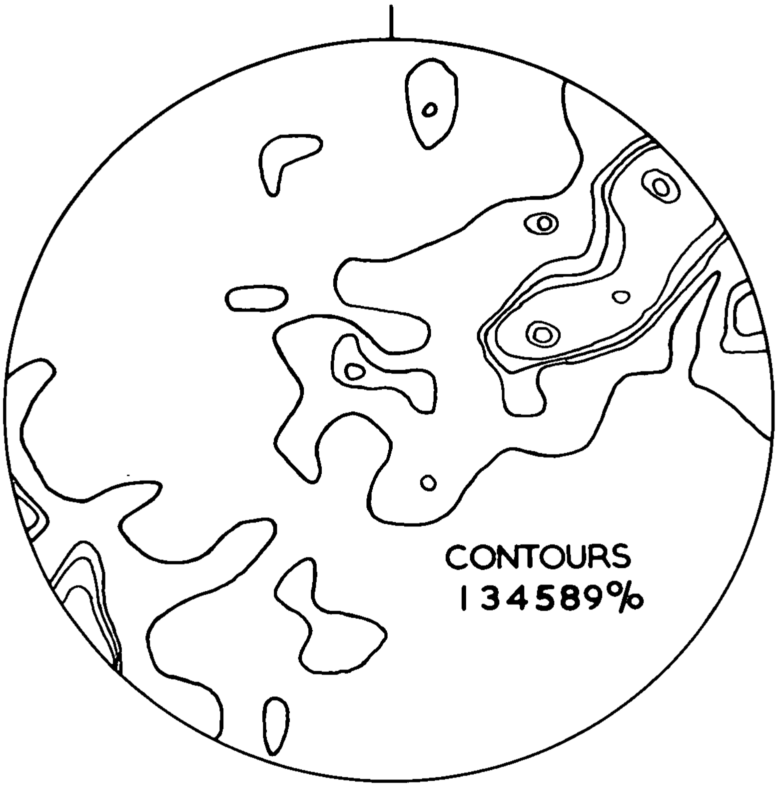
Below Fig. 45   13 Cleavage - Bedding intersections

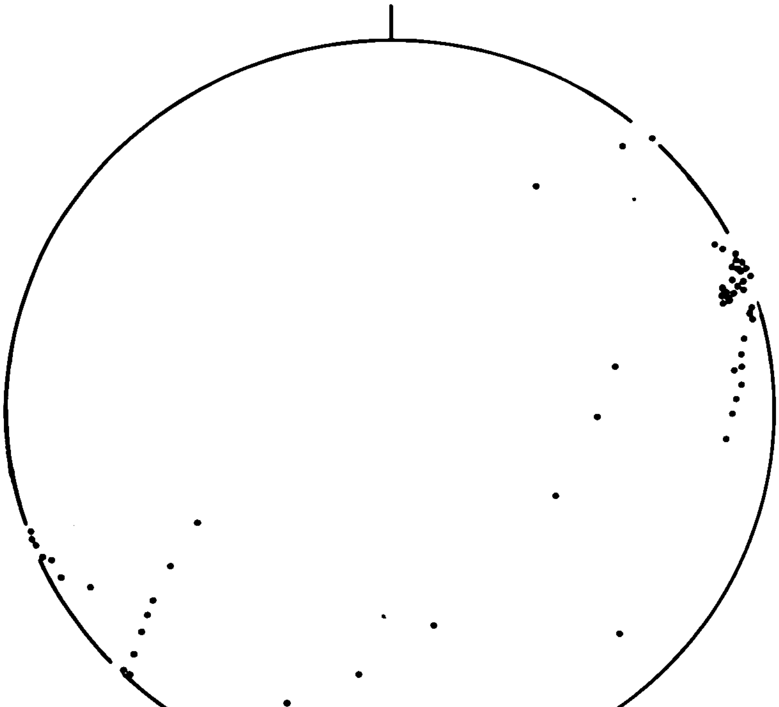




Above Fig. 46 13 poles to axial plane cleavages

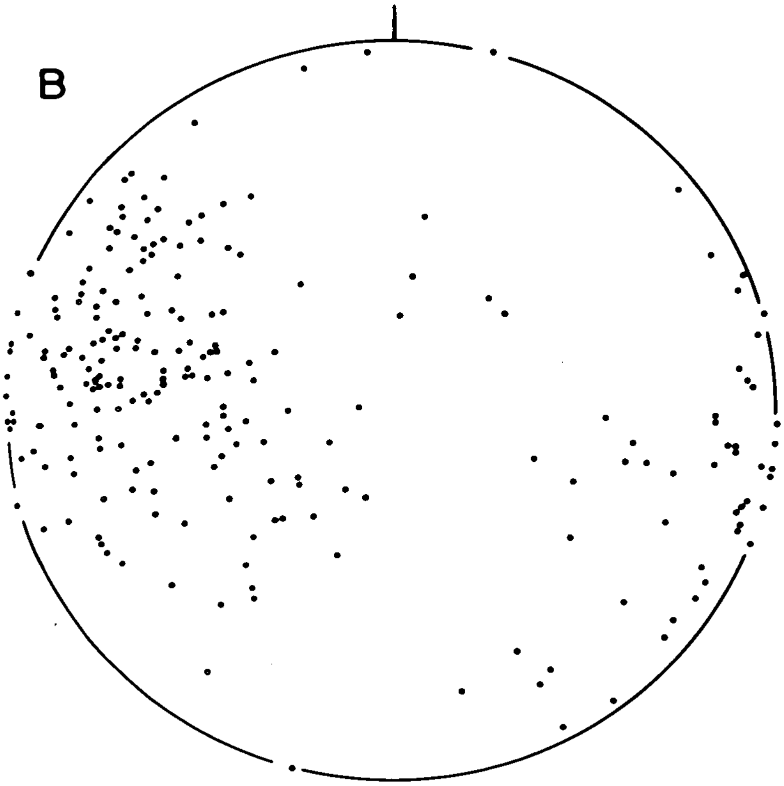
Below Fig. 47 103 fold axis plunges from whole area

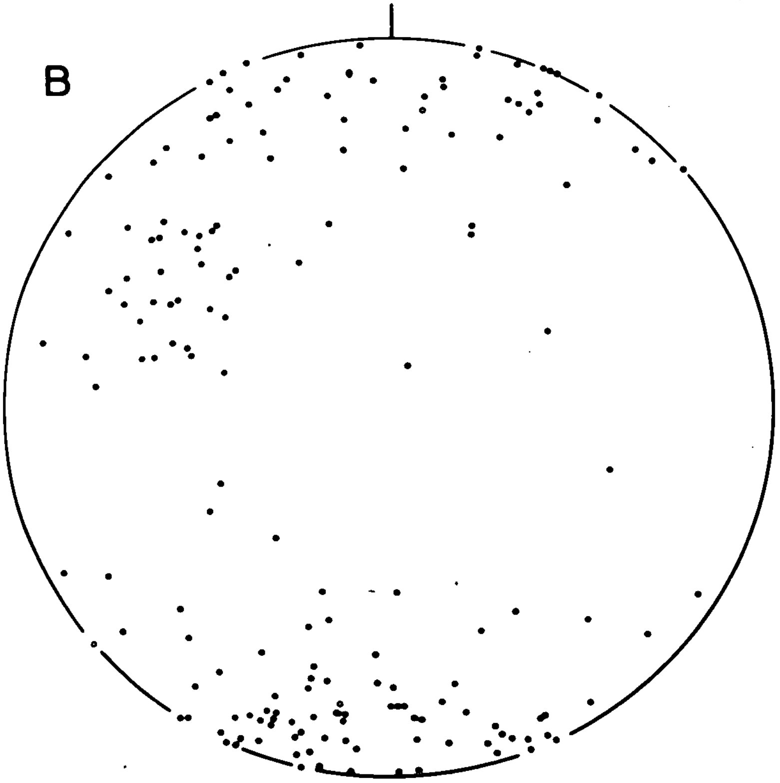




Above Fig. 48 Contour diagram of fig. 47

Below Fig. 49 61 intersections of faults with slickensides dip

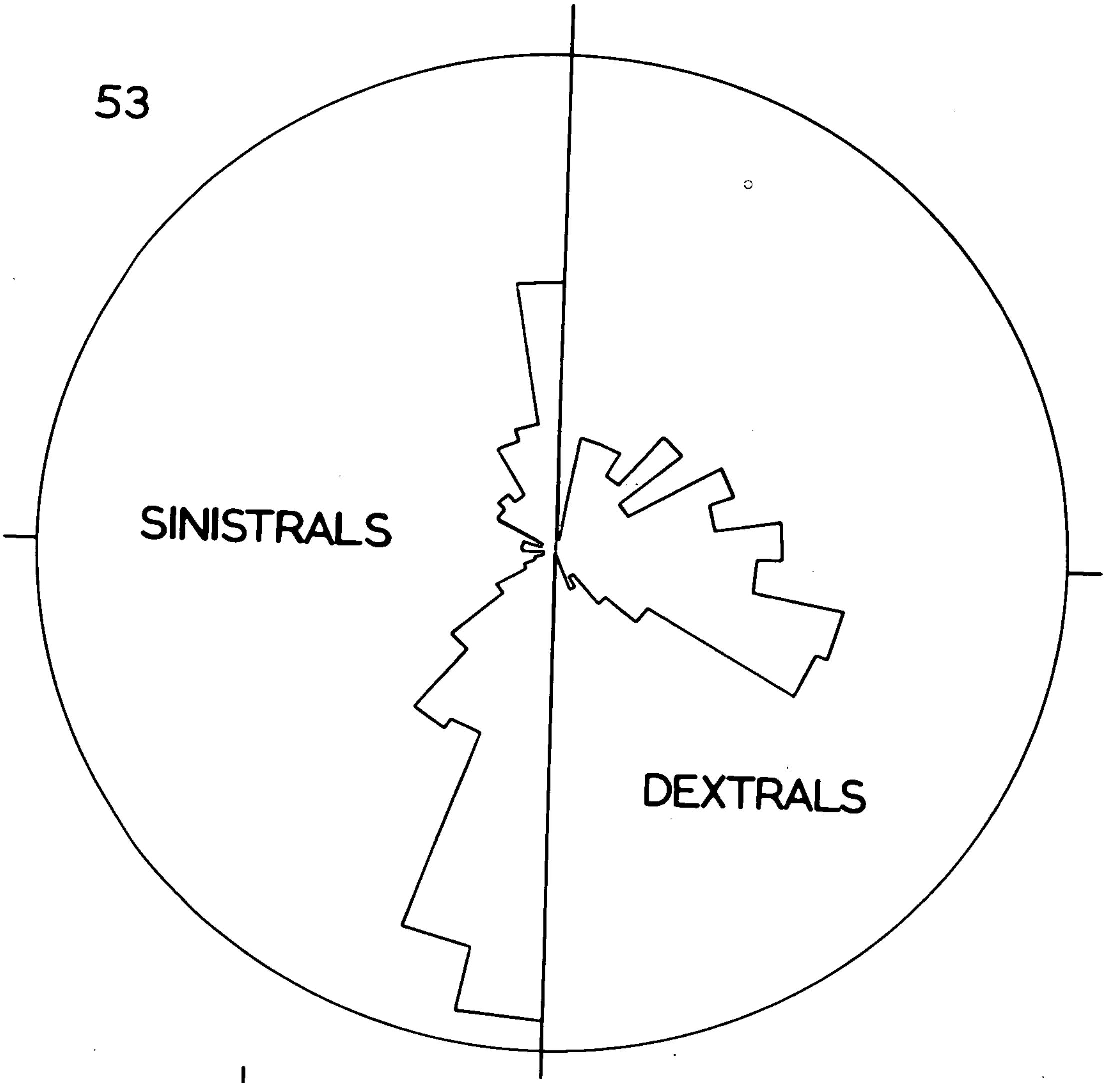


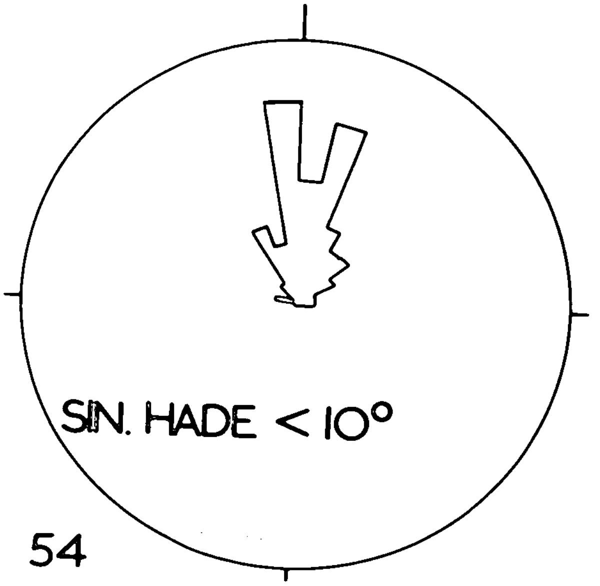


Above Fig. 51 215 poles to sinistral wrench faults

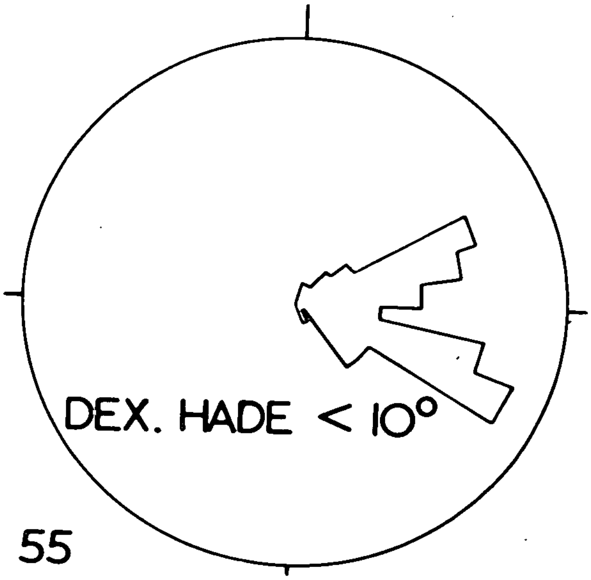
Below Fig. 52 163 poles to dextral wrench faults

53





54

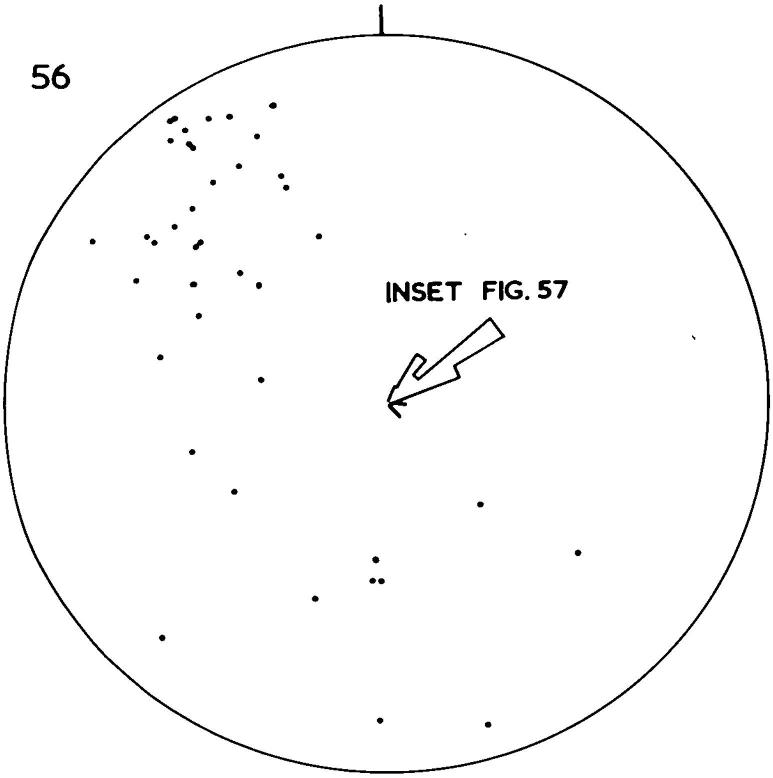


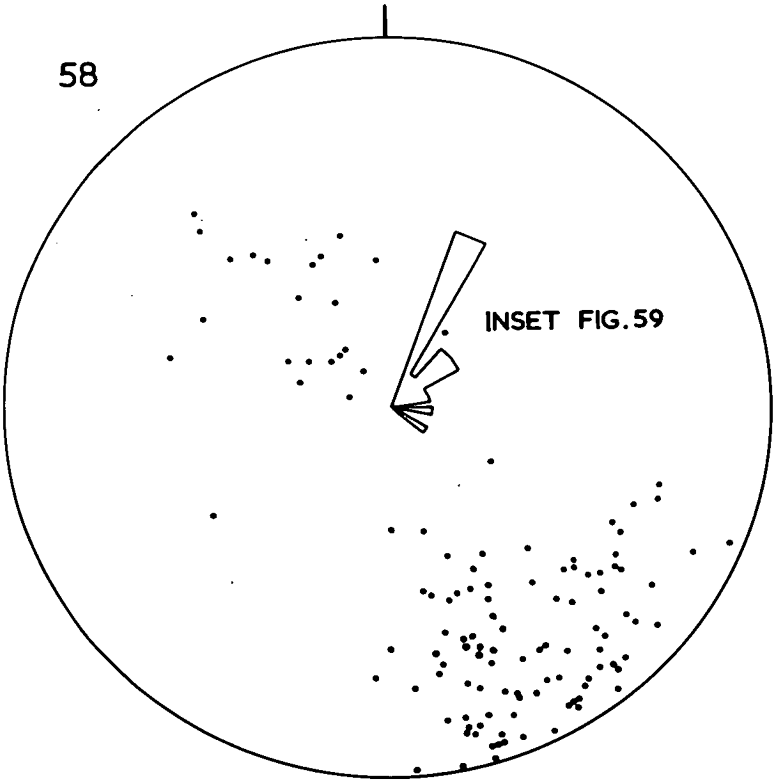
55

Above Fig. 53 Histograms of azimuths of 215 sinistral, 163 dextral wrench faults

Below Fig. 54 Histogram of azimuths of 49 sinistrals with hade less than 10°

Fig. 55 Histogram of 63 dextrals with hade less than 10°





Above Fig. 56 40 poles to normal faults

Fig. 57 (inset) Histogram of azimuths of 21 normals with hade less than 30°

Below Fig. 58 119 Poles to reverse faults

Fig. 59 (inset) Histogram of azimuths of 14 thrusts

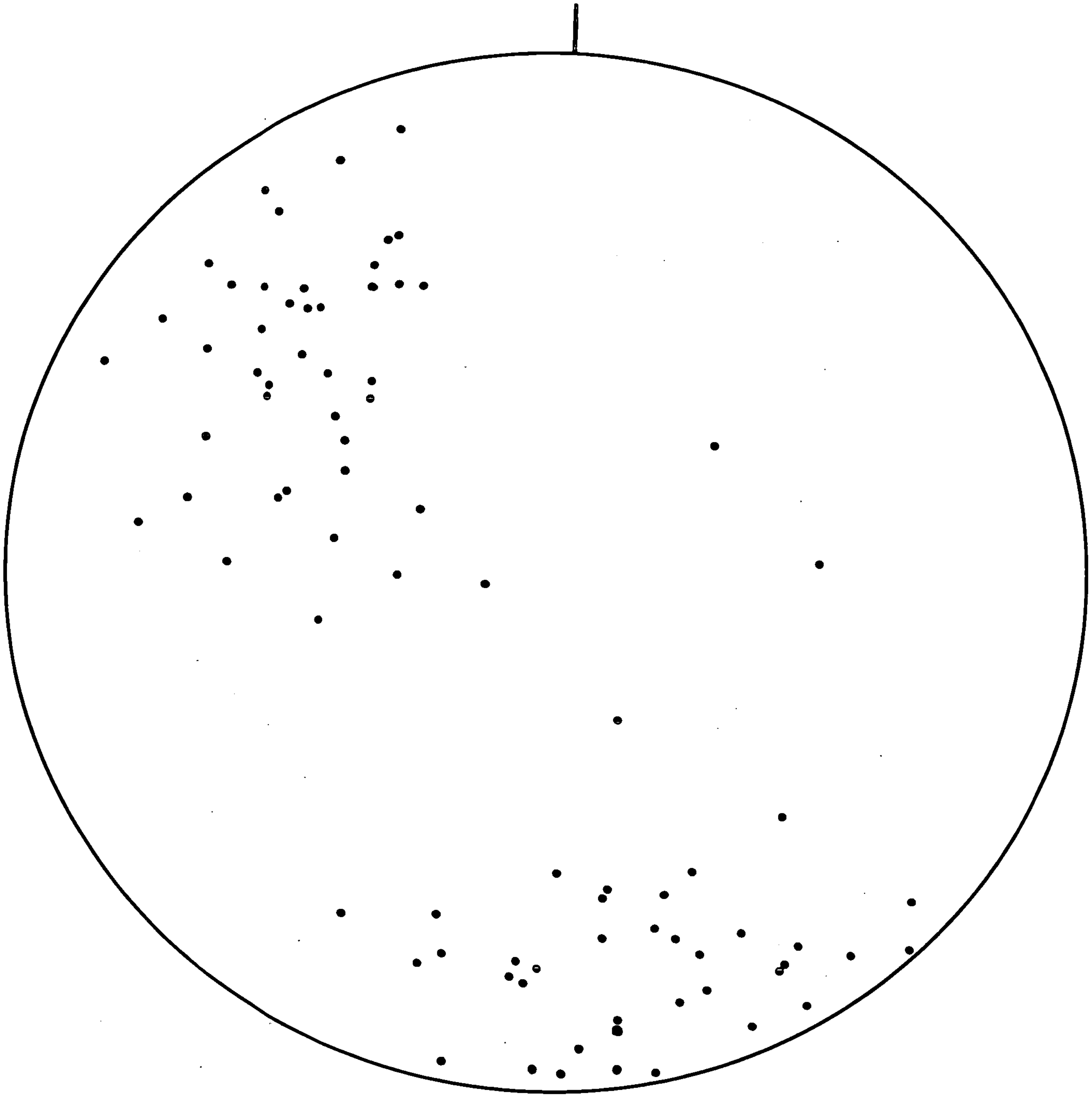


Fig. 60 83 poles to slickensided faults

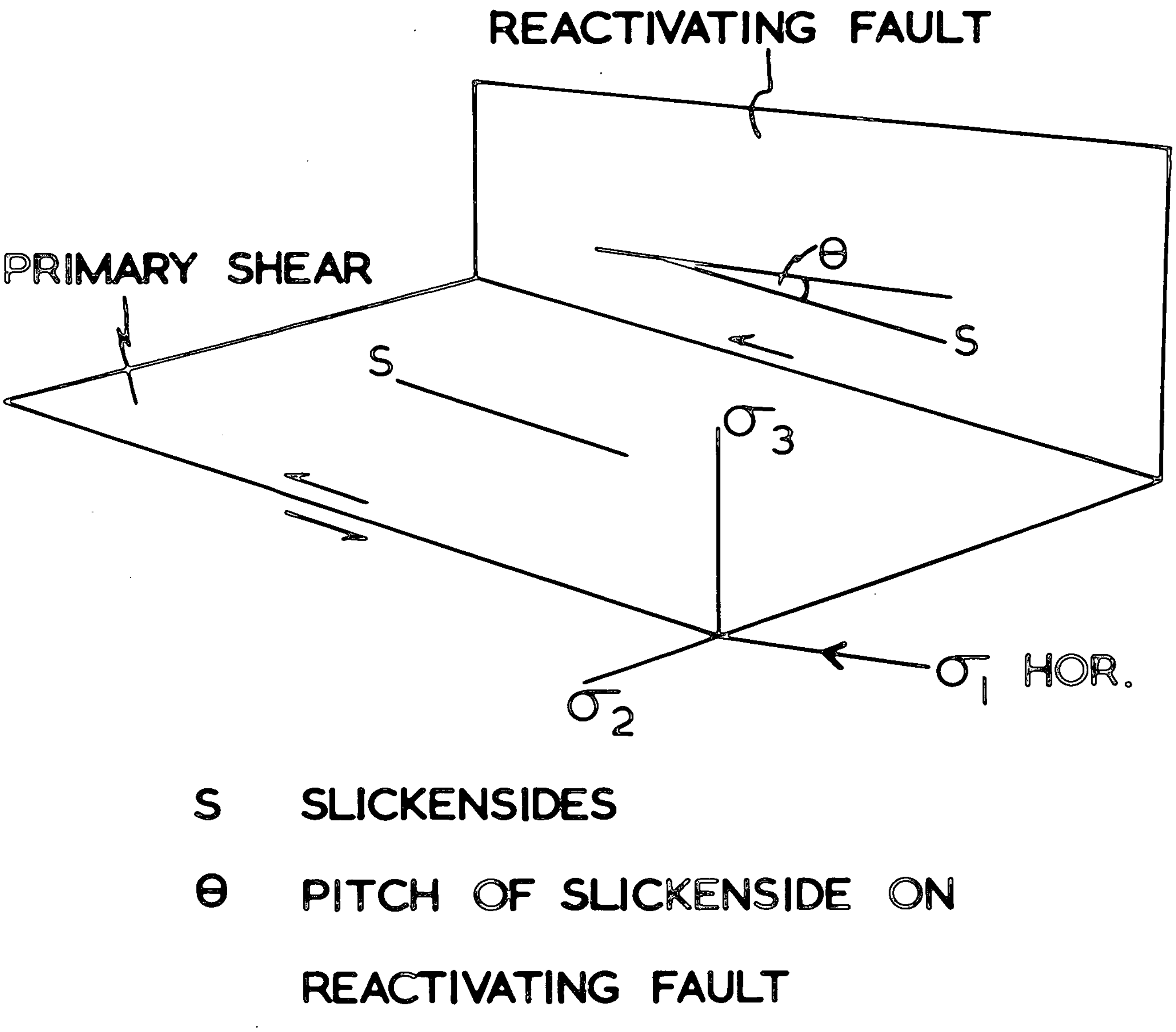


Fig. 61 Production of oblique slickenside by a horizontal maximum principal stress

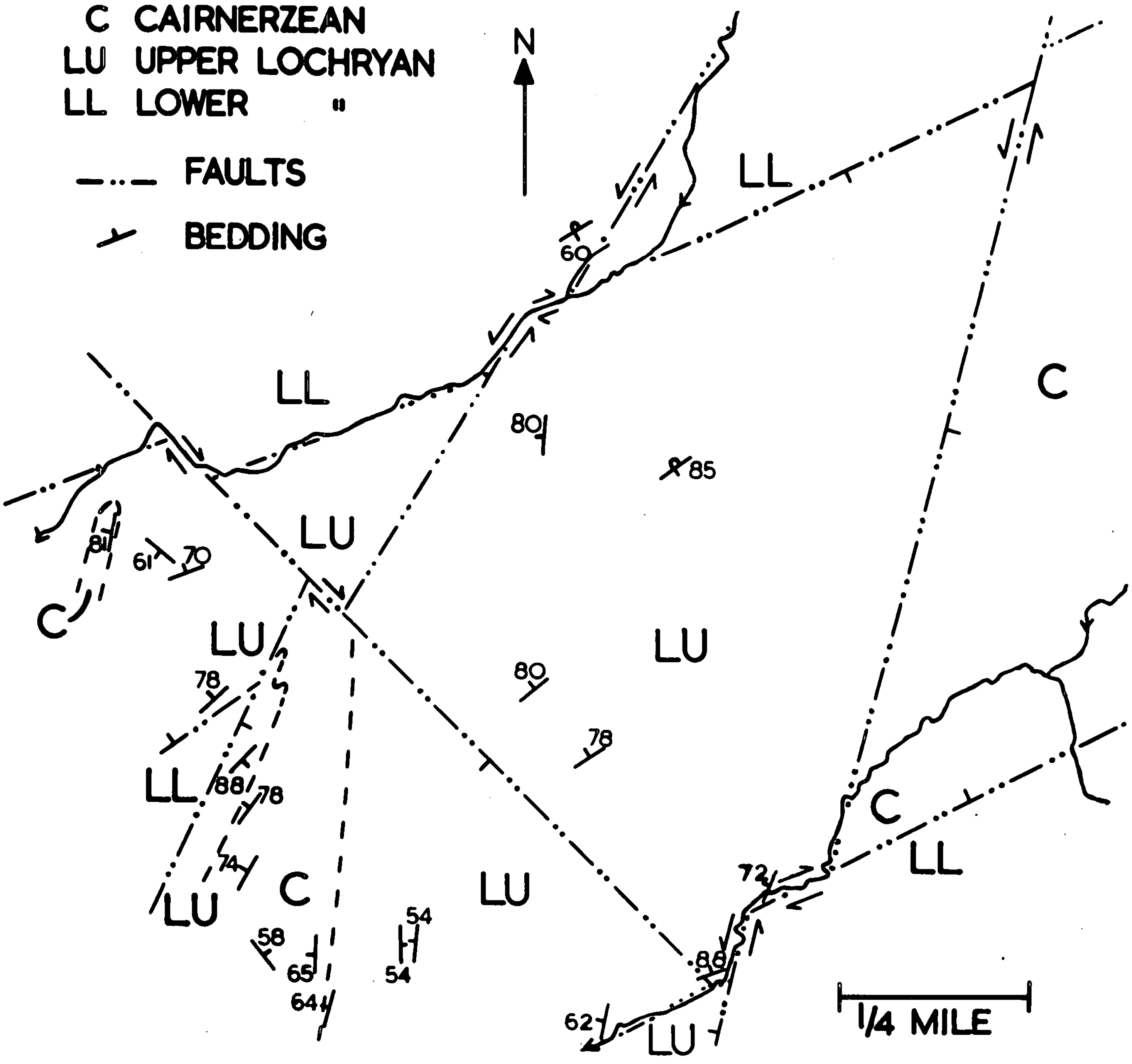


FIG62 CAIRNERZEAN FAULT PATTERN

Chapter 8 Abstract

The results of the present investigation can be summarised under three headings: Stratigraphical, Statistical, and Structural.

Stratigraphical

Eight months field work and detailed examination of nearly 500 specimens have enabled the rocks of the area to be divided into three main formations---the oldest Lochryan Rocks, the youngest Glenwhan Rocks, and the Cairnerzean Rocks between these two---which differ from each other in petrology, quantitative composition, sedimentary features, and environment of sedimentation. The differences between the formations are described and discussed, showing that the Lochryan and Glenwhan Rocks are formations with discrete features while the Cairnerzean Rocks are a passage group between the Lochryan and Glenwhan and therefore have some of the characteristics of both formations.

The provenance of the rocks is discussed within the context of the Scottish Caledonian geosyncline. It is suggested that the main source of sediment was a mixed acid igneous--metamorphic land mass lying to the south of the area and that weathering of contemporaneous volcanic rocks in this land mass also contributed a large volume of detritus to the geosyncline.

Statistical

Petrographic modal analyses were used extensively in the definition of the various formations and sub-divisions of formations. The validity of the application of modal analysis to this use was examined by the analysis of a large number of thin sections and the employment of various statistical tests to the results. The use of Modal Analysis was found to be valid within

the area of a single worker but discrepancies between results were found when more than one operator analysed a control suite of specimens, suggesting that modal analysis results from the areas of different workers are not directly comparable due to operator variance. A technique was devised so that results from different areas could be adjusted and made comparable.

Structural

The major structure of the area was elucidated by combining minor-structural and stratigraphical data, and found to be formed of four anticline--syncline units modified by strike faulting so that most of the beds are nearly vertical and face northwards. In addition the minor-structures show a complex structural history in which the rocks have been affected by at least four periods of folding and/or faulting.

Acknowledgements

The writer wishes to thank Dr. E.K. Walton who supervised the work and gave constructive criticism of the manuscript, Dr. Gilbert Kelling for acting as a control operator in the modal analysis work, Drs. A.J. Gordon and B.R. Rust for the use of their cross-sections of parts of South-West Scotland, Dr. W.E. Fraser for discussions on the structure of folded geosynclinal areas, Dr. Isles Strachan for identifying graptolites, and Miss Jennifer Smith who drafted some of the tables.

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APPENDIX

TABLES INDEX

Tables are bound after chapter of first reference.

FIGURES INDEX

Most figures are bound after chapter of first reference.

ABSTRACT OF THESIS

Name of Candidate William Welsh

Address 23 Kingshill Avenue, Aberdeen

Degree Ph.D (Science) Date March, 1964

Title of Thesis The Ordovician Rocks of North West Wigtownshire

Abstract

The results of the present investigation can be summarised under three headings: Stratigraphical, Statistical, and Structural.

Stratigraphical

Eight months field work and detailed examination of nearly 500 specimens have enabled the rocks of the area to be divided into three main formations---the oldest Lochryan Rocks, the youngest Glenwhan Rocks, and the Cairnerzean Rocks between these two---which differ from each other in petrology, quantitative composition, sedimentary features, and environment of sedimentation. The differences between the formations are described and discussed, showing that the Lochryan and Glenwhan Rocks are formations with discrete features while the Cairnerzean Rocks are a passage group between the Lochryan and Glenwhan and therefore have some of the characteristics of both formations.

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Statistical

Petrographic modal analyses were used extensively in the definition of the various formations and sub-divisions of formations. The validity of the application of modal analysis to this use was examined by the analysis of a large number of thin sections and the employment of various statistical tests to the results. The use of Modal Analysis was found to be valid within the area of a single worker but discrepancies between results were found when more than one operator analysed a control suite of specimens, suggesting that modal

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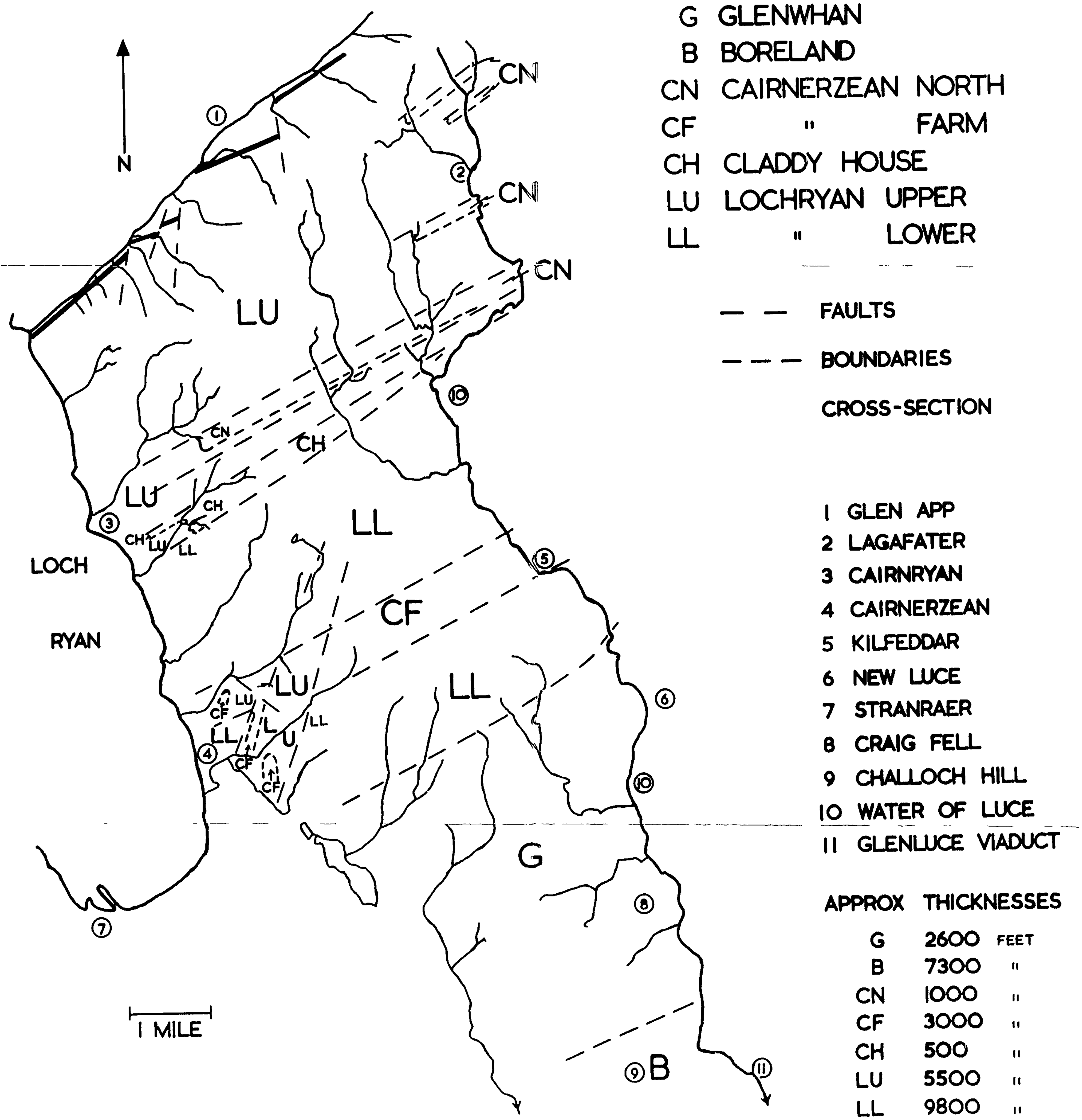


APPROX	THICKNESSES
G	2600 FEET
B	7300 "
CN	1000 "
CF	3000 "
CH	500 "
LU	5500 "
LL	9800 "

FIGURE 2 STRATIGRAPHIC MAP

FIG 63A

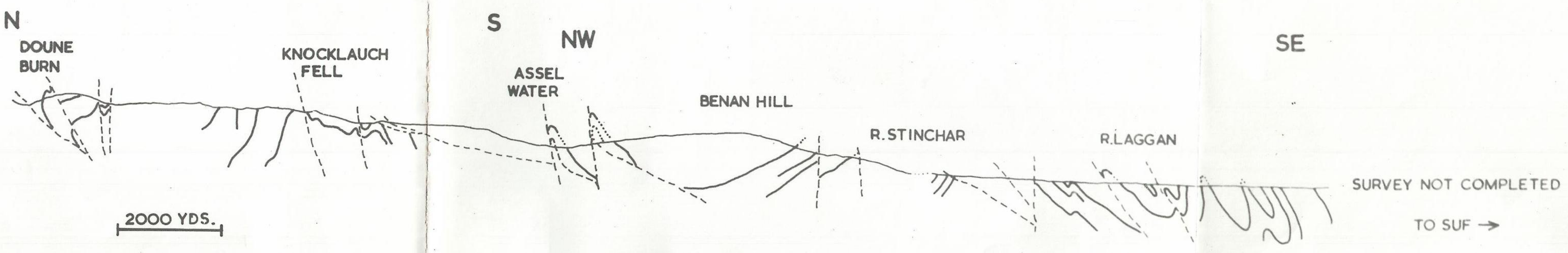


FIG 50
(FAULTS STYLISED)
⸸ "younging"

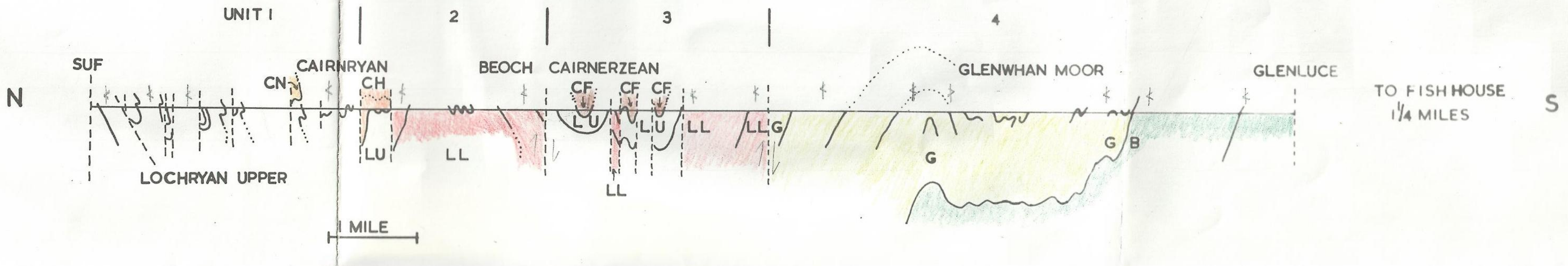


FIG 63B

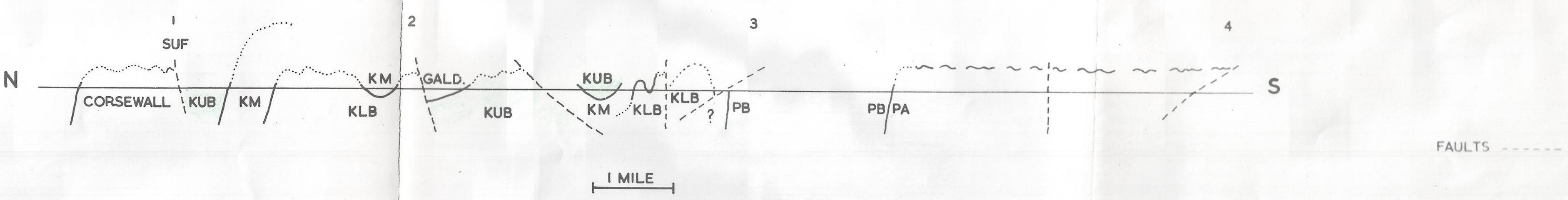


FIG 63C

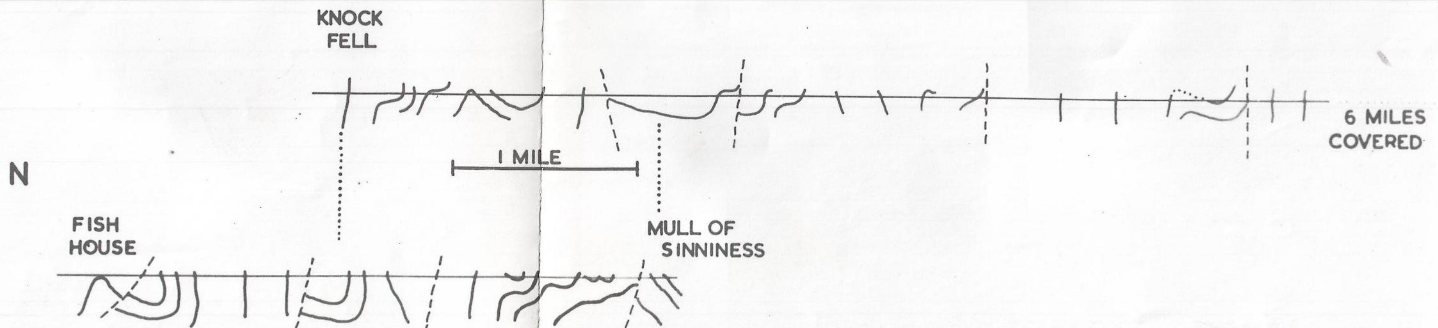


FIG 63D

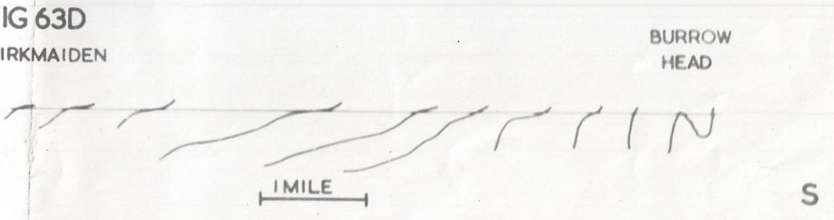
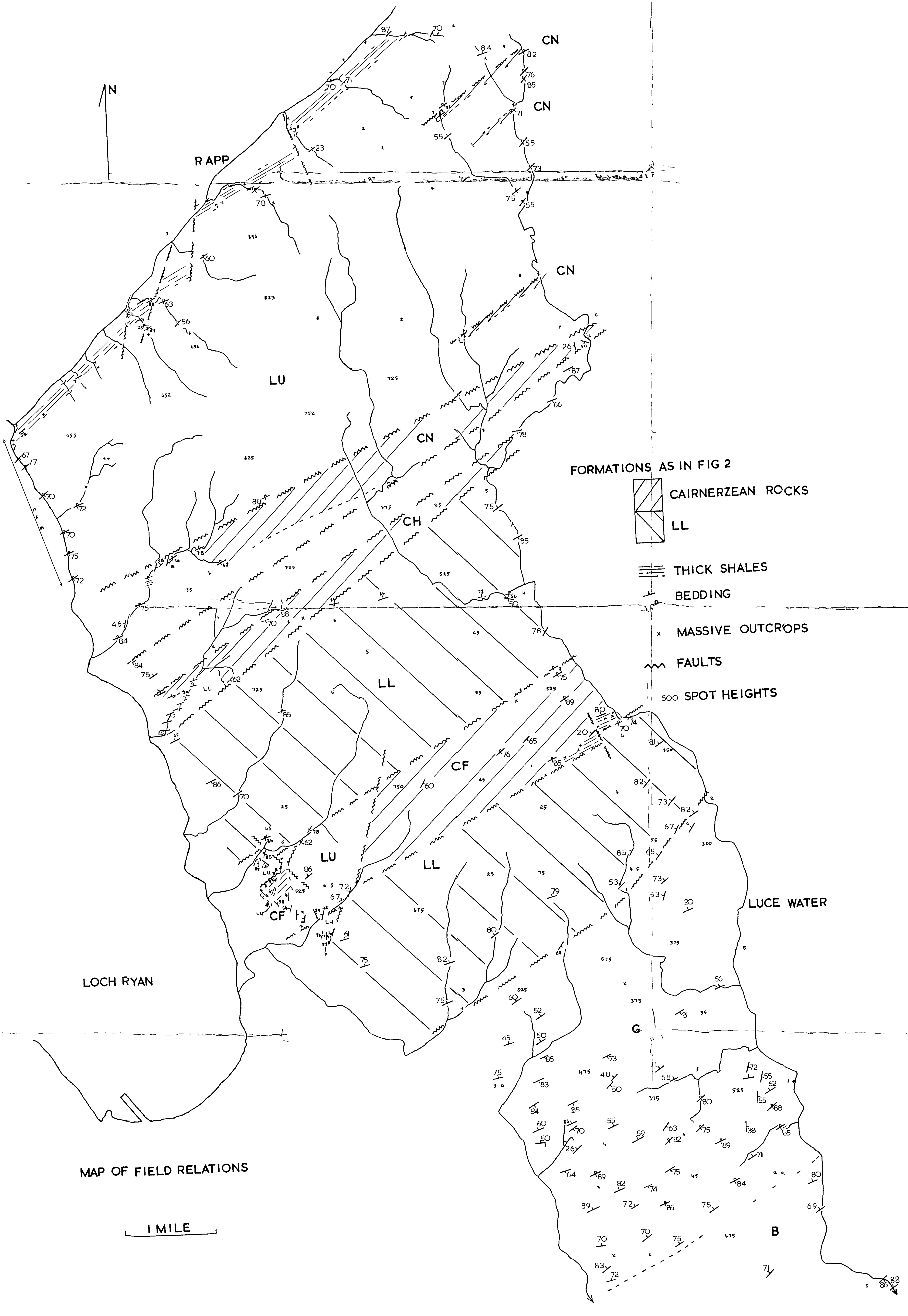


FIG 50 SECTION ACROSS NORTH WEST WIGTOWNSHIRE (LINE OF SECTION ON FIG 2)

FIG 63 " " SOUTH WEST SCOTLAND A GIRVAN WILLIAMS 1959 B RHINNS KELLING 1961 (PARALLELS FIG 50)
C CENTRAL WIGTOWNSHIRE GORDON 1962 D SOUTH WIGTOWNSHIRE RUST 1963



MAP OF FIELD RELATIONS