SEDIMENTARY PETROLOGY, METAMORPHISM AND STRUCTURE OF THE MANX SLATES.

A thesis presented for the degree of Ph.D. in the University of Liverpool
by

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The field work involved in the research was spread over three summers and amounted to about ten months in all. The remainder of the time was chiefly devoted to laboratory work in which over 350 microscope slides were examined in addition to those borrowed from H.M. Geological Survey and Museum.

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Table of Contents.

	Page
Summary	IS - 5S
Introduction	I - 2
The Nature and Origin of the Breccias	3 - 72
Description of the Breccias	3 - I5
The Nature of the Fragments	3 - 4
The Arrangement of the Fragments	4 - 5
Size and Distribution of the Fragments	5 - 6
Origin of the Fragments	6
Matrix	6
Contact Relations	7
Description of Breccia and Undisturbed Beds	7 - I2
Relation of the brecciation to other Structures	I2 - I5
Figures	I6 - 27
Discussion of the Origin of the Breccias	28 - 45
Fault Breccia	28 - 30
Fragmentation by Folding or Cleavage	30 - 38
Fragmentation by Sliding which post-dates Sedimentation	39 - 40
Fragmentation by Slumping or Sliding during Sedimentation	4I- 45
Theoretical Principles which Relate to the Breccias	46 - 53
Definitions	46
Causes of Slides	46 - 5I
i)Passing of the angle of instability	46 - 47
ii)Overload	48
iii)Thixotropy	49
iv)Earthquakes	50- 5I
Effect of Slides on various types of Strata	52
Type of Strata preferentially affected by Slides	53
Possible Cause of Manx Slides	53
Small-scale Disturbance of Bedding	54 - 69
Extent of Fragmentation	54
The Fragments	54
The Matrix	54
Relation of the Fragments to the Cleavages	55
Description of Specimens	55 - 56
Cause of the Fragmentation	57 - 58
Possible cause for Fragmentation parallel to strike ("b" axis) and dip ("a" axis)	59
Druidale,Upper Sulby River	6I
Possible Cause for the Features seen at Druidale	62 - 63
Lonan Flags - Disturbance of Bedding	64 - 65
Figures	66 - 69
Stratigraphic Position of the Breccias	70
Figure	7I
The Possible use of the Breccias as a Marker Horizon	72

	Page
Stratigraphy	73 - 92
Lithology	73 - 74
Figure	75
Petrography	76 - 79
Distribution of the Rock-types	80 - 82
Order of Succession	83 - 85
Age and Correlation	87 - 90
Figures	9I - 92
Nodules	93 - 94
Cone-in-cone	94 - 95
Figures	96
Folds	97 - I23
The Early Folds	97 - I02
Figures	I03 - I07
Intermediate Folds	I08
Figures	I09 - II0
Overturned Folds	III - II6
Figures	II7 - I23
Cleavages	I24 - I33
Flow-cleavage	I24 - I25
Fracture cleavage	I25 - I27
Shear cleavage	I28 - I30
Steeply inclined Fracture Cleavage	I30 - I32
Figure	I33
Regional Structure	I34 - I37
Figure	I38
Port Cornah Syncline	I39 - I43
Figure	I44
Sky Hill - Gob y Volley - Kirkmichael Syncline	I45 - I5I
Mechanics of Folding	I52 - I56
Succession of Movements	I57 - I59
Faults	I60 - I63
Joints	I64
Lineations	I64 - I65

	Page
Dykes	I66 - I74
Pre-Flow-cleavage Dykes	I66 - I67
Post Flow-cleavage, Pre-Fracture cleavage, basic Dykes	I67 - I68
Post cleavage Basic Dykes	I68
Microgranite Dykes	I69
Lamprophyres	I70 - I7I
Sequence of Magmatic Episodes	I7I - I72
Correlation with Dykes Elsewhere	I72 - I73
Order of Intrusion of Dykes	I73
Figure	I74
Economic Deposits	I75 - I80
Description and Distribution of Ores	I75
Effect of Country Rock on Lode	I76
Age of Mineralisation	I76 - I77
Nature of the Vein-filled Fractures	I78 - I80
Metamorphism and Metasomatism	I8I - 2I9
Description of Chief Minerals	I82 - I88
Chemistry of Garnets	I85 - I86
Characteristics of Facies	I89 - I98
i) Greenschist Facies	I89 - I92
ii) Albite-Epidote Amphibolite Facies	I93 - I94
iii) Amphibolite Facies	I94 - I98
Relation to Movements	I99 - 20I
Figures	202 - 206
Hydrothermal Effects	207
Cause for patchy distribution of Spessartite-Almandine	207 - 208
Boron Metasomatism	208 - 209
Quartz Veins	2I0 - 2II
Causes of Metamorphism	2II - 2I6
a) Regional	2II - 2I3
b) Localised High-grade Metamorphism	2I4 - 2I6
Summary of Evidence in Favour of the Postulate that a Buried Granite underlies the Axial Belt	2I7 - 2I9
Summary of Events in the Geological History of the Manx Slates	220
Maps - I, 2, "Metamorphism", "Structures"	see folio
Diagrams I - 9	see folio

Summary.

Earlier work on the Manx Slates is reviewed and the chief discoveries are enumerated.

The Manx breccia is described;significant features are:-

I.All fragments can be matched petrologically in the Manx Slates.

2.The fragments rarely retain their original shapes.

3.The fragments are generally small (4-5 cm in longest diameter for the larger examples) but the largest recorded reaches I4ft by 8ft by 6ft.

4.There are fragments which are themselves composed of fragments.

5.Unbrecciated banded sediments are interbedded in the breccia.

6.Contacts between the breccia and normal sediments are normal and conformable.

7.Passages occur along the strike from brecciated to non-brecciated rock.

8.The fragmentation pre-dates the cleavages,metamorphism,and intrusions.

Lamplugh's hypothesis that the breccia resulted from tectonic shearing and crushing is critically examined;it fails to explain certain facts and is not accepted.Alternatives are reviewed and it is concluded that the best explanation is based on sub-aqueous sliding during sedimentation.Various theoretical considerations which may have had a bearing on the conditions at the time of sliding are discussed.

The chief lithological types of the Manx Slates Series are described. Their order of succession in the northern part of the Isle of Man, based on available way-up evidence, is deduced. This is:

Cronk Sumark Slates

Sulby Flags

Breccia

Barrule Slates

Banded Beds

Agneash Grits

Lonan Flags

The significance and position of fossils which Bolton claimed to have discovered in the Manx Slates are reviewed and it is concluded that the Dictyonema probably came from the Isle of Man. The way-up evidence indicates that the slate at the alleged locality (Cronk Sumark) is the youngest division of the series so that other divisions are older than Tremadoc.

Nodules and cone-in-cone structure are briefly described.

Structures including folds, cleavages, faults, joints, and lineations are described. The folds are of different ages. The earliest set are sharp crested with axial-plane flow-cleavage. The short limb of the folds is directed towards the central axis of the island (structural axis) and the axial planes are inclined to north-west or south-east on the north-west or south-east side of the structural axis.This is taken to indicate overthrust towards the central axis from both north-west and south-east. Somewhat later movements produced near-upright folds with an axial-plane fracture cleavage.This has been recognised at only a few localities.The latest important folding produced overturned folds which suggest overthrust directed away from the structural axis.These are related to the dominant fracture cleavage.Thus there are at least three cleavages.The earliest is a flow-cleavage which appears to have the form of an inverted fan and dips at about 50 degrees to north-west on the north-west side of the island and to south-east at a similar amount on the opposite,or south-east side of the island.It is near vertical in the axial region.There is a steeply dipping but patchily distributed fracture cleavage and a shallow-dipping fracture cleavage which is anticlinal in form and inclined at about 30 degrees on the flanks of the island but which has low dips in the axial region.

The evidence suggests overthrust towards the axial region with compression from south-east and north-west during the earliest movements and suggests vertically directed forces during the latest folding in which overthrust was away from the structural axis.

The predominant north-westerly dips on the north-west side of the island are replaced by south-easterly dips on the south-east side of the island.The structural axis is anticlinorial in form.

A syncline is described which extends for a total distance of 8 miles along the northern limit of rock exposures of the Manx Slates. Its position relative to the pre-glacial coast is similar to the east coast syncline described by Clifton Ward and Lamplugh.

It is suggested that inverted strata on the east coast possibly form the upper limb of an overturned syncline the lower limb of which outcrops to the west. This structure appears to be related to the fracture cleavage.

The main fault systems are considered and faulting is suggested as a possible cause for certain apparently anomalous structural relationships.

Lineations trend in two main directions north-west - south-east and north-east - south-west. The "b" axis of the folds follows an arcuate pattern trending east-north-east in the north-east of the island and swinging round to north-north-east in the centre. "ac" joints are dominant.

The sequence of magmatic episodes is related to movements. The order of intrusion is compared with that deduced elsewhere as characteristic of geosynclinal regions.

Mineralisation occurs in north-south, east-west lodes. Both north-south and east-west fractures hade in complementary directions. In the light of theories of faulting it is concluded that Lamplugh's contention, that the fractures are normal faults, is supported. The north-south and east-west trend of the faults is taken to indicate a

Hercynian age for the mineralisation but the north-east - south-west course of the belt along the structural axis is regarded as evidence for a Caledonian control of the distribution of the minerals.

The chief metamorphic minerals are described and in addition to those reported by Lamplugh, cordierite (at scattered localities along the structural axis) and staurolite (at Glion Darragh, Archallagan) are found to occur. The distribution of metamorphic minerals recorded by Lamplugh is confirmed. The age relation of the new minerals to the movements is deduced from microscopic evidence. This is: early folding and development of biotite; relaxation of stress and development of cordierite; shearing and recrystallisation of biotite along planes of fracture cleavage; high grade metamorphism at Archallagan which outlasted the fracture cleavage producing movements.

It is concluded that the postulate of a buried granite beneath the axial belt most readily accounts for the distribution of the metamorphism.

Introduction.

The purpose of the present work was to re-examine the stratigraphy, structure,and metamorphism of the Manx Slates and to review the interpretation of the so-called "crush conglomerate".

The most comprehensive account of Manx geology is contained in the Survey Memoir "The Geology of the Isle of Man" by G.W.Lamplugh published in I903.This contains complete references to previous work.

Lamplugh accurately described the distribution and lithology of the sub-divisions of the series which comprise the Manx Slates and concluded that they form a normal stratigraphic succession for which the names

Barrule Slates
"Crush conglomerate"
Agneash Grits
Lonan flags and Niarbyl flags

were proposed.Earlier workers had regarded the structure as a simple anticline but Lamplugh recognised that this anticlinal arrangement referred to the disposition of the fracture cleavage,not to bedding.He realised that there had been distinct periods of movement in which more than one cleavage had developed and suggested that the true structure was a synclinorium.

Shortly after the publication of the Survey Memoir,J.F.Blake [I] suggested that the "Agneash Grits,and Snaefell and Barrule Slates were laid down in regular order" and that these then formed a nucleus by settling "down along sub-radiate faulted blocks.....round (and partly over) which the long series of Sulby and Lonan Flags accumulated,without their stratification being governed by the strata buried beneath them".In the discussion following Blake's

I.Blake,J.F. "The Order of Succession of the Manx Slates,etc."Q.J.G.S. I905 p368.

paper,Lamplugh maintained that there was "no acceptable evidence" for the "great unconformity" postulated between the Lonan Flags and remainder of the Manx Slates Series.

The breccias in the Manx Slates were first described by Henslow in 1820 but it was not until 1895 that a discussion of their origin and distribution was seriously attempted.They were described as "crush conglomerates" and attributed to tectonic crushing during folding (Lamplugh and Watts,1895).This paper forms the basis for the account given in the Survey Memoir.

Lamplugh accurately described the distribution of the main metamorphic minerals.Reference was made to the intensification of recrystallisation along the central zone (structural axis) of the island which reaches its maximum at Archallagan to the north of the Foxdale granite.Tourmaline was found to be concentrated in certain regions (e.g.Whallag and Reash) and patches of garnetiferous slate were discovered on Snaefell.Garnets were also found in calcareous nodules on the coast south of Ramsey.

The Nature and Origin of the Breccias.

The rocks which have generally been referred to as the crush conglomerates of the Isle of Man consist of lenticular and angular fragments, in a dark greyish matrix.Few of the fragments are rounded and the rocks are therefore properly described as breccias rather than conglomerates.

The Nature of the Fragments.

The fragments are composed of both light and dark material but the light, gritty fragments are numerically preponderant.The finer grained fragments consist of clayey and silty material while the coarser ones are greywackes comparable with the "coarse grits" described by Lamplugh (Memoir I903 p97-99). The largest grains in the coarse fragments are about 6mm by 2mm and many of the grains are about 2mm; sorting is poor and there is much finer grade material.There are small rock fragments in some of the coarse grits:spilitic andesite,chert, and spotted slate occur (slides Y,Z,I48IA).The quartz grains in these greywackes often show granulation and strain.Orthoclase and plagioclase occur in accessory amounts.The plagioclase in one fragment (slide 53I) shows a narrow rim of clear felspar optically continuous with a clouded core.Small detrital grains of green,pleochroic tourmaline,pyrites and leucoxene,tiny zircon,and occasional crystals of rutile and sphene,are the chief accessory minerals.The matrix of the coarse fragments consists of micaceous and cryptocrystalline material.

Silty fragments are common.They consist of grains of quartz (0.25mm) in a matrix of micaceous and cryptocrystalline material.The quartz is generally angular and sometimes there are interlocking aggregates.Grains of orthoclase and plagioclase,generally altered,are an accessory.Other accessory minerals include green pleochroic tourmaline,and tiny grains of leucoxene and magnetite.Limonite is often present as grains or staining.There are sometimes detrital laths of muscovite.The matrix of the silty fragments consists of cryptocrystalline and micaceous material.Sericite is generally more abundant than biotite or chlorite.

Pelitic fragments consist chiefly of micaceous minerals,biotite predominating within the isograd for that mineral,sericite and chlorite outside it (see metamorphism and map).Fragments of dark slate occur which are opaque under the microscope.In some fragments bedding is well seen, often at an angle to the elongation of the fragment and without relation to any other linear structure in the rock.

As recorded by Lamplugh (Memoir p62) there are in the breccia fragments of breccia which differ in tone and texture from the mass of the breccia.These were noted in Sulby Glen but are especially well shown on the wave-washed rock surfaces to the north of Peel.One from the floor of a sea-cave there measures 30cm by 22cm and is composed of randomly oriented fragments which vary in size from about 20mm by 10mm down to the smallest visible to the naked eye.

The Arrangement of the Fragments.

The fragments show a strong preferred orientation (see fig.I).The averages of measurements of long and short axes of fragments on three faces of a polished specimen from Ballure Glen (flow-cleavage taken as "ab" plane) are:parallel to the strike,"bc" section,7.68mm by I.58mm,parallel to the dip,"ac" section,8.3mm by I.9mm,and parallel to the dip surface,"ab" section, 6.4mm by 3.I4mm. The fragments not only flattened in the flow-cleavage but have frequently also been slightly distorted by minute slips along fracture cleavage planes.Some fragments have been sharply folded together with their matrix (slides I496A,II70,44I).This folding occured in the early flow-cleavage producing movements and in the later movements when the fracture cleavage developed (see folding below).The axial plane of a folded fragment in slide I496A lies parallel to the flow cleavage but is crossed obliquely by the fracture cleavage and therefore the fragment was folded during the early flow-cleavage producing movements.Slide II70 shows a sharp fold the axial plane of which is parallel to the fracture cleavage (see fig. 2).When the flow-cleavage has been subsequently folded the fragments have taken on the form of the fold (see fig. 3).The fold shows well-developed axial-plane fracture cleavage; in the centre of the plate the concentration of shear planes in the vicinity of a fragment of grit demonstrates the intense shearing which must have accompanied these movements thereby modifying the original shapes of the fragments.

Size and Distribution of the Fragments.

The fragments are of various sizes.The largest one recorded is "a boulder-like mass of coarsish grit or quartzite" in the right bank of the stream at Narradale to the east of Sulby Glen (Lamplugh, I903 p59).Its dimensions are I4 ft by 8ft by 6ft.Quite coarse grit fragments occur in the breccia to the north of Peel (see fig I7).Some of these are rounded; the largest seen, 60cm by 50cm, was apparently quite isolated from any other fragment comparable either in size or coarseness. A"large piece like Agneash Grit",from this locality was referred to by Blake[I] .Two unusually large

I. Blake,J.F. op cit I905 p37I.

fragments of grit in the breccia at Druidale (see fig 4) lie only four feet from straight and thin-bedded slate into which the breccia rapidly passes, as shown in the diagram (No. 7).Sections were prepared from specimens of these fragments to determine whether they were lithologically the same since,as they are close together and larger than their neighbours,it appeared possible that they had originally been continuous, but the rock in one slide (I52I) is finer grained than the other (I522) and less chloritic, so that it seems probable that they were derived from distinct bands of sediment.Most of the fragments in the breccia are very much smaller than the above;the maximum dimension of the large fragments is usually of the order of 4 - 5cm.

The fragments are evenly distributed but an appearance of grading in their sizes occurs at a contact with normal sediment (see fig I3).

Origin of the Fragments.

Lamplugh correctly states that "the fragments exhibit a great uniformity,and nothing has hitherto been found in them but the grits and slates". He records that the "fragments found in the crush conglomerates could all be matched in the transition series or else in the main grits or slates.Although the importance of looking out for the existence of fragments and other strangers was fully recognised and a number of specimens were collected with this point in view,not a single fragment of any other rock has so far been detected" (Memoir p I04).Similar searches during the present work have met with the same results.

Matrix.

The matrix consists predominantly of dark material.Grains of quartz (0.Imm) are also quite common.They are sometimes angular but where shearing has been strong they are often phacoidal.They are generally strained.

Irregularly distributed laths of muscovite (0.Imm) of detrital origin occur in accessory amounts. The finer grade portions consist of an aggregate of cryptocrystalline material, chlorite, biotite (within the appropriate isograd), and sericite. Cherty material is often present and sometimes there are patches of calcite. Rounded or irregular grains of leucoxene and magnetite (0.03mm) are common. They impart a dusty appearance to the matrix. Fracture cleavage is generally strong and the shear planes are often coated with platy minerals. This cleavage swirls round the fragments and drags the matrix.

Contact Relations.

It is common to find undisturbed sediments associated with the breccias. Visible contacts at both top and bottom of breccias are sharp but apparently unmoved. Planes of fracture cleavage can be traced from breccia into undisturbed beds indicating that the two were in contact when the folding took place. The contacts between breccia and under- and over-lying unbroken beds are similar to those between the breccia and interbedded normal strata.

Description of Breccia and Undisturbed Beds.

The undisturbed beds are often banded. In Sulby Glen argillaceous layers average 5 - 8cm in thickness and alternate with layers of greyish grit, commonly about I5mm in thickness but some coarser bands up to I5cm in thickness also occur. In Sulby Glen the most southerly undisturbed zone is traceable on the slope for about 250 feet before being lost under drift (see map). The thinly bedded nature of the undisturbed strata and abrupt transition to rock in which the bedding has been completely disrupted is shown in diagram I and figure 8. A series of slides from specimens which straddle the contact were prepared (774D,774C, 774,774B,I488). 774 and 774D represent the breccia to the south and north of the undisturbed zone;774B represents a grit band in the undisturbed beds,774C the thinly banded strata,and I488 similar material showing a small fold.In 774C the light bands are of the order of I - 2mm in thickness and the dark bands vary from I - 6mm. The two thin sections from the breccia are typical.The breccia is composed of fragments lithologically similar to the normal interbedded sediments.This indicates that brecciation affected similar beds to those comprising the interbedded unbrecciated sediments.The sediments show no sign of partial disruption.The breccia shows no greater development of fracture or flow cleavage than the normal sediment and the fragments pre-date both cleavages.There are no shear planes which can be related to the fragmentation.The top and bottom contacts between breccia and sediment appear indistinguishable.

The second group of unbrecciated beds in Sulby Glen may be traced for a greater distance up the slope but cannot be followed so far in the opposite direction since the drift rises higher and they are visible for I50 feet only.Across the strike the contact with breccia on both sides is exposed and the thickness of the undisturbed zone is about 8 feet (see diagram 2).As mentioned above bands of coarse grit occur and are well seen in this group of exposures.A further undisturbed zone occurs sandwiched between breccia just below the contact with the wide expanse of current-bedded flags which succeed it to the north (see fig.9,diag.3).From this tract two specimens show the top contact of breccia with normal strata (see figs.I2 & I3).The fragments in I497 are smaller than usual.The largest are about I-I.5 mm in length but at the contact the rock is chiefly composed of silty material in which quartz grains are of the order of 0.08 mm. Figs.IO & II illustrate breccia and undisturbed beds which are adjacent across a contact. In slide 776 (fig.II) the bedded fragment deflects the fracture cleavage which puckers other fragments of a softer more argillaceous nature;the complete freedom from disturbance in strata of thinly bedded type is admirably displayed by 776A (fig.IO) which, as stated is in contact with the breccia shown in 776.

The beds of breccia exposed in Sulby Glen vary in thickness. The most northerly bed is only 80-IOO feet thick but the three beds which outcrop farther south are each about 400-500 feet thick.

In Narradale it is noted by Lamplugh (Memoir p59) that undisturbed slate is interbedded in the breccia.Slide II54 was prepared from a specimen of banded slate taken from near the contact with breccia.This shows thin gritty bands which are generally only I - 2mm thick,but reach 8mm as a maximum, interbedded with wider argillaceous layers of the order of I - 2cm in thickness.The bedding in the slide shows no sign of brecciation. Slide II53 is from typical breccia which occurs just north of the slate illustrated in II54.

Similar exposures occur in the stream to the east of Narradale and in the small glen draining down to Glenduff there are zones of undisturbed strata.The breccia also outcrops on the moorland to the east of this point (see slide 538A).Contacts between breccia and undisturbed beds are exposed at Cronk Sumark (see slides II46,I488A,I488B,I488C).

In Druidale there are transitions both along and across the strike between banded sediments and breccia.In some instances a narrow fragmental band may be traced to a point at which the unbrecciated confining bands suddenly terminate in a mass of breccia.Thin bands of breccia (2 - 3cm thick) can be traced for distances measurable in yards,and often to the limit of the exposures.They maintain a constant position relative to the undisturbed confining beds which in some instances are of thinly banded slate.In many cases the fragments in the breccia differ from the interbedded normal sediments.While in the fragments thin argillaceous layers alternate with wider gritty bands in the normal sediment,the grit bands are thinner than the argillaceous ones.A series of thin sections from specimens of the normal sediment and breccia was prepared.I523 illustrates breccia in contact with the thinly stratified beds of which I524 is representative (see diag.7) and I500,I502, and I503 are samples obtained at short intervals across the contact illustrated in diagram 4.The breccia is comparable to that in other areas such as Sulby Glen but the strata beyond the contact is more disturbed and the bands are continuous for only short distances in both dip and strike direction (see diag. 4).In section the breccia appears typical (slides I523, I500).The undisturbed sediment is illustrated by I502,I503, and I524 in which light bands of I - 3mm, Imm or less, and I - 2mm,are interstratified with dark bands of 2mm to over 3cm, 8 - IOmm, and 3mm and upwards, respectively.

Slide I498 was made from a specimen of the band of fragments set in a light matrix which is illustrated in diagram 5. The breccia appears typical; the elongation of the fragments, the flow-cleavage, and the fracture cleavage are about parallel ("ab" section). The most remarkable feature is the size difference between the fragments in the light band (from a specimen of which the slide was made) and those in the surrounding rock where the fragments are long thin strips. These are separated by only short distances and the rock resembles normal sediment more than breccia (see diag. 5).

Both megascopically and microscopically the breccia exposed at Druidale appears similar to that elsewhere in the Isle of Man and was clearly produced by a similar process. The contact relations and partially brecciated strata make it tolerably certain that conditions were not exactly the same as at Sulby Glen for example, where the undisturbed sediment is more evenly bedded though in sharp contact with rock in which stratification is as completely lacking as in the most thoroughly fragmented beds at Druidale (see below p62).

Slides II7I and II72 were made from samples of breccia and fine grit respectively, on either side of a junction at Glen Mooar and while bedding is not seen in slide II72 the section illustrates the absence of fragmentation.

Undisturbed sediments are interbedded in the breccia on Sky Hill. Sections were made from breccia above and below the undisturbed sediments (493A - fig. I3A, 493C); from breccia exposed on the southeastern part of the hill (490) and from the sediments interbedded in the breccia (493B). Slide 493A' is a fine-grained grit made from a specimen of a lenticular fragment.

The sediment (493B - fig. I4) shows thin,completely undisturbed beds which reach 8mm as a maximum, average 4mm,but are only I.5mm in minimum thickness. The layers are graded and upwards small quartz grains become gradually reduced in numbers until succeeded on top by a layer of micaceous material in which the individual crystals lie parallel to the bedding (see fig. I4); chlorite and muscovite occur and biotite is present as tiny crystals showing a greenish-brown pleochroism.This grading indicates that the beds are right way up.

In "Elfin Glen" there are similar exposures of breccia and interbedded bands of unbroken sediment (see fig. I5 & I6, slides 7I2,7IIB,422,7I4,7I5).

To the north of Peel there are at least two zones of breccia (see fig. I7), the uppermost of which has a matrix of fine black slate while that of the underlying zone is greyish.The contact is a sharp but slightly irregular surface and does not appear to be a thrust.A microscope section from a specimen of this junction displays a thin vein of quartz and micaceous material,and under the microscope it is possible to confirm what was observed in the field,that while this vein is invariably close to the junction it does not always exactly coincide with this.

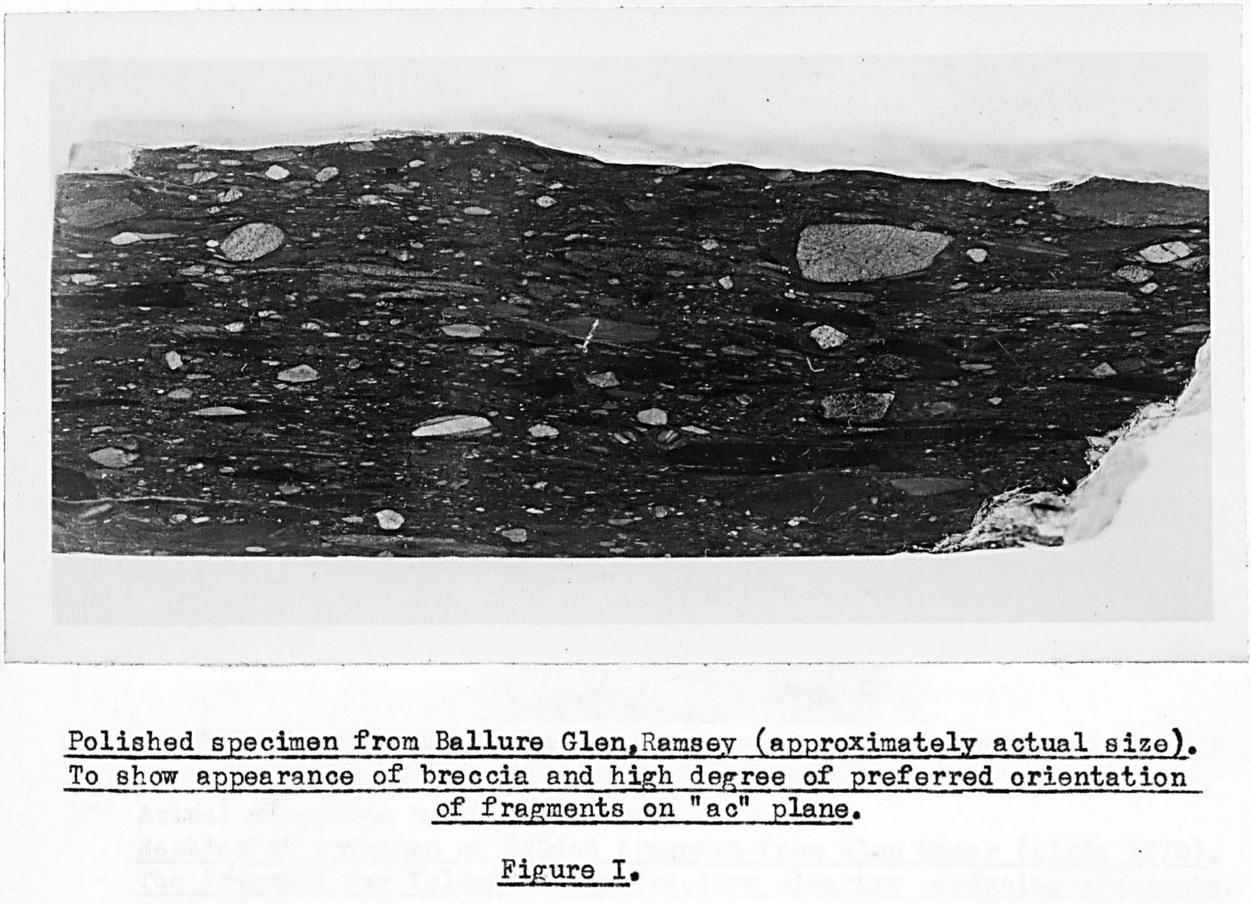
Relation of the Brecciation to other Structures.

The flow-cleavage generally remains parallel in both groundmass and fragments.Most fragments (approximately 80%-85%) are not bedded but when present,bedding does not always coincide with the fragments elongation. The fragments are generally elongated parallel to the flow cleavage.

In slide I486 (Sulby Glen) the fragments are elongated parallel to the cleavages (flow and fracture cleavages are parallel);one fragment is particularly interesting in that it displays thin bedding which crosses its elongation,while the small micas are parallel to those of the groundmass.In this slide the fracture and flow cleavages in the groundmass are parallel but since there is no fracture cleavage in the fragment it can not have modified the original arrangement of the micas contained therein which pass straight from the groundmass into the fragment without regard and obliquely intersect the bedding shown by the fragment.It follows that the flow-cleavage was impressed on the rock after the fragment came to occupy its present position.A similar relationship is shown by one of the fragments in 538A (west of Glentrammon).In regions where recrystallisation has been slight clastic micas appear to have survived since the micas in bedded fragments occasionally retain a parallelism to the bedding within the fragment even when this lies at an oblique angle to those of the groundmass.This feature is illustrated by I488B (Cronk Sumark) which is of typical breccia.Bedding is preserved in one of the fragments seen in the section and tiny crystals of sericite or muscovite extinguish parallel to this bedding and at a low angle to the micas in a neighbouring fine-grained fragment.The groundmass is fine-grained and strain-slip cleavage is strongly developed.The micas commonly remain parallel to the bedding in bedded fragments in the breccia which outcrops on Sky Hill and lie oblique to those of the groundmass (slides 493A,493C, & 490).The fragments have also been displaced by later movements than those in which the flow-cleavage developed so that the micas within the fragments and those of the groundmass are no longer parallel.The micas lie parallel to the bedding in a fragment in slide 7IIB (e.g. the long fragment on the top right of fig.I6) and diverge somewhat from those of the groundmass.The precise cause of this is somewhat difficult to determine but the intense effects produced by the fracture cleavage make it not unlikely that this fragment may have suffered slight displacement during the period of movement in which this structure developed (see below "Cleavages").Commonly, small fragments and groundmass micas flow around the larger fragments and two clear examples are provided by 7IIB (see fig.I6), and 546.In slide 546 the micaceous folia of the groundmass are deflected by a zoned fragment and conform to its lense-like shape but the small micas within its boundaries lie parallel to its elongation.In 7IIB the smaller fragments appear to swirl around the larger as is particularly well shown by those which surround the broken fragment (left centre of fig.I6).This demonstrates that the fragments existed before the development of the flow-cleavage.The earliest metamorphic effects were contemporaneous with these movements and therefore similarly post-date the fragmentation.

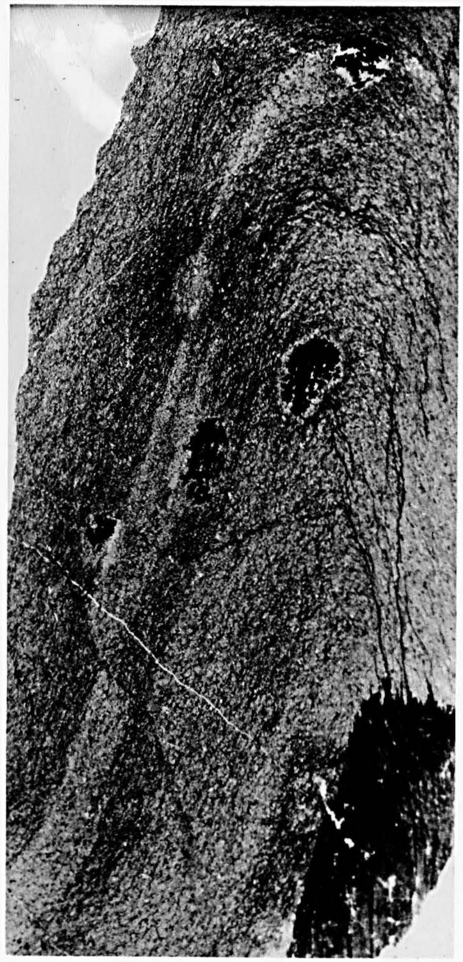
As Lamplugh records the fracture cleavage post-dates the brecciation of the deposit since it is deflected by the hard gritty fragments and displaces those of soft argillaceous material along minute slips.In many cases fracture cleavage is concentrated in argillaceous necks separating fragments of harder material.Watts suggests distortion of this structure, where the matrix has been nipped between adjacent fragments,may indicate the fragments to have undergone late stage movements after their formation.This may well be so but it seems probable that in many cases the concentration is due to shearing having followed the line of least resistance.This feature is seen in slide 7IIB (right side of fig. I6) where fracture cleavage is concentrated between two grit fragments.These are dissimilar,one being coarser-grained than the other,and so cannot formerly have been continuous as a single larger fragment or band.The intense effects produced by the fracture cleavage are also illustrated by the grit fragment near the left centre of the plate which is broken by the fracture cleavage.Narrow quartz veins cut both fragments and groundmass indiscriminately and while they are often broken by the fracture cleavage they never contribute fragments to the breccia (e.g. slides 7I5,44I,442).In 442 a thin quartz vein cuts some fragments but is deflected by others showing that it is later than the brecciation,but it is itself broken by the fracture cleavage.

Dykes intersect the breccia at Kerroomooar,Narradale,stream south of Sky Hill farm,and north of Peel.Though often sheared the dykes have never been brecciated and it is concluded that the intrusions post-date the fragmentation.



Polished specimen from Ballure Glen, Ramsey (approximately actual size). To show appearance of breccia and high degree of preferred orientation of fragments on "ac" plane.

Figure I.



Actual size:35mm by I5mm.
Section of specimen of folded fragment from Glen Mooar (slide II70).
The fragment was folded in the fracture cleavage producing movements.
Most of the section is composed of fine-grained grit but an argillaceous patch occurs at the bottom right of the field of view where fracture cleavage is better developed.

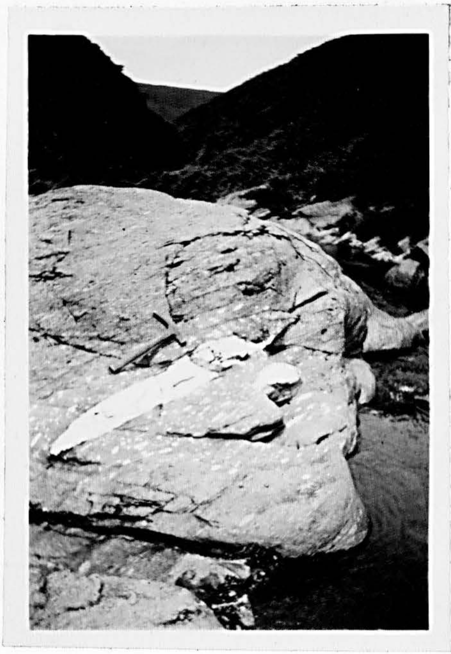
Figure 2.

Actual size: 5.5cm by 3.5cm.
Folded breccia with axial-plane parallel to fracture cleavage ("ac" section).

Figure 3.

Flow cleavage.

West.



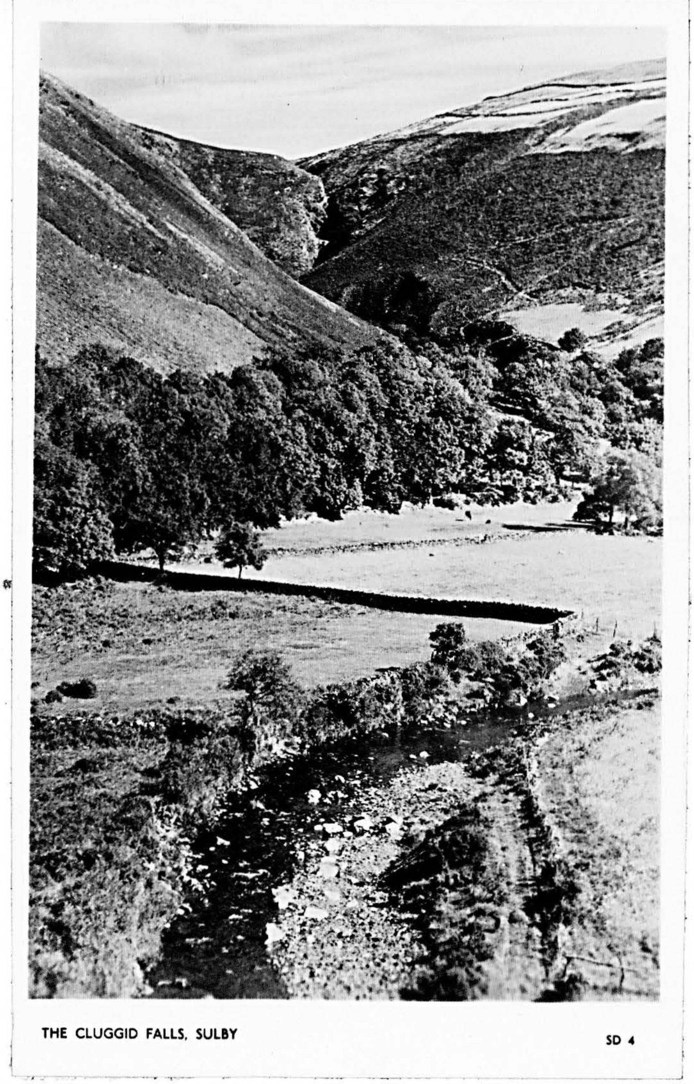
East.

Fracture cleavage.

Coarse grit fragments near contact with thinly bedded sediments shown in diagram 7.

Figure 4, Druidale.

East.



West.

The Cluggid-cliffs exposing breccia on left.

Figure 5.

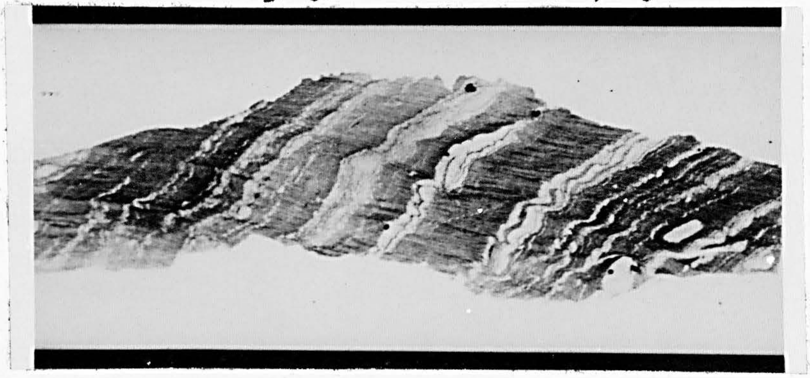
East.

West.

Sulby Glen-general view of exposures of breccia.

Figure 6.

175' E. 88'   Observer facing West.



Actual size: 4.5cm by I.2cm
Thinly bedded sediment which underlies the breccia exposed in Sulby Glen. To show absence of fragmentation. Enlargement of slide 772.

Figure 7.

N.

S.N.

S.

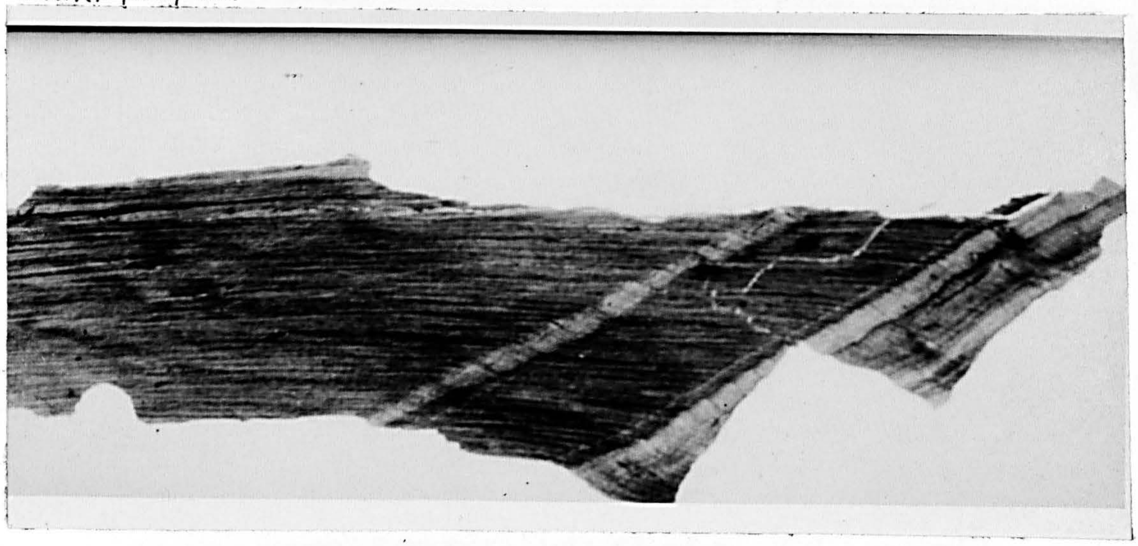
Top contact of undisturbed thinly banded strata and breccia exposed in Sulby Glen (see diag.I).

Figure 8.

Top contact of undisturbed beds with breccia - Sulby Glen.

Figure 9.

Observer facing East



Actual size:4.8cm by I.0cm
Undisturbed strata interbedded with the breccia in Sulby Glen.
Enlargement of slide 776A.

Figure IO.

Observer facing East

Actual size:3.4cm by I.9cm
Sulby Glen breccia in contact with the unbroken beds illustrated in figure IO.(slide 776).

Figure II.

178 / V75 W.

Facing West

Actual size: 3.6cm by 2cm
Top contact of breccia with undisturbed strata.
Enlargement of slide (I495) of specimen obtained in Sulby Glen.

Figure I2.

Observer facing W.

330/75 S.W.

Actual size: 6.8cm by I.2cm.
Top contact between breccia and normal sediment showing grading. Enlargement of slide I497 - Sulby Glen. Note thinly bedded nature of homogenous sediment and continuity of fracture cleavage across contact.

Figure I3.

Actual size: I.8cm by I.2cm

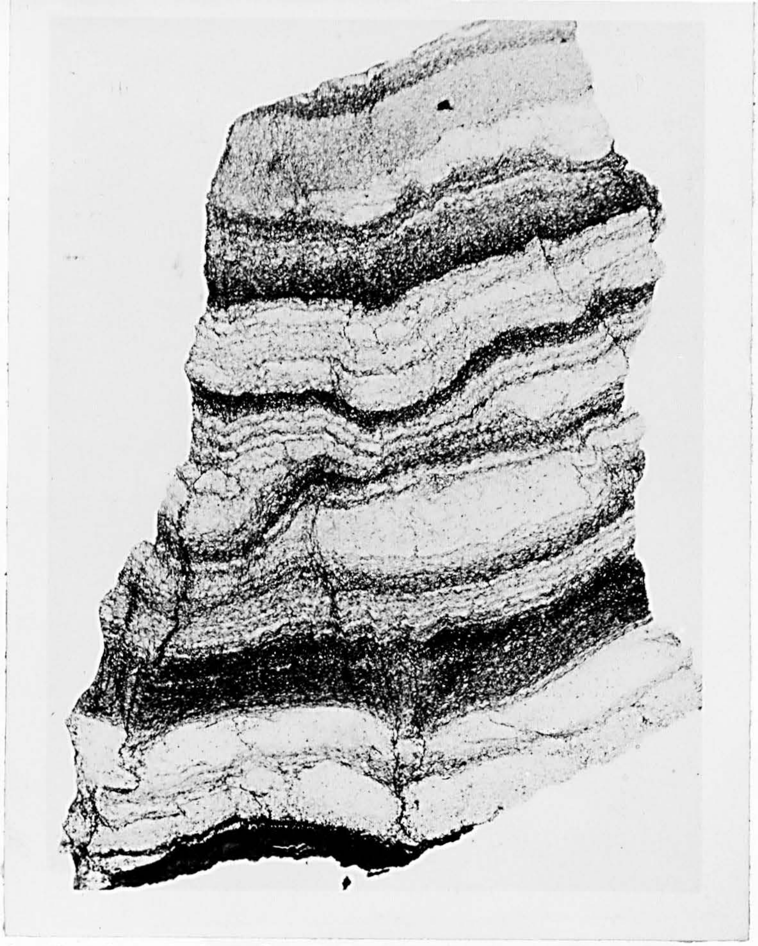
Enlargement of slide 493A. Specimen of typical breccia from Sky Hill.

Figure I3A.

Actual size: I.0cm by 2.3cm

Enlargement of slide 493B (Sky Hill). Unbroken graded sediments (right way up) interbedded with breccia illustrated in figure I3A.

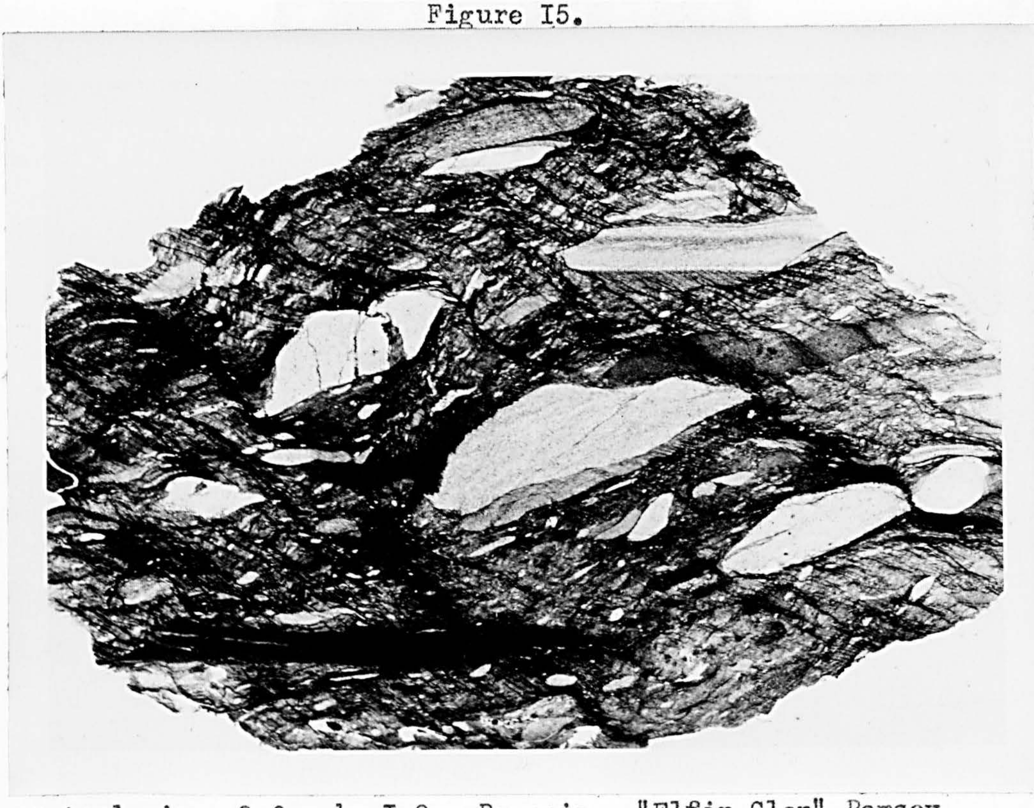
Figure I4.



Actual size: 2.2cm by I.5cm

Enlargement of slide 7I2 ("Elfin Glen", Ramsey). Normal beds interbedded with breccia.

Figure I5.



Actual size: 2.6cm by I.8cm. Breccia - "Elfin Glen", Ramsey.

North.

South.

Contact between two bands of breccia. North of Peel.

Figure I7.

Discussion of the Origin of the Breccia.

The Manx breccias are characterised by the following principal features:

I. The fragments can be matched petrologically in the Manx Slates.
2. The fragments rarely retain their original external form.
3. The fragments are generally small in size (4 - 5cm in longest diameter for the larger fragments) but the largest recorded reaches I4ft by 8ft by 6ft.
4. There are fragments which are themselves composed of fragments.
5. Unbrecciated banded sediments are interbedded with the breccia.
6. Contacts between breccia and normal sediments are conformable.
7. Passages occur along the strike from brecciated to non-brecciated rock.
8. The fragmentation pre-dates the cleavages, metamorphism, and intrusions.

The breccia shows features not associated with the gradual accumulation of a deposit by normal processes of sedimentation. Breccias may be produced by faulting, folding, cleavage, slumping or sliding either during deposition or at some subsequent time.

Fault Breccia.

Fault breccias are generally formed relatively near the surface since at greater depths the fault becomes a "shear zone with foliation and mylonite" (Nevin[I]). A fault breccia which attains a width of half a mile is associated with the San Andreas strike-slip fault and in Death Valley, California, thrust fault movements have produced very large blocks (average 200ft but largest up

I. Nevin, C.M. "Principles of Structural Geology" 4th Edit. pI34 I949 J. Wiley & Sons.

to half a mile). Crush conglomerates have been regarded as an extreme result of fragmentation by faulting, and Lamplugh[I] doubts whether the distinction between thrust and crush conglomerates drawn by Gardiner and Reynolds[2] can be maintained. S.H. Reynolds[3] and Harker[4] state that breccias can be formed on a considerable scale beneath overthrusts, and a zone of breccias associated with the Lizard boundary thrust is described by Hendricks[5]; others from the Moine thrust zone were described by Peach and Horne[6]. Barrington Brown and Baldry[7] claim that "pebble beds" can be formed even in soft rocks, but Illing[8], in describing the Naparima region of Trinidad, maintains that soft rocks are not competent to give a crush conglomerate and simply flow almost immediately under stress. Angular fragments are common in the Manx breccias certain bands of which evidently possessed sufficient cohesion to suffer fracture at the time of brecciation.

While contacts between Manx breccia and normal sediment are sharp they are conformable and neither the breccia nor the interbedded sediments have ever been observed to transgress a contact. As fracture cleavage can be traced across these contacts and slickensides are absent the junctions are considered normal and since there is no other evidence for faulting or

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I. Lamplugh, G.W. Discussion to Gardiner and Reynolds I897 see below.
2. Gardiner & Reynolds "The Portrane Inlier Co. Dublin" Q.J.G.S. I897 Vol 53 p53I
3. Reynolds, S.H. "Breccias" Geol. Mag. I928 LXV p97 - I07
4. Harker, A. "Metamorphism" I950 3rd Edit. pI66 Methuen & Co. Ltd. London.
5. Hendricks, E.M.L. "Succession in S. Cornwall etc." Q.J.G.S. I937 Vol 93 p322-358.
6. Peach & Horne M.G.S.S. I9IO No.7I
7. Barrington Brown & Baldry "On the Clay Pebble Beds of Ancon, Ecquador" Q.J.G.S. I925 p454-60
8. Illing, V.C. "Geology of the Naparima Region of Trinidad" Q.J.G.S. I928 Vol LXXXIV pI - 56.

thrusting connected with the brecciation this does not offer a possible explanation for the formation of the breccia.

Fragmentation by Folding or Cleavage.

C.R.Van Hise[I] states that "when rocks are folded by strong orogenic forces,and they are not so heavily loaded as to render them plastic they are frequently broken into fragments,and 'autoclastic' rocks are produced" - the latter term having been introduced by Smyth[2] in I89I.The unlikelihood of brecciation under considerable load has already been mentioned in connection with fault breccia and this point is also referred to by Greenly[3] in connection with the melange in Anglesey.He describes sharply folded fragments and assumes that the rocks were first fragmented and then lowered from the "zone of fracture" to the "zone of flowage" where both the folding of the fragments and the metamorphism were produced.

Folded fragments occur in the Manx breccias and are of at least two generations since in one type the axial plane of the fold is parallel to the fracture cleavage while the other type shows no relationship to this structure and is of earlier date having formed in the flow-cleavage producing movements.

According to Lamplugh (Memoir p57) the descriptions of Pre-Cambrian rocks of the Lake Superior region in North America given by Van Hise apply "....in every particular to the 'autoclastic' or 'dynamic' conglomerates of the Isle of Man" and he concludes that the breccia was formed "by a force acting slowly and intermittantly,during a considerable period.The beds seem

I.Van Hise,C.R. "Principles of North American Pre-Cambrian Geology" I6th Annual Rept. I896 U.S.G.S. Pt.I p679.

2.Smyth,H.L. "Structural Geology of Steep Rock Lake,Ontario" Am.J.Sci. I89I XLII Ser.III p33I

3.Greenly,E. "The Geology of Anglesey" M.G.S. of England and Wales.

first to have been thrown throughout into acute plications,during the formation of which there was time for an extensive 'creep' of material from one part of the fold to another,as shown by thickening of the layers in certain portions and their attenuation elsewhere.Subsequently when the folds were closed up and could no longer yield,the pressure gradually overcame the cohesion of the bedding planes along certain zones of intense shearing,and the folded rocks were broken into fragments".Lamplugh therefore distinguishes three processes which led to brecciation - folding, creep, and brecciation.

There can be no doubt as to the incompetence of many beds during the folding of the Manx Slates Series as may be well seen for example,in the Agneash Grits near Maughold Head,but the tectonic folding is not connected with the brecciation.As stated by Lamplugh (Memoit p62) fragments in the breccia follow round the crests and troughs of folds but if thickening of some bands in the axial region of the fold,due to creep,had preceded brecciation,a relatively greater concentration of certain types of fragments in that region would be expected,but in fact, this is never the case.Furthermore,the cleavage which is parallel to the axial planes of these folds can be shown to post-date the production of the fragments which frequently deflect this cleavage.W.W.Watts[I] shows that the fragments are often "contorted and even faulted together" with the groundmass by this cleavage.The axial plane of the fold shown in figure 2 is parallel to the fracture cleavage which was described as "shear cleavage" by Lamplugh[2] .This

I.Watts,W.W. Q.J.G.S. I895 Vol 5I p592,Memoir pI02-I03
2.Lamplugh,G.W. Q.J.G.S. I895 p567.

structure developed at a late stage in the movements as did the folds to which it is related but while Lamplugh recognised that it post-dates the brecciation the presence of other,earlier cleavages,led him to suppose that they were responsible and he states that there are "wider-placed and better-defined planes of slipping or 'close-joints-faulting' which are more intimately connected with the brecciation movements".He asserts that the tendency for this "shear strain" to produce brecciation is most intense on the northwestern side of the island,and increases markedly from south-west to northeast becoming especially strong "in the vicinity of masses of grit" (Memoir p58,Q.J.G.S. 1895 p568).At Sulby Glen however,one of the undisturbed zones of sediment contains a band of grit (or quartzite) which is in contact with thinly bedded rocks which show no sign of fragmentation but where,judging from the surrounding breccia in which fragments of similar grit are quite common,the optimum conditions for brecciation must have prevailed.Similar considerations apply to the grit overlain by thinly banded rock which is in contact with breccia at Cronk Sumark.The earlier cleavage to which Lamplugh attributes the brecciation may be the first strain-slip or fracture cleavage which has been positively identified microscopically during the present work,but it is patchily distributed and is clearly seen in but few field exposures,which in any case are outside the "crush conglomerate" areas.The best locality for its study is on the shore south of Maughold Head in Port Mooar,where it is seen parallel to the axial planes of folds and also in the stream south of Snaefell,north of Beinn-y Phott.In sections of specimens of breccia from Druidale two fracture cleavages seem to be present,but both are deflected by the fragments which are of earlier date than either cleavage. Slide 39 clearly shows two fracture cleavages and the flow-cleavage (which is parallel to the bedding) is displaced along minute slips by the early fracture cleavage, and the flow-cleavage is therefore the oldest cleavage. This flow-cleavage is parallel to the axial planes of isoclinal folds and lies parallel to the bedding except in their axes. Fragments occur in which bedding is preserved. The flow-cleavage obliquely intersects this bedding, unless the bedding and cleavage happen to lie parallel, and the platy minerals within the fragments lie parallel to those of the matrix. In some slides the flow-cleavage and smaller fragments appear to flow round the larger fragments (e.g. slides 546, 7IIB see fig. I6) indicating that they existed when the flow-cleavage producing movements took place. Furthermore, there is strong flow-cleavage in unbrecciated thinly bedded strata (e.g. Port-e Mwyllin, Sulby Glen) and this leaves little doubt that the flow-cleavage producing movements were not responsible for the brecciation. In general when these movements occured the rocks obtained relief from strain by "inter-atomic plasticity" (Mead[I]) and little fracturing took place. In the gritty bands there are occasional shear planes which lie near parallel to the flow-cleavage but they do not produce brecciation in any of my specimens. Thin grit bands are sometimes regularly offset by the fracture cleavage but this cleavage post-dates the breccia and the small-scale off-setting is not related to the breccia-producing movements.

W.W.Watts (I895 p594) notes that the fragments are often "phacoidal in outline, and drawn out along the foliation planes". Similar relations are

I. Mead, W.J. "Rock Flowage and Foliate Structures" Journal of Geol. I940 Vol 48 pI007-I02I.

described by Peach and Horne[I] in a pseudo-conglomerate which occurs in the Lewisian gneiss. They attribute the conglomerate to "mechanical movements, the several bands of gneiss having first been plicated and then subjected to still further crushing and shearing, whereby lenticular pieces of them were wrenched off and arranged with their long axes parallel with the foliation planes of the schist". The fragments are stated to be identical with the enclosing gneiss and phacoidal in the initial stages. After a greater amount of "interstitial movement...the included blocks present subangular or rounded edges, and the matrix winds round the pseudo-pebbles". When tectonic fragmentation has occured separated parts of once continuous bands are generally linked by shear planes. They are referred to by Bailey and Mc.Callien[2], Krishna Murthy[3], and Hill[4] in their descriptions of tectonically produced breccias.

If in the Isle of Man fragmentation had been caused by "intense shearing" (Q.J.G.S. I895 p585) due to tectonic action, similar movement planes would have been expected, but they have never been detected on either the megascopic or microscopic scale. The absence of shear planes is used by Bailey and Weir[5] as evidence against a frictional origin for the Kimmeridgian boulder beds of Sutherland and this evidence may be similarly applied to the Manx breccias. The shape orientation of the fragments is

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I. Peach and Horne op cit I9I0 p44
2. Bailey & Mc.Callien "The Ankara melange and the Anatolian thrust" Maden Tetkik ve Arama Enstitusu No.40 I950, Ankara.
3. Krishna Murthy, L.S. "Autoclastic Conglomerates" Sect.C J. Hyderabad Geol. Surv. pI05-III I934.
4. Hill, J.B. "On some structures in North Cornwall" Trans. Roy. Geol. Soc. Cornwall, Vol. XII Pt. VI I900 p403-430.
5. Bailey and Weir "Submarine Faulting in Kimmeridgian Times" Trans. Geol. Soc. Edinburgh I932 Vol. LVII Pt. II p429-467.

related to the cleavages and was produced subsequently to the brecciation.

Lamplugh (Memoir p57) notes that in some localities many of the "smaller inclusions are well rounded". Van Hise[I] states that fragments in autoclastic conglomerates may be rounded by being "ground over one another". Harker[2], Watts[3], and Wagner[4], express support for this view. Wagner describes how there seems to be a relationship between the rounding of the pebbles and the amount of matrix and observes that the coarser the matrix the coarser the pebbles. In the Manx breccia there appears to be no such relationship and the matrix is generally composed of fine-grained argillaceous material which is no less abundant where the fragments are angular than where rounded. According to Van Hise shale yields by flow when more resistant material suffers fracture and thus "fills the space between the fragments" but in the Manx breccias pelitic fragments are common and the matrix is also composed of pelitic material. In my opinion Van Hise's view does not explain these facts (see p43 below).

If the pebbles in a conglomerate can be proved to have been contributed by rocks of a later age than their matrix the rock must evidently be a pseudo-conglomerate. In the Isle of Man all the intrusions post-date the brecciation as do the quartz veins and while these "have been stretched and broken and the rock around them has been bruised and crushed, (but) they have not contributed fragments to the breccia" (p68-69

I. Van Hise, C.R. op cit.
2. Harker, A. op cit. pI66.
3. Watts, W.W. "Geology for Beginners" pIII I945 Macmillan, London.
4. Wagner, P.A. "On a pseudo-conglomerate" Trans. Geol. Soc. South Africa I927 Vol. XXIX p47-58.

Memoir).No evidence has been found that in any of the Isle of Man breccias have beds younger than the matrix contributed fragments.

In discussions of breccias and conglomerates of tectonic origin it is frequently stated that disruption occurs preferentially along the contacts of different kinds of strata since the variable mechanical properties of the alternate laminae differ in their resistance to the stress and produce conditions conducive to brecciation.The hard bands break-up while the soft flow plastically around them to form the matrix. J.B.Hill[I] ,Harker[2] ,Matley[3] ,Norton[4] ,Wagner[5] ,Van Hise,Bayley,and Smyth[6] , Proudy[7] ,West[8] ,Krishnan[9] ,and Balk[IO] , are authors who express support for this viewpoint.This theory was familiar to Lamplugh who stated that "... in almost every case the autoclastic structure occurs where strata of different characters are in juxtaposition,and (that) the disruption has taken place chiefly among the passage beds between these dissimilar masses" (Memoir p 70).

Lamplugh describes how breccia "...isolates and surrounds irregular patches of disturbed but still continuous strata" (Memoir p60) which are "from a few feet to a few yards in diameter" (Memoir p62) and which he

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I.Hill,J.B."On the Crush Conglomerates of Argyllshire"Q.J.G.S. I90I Vol 57 p3I3-327.

2.Harker,A. op cit I903 Q.J.G.S.
3.Matley,C.A. Q.J.G.S. I928, I9I3.
4.Norton,W.H."A Classification of Breccias" J. of Geol. XXV I9I7 pI60 - I94
5.Wagner,P.A. op cit
6.Van Hise,Bayley, & Smyth U.S.G.S. Mon 28 I897 p242-3
7.Proudy,W.F. Geol.Surv.Ala.Bull. I8,I9I6, pI70.
8.West,W.D. "Exhibit of Autoclastic Conglomerate" Proc.Ind.Sci.Cong.Calcutta 25th Congress I938 Pt. 3 Abstracts.
9.Krishnan,M.S. Records Geol.Surv.Ind.LXVII Pt.4 I934 p455-63
IO.Balk,R."Structural and Petrologic Studies in Dutchess Co.,New York" Bull.Geol.Soc.Am. I936 p685-774 Vol 47.

states are dimensionally "very much larger" than the largest single boulder (I4ft by 8ft by 6ft) ever found in these breccias. He records that the "continuous strata" is best exposed in Sulby Glen where in his opinion it is "as though the brecciation had commenced and spread more readily along certain selected beds" (I895 p575). Other places where there are undisturbed sediments in the breccia are in Narradale, in the bed of the Sulby River under Druidale farm, on Sky Hill and on the ridge to the south, and on the west coast south of Gob-y-Deigan. These undisturbed sediments are not accurately described as "surrounded" by breccia, since in each case they are lost under drift before they are replaced by breccia on their line of strike. The unbrecciated rocks are often banded sediments (alternating pelitic and silty beds) and it is precisely along the junction of such dissimilar layers that the optimum conditions for tectonic brecciation should prevail (see p 36) and in consequence Lamplugh's explanation that the brecciation "had pushed its invasion more readily along some beds than others" is not accepted (Memoir p 62).

J.F.Blake[I] rejected Lamplugh's conclusion for three principal reasons. These were:-

I. Autoclastic means will not bring fragments of a different lithological nature together.

2. No proof is offered that fragments of overlying rocks occur in the breccia as they should to satisfy the definition of 'autoclastic' given by Van Hise.

3. The passage from brecciated to non-brecciated rock is not transitional via a semi-brecciated zone.

I. Blake, J.F. op cit I905.

He concluded that the rock is not autoclastic and that "the fragments... have never been brought to their present position by two rocks shearing together under pressure".

Other reasons that show Lamplugh's view is inadequate are:-

I. No evidence is available in support of Lamplugh's view that folding and creep preceded brecciation - certain types of fragments are not concentrated at the axes of any of the folds. There are no pre-cleavage folds.

2. The fragments occupied their present position before the impression of both flow and fracture cleavages.

3. "Partial brecciation" which is believed to be connected with the production of the breccia by both myself and Lamplugh is not related to tectonic structures such as cleavages (see p 55).

4. There are no planes of movement or slickensides which can be related to the brecciation.

5. Pelitic material occurs both as fragments and groundmass and there is no relationship between the amount of matrix and the rounding of the fragments.

6. Quartz veins and dykes cut the breccia and no fragments of either are ever included in it. The breccia was formed before either quartz veins or dykes.

7. Undisturbed strata, frequently banded, are interbedded in the breccias. This is difficult to explain if the breccias are autoclastic since the junction of contrasting lithological types should provide the most favourable situation for tectonic brecciation.

8. There is evidence indicating a migration of material that is hard to account for if the brecciation was brought about by tectonic means (see p 45).

Fragmentation by Sliding which Post-dates Sedimentation.

"Differential movement" is believed by Miller[I] to account for "many, if not most, cases" in which disturbed sediments are interbedded with undisturbed beds. He believes that the folded or broken layers were "horizons of weakness" along which no great amount of movement was necessary to disrupt the bedding. He maintains that the movements occured after the deposition of the overlying undisturbed sediments. In cases to which he applies his hypothesis he finds that "the lower surface of the contorted zone is very straight, while the upper surface is commonly somewhat irregular". He maintains that it is "out of the question to look upon the upper surfaces of the corrugated zones as erosion surfaces" because stratification is perfect in overlying thinly bedded rocks which "plainly show that they were deposited without a break in very quiet water". Turbulence associated with a submarine slide is likely to stir up a muddy suspension (density current) which may act with considerable erosive power in what at other times may be very quiet water (c.f. Kuenen[2], Jones[3], Beets[4]). A short time after the slide normal sedimentation in quiet water may be resumed. In my opinion, slides which occur during sedimentation are as likely to produce horizons of breccia interbedded with thinly bedded sediment as is differential movement. Cummings and Shrock[5] call attention to

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I. Miller, W.J. J. of Geol. I908, I922.
2. Kuenen, Ph.H. "Density Currents in Connection with the problem of Submarine Canyons" Geol. Mag. I938
3. Jones, O.T. I939
4. Beets, C. "Miocene Submarine Disturbances in Strata in Northern Italy" J. of Geol. I946.
5. Cummings and Shrock. Dept. of Conservation State of Indiana, Publ. 75 pI-226 (pI20)

the following points which favour sliding during sedimentation in the Kokomo limestone:-

"I. The contorted bed may not be present everywhere at the same horizon, indicating that the movement was local;

2. The thickness of the beds varies considerably, indicating that the intensity of movement was variable;

3. The absence of any indications of disturbance in either the underlying or overlying normally stratified sediments points to the conclusion that the crumpling must have taken place before the deposition of the overlying beds; and

4. The crumpled beds are as competent as the beds above and below".

These points are applicable to the Manx breccia. a) It is probably of variable thickness since there are localities where it is likely that the same horizon is exposed (e.g. above the Barrule Slate) but where breccia is not always present. b) The banded sediments interbedded with the Manx breccia show no sign of brecciation. c) The unbrecciated sediments are of the same type as those which suffered brecciation and the brecciated and unbrecciated beds are unlikely to have differed in competence. There is hence no support for the postulate that the beds of breccia represent "horizons of weakness".

Differential sliding seems unable satisfactorily to explain the above facts and therefore it is not considered a probable explanation for the origin of the Manx breccia.

Fragmentation by Slumping or Sliding during Sedimentation.

Breccias may be formed by slumping or sliding during sedimentation. Rettger[I], Fairbridge[2], and Cartwright[3], have listed characteristics of slump-produced deposits.

In my opinion the postulate of contemporaneous sub-aqueous slides better accounts for the following characteristics of the Manx breccia than does any other hypothesis.

I. Interbedded with the breccia there are undisturbed banded beds.

2. The contacts between breccia and sediments are normal and conformable.

3. In at least one instance the sizes of the fragments are graded. This evidence agrees with other way-up evidence that the strata are right way up.

4. Pelitic material forms a proportion of the fragments and also comprises much of the matrix.

5. There are fragments which differ in lithology from nearby undisturbed sediments.

6. There are fragments of breccia within the breccia which differ in tone and texture from the mass of the breccia.

Undisturbed sediments interbedded with breccia were reported as early as I846 by Emmons. It has been suggested that such undisturbed beds accumulated

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I. Rettger, R.E. "Experiments in Soft Rock Deformation" Bull.A.A.P.G. Vol I9 1935 p27I-92.

2. Fairbridge, R.W. "Submarine Slumping and the location of Oil Bodies" Bull.A.A.P.G. Vol 30 No.I 1946 p84-92.

3. Cartwright, L.D. "Sedimentation of the Pico Formation in the Ventura Quadrangle, Calif." Bull.A.A.P.G. Vol I2 No.3 1928 p235-269.

during periods of quiet sedimentation between successive slides. Authors' who express support for this viewpoint include Norton[I], Clarke[2], Grabau[3], Lamont[4], Jones[5], Alexander[6], and Kuenen[7]. This interpretation may account for the unbrecciated sediments interbedded with the Manx breccia.

Contacts between breccias and undisturbed sediments are often conformable and the undisturbed sediments accomodate themselves to any irregularities in the surface of the breccia (e.g. Bailey and Weir[8]). This is taken to indicate that no movement between breccia and sediment has occured since deposition. No movement has occured between the Manx breccia and interbedded sediments since the impression of the fracture cleavage. Movement between the breccia and sediment which pre-dates the fracture cleavage is unlikely as the contacts are conformable and slickensides are absent. The contacts are often smooth. Elsewhere this has been interpreted as due to erosion by the muddy suspension (density current) generated by turbulence associated with the slide. Authors' who have reported disturbed beds the tops of which show erosion include Bailey and Weir, Clough and Carruthers[9], Beets[IO], Nicholas[II], Jones[I2], Alexander[I3], Kuenen[I4], Cooper[I5], and Kent[I6].

I. Norton, W.H. op cit I9I7.
2. Clarke, J.M. Quoted by Miller from personal communication. J. of Geol. I922 Vol.30 p592.
3. Grabau "Principles of Stratigraphy" I9I3 p478.
4. Lamont, A. "Contemporaneous Slumping in the Bray Series, Co. Dublin" Proc. Royal Irish Acad. I938 Vol.45 pI-32.
5. Jones, O.T. I937, I939, I947.
6. Alexander, F.E.S. "The Aymestry limestone of the Main Outcrop" Q.J.G.S. I936 Vol XCII pI03-II5.
7. Kuenen, Ph.H. "Slumping in Pembrokeshire" Q.J.G.S. I948 Vol.CIV p365-79.
8. Bailey and Weir op cit I932.
9. Clough and Carruthers "Geology of the Cheviot Hills" M.G.S. England and Wales.
IO. Beets, C. op cit I946.
II. Nicholas, T.C. "The Geology of St. Tudwalls Peninsula, Caernarvonshire" Q.J.G.S. LXXXI I9I5 p83-I4I (pI04).
I2. Jones, O.T. op cit.
I3. Alexander, F.E.S. op cit.
I4. Kuenen, Ph.H. op cit

refs. cont'd. over/

Grading. The sizes of the fragments comprising slide-produced breccias are sometimes graded and the smallest fragments lie near the top contact (e.g. Bailey and Weir and Lamont). When deposited the muddy suspension (density current) generated by turbulence associated with the slide is often graded and slump-produced deposits are often overlain by a graded band of silt. In general, neither the Manx breccia, nor the interbedded sediments display grading. An exception is seen in slide I497 (see fig. I3) from a specimen of a top contact obtained in Sulby Glen. Graded thinly banded sediment is interbedded with breccia on Sky Hill (see fig. I4) but the deposition of a density current commonly results in graded units of the order of Ifoot thick whereas the sediment on Sky Hill is millimetre banded. It is therefore not likely to have originated by the deposition of a density current.

Origin of Pelitic Fragments. As stated (p.3-4) fragments of shale or slate (along with greywacke, banded beds, quartzite etc.) are common in the Manx breccias. A. Lamont[I] postulates that shaly fragments in a silty matrix were introduced by tsunamis which accompanied earthquake-triggered slides. Hadding[2] describes a slide-produced "edgewise conglomerate" which contains shaly fragments. He points out that these must have possessed a certain solidity through cementation before sliding. The shaly matrix of the deposit is likely to have been wholly or in part derived from the unconsolidated sediments which covered the subaquatic region in which the

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I5. Cooper, J.R. "Flow Structures in Berea sandstones etc.," J. of Geol. I943 Vol 5I pI90-203

I6. Kent, P.E. "Contemporaneous Disturbances in lacustrine beds in Kenya" Geol. Mag. I945 Vol. 82 pI30-I35.

I. Lamont, A. op cit I938

2. Hadding, A. "On sub-aqueous Slides" Med. Lunds. Geol. Min. Inst. 47 I93I p377-93 also Geol. Foreningens I93I Band 53 Haft 4 No 387 p377-93.

sliding took place. It seems to me that Hadding's view more readily accounts for the presence of pelitic fragments in a pelitic matrix (as in the Manx breccias) than does a tectonic hypothesis (see p35).

<u>Origin of Fragments which are distinct from their surroundings.</u>

Movement of the material comprising breccias has sometimes been demonstrated. O.T.Jones[1] describes slumped beds which he maintains were originally deposited in a different bathymetric zone to that of the enclosing sediments (see also Lamont[2]). Bailey, Collet, and Field[3] describe how shale in contact with large limestone fragments is contorted. They conclude that the limestone fragments ploughed into the then plastic shale. Elimination of strata is quoted by Baldry[4] to demonstrate mass movement of sediment and stratigraphic increase is similarly quoted by Beets[5] and Heim[6].

In the Manx breccia there are sometimes fragments of quartzite (see fig.4) close to the contact with thinly bedded slate which is lithologically distinct from the quartzite fragments (e.g. Druidale and north of Peel). It seems impossible to explain the presence of such fragments by any mechanism which postulates brecciation in situ. Blake[7] describes a fragment "like Agneash Grit" which he maintained is "much too hard to be touched by the matrix in which the fragments are embedded". He

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I. Jones, O.T. "On Sliding or Slumping of Submarine Sediments in Denbighshire, etc.," Q.J.G.S. 1937 Vol.93 p241-283.
2. Lamont, A. op cit 1938.
3. Bailey, Collet, and Field. "Palaeozoic Submarine Landslips near Quebec City" J. of Geol. XXXVI No.7 1928 p577-614.
4. Baldry, R.A. "Clay Pebble Bed of Ancon, Ecuador" Geol. Mag. 1932 Vol.69 p46.
5. Beets, C. op cit 1946.
6. Heim, A. Geol. Rundschau Vol. XV 1924 p1-47 see p21.
7. Blake, J.F. op cit.

concluded that the fragments must have "been rounded irregularly before being buried" thereby showing that he clearly appreciated the impossibility of assuming fragmentation in situ for this type of rock. Fragments distinct from their surroundings are to be expected in a slide-produced breccia.

There are fragments of breccia within the breccia (see p.4). It seemed to Lamplugh "as though portions already in the state of crush-conglomerate had been broken up a second time" (Memoir p 62). Two tectonic brecciations would seem to be implied on this view. Various authors' (O.T.Jones[I], Cooper[2], Hadding[3]) have referred to "snowball" type structures in slumped beds. In the Isle of Man the grains of which the fragments of breccia are composed are randomly oriented. Had these fragments of breccia grown by accretion due to rolling, a spiral arrangement of the constituents, as in the above mentioned 'snowball' structures would have been anticipated. It is suggested, that if a fragment of breccia became detached from a recently slumped deposit and was re-deposited in breccia, the matrix of which was different in tone and texture to that of the fragment, the facts would be explained. On this view no second breaking-up would be required.

The conclusion reached is that the Manx breccia was formed as the result of sub-aqueous slides which occured during sedimentation. It is therefore "a highly sheared rock of original fragmental character" (Lamplugh I895 p565).

I. Jones, O.T. op cit I937
2. Cooper, J.R. op cit I943
3. Hadding, A. op cit I93I

Discussion of Theoretical Principles which relate to the Breccias.

Definitions.

Walcott[1] defines intra-formational deposits as "formed within a geologic formation of material derived from and deposited within that formation". As Lamplugh asserts, no fragments have so far been found in the Manx breccia which cannot be matched lithologically with rocks of the Manx Slates Series. Hence the breccias may be described as intra-formational.

According to Terzaghi[2] the term "slump" should be restricted to movements of sediments which have no definite yield point. The constitution of the Manx breccia indicates that some bands had a measurable cohesion when mass-movement occured. Such movements are defined as "slides".

Causes of Slides.

i) Passing of the Angle of Instability.

The angle at which sediments resting on a slope become unstable has been credited with a wide range of values. Sorby[3] carried out experiments with various grades of sand; with grains varying in size from about .03-.07 inches and averaging about .05 inches he "found that the angle of rest in water was about 4I degrees when coming to rest, but about 49 degrees when giving way after being at rest. In the

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I. Walcott, C.D. "Palaeozoic Intra-formational Conglomerates" Bull. Geol. Soc. Am. Vol. 5 I894 pI9I-I98.

2. Terzaghi, K. "Theoretical Soil Mechanics" J. Wiley & Sons I943.

3. Sorby, H.C. "On the Application of Quantitative Methods to the Study of Rocks" Q.J.G.S. I908 pI7I-232 (pI74).

case of sand varying in size from .005-.020 inches, and averaging about .010 inches, the angle when coming to rest was about 34 degrees, and after being at rest it gave way at 36 degrees. In the case of very fine-grained sand from Alum Bay, in which the grains varied from .001-.005 and averaged about .003 inches, the angles were respectively 30 and 33 degrees". Heim[1] reported the average angle of slope in a sub-aqueous slide in Lake Zuger, Switzerland to be as low as 2° 31". In the Black Sea Archanguelski[2] found slides to be particularly common on slopes of 2 - 3 degrees. They also occured on slopes as low as 1 degree. Escher[3] accepts the importance of slides in deep sea depressions with slopes of 5 - 20 degrees and believes slides to be most common when the angle is 4 - 10 degrees. According to Twenhoffel[4] angular sands may rest on slopes of 43 degrees and rounded sand on slopes of 38 degrees but clays become unstable if the angle exceeds 30 degrees. In view of the considerable range of values given for the critical angle of rest for the same sediments Beets[5] concludes "that more investigations of recent and fossil slides are needed before reliable comparisons can be made". This statement seems to be supported. What does seem to be fairly well established however, is that once the critical angle has been reached (whatever it may be) very little disturbance is required to cause sliding.

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1. Heim, A. op cit.
2. Archanguelski, A.D. "Slides of Sediment on the Black Sea bottom and the importance of the phenomena for Geology" Soc. Nat. Mosc. Bull. Sci. Geol., New Series 1930 Tome 38, p80.
3. Escher, B.G. Verhand. Geol. Mijnbouwk. Gen. v. Ned. en Kolonien, Geol. Sur., Vol. 3 1916 p79-88.
4. Twenhoffel, W.H. "Principles of Sedimentation" Mc. Graw Hill Book Co. 1939 p530.
5. Beets, C. op cit.

ii)Overload.

Rettger[I] and Kindle[2] experimented as to the effects of differential loading on unindurated sediments.They produced folds,overturned towards the point of no loading,and normal faults downthrown on the side of lesser loading.Kindle showed that "extensive disturbance and lateral movement may be produced in the higher beds of the experimental section with little or no effect on the beds immediately below".This result is relevant to the lack of disturbance frequently shown by the beds below a slumped deposit.

O.T.Jones[3] points out that in a geosyncline coarser deposits accumulate nearer the source of origin than those farther out so that the slope is increased and overload instability results.Kindle postulates that overload may have been responsible for disturbances which produced contorted strata at the junction of the Avon and St. Croix Rivers.Shaw[4] postulates a similar mechanism to explain the mud-lumps at the mouths of the Mississippi.Knight[5],De Terra[6],Goodchild[7],and Beets[8],have also made similar suggestions.

I.Rettger,R.E. op cit.
2.Kindle,E.M. "Deformation of Unconsolidated beds in Nova Scotia and S. Ontario" Bull.Geol.Soc.Am. I9I7 Vol.28 p323-34.
3.Jones,O.T. op cit.
4.Shaw,E.W. "The mud-lumps at the mouths of the Mississippi" U.S.G.S. Prof. paper 85B I9I3.
5.Knight,S.H. "The Fountain and Casper Formation of the Laramie Basin" Univ.Wyoming Publ.in Sci.Geol.Vol.I No.I pI-82 I929.
6.De Terra,H. "Structural Features in Gliding Strata" Am.J.Sci. Vol.2I Ser.5 I93I p204-2I3.
7.Goodchild,J.G. "Notes on some irregular forms of Stratification" (abstract) Trans.Edin.Geol.Soc. I890 pI-3.
8.Beets,C. op cit.

iii) Thixotropy.

Ward[I] states that if a fine sand for example, is lying on a slope, a slight disturbance may render the packing of the grains less close and when compaction occurs the material "becomes momentarily oversaturated" and flows like a heavy liquid carrying overlying strata with it. He states that the stability of a saturated deposit, provided it is not very fine and loose, resting on a slope is a function only of its "density of packing" and is uninfluenced by the height of the slope. This possibly accounts for the failure to obtain consistent values for the angle of instability.

The great decrease in strength which accompanies the remoulding of certain clays at constant water content was first noted by the Swedish Geotechnical Commission. The causes of thixotropy have been discussed by Boswell[2] and Terzaghi[3]. Jones[4], Cassagrande[5], Brueren[6], Lippert[7], Beets[8], and Anderson[9], are authors' who have suggested that thixotropic mechanisms may have been responsible for slides. The conclusion is that if one band of a series becomes plastic a heavy overlying mass will slide on this surface. Sudry[IO] carried out experiments on the buoyancy of muddy water and derived a formula from which it has been calculated that a medium of 25% clay and 75% water will transport blocks 9 times as large as those carried by pure water and hence a heavy overlying mass may be readily transported.

I. Ward, W.H. "The Stability of Natural Slopes" Geog. Journ. I945 Vol CV Nos. 5 & 6 pI70-I97.

2. Boswell, P.G.H. "Thixotropy of Sedimentary Rocks" Q.J.G.S. I949.

3. Terzaghi, K. op cit.

4. Jones, O.T. "The Compaction of Muddy Sediments" Q.J.G.S. I944 Vol IOO pI37-56.

5. Cassagrande, A. "Characteristics of Cohesionless Soils etc.," Boston Soc. Civil Eng. Journ. I935 Vol 23 p27.

refs. cont'd. over

iv) Earthquakes.

Earthquake shocks have been suggested as a possible cause for slides by Goodchild[I], Greenly[2], Bailey and Weir[3], and Lamont[4]. It has also been postulated that slides caused by earthquakes should be of wide lateral extent (O.T.Jones[5]). Norton[6], and Bailey, Collet, and Field[7], point out that earthquakes tend to recur in the same locality and hence may cause slides in strata through a succession of geological ages. It was suggested by Tiddeman[9] and Kendall[8] at an early date that a fault scarp may provide the material for a breccia or scree and Kendall applies this hypothesis to the composition of the Brockram. Fault scarps have also been suggested as the possible source of breccias by Lamont[IO], Bailey, Collet, and Field, Dixon and Hudson[II], Moore[I2], and Schuchert and Dunbar[I3].

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refs. cont'd.
6. Brueren, J.W.R. Univ. Leyden thesis Assen van Gerkum Co. I94I.
7. Lippert, H. "Gleit-faltung in subaquatischen und subaerischem Gestein" Senchenbergiana Vol XIX I937 p355-375.
8. Beets, C. op cit
9. Anderson, R. Geol.Soc.Am.Bull.I8,643. I908.
IO. Sudry, L. Ann.l'Inst.Ocean., tome 4, fasc.4, 68.
I. Goodchild, J.G. op cit I890
2. Greenly, E. op cit.
3. Bailey and Weir op cit.
4. Lamont, A. "Landslides in the Geological Column" Quarry Managers Journ. Vol. 22, I939.
5. Jones, O.T. op cit.
6. Norton, W.H. op cit.
7. Bailey, Collet, and Field. op cit.
8. Kendall, P.F. "On the Brockrams of the Vale of Eden, etc." Geol.Mag. XXXIX p5IO-5I3.
9. Tiddeman, R.H. "On concurrent faulting and deposition in Carboniferous times in Craven, etc." Rept. of B.A. I899 p600 (Newcastle).
IO. Lamont, A. op cit I939
II. Dixon and Hudson. "A mid-Carboniferous boulder bed near Settle" Geol.Mag. I93I p8I-92.
I2. Moore, R.C. Am.J.Sci. I934 p432-453 Ser.5 Vol.27
I3. Schuchert & Dunbar Geol.Soc.Am. I934, Memoir I. Bull.Geol.Soc.Am. I937 pI069

Henderson[I], Mc.Callien[2], and Baldry[3], describe sandstone dykes which are associated with slide produced breccias. O.T.Jones[4], Boswell[5], Norton[6], and Bailey and Weir[7], regard neptunean dykes as the most direct evidence of ancient earthquakes. The dykes are believed by these authors' to be sand-filled cracks which were opened by the earthquake shocks. There are however many other possible causes for the development of clastic dykes (see J.F.Newsom[8]).

Recent observations indicate that a connection sometimes exists between earthquakes and slides. Milne[9] has collected evidence pointing to this conclusion and depth changes in Sagami Bay are believed to have been connected with the Tokyo earthquake (see Shepard[IO] and Yamasaki[II]).

I. Henderson, G.K. "Ordovician Submarine disturbances in the Girvan district" Trans. Royal Soc. Edin. LVIII I935 p487-509.
2. Mc.Callien, W.J. "The Metamorphic rocks of Inishowen, Co. Donegal" Proc. Royal Irish Acad. Vol. XLII Sect. B No. I5 Sept. I935 p407-442.
3. Baldry, R.A. "Slip-planes and breccia-zones in Peru" Q.J.G.S. I938 Vol. 94 p347-358.
4. Jones, O.T. op cit. Q.J.G.S. Vol. 93.
5. Boswell, P.G.H. "The Tectonic problems of an area of Salopian rocks in N.W. Denbighshire" Q.J.G.S. I937 Vol. 93 p284-32I.
6. Norton, W.H. op cit.
7. Bailey and Weir. op cit.
8. Newsom, J.F. "Clastic Dykes" Geol. Soc. Am. Bull. Vol. I4 I903 p227-68.
9. Milne, "Sub-oceanic Changes" Geog. Journ. X, pI29-246, 259-85.
IO. Shepard, F.P. "Depth Changes in Sagami Bay during the great Japanese earthquake" Journ. of Geol. I933 Vol. 4I p527-36.
II. Yamasaki, N. "Physiographical Studies of the great earthquake" Journ. Faculty of Sci. Imp. Univ. Tokyo I926 Sect. 2 Pt. 2 Geol. Vol. 2 p77-II9.

Effect of Slides on Various Types of Strata.

Movement of unconsolidated material takes place on the basal plane and "only rarely is there shearing within these beds" (Kent[I]). In the case of banded sediments with varying physical properties the slip surfaces are composite and according to Baldry[2] "tend to remain as far as possible in the soft strata" and to "break quickly across the hard strata". This results in the more massive formations breaking into lenses (sometimes up to 2-3 miles in length - Busk[3]). A similar mechanism may operate on a small-scale and Krumbein and Sloss[4] support the view that during sliding "stiffer material in the beds may break into angular fragments, developing intra-formational conglomerates". Brown[5] describes pebble beds in the Beekmantown limestone. The fragments appear to be arranged in all positions to the bedding, but when properly exposed they show a wave-like form interpreted as due to slumping when the calc-mud matrix was plastic. Sherbon Hills[6] describes folding of this type as "disjunctive folding". Angular fragments also occur in the slump-produced breccias at Howth, in the Bray Series, Eire (Lamont, A.[7]). The composition of the Manx breccia suggests the brecciation of banded sediments. At the time of brecciation it is likely that lithification had proceeded to a varying degree in neighbouring bands depending on their mineralogical composition and particle size. When sliding occured some layers flowed plastically, lost their original bedding and formed the matrix; the hard bands were unable to adjust themselves to the strain in this manner and broke-up to form the angular fragments of the breccia.

I. Kent, P.E. op cit.
2. Baldry, R.A. op cit.
3. Busk, H.G. "The clay pebble-bed of Ancon, Ecuador" Geol. Mag. I93I Vol. LXVIII p240.

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Type of Strata Preferentially Affected by Slides.

Banded strata have a strong pre-disposition to slide due to their varied mechanical properties (Hadding [I]).Hence the properties of banded strata conduce both to slides and to tectonic brecciation. The development of the Manx breccias from banded strata is not significant as evidence in favour of either tectonic brecciation (e.g.Lamplugh - Memoir p70-7I) or brecciation caused by slides.

Possible Cause of Manx Slides.

Instability resulted only in small-scale fragmentation (see p54) until quite late in the deposition of the Manx Slates Series when major sliding occured.The breccia exposed in the northern part of the island forms part of the transition strata between the Barrule Slates and Sulby Flags (see stratigraphy).The Barrule Slates are fine-grained but the Sulby Flags are a coarser-grained deposit and were commonly influenced by currents.The change in sedimentation, possibly resulted in,or was dependent on,a change in slope of the sea-bed.This may have caused the instability which resulted in slides.The breccia cannot be correlated between neighbouring localities due to lack of distinguishing features,and hence it is not possible to determine the lateral extent of horizons.No evidence has been found for contemporary earthquakes such as neptunean dykes and it seems undesirable to infer a seismic-trigger mechanism for the slides.

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refs.cont'd.
4.Krumbein and Sloss."Stratigraphy and Sedimentation" Freeman & Co.I95I pI00.
5.Brown,T.C. Journ.of Geol. I9I7.
6.Sherbon Hills,E. "Outlines of Structural Geology" p86 Methuen I953.
7.Lamont,A. op cit.
I.Hadding,A. op cit.

Small-scale Disturbance of Bedding.

"Partial brecciation" in the Manx Slates is referred to by Lamplugh (Memoir pI39) and is commonly seen where the rock is banded. If the brecciated strata are viewed without reference to the surrounding bedded rock the appearance is often strikingly similar to slide breccia (see diags.8 & 9).In my opinion,the movements which led to the small-scale brecciation are similar,but smaller scale,to those which produced the big deposits of breccia.

Extent of the Fragmentation.

Fragmentation frequently affects two or three thin bands only for distances of the order of a few inches or a few feet.Over- and under-lying bands remain intact;bands broken at one point are often continuous in nearby areas for long distances parallel to the strike. Bands are generally broken parallel to both strike and dip (parallel to the "a" and "b" fabric axes).At Druidale (upper Sulby River) brecciation extends for distances measurable in yards but is otherwise often comparable to the above.

The fragments generally consist of light gritty material.On the "bc" surface they appear lenticular and on the "ac" surface are often rounded.Their sizes vary from a few millimetres to several centimetres. They can sometimes be related to still continuous bands.

The matrix consists of dark argillaceous material.It has behaved plastically and flows around the fragments.In some instances there are only narrow necks of matrix between fragments but more commonly there are several centimetres of matrix separating the fragments.

Relation of the fragments to the cleavages.

The fragments have similar relations to the flow- and fracture-cleavages as do the fragments in the breccia. Both cleavages post-date the fragmentation. The flow-cleavage is sometimes continuous through both fragments and matrix and at other times flows round the fragments. The fracture cleavage stops short at the fragments or is deflected by them. Sometimes the fracture cleavage penetrates the fragments for a short distance.

Description of specimens.

A sample of banded strata obtained in the stream bed south of Snaefell and north of Beinn-y Phott (slide I532) shows fragmentation. The pelitic bands are from 5 - I5mm thick. The light bands (2 - I0mm thick) are brecciated parallel to strike ("b" axis) and dip ("a"). The fragments form 2 - 5mm lenticles parallel to the strike ("bc" plane) and are approximately equidimensional (of the order of 4mm diameter) parallel to the dip ("ac" plane). In section two of these fragments may be seen in process of development. Two partially separated oval masses of silty material are joined by a thin neck of silt. Fracture cleavage is strongly developed but is deflected by these fragments which it therefore post-dates. The fracture cleavage is concentrated in the neck between the fragments, due no doubt, to the greater ease of penetration in this locality. The flow-cleavage, which lies parallel to the bedding, bends around the fragments but conforms to their elongation. The micas in the fragments are imperfectly oriented parallel to those in the enclosing matrix.Other fragments in the rock are in various stages of separation;some are quite isolated from parent bands.

The fragments in slide I22I (see fig.I8) are separated parallel to the strike and dip.They are lenticular parallel to the strike ("bc" surface) but rounded in the "ac" plane.The lenticles of one narrow string visible in hand specimen each contain a thin black band sandwiched between light layers,and since the black band persists from one lenticle to the next it confirms their former continuity.

Slide 772 (see fig.7) is a specimen of undisturbed beds which underlie the breccia in Sulby Glen.Small fragments of similar appearance to those above described are visible.

Slide 244 represents rocks exposed on the coast south of Ramsey (see fig.I9).The bedding is impersistent and there is a feature with the appearance of a miniature delta.The irregular lenticle on the left of the plate deflects the bedding and flow-cleavage demonstrating that it pre-dates this cleavage.

Fig.20 illustrates a particularly good example of the small-scale disruption of bedding.In the centre of the plate there is what seems to be a very flat recumbent fold;folding is also suggested by the neighbouring bed (see upper right of centre of plate).For comparison,a photograph from Hadding's paper "On Sub-aqueous Slides" is reproduced - fig.2I. It shows comparable features to those seen in fig.20.

Cause of the Fragmentation.

The fragments pre-date the cleavages and there is no shearing connected with the brecciation. In appearance the structures are similar to those elsewhere ascribed to a sedimentary origin. In my opinion the small-scale fragmentation was caused by local movements of the sediments which occured shortly after deposition.

According to Hadding[I] the mass-movement of material which is slow is described as "creep". The first sign of the commencement of a slide in unconsolidated, sub-aquatic sediments is the appearance of frontal wrinkles and crumpling, with local duplication of single laminae, and on stronger movements there is complete separation of parts of beds. He states that the rate is determined by factors such as the slope, and the condition of the surface of deposition. The nature of the sediments is also of importance, and Sharpe[2] maintains that creep becomes pronounced in loosely consolidated material containing a high proportion of rounded particles. The cohesive properties of the sediments will determine whether or not small-scale movements lead to fragmentation. The cohesive properties will depend on how much the sediments have been compacted, and on their composition. Brown[3] concludes that different types of movement should occur at different stages in the process of compaction. He distinguishes four zones dependent on the water-content and density of the layers; i) where the sediment is least compacted,

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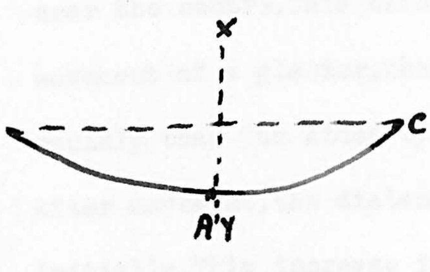
I. Hadding, A op cit.
2. Sharpe, C.F.S. "Landslides and Related Phenomena" Columbia Univ. Press I938.
3. Brown, C.B. "On a theory of Gravitational Sliding applied to the Tertiary of Ancon, Ecuador" Q.J.G.S. I938 p359-368 Vol. 94.

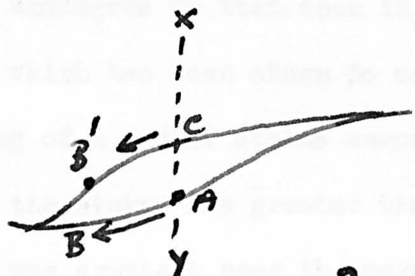
and hence most waterlogged,flow will be like a "very viscous fluid" and result in "small scale contortions and lenses";ii)below this the movement should take the form of "a sliding of layer over layer" and result in "crumpling,brecciation,slickensiding,and lensing".This movement is superimposed on beds which have already been affected by the first kind of movement;iii)a third zone is based on lithological differences where large-scale near horizontal displacements occur; iv)there is a possible lowermost zone of splintering and cracking. These zones are gradational and as a particular band of sediment is slowly buried to greater depths,so it undergoes movement characteristic of its particular state of compaction and the various types of movement are superimposed one upon another.When one band is undergoing one type of movement a neighbour with different physical properties may be experiencing movement of another type and thus while the effects are found throughout the column they are not continuous.Surface phenomena due to micaceous minerals will have an important effect on the behaviour of the argillaceous layers which may therefore be expected to behave differently from more gritty bands.In thinly banded strata,such as much of the Manx Slates,the sporadic appearance of fragments surrounded by apparently undisturbed beds may be expected as a natural consequence of small-scale but widespread movement.In the breccias of Ecuador fragments when sectioned,frequently "show minute fault and flow structures" and while it is not inherently improbable that parts of the Manx Slates subsequently involved in mass-sliding had earlier undergone small-scale movements,little sign of this has been detected and on the contrary bedding preserved in fragments is generally free from disturbance.

Possible Cause for fragmentation Parallel to strike ("b" axis) and Dip ("a" axis).

As stated above the beds are fragmented both along and across the strike (parallel to "b" and parallel to "a" if flow-cleavage taken as "ab" plane). Frequently the brecciation appears to have resulted from the stretching and pulling apart of once continuous bands (see diags. 8 & 9). If this was brought about by down-slope creep of material the stretching and hence fragmentation, should have occured parallel to the movement direction and not at right angles to this along the strike. Now as noted by Hyde Forbes[I] slip surfaces tend to be cylindrical in cross-section and in the longitudinal direction they are curved surfaces passing through the lower edge of the slope. In practice the situation is rendered more complicated since within a moving mass there may be several such surfaces and therefore the forces acting on particles at different points on the cross-section will vary in direction.



1.



2.

A particle at point "A" will experience a force in the direction "AB" (diag. 2) and will tend to move in this direction only; a particle in

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I. Hyde Forbes "Landslide Investigation and Correction" Proc. Am. Soc. Civil Engineers, 1946 Vol. 72 p169-198.

position "C" however,will not only have a tendency to gravitate downslope in the direction "CB' " (diag.2) but also in the direction "CA" (diag.I) and its actual direction of movement will be the resultant direction determined by the two sets of forces.It may be expected to travel a shorter distance in the down-slope direction " CB' " in a given time than a particle initially at point "A" will travel in its downslope direction "AB".When the section illustrated is filled by a mass of sediments the movement of a particle in the direction "CA" will be more hampered than in the direction "AB" and in consequence its movement parallel to "CA" may be expected to be less than the theoretical amount.Nevertheless,the tendency to move in the direction "CA" will place the sediments in a state of tension in this direction in addition to that existing due to the tendency to move in the direction "AB".The nett result will be to produce stretching both along and across the strike which may lead to fragmentation.Friction along the sides of a moving mass will exert a greater retarding influence than on parts near the centre.This effect will be analogous to that seen in the movement of a glacier,the centre of which has been shown to move more rapidly than the sides by the placing of a row of stakes across the ice. After movement,the distance between the stakes was greater than initially.This increase in distance was greatest near the margins and stretching must there have been at its maximum.The above suggestions may account for the two-fold direction of fragmentation.

Druidale - Upper Sulby River.

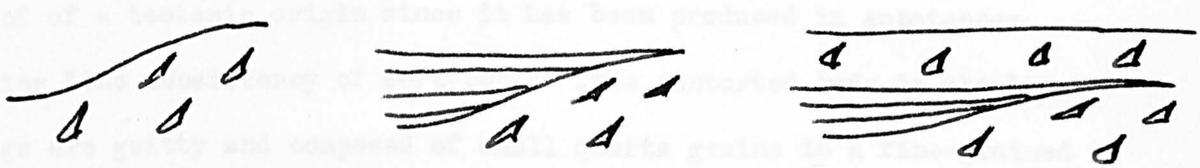
At this locality there is similar but more extensive brecciation to that described above. There are bands, indistinguishable from breccia, enclosed by beds in which there is only slight separation of strips of sediment. Sometimes bands of breccia a few centimetres thick, which maintain a constant position relative to the enclosing beds, are traceable for several yards and often to the limit of the exposures. On occasion the normal sediment by which a thin band of fragments is enclosed abruptly terminates in a mass of breccia. The breccia is sometimes distinct from the normal sediments with which it is in contact in that coarse grit fragments occur while the normal sediment is thinly bedded. Although thinly bedded sediment sometimes passes into breccia parallel to the dip ("ac" section) it shows no contortion at the junction (see diagram 7). The appearance of the rocks is illustrated by diagrams 4,5,6, and 7. The similarity between the diagrams illustrating exposures at Druidale and those illustrating small-scale brecciation (see diag. 8 & 9) can hardly be coincidental and it seems highly probable that similarity in appearance reflects at least a partial correspondence in conditions.

Possible causes for the features seen at Druidale.

In Pembrokeshire, Kuenen[I] describes a band of "more or less brecciated composition" the appearance of which suggests that it has been "stretched and drawn apart" and he concludes that this is what may be expected "at the upper end or margins of a slump on a slight slope". If the beds now exposed at Druidale were at the upper part of a slope down which sliding occured they may have been expected to be in a state of tension and also to have undergone local movement. As stated above the physical properties of neighbouring bands vary, and this variation results in a differing response to movement. Some bands break into fragments when others are near continuous strips. Such a deposit viewed in section, may appear to show breccia prolonged between beds of but slightly disturbed material; as is seen at Druidale. These slightly broken bands would however pass into breccia at the point at which the stress had overcome their natural cohesion. In my opinion it is likely that the beds now exposed at Druidale were at the upper parts of a slope down which sliding took place. In some instances the conclusion that large scale movements occured seems inescapable since there are fragments of coarse grit in immediate contact with thinly banded slate. These grit fragments appear to be quite isolated from any other fragments of a similar nature (see fig. 4 slides I52I, I522) and it is unlikely that their presence can be explained by any mechanism, tectonic or otherwise, which requires fragmentation in situ of pre-existing bands of sediment. It seems evident that they came to occupy their present positions by

I. Kuenen, Ph.H. op cit I948.

migration from some point an unknown distance away. As we have already noticed the lithology of the banded fragments is sometimes different to that of the thinly banded sediments with which they are in contact. The banded slate in contact with the breccia at Druidale appears quite undisturbed and it seems most unlikely that this would be the case had it been deposited before the slide took place and it is therefore probable that these bands were formed later by normal sedimentation. Breccia and undisturbed sediment sometimes dovetail together (see diag. 7). Sedimentation possibly occured on the flanks of a mass of breccia, and both breccia and sediment were then overridden by a later slide. It has been pointed out by Hadding[I] that undisturbed sediments beneath a slidden mass will show hardly any sign of deformation. This may therefore explain the lack of disturbance shown by the thinly banded slate in the diagram. The experimental work carried out by Kindle[2] is also relevant in this respect.



I. Termination of slide. II. Sedimentation round flanks of slide I. III. New slide covers I & II giving wedge-shaped termination of sediment between breccia.

The contact between the two slides may be obscure because of compaction.

I. Hadding, A. op cit.
2. Kindle, E.M. op cit.

Lonan Flags - disturbance of bedding.

Small-scale creep of plastic sediment may have been responsible for contortions seen in the Lonan Flags. Individual bands are contorted while over- and under-lying beds are unaffected. Two microscope slides were prepared (I272, I269). As seen in fig. 22 which is an enlargement of the slide (I272) there are small recumbent folds which indicate considerable plasticity at the time of their formation but while their appearance is suggestive of a contemporaneous rather than a tectonic origin, shear planes lie about parallel to the axial plane of those seen in I269. Cope[I] describes somewhat similar folds in the upper Carboniferous of the South Pennines where contorted shale occurs at certain definite horizons and he concludes that the folds were produced by drag in response to a couple, due to the sliding of the over- and under-lying more competent layers. In addition to shear planes he lists many other features in support of his argument, quoting Willis to the effect that shearing in itself does not constitute proof of a tectonic origin since it has been produced in substances having "the consistency of soft butter". The contorted beds in the Lonan Flags are gritty and composed of small quartz grains in a fine-grained micaceous groundmass and would certainly be more competent than the thin pelitic layers with which they are interbedded, so that the mechanism proposed by Cope is not here applicable. Small-scale folding is seen in many bands of the Lonan Flags and the folds can often be

I. Cope, F. W. "Intra-formational contorted rocks in the Upper Carboniferous of the South Pennines" Q.J.G.S. I945 Vol. IOI pI93-I72.

linked with current-bedding.These folds apparently developed due to the angle of deposition of the foresets exceeding the critical angle of stability so that small-scale sliding occured with folding of the newly deposited material.In these cases there can be no doubt that the folds are of contemporaneous origin and it is not unlikely that the contortions shown in figure 22 are an extreme modification of the above,on a slightly larger scale.Examples of slight disturbance of normal sedimentation produced in this way are illustrated by specimens 905, I064, 906, I045, I085, I086, I08I, I078, I8I4, 965.

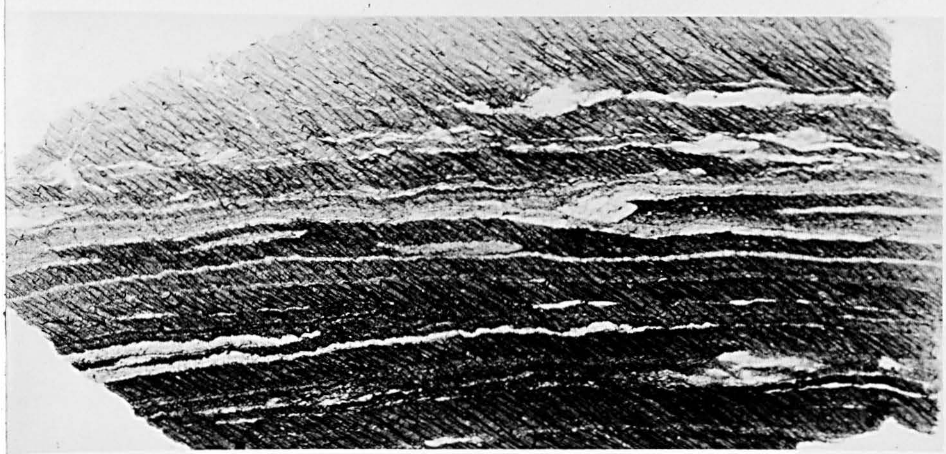
Observer looking N.E.

Actual size: 2.5cm by 4.2cm
Enlargement of slide I22I (stream bed near Corrany) at right angles to the strike - "ac" plane. Small-scale fragmentation of normal beds.

Figure I8.

Actual size: 3.5cm by I.2cm.
Enlargement of slide 244 showing impersistence of bedding.

Figure I9.



Actual size: 4.5cm by 2.2cm
Enlargement of slide 44.Small-scale disturbance of bedding.

Figure 20.

laystone with light sandstone imbeddings. The irregular form
l during subaqueous sliding of the unconsolidated sediment.
Billesholm, Scania. Drilling core as fig. 2. Natural size.

Reproduction from paper by A.Hadding "On sub-aqueous slides".

Figure 2I.

Actual size: 4.2cm by 2.5cm
<u>Contorted bedding in Lonan Flags.Enlargement of slide I272.</u>

<u>Figure 22.</u>

Stratigraphic Position of the Breccia.

The breccia is regarded by Lamplugh as the product of tectonic crushing but he assigns to it a stratigraphic position "below the Barrule Slates and above the Flags and Grits" (Memoir p7I) on the grounds that its development was pre-determined by the particular nature of the sediments.

Blake[I] concludes that the breccia formed contemporaneously with the normal sediments and he assigns to it a definite stratigraphic position "near,or at the summit of," the Barrule Slates and declares that it is always closely associated with the western side of that division "of which except for the fragments it contains,it would appear to be a mere accident."

The best exposures of breccia are at Sulby Glen and it is there also that its stratigraphic position is most clear.The way-up evidence (current bedding - see fig.23) indicates that the breccia lies above the Barrule Slates and below the Sulby Flags (see stratigraphy). At Ballastowell and Elfin Glen,near Ramsey the breccia also lies above the Barrule Slates;at Druidale and Glen Mooar in the southern part of the Sulby River the breccia is similarly situated above the Barrule Slates.

The way-up evidence therefore supports Blake's conclusion that the breccia overlies the Barrule Slates.

I.Blake,J.F. op cit.

Top.

Actual size: 4.8cm by I.2cm.
To show current bedding (right way up) in undisturbed sediments underlying the breccia in Sulby Glen (slide I483).

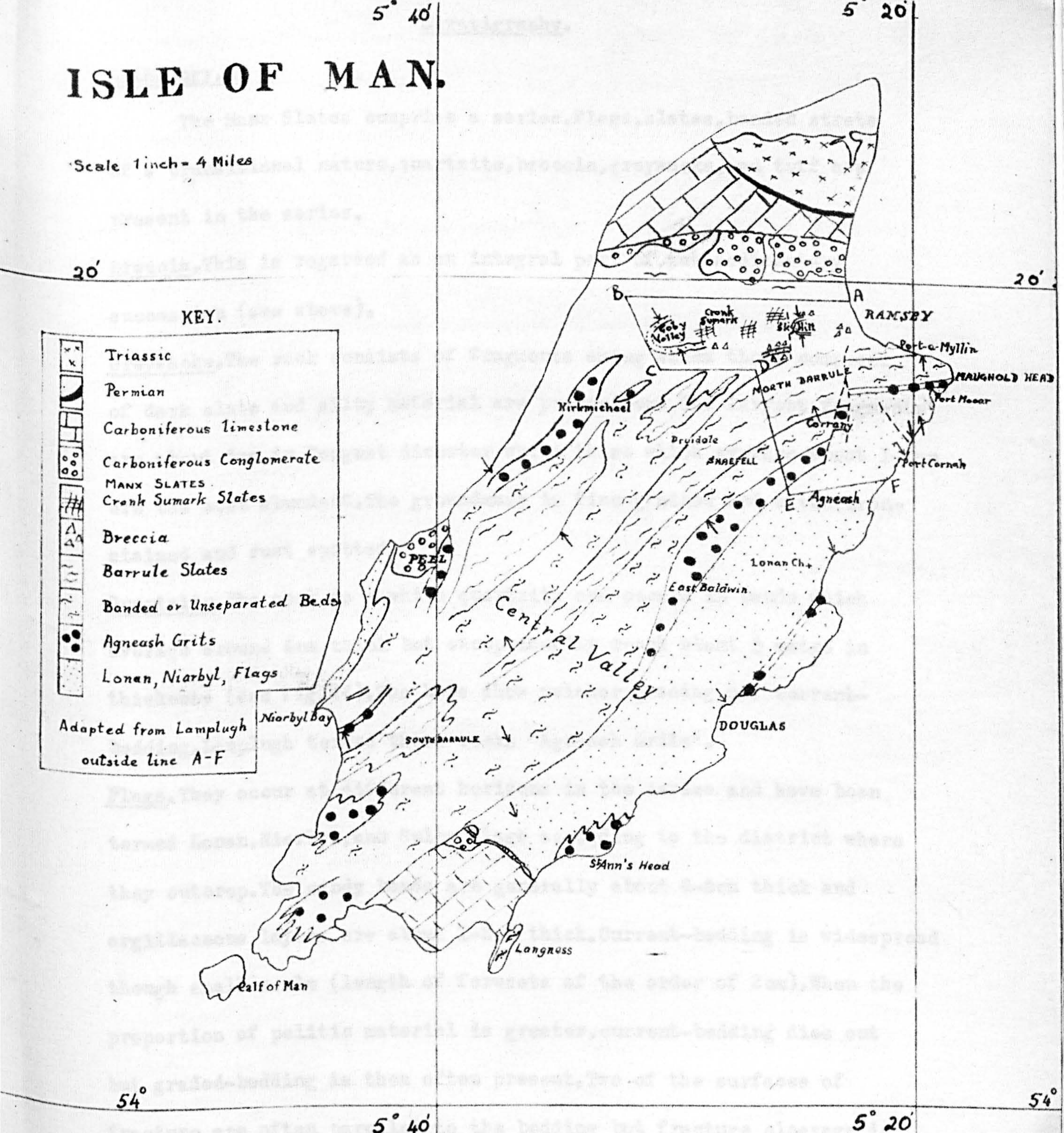
Figure 23.

The Possible use of the breccia as a stratigraphic marker horizon.

The breccia to the east of Sulby Glen was considered by Lamplugh to lie on one stratigraphical horizon which once formed a continuous sheet but which has since been "reduced by denudation to a series of isolated wedges set en echelon" (Memoir p65). Breccia to the west of Sulby may, in his opinion, occur independently or be part of a definite plane (Memoir p66).

Breccias are sometimes of very wide lateral extent, as for example those of Peru and Ecuador (Baldry and Brown[I]) and the similar appearance of isolated field exposures has resulted in attempts to correlate these as one extensive horizon. O.T. Jones[2] attempts such a correlation in the slumped beds of the Silurian of North Wales. It is concluded by Boswell[3] on the basis of the fossil evidence, that there is no justification for "joining up these isolated outcrops of disturbed beds" and therefore that stratigraphic correlations based on their similar appearance at different exposures, are unreliable. In the Manx Slates undisturbed sediments are often inter-bedded with different bands of breccia. The different bands of breccia appear indistinguishable. Furthermore the breccia is difficult to trace on its line of strike and this suggests that the deposit is lenticular. Separate exposures of breccia therefore cannot be joined as more than one horizon is present in the Manx Slates. A band of breccia may be used as a member of a sedimentary sequence to be correlated with a similar sequence in a neighbouring area (e.g. see Sky Hill Syncline pI45).

I. Baldry and Brown "Breccia Zones in Peru etc." Q.J.G.S. I938 p347-58 Vol. 94.
2. Jones, O.T. op cit
3. Boswell, P.G.H. "Alleged Sliding in North Wales etc." Liverpool & Manchester Geol. Journ. I952 Vol. I pt. 2 pI48-I52.


5° 40'
5° 20'
ISLE OF MAN.
Scale 1 inch = 4 Miles
20'
20'
KEY.
Triassic
Permian
Carboniferous limestone
Carboniferous Conglomerate
MANX SLATES
Cronk Sumark Slates
Breccia
Barrule Slates
Banded or Unseparated Beds
Agneash Grits
Lonan, Niarbyl, Flags
Adapted from Lamplugh outside line A-F
A
B
C
D
E
F
RAMSEY
Cronk Sumark
Sky Hill
Port-e-Myllin
MAUGHOLD HEAD
Port Mooar
NORTH BARRULE
Kirkmichael
Druidale
Corrany
SNAEFELL
Port Cornah
Agneash
PEEL
Lonan Ch.
East Baldwin
Central Valley
Niarbyl Bay
SOUTH BARRULE
DOUGLAS
St Ann's Head
Langness
Calf of Man
54°
54°
5° 40'
5° 20'

Stratigraphy.

Lithology.

The Manx Slates comprise a series.Flags,slates,banded strata of a transitional nature,quartzite,breccia,greywacke,and tuff are present in the series.

Breccia.This is regarded as an integral part of the sedimentary succession (see above).

Greywacke.The rock consists of fragments among which those composed of dark slate and silty material are predominant.The largest fragments are about 5mm in longest diameter while those which average about I-2mm are the most abundant.The groundmass is fine-grained and often iron-stained and rust spotted.

Quartzite.The rock is a white quartzite and occurs in bands which average around 8cm thick but exceptionally reach about ½ metre in thickness (see fig.24).The beds show neither grading nor current-bedding.Lamplugh termed these rocks "Agneash Grits".

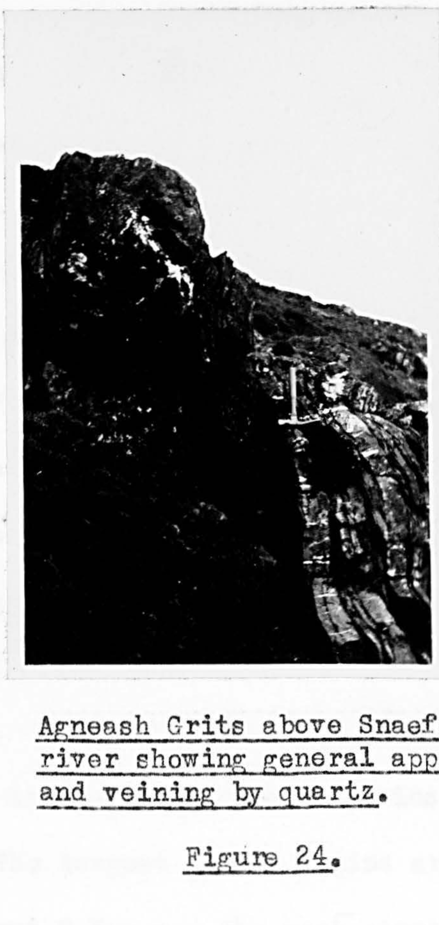
Flags.They occur at different horizons in the series and have been termed Lonan,Niarbyl,and Sulby Flags according to the district where they outcrop.The sandy bands are generally about 6-8cm thick and argillaceous layers are about I-2cm thick.Current-bedding is widespread though small-scale (length of foresets of the order of 2cm).When the proportion of pelitic material is greater,current-bedding dies out but graded-bedding is then often present.Two of the surfaces of fracture are often parallel to the bedding but fracture cleavage is usually well developed and determines the other two planes.

Banded Beds form the transition strata between the flags and quartzite and the slate. The proportions of shaly and silty material are near equal and bands are typically of the order of I-2cm thick though wider quartzite bands do occur at intervals and attain thicknesses of the order of IO - 20cm. Way-up evidence is scarce though it has been found at various localities. Fracture cleavage is strongly developed.

Slate. This rock is dark blue and of homogenous aspect. The homogeneity is sometimes broken by thin silty bands but cleavages form the dominant structural planes.

Tuff. In the field this rock has an ashy appearance and is frequently iron-stained. The largest fragments are of the order of 8mm in longest diameter. Shear planes are visible in hand specimen.

West.



East.

Agneash Grits above Snaefell river showing general appearance and veining by quartz.

Figure 24.

Petrography.

Greywacke. The rock consists of rounded and angular grains in a fine-grained matrix. The largest grains are about 6mm in length and those about 2mm the most common. They grade down to microscopic dimensions. Quartz grains are common. They are nearly always strained and the larger grains show granulation. The largest quartz grains are sometimes surrounded by a narrow margin of minutely granulated quartz. They almost always contain small dark inclusions. Grains of orthoclase and plagioclase occur but only as an accessory. They are generally altered. Rock fragments of slate, silt, and chert are often present. The pelitic fragments in particular are often intensely puckered and sheared out between the harder grains. Grains of andesite are sometimes present (EI959, E2I3I, Y, I48IA). The matrix generally consists of micaceous and cryptocrystalline material with small quartz crystals. The platy minerals include chlorite and sericite. Tiny grains of leucoxene and magnetite often give the matrix a dusty appearance. In 2030 (Sulby Glen) the interstices are filled by large amounts of black opaque iron and limonite.

Quartzite. The quartz occurs as irregular or rounded grains which are occasionally interlocking. The largest quartz grains are of the order of Imm while those of about 0.3mm are the most common. They are generally strained and the larger ones are granulated. They contain minute dark inclusions. Muscovite occurs as laths the largest of which reach 0.75mm in length. Detrital, green pleochroic, tourmaline (0.05mm), orthoclase,and plagioclase (both generally somewhat altered to sericite or saussurite) form the chief accessories.Limonite and irregular grains of leucoxene are common and there are occasional grains of zircon.The small amount of matrix consists of sericitic and cryptocrystalline material and aggregates of small quartz crystals.

Flags.Quartz is dominant as grains (largest 0.25mm) or interlocking aggregates in the sandy bands where it comprises about 70% of the band.The grains are often strained and sometimes are phacoidal. They occur individually and as interlocking aggregates.Grains (0.08mm) of green pleochroic tourmaline (z-mid green,x-pale green or colourless) are a common accessory.Other accessory minerals included in the sericitic and cryptocrystalline matrix are leucoxene,magnetite,haematite,zircon,and sphene.Biotite and chlorite also occur and there are sometimes intergrowths of chlorite and muscovite.

Argillaceous partings consist of a felted mass of platy minerals;biotite,chlorite and sericite occur.

Fracture cleavage is less strong than in the banded beds and slate.It puckers and shears the micas disturbing their parallelism to the bedding.

Banded Beds.Quartz grains (0.25mm) are predominant in the light bands of which they constitute about 70%.The grains are often strained and sometimes are phacoidal.They occur individually and as interlocking aggregates.The accessory minerals are the same as in the Lonan Flags.

The dark bands contain more biotite and quartz grains constitute only about 5-I0% of the minerals in the band. Chlorite, sericite, and cryptocrystalline material are the other chief constituents.

The platy minerals generally lie parallel to the bedding. Fracture cleavage is almost invariably strong and causes puckering of the micas which are often sheared parallel to the planes of fracture cleavage.

Barrule Slates. Platy minerals are the chief constituents in the Barrule Slates. Bedding is often quite lacking but thin laminae are sometimes present particularly near the margin of the slate belt. Sericite is dominant in the light laminae but in the dark layers biotite and chlorite are predominant. The light laminae vary from 0.25-2mm thick and the dark from I-5mm thick. The light bands die out towards the centre of the slate belt and the rock becomes dark and homogenous though sericite or muscovite are seldom completely absent. Grains of quartz (0.05mm), commonly irregular but sometimes phacoidal, are occasionally present as an accessory and lenticular intergrowths of chlorite and muscovite are common. Fracture cleavage is strong and puckers and shears the micas. Randomly distributed laths of leucoxene (max. 2mm) are common in all rocks from the central parts of the island (see metamorphism).

Tuff. The rock consists of fragments (largest 8mm) in a fine matrix of cryptocrystalline material. Irregular fragments of andesite occur containing laths of oligoclase which impart trachytic texture to the fragments (e.g. 20I2,E2II8).The matrix of the andesite fragments is cryptocrystalline.Other fragments contain rounded objects composed of cryptocrystalline material or a mosaic of quartz which seems to represent some kind of devitrification feature and it is likely that these fragments were originally volcanic glass.Some of the fragments, as seen in hand specimen,appear red due to staining by haematite.The groundmass consists of alteration products.Limonite (and haematite), calcite,chlorite,and cryptocrystalline material are predominant. Shearing has been intense and the platy minerals wind round the hard fragments.E2II8 contains more oligoclase laths and less cryptocrystalline material in the matrix than E2985.

Distribution of Rock-types.

As indicated on the accompanying map the main rock-types occur in fairly well-defined belts.

The Lonan Flags are exposed on the south-eastern side of the island and occupy practically the whole of its east coast south from Maughold Head (see map). The quartzites or Agneash Grits might "be considered as a gritty phase" of the Lonan Flags. The passage from flags to quartzite is gradational and the boundary line is "therefore necessarilly to some extent arbitrary and diagramatic" but under favourable conditions it can be defined to within about 30ft. The gradation is most rapid at Maughold Head but to the south-west the boundary is more arbitrary. The change in lithology is well exposed in the tributaries to the Snaefell River and along the Snaefell railway. The most northerly outcrops of Agneash Grit are at Maughold Head and further exposures occur on the crags south-west of Corrany, and on Slieau Ouyr and Creg Agneash.

To the north-west the quartzite passes by a transition into banded slate. The boundary as indicated on the map is arbitrary to within about 100ft. It is most clearly defined at Maughold Head, but in the higher parts of the Snaefell River system the gradation is more gradual and the boundary is correspondingly more arbitrary. The banded beds occupy the east coast between Port-e-Mwyllin and Maughold Head and are traceable inland on Slieau Lewaigue. To the south their strike approximates to the course of the Cornah valley and south-westwards they extend into the upper valley of the Snaefell River.

The line drawn on the map between the banded beds and the Barrule Slates,which form a belt on the north-west side of the banded beds,is arbitrary to within a few hundred feet.Barrule Slates outcrop on the east coast south from Ramsey to Port-e-Mwyllin and form the central highland ridge of the island from North Barrule to Clagh Ouyre,Snaefell,Beinn-y Phott,Greeba Mountain,and South Barrule.

In the north of the island bands of breccia are often exposed to the north-west of the Barrule Slates.The contacts are sharp and similarly sharp junctions separate the breccia from the Sulby Flags exposed farther to the north-west.These flags are most clearly defined in the region of Sulby Glen.On the western side of this glen on Mount Karrin (see 6 inch map),there are two zones of flags separated by homogenous slate.The most southerly zone of flags is well defined on the east side of Sulby Glen but it could not be traced farther east into the Narradale streams.To the east of Narradale there are flags south of Sky Hill farm and also on the summit of Sky Hill (see 6 inch map).Still farther east flags outcrop to the south of Claghbane and may represent the faulted eastern continuation of the Sulby Flags.The Niarbyl Flags outcrop on the south-cast coast of the island in the region of Niarbyl Bay.

Very homogenous slate,for which the name Cronk Sumark Slate is here suggested, is exposed to the north-west of the Sulby Flags. This slate outcrops on Mount Karrin and Cronk Sumark and in the region of Glen Trammon (see 6 inch map).

In the northern part of the Isle of Man greywacke is restricted to a band about 6 inches thick which is interbedded with the Sulby Flags. Rock of a similar type occurs in the south-east (Santon District) and north-west (Kirchmichael) parts of the island (Memoir p98-99).

The andesitic tuff occurs as a thin band at Ballnalargy in the south-west of the Isle of Man.

Order of Succession.

Cronk Sumark Slate

Sulby Flags

Breccia

Barrule Slates

Banded Beds

Agneash Grits

Lonan Flags

The above succession outcrops successively towards the north-west from the coast south of Maughold Head where the Lonan Flags are exposed. If a traverse is made in a north-westerly direction from Port Mooar, south of Maughold Head, the above divisions are crossed in the dip direction and hence it is possible to examine the order of deposition. This traverse does not include the Niarbyl Flags, andesitic tuff, or certain bands of greywacke described by Lamplugh.

On the east coast, Port Mooar provides a particularly favourable locality for the detailed examination of the Lonan Flags since exposures are wide and the surface of the rocks is washed clean by wave action. Current-bedding is common though small scale (see fig.26). Further way-up evidence in the north-west dipping Lonan Flags occurs at:

Dreemskerry	)	
	)	Current-bedding
Stream south of Cronk y Vaare	)	

Glen Mooar, Laxey River - graded bedding (slide 2100).

The way-up evidence in the above cases indicates that the strata are right way up.

To the north-west the Lonan Flags are succeeded by white quartzites (Agneash Grits) which display no way-up evidence. The quartzites are succeeded by banded strata and as one proceeds north-westwards there is a gradual reduction in the proportion of gritty material and one passes from banded strata into homogenous Barrule Slates. The banded strata generally show no reliable way-up evidence but isolated, rather poor current-bedding, has been found at:

Injebreck

South of the Bungalow Hotel on the Snaefell railway

Northern branch of the Snaefell River.

This way-up evidence indicates that the younger beds lie to the north-west and the constancy of strike and general dip suggests that it may be extrapolated over a wide region.

To the north-west the Barrule Slates pass by a sharp contact into breccia but the slate which underlies the breccia within about 30 - 40ft of the junction often differs from the main mass of Barrule Slates in that it is banded. Way-up evidence has been found in this banded strata at:

Sulby Glen (see fig.23) Glen Auldyn	Current-bedding
West of the farmstead of Lhergyrhenny in the stream between Snaefell and Beinn-y Phott	Graded bedding

This way-up evidence indicates that the beds are right-way-up and that the younger beds lie to the north-west.

To the north-west the breccia is succeeded by flags which in Sulby Glen display right-way-up current-bedding.The younger beds outcrop to the north-west.The Sulby Flags pass conformably upward into the Cronk Sumark Slates.The succession based on the way-up evidence is:

Cronk Sumark Slates

Sulby Flags (with which a thin band of greywacke is interbedded in Sulby Glen)

Breccia

Barrule Slates

Banded Beds

Agneash Grits

Lonan Flags.

The relation and age of the Niarbyl Flags relative to the other divisions is not known since they do not outcrop in the northern part of the Isle of Man.Near Ballnalargy a thin band of andesitic tuff is exposed.Graded bedding and current-bedding in the Niarbyl Flags to the west indicate that the strata are inverted and that the tuff lies above the Niarbyl Flags (the nearest rocks displaying way-up evidence are situated 300-400ft north-west of the tuff).

West.  East.

General view of Port Mooar to show expanse of wave-washed rock at this locality.

Figure 25.

Actual size: 10cm x 11cm

Current-bedding, right way up. Gob ny Garvain, south of Port Mooar.

Figure 26.

Age and Correlation.

Worm casts are the only common indications of animal life in the Manx Slates but in 1898 Bolton [I] claimed the discovery of the cast of the thorax and pygidium of a trilobite, identified as Aeglina or Asaphus, in the "crush conglomerate at Ballastowell, near Ramsey", and a specimen of Dictyonema sociale on the scree below the quarry at Cronk Sumark. These claims were not accepted by Lamplugh on the grounds that further specimens could not be found at the same localities and he points out that the supposed trilobite had been found "in the midst of highly sheared crush conglomerate" (Memoir p94). While he does not deny this possibility he considers that "the cast in question may be that of an exceptionally striated grit fragment in the conglomerate" and remarks that the graptolites on the other specimen "are thickly spread, as if the fossils were abundant" but that later searches at the same quarry had failed to find further examples. My own further search similarly failed to confirm Bolton's claim. Bolton's specimens have been re-cxamined by Drs. O.M.B. Bulman and C.J. Stubblefield and while they were far from convinced that the trilobite was of organic origin they confirm that the other specimen is a true dendroid. Dr. Bulman states:

"The rhabdosomes are all fragmentary and are greatly distorted by cleavage. Bolton's figures are not exactly accurate, but give a good general impression of the material and its state of preservation. The distortion affects differently orientated rhabdosomes so that the stipes vary from 6-7 in 10mm in one direction to 16-20 in 10mm for those disposed at right angles; I feel sure that only one species is present. Bolton's association of D. sociale with Dendrograptus flexuosus is, of course, in the highest degree improbable, the one being a Tremadoc and the other an Arenig species.

Cleavage has obliterated most of the dissepiments, but traces occur on almost every fragment though it is impossible to estimate their original frequency. I cannot agree with the recognition of Dendrograptus, but it is difficult to eliminate entirely the possibility of Callograptus in the absence of any proximal ends. Were it a Callograptus, it would be something of salteri type.

I think, however, it is more probable that the specimens represent Dictyonema flabelliform, and indicate the existence of Tremadoc in the Manx Slates. This identification lacks certainty, and apparently the associated fauna is of no help. On one specimen however (449I) there are what appear to be Protospongia spicules."

Dr. Stubblefield is "impressed by the abundance of the Dictyonema fragments and the evidence from these two slabs that the fossils are not merely on single bedding planes;" he continues "that if Dendroids do in fact occur in the Manx Slates, the find should be capable of confirmation by the finding of new duplicate material. Until this is found I regard Bolton's original locality record as suspect, particularly, in view of Lamplugh's comments published in the Geological Survey Memoir."

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refs. from p 87.

I. Bolton, H. "The Palaeontology of the Manx Slates of the Isle of Man" Mem. & Proc. of the Manchester Lit. & Phil. Soc. Vol. 43 Pt. I 1898-99 pI-I5. Pl. I, fig. I.

The rock bearing the Dictyonema is similar in hand specimen to the slate in the quarry at Cronk Sumark.A thin section of the rock was prepared at the Geological Survey & Museum (Enq I276) for comparison with slides of rocks from the alleged locality.The rocks consist of grains of quartz evenly distributed in a matrix of micaceous and cryptocrystalline material.The largest quartz grains reach 0.05mm in Enq I276 but some of those in slides from specimens obtained at Cronk Sumark are slightly larger and reach 0.Imm maximum diameter.The largest laths of muscovite are of the order of 0.Imm. Intergrowths of chlorite and muscovite which reach 0.2mm have been seen. These intergrowths are present in small amounts in Enq I276 and also in the slides from Cronk Sumark. Green pleochroic tourmaline (0.Imm) forms an accessory in some of the Cronk Sumark slides but has not been seen in Enq I276.Leucoxene,limonite,black opaque iron, and pyrite form accessories in all the slides but pyrite was not seen in Enq I276. Fracture cleavage is less strong in this region than in other parts of the Manx Slates but is present in all slides including Enq I276. The micaceous constituents in Enq I276 and the Cronk Sumark slides show preferred orientation imparting flow-cleavage to the rock. In Enq I276 bedding is not visible but occurs in certain,though not all,of the Cronk Sumark slides.It cuts the flow-cleavage at an angle of between 20-30 degrees. (see figs. 28A & B). A slide of Dictyonema-bearing slate from Portmadoc,Caernarvonshire,was prepared for comparison.This has a similar fine-grained base of sericite and cryptocrystalline material.Fracture cleavage is weak and there is a faint flow-cleavage parallel to the bedding.The grain size of the larger crystals is greater than in any of the Cronk Sumark slides or Enq I276 and consists of small irregular grains of quartz (0.2mm for the largest) and larger irregular shaped patches (0.8mm) of a sericitic aggregate possibly derived from felspar.Small crystals of unaltered plagioclase are also present.Intergrowths of chlorite and muscovite are also common (longest diameter 0.2MM).The pseudomorphs after felspar (?) distinguish the Portmadoc rock from the Cronk Sumark slides and Enq I276.

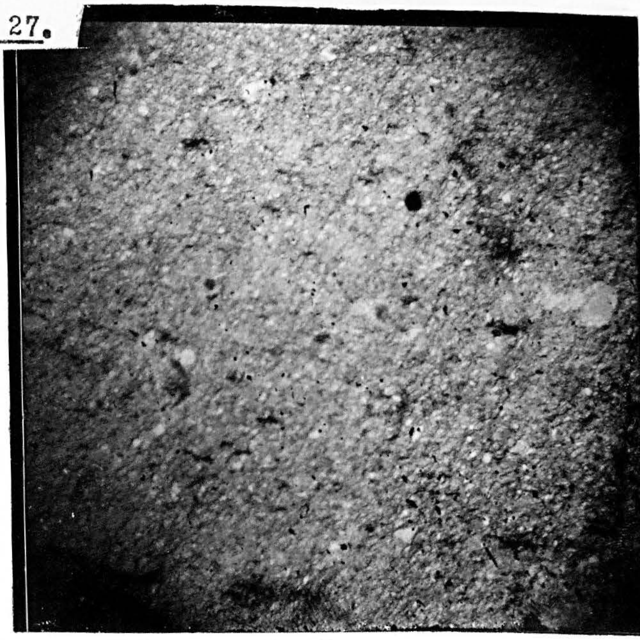
In my opinion the lithological similarity between the Cronk Sumark rock and that bearing the Dictyonema (Bolton's specimen) supports Bolton's claim and it is likely that the specimen did come from the Isle of Man at Cronk Sumark.According to the order of succession based on the above stated way-up evidence,the slate at Cronk Sumark is the youngest exposed division of the Manx Slates in the northern part of the Isle of Man and the underlying parts of the series must be older than Tremadoc.

Dictyonema flabelliform - Bolton's specimens.

Figure 27.

Enlarged 35 times.

Figure 28A



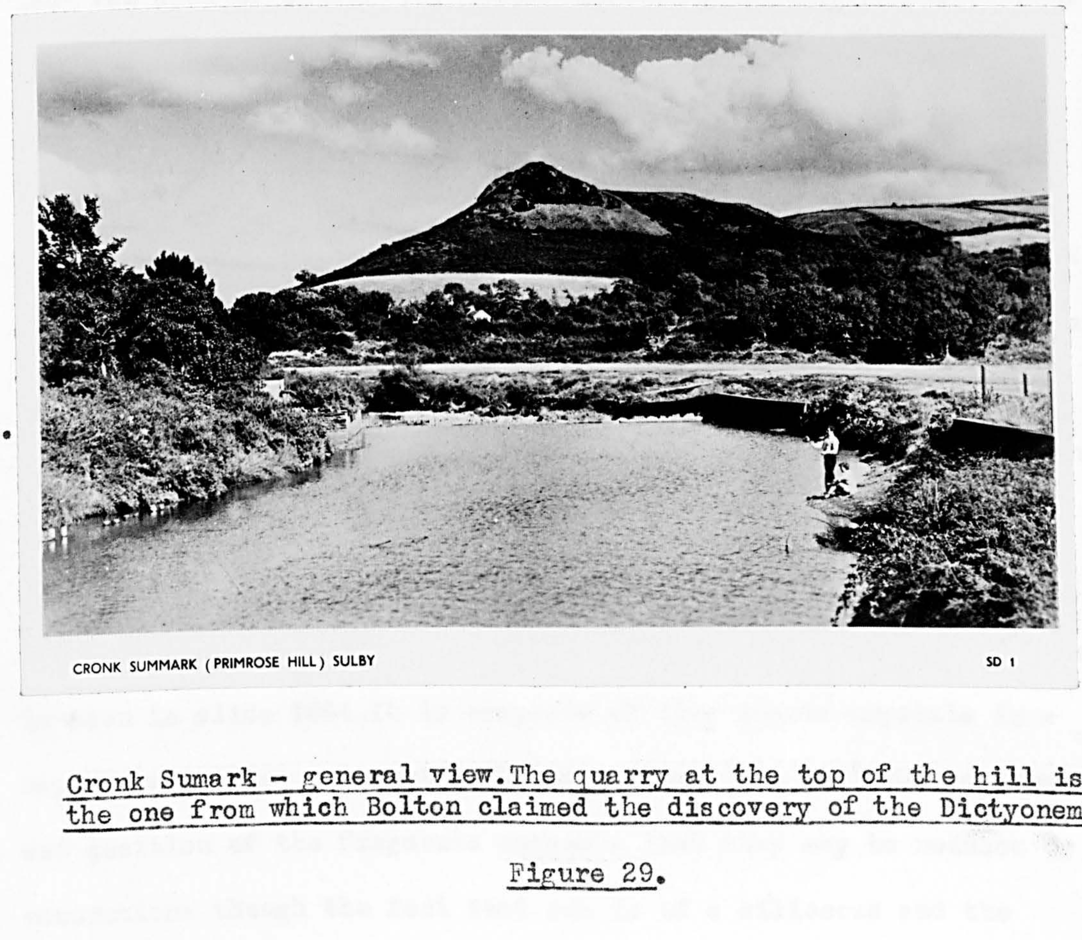
Enlarged 35 times.

Figure 28B

A - Microphotograph of specimen from Cronk Sumark (slide I49I)

B - Microphotograph of slide Enq I276.

East.



West.

Cronk Sumark - general view. The quarry at the top of the hill is the one from which Bolton claimed the discovery of the Dictyonema.

Figure 29.

Nodules.

In the slate of the quarry at Cronk Sumark there are two curious fragments (see fig.30) lying with their long axes parallel to the bedding which appears to be deflected upwards over the smaller elliptical shaped example,as if due to compaction. However the beds are not so affected by the other,somewhat larger fragment which is rectangular with irregular terminations.Slides were made of specimens of both of these and the surrounding slate. Slide I493 illustrates the larger of the two fragments and shows it to be a fine-grained rock made up largely of calcite and cryptocrystalline material.Small quartz crystals are quite common and quartz veins also occur;limonite has stained much of the rock brown.I492 is also fine-grained and composed of very tiny quartz crystals in a cryptocrystalline matrix.Calcite is absent and the rock is distinct from the previous example.The intervening slate is also distinct as is seen in slide I494.It is composed of tiny quartz crystals in a cryptocrystalline and partly micaceous base (see p89).The appearance and position of the fragments suggests that they may be nodules or concretions though the fact that one is of a siliceous and the other of a calcareous nature is curious.

Nodules occur in the Lonan Flags especially in the Port Cornah district.

Two thin sections (2032,2034) of specimens from Niarbyl Bay consist of fine-grained micaceous and cryptocrystalline material. In both slides there are characteristic rounded patches made up of a bright polarising aggregate consisting of calcareous and,or, sericitic material. They are often dusky due to small inclusions and have a radiating appearance with a dark, possibly carbonaceous, core. These aggregates are virtually confined to thin sedimentary layers of which they constitute practically the sole constituent; they show a tendency to form separate aggregates. Their precise nature is obscure but it is suggested that they are spherulites (Twenhoffel, 1939 p570), or oolites and are an original sedimentary feature.

Cone-in-cone.

Cone-in-cone in the outer crust of nodules was described by Lamplugh (Memoir p35,128,182). It does not appear to have been previously described from the normal sediments, but an example was found to the north of Peel (see fig.31). It is stated by Tarr[1] that it is commonly found in association with concretions being due to pressure often associated with the change of aragonite to calcite and at this locality in the Isle of Man, there are oval-shaped structures possibly of a concretionary nature (Memoir p121). These occur singly and also in groups of three or four arranged in strings which are straight or curved. A thin section (2043) shows that this particular example is composed of fine-grained calcite which is granular in the centre, showing thin banding parallel to the longest diameter, simulating bedding but fibrous near the edge with the fibres arranged vertically. The section is crossed by a strain-slip cleavage.

1. Tarr, W.A. "Cone-in-cone" Am. J. Sci. 1922 Vol.5, No.4 p199-213

The cone-in-cone occupies an area of about 30cm by 45cm in the field and the individual cones have a height of from 2.5 - 5mm and a diameter which varies from 3 - 9mm and are developed in homogenous black slate. They are small, conical impressions which show vertical ribbing and a slight crinkling which is concentric to the apex of the cone and on a finer scale than the vertical ribs.

Concretions? Cronk Sumark.

Figure 30.

Cone-in-cone. Found to the north of Peel.
Actual diameter of cones 3 - 9mm.

Figure 3I.

Folds.

Folds in the Isle of Man belong to two well-defined generations related to two dominant cleavages,though the local development of other cleavages implies that other movements also took place.The earlier folds are sharp-crested and isoclinal,with axial plane schistosity or flow-cleavage.The later folds are less sharp and fracture cleavage is parallel to their axial planes.

a) The early folds.

In field exposure and thin section the flow-cleavage appears to lie parallel to bedding except at the apex of the folds.Any divergence from true parallelism to the bedding is difficult to detect microscopically because of intense puckering of the micaceous folia by the later fracture cleavage.Until sections showing the axial region of the early folds had been prepared,doubt existed as to the precise nature of the cleavage parallel to their axes and the possibility was considered that the parallelism of the micas was more strictly to be regarded as bedding foliation rather than true cleavage.

The axial planes of these folds are steeply inclined at angles of about 55-60 degrees to the north-west on the north-western side of the island and at a similar amount to south-east on the south-eastern side.The frequent vertical dips on bedding (to which the flow-cleavage is virtually parallel) in the axial region,as along the Baldwin Valley (see Memoir p159),indicates that this cleavage has the form of an inverted fan.The geometry of the folds suggests overthrust towards the central axis of the island from both north-west and south-east.

These folds can be most readily examined on the coast due to the wide expanse and continuity of the exposures,and south of Ramsey particularly favourable localities for study are Port-e Mwyllin,Maughold Head,Port Mooar,and Traie ny Uainaigue.

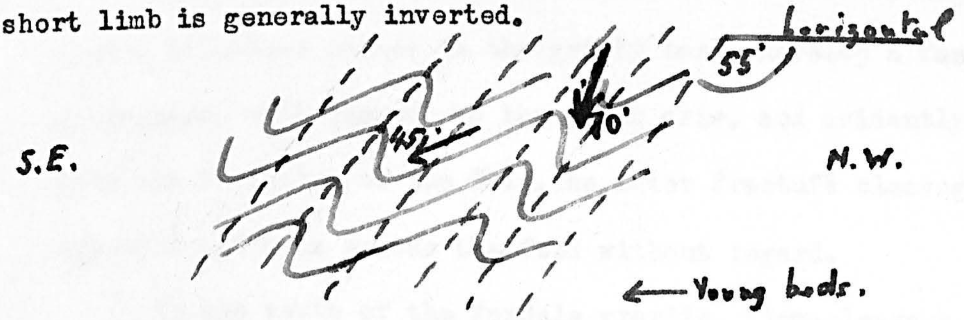
Fig.32 and 33 show the sharp nature of these folds in Port-e Mwyllin and illustrate the incompetent behaviour of the argillaceous bands which are greatly thickened in the axial region,as also are the grit bands but to a smaller extent.Both the steeply inclined flow-cleavage which is parallel to the axial plane of the folds and the later,cross-cutting fracture cleavage,which dips at a lower angle in the same direction can be seen in the figures.In the lower part of fig,32 there are quartz veins parallel to the fracture cleavage and other veins which cut irregularly across all structures (top right of fig.).

In the inlet of Traie Curn at Maughold Head,folds of this type occur in more thickly bedded strata in which grit bands up to 15cm thick are common,and those around 7cm most typical;the argillaceous partings between these bands are generally only of the order of 2.5cm in thickness.Two synclines and an anticline are exposed. This anticline is of interest because both limbs have been refolded in the later movements during which the fracture cleavage developed and it is therefore a re-folded fold.

Fig.34 shows one of the synclines the axial plane of which is inclined at 85 degrees north-west. Thin sections were prepared from a specimen of this syncline. One section shows the axis and the other the banded slate on the limb of the fold. Microscopically the section of the axis shows that the small micas are parallel to the axial plane of the fold. Fracture cleavage seems absent. In the section which illustrates the banded slate on the folds limb the fracture cleavage is clear and has a dip of 5-6 degrees to east-north-east. It is quite unrelated to the axial plane of the fold. The fracture cleavage puckers the flow-cleavage and renders the slight angular discordance between this and the bedding hard to detect, so that its cross-cutting relation may not have been recognised but for the accompanying section from the folds axis.

Fig.35 shows folds of this generation in the Agneash Grits above Maughold Head. The plunge is sometimes steeper on these folds at this locality (35 degrees) than is the plunge of folds of later generation related to the fracture cleavage. A steep plunge has also been recorded on early folds elsewhere (e.g. Slieau Lewaigue, stream bed south of Snaefell).

Early folds are exposed near Traie ny Uainaigue. The figs. (36,37, 38) illustrate the folds and the systematic change in dip (see pI34). Fig. 36 shows an early movement syncline, the axial plane of which dips at 55 degrees to south-east. The regional fracture cleavage is indistinctly seen on the lower left of the figure (though it is more evident in the field). The axial plane cleavage is clear near the centre of the photograph. Erosion has found easy access along the crests of the anticlines (fig. 38) which have not infrequently been breached leaving the south-east dipping limb isolated and surrounded by the sea to form a small stack. In the foreground fig. 37 shows the steeply south-east dipping flags which outcrop to the south of Traie ny Uainaigue; to the north, through a cleft, the landward (north-west) dipping beds can be made out (see pI35). In the folds of this generation exposed at this locality the short limbs face north-west and the axial planes dip south-east at about 55 degrees. The folds are normal synclines and anticlines but the short limb is generally inverted.



Folds of this type are not confined to the coast and a particularly good example is provided by slide I535 (see fig. 39).

This fold has a steep plunge to north-north-east (65 degrees) while the axial plane is inclined at 70 degrees west-north-west. The fracture cleavage dips at 45 degrees to north-east and is unusually steep for this structure.

Fig. 4I illustrates a specimen (I533) of an isoclinal fold. A slide of the axis, when examined under the microscope, shows that the small platy minerals cut the bedding and are parallel to the axial plane of the fold. Planes of shear also occur which are parallel to the folds axis and in the crest, a gritty band (8 - I0 mm) is fractured. The curious point about this fold is that the axial plane lies at about the inclination to be expected if it were parallel to the fracture cleavage (north-west at 20 degrees). Flow-cleavage is parallel to the folds axis and this suggests that it developed in the early movements so that it is possible that the original inclination of the axial plane has been altered by later movements.

There are folds of this generation on Slieau Lewaigue (slide 33).Shear planes in the gritty bands develop a fan-like arrangement with respect to the folds axis, and evidently date from the formation of the fold.The later fracture cleavage is distinct and cuts across the fold without regard.

To the south of the Foxdale granite, flow-cleavage folds still occur and are illustrated by a specimen (I898,fig.4I) obtained in a quarry just above Awin Ruy - the stream draining south to form the Silverburn.Fracture cleavage is generally weak in this area and is not seen in the photograph.

Slide I998 from Cronk Breac,east of Greeba Mountain and 2I42 from the road near Lonan Church also illustrate small folds of this generation.

South-cast.

North-west.

Port-e Mwyllin - field view of syncline. The flow-cleavage is parallel to the folds axial-plane and is inclined north-west.

Figure 32.

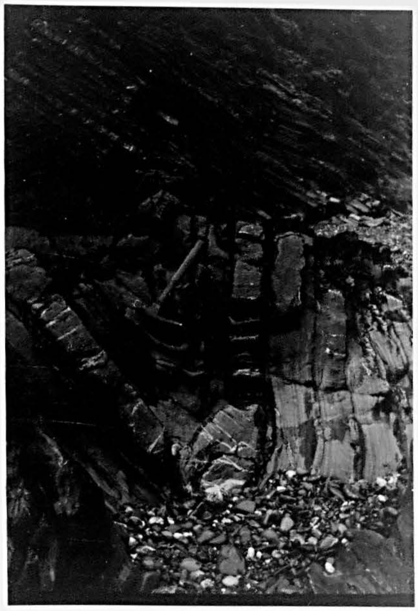
Observer facing East W. 355. 85.

Actual size: 5.2 cm by 2.0 cm.

Enlargement of slide 2062, Port-e Mwyllin. To show cross-cutting relationship of fracture cleavage and axial-plane schistosity.

Figure 33.

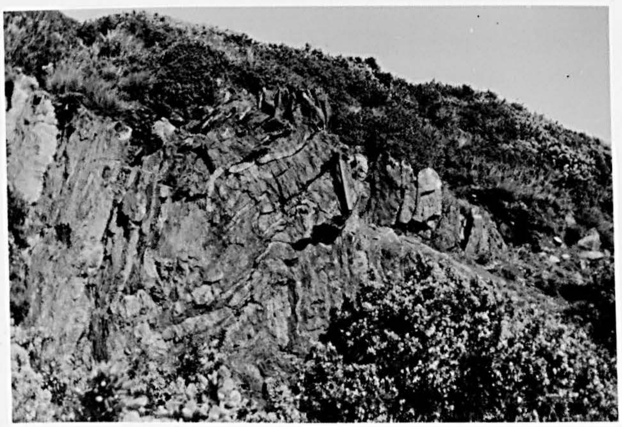
South-east



North-west

Syncline in grits at Traie Curn, Maughold Head - flow-cleavage parallel to the folds axial plane.
Figure 34.

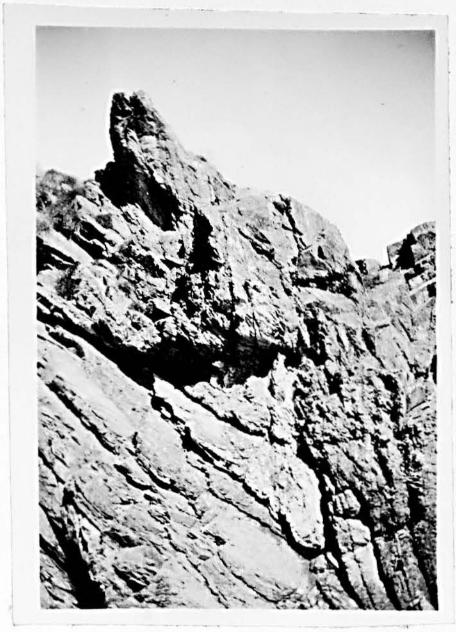
North-west



South-east

Folds in Agneash Grits - early movements.
Figure 35.

North-west



South-east

Syncline of early movements with axial-plane inclined steeply south-east. Traie ny Uainaigue.

Figure 36.

W.

E.

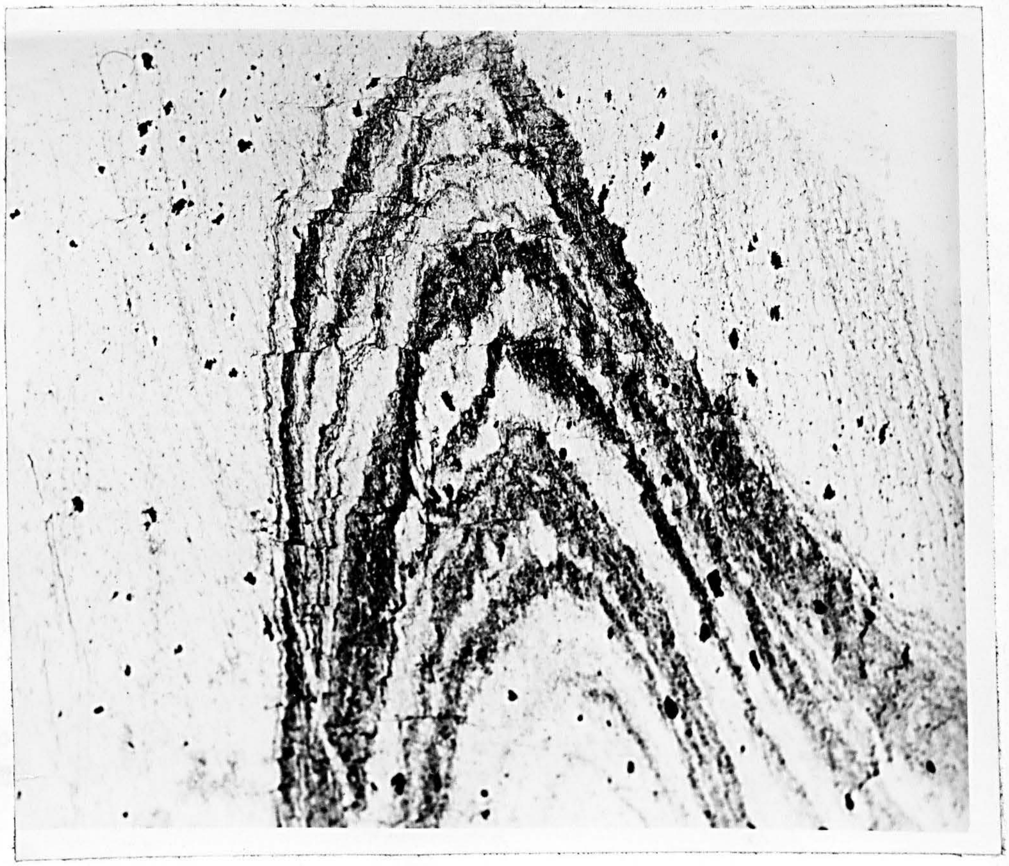
Easterly dipping flags in foreground-note landward dips to north. Traie ny Uainaigue.

Figure 37.

Removal of crest of fold by erosion. Traie ny Uainaigue.

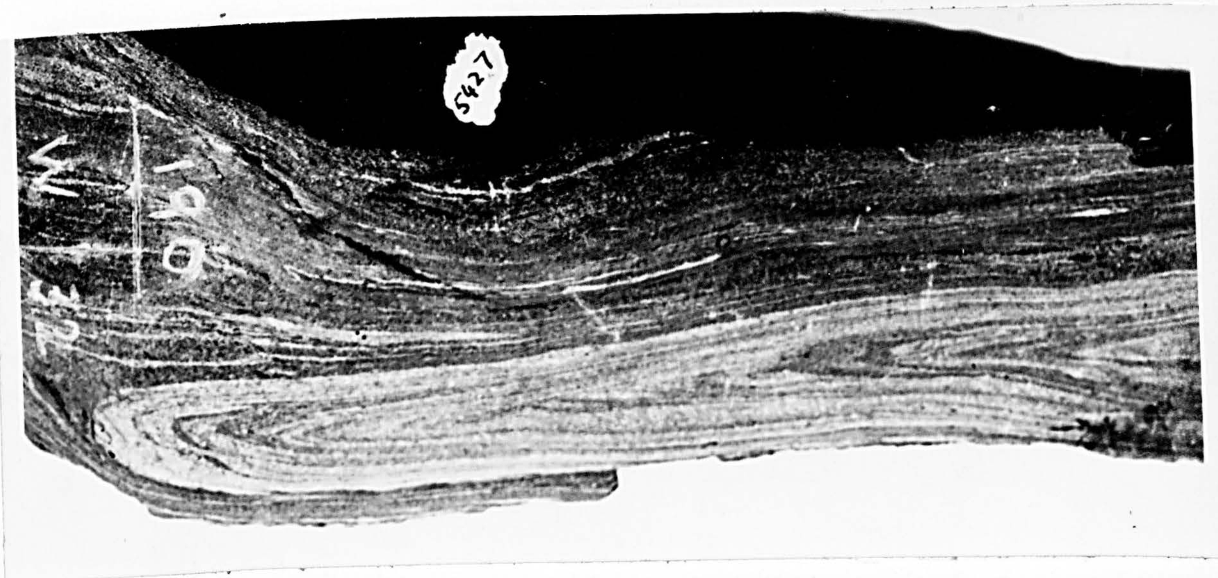
Figure 38.

Observer facing north-east. 120° / S.W. 60



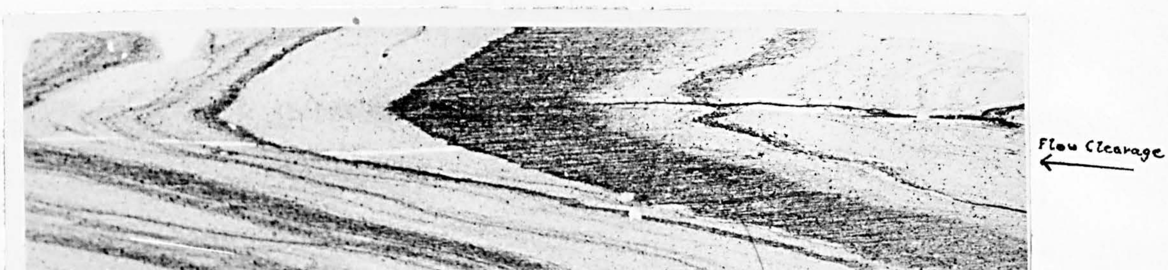
Actual size: 2.5cm by 2.0cm.
Enlargement of slide I535. Specimen obtained in stream-bed between Snaefell and Beinn-y Phott. Fracture cleavage cuts axial-plane flow-cleavage at about 90 degrees.

Figure 39.



Actual size:20cm.
Hand specimen of isoclinal fold obtained in stream bed south of Snaefell north of Beinn-y Phott.

Figure 40.



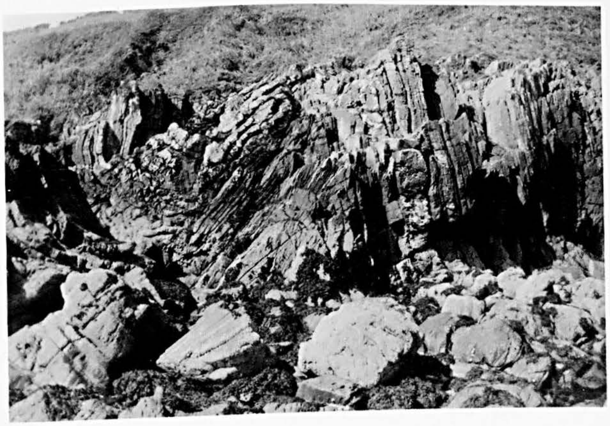
Actual size:5.2cm by I.7cm
Enlargement of slide I898 obtained in the quarry above Awin Ruy, Foxdale.

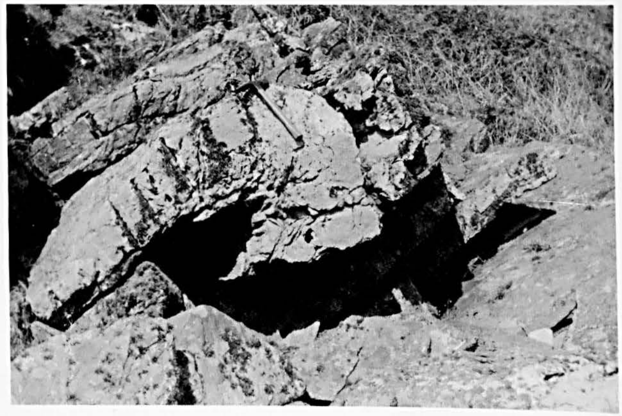
Figure 4I.

Intermediate Folds.

In Port Mooar there are shallow near-upright folds. They are overturned to north-west on the south-eastern side of the bay (see fig.42,43) but at the north-western end of the inlet they are overturned towards south-east. The inclination of the folds axial-planes suggests that they belong to the early generation but sections from specimens near the axes of several different ones do not bear this out, since the micas are parallel to the bedding, and the only cleavage which seems related to the folds' axial planes is a wide-spaced fracture cleavage (e.g. slide 1065). Fig.44 shows one of the anticlines on the north side of the bay the crest of which has been removed by erosion. This shows the wide-spaced, near vertical, axial plane cleavage and the shallow-dipping regional fracture cleavage. The gently inclined fracture cleavage is better seen in fig.45 which shows the eastern limb of a fold. Small overturned folds with axial planes parallel to the shallow-dipping fracture cleavage occasionally occur on the limbs of these upright folds.

To the south of Port Mooar a near-upright anticline (axial plane inclined 80 degrees south at 10 degrees north of east) occurs on Gob ny Garvain (fig.46). This has a very gentle plunge to west. The regional fracture cleavage is not so strongly developed in the flags exposed at this locality as in the slates, and is imperfectly seen in the plate. It intersects the axial plane of the fold at a low angle. A widely spaced system of fractures parallel to the folds axial plane are visible in the plate.





S.E. N.W. S.E. N.W.

South-east side of Port Mooar - overturning of folds to north-west.

Figure 42. Figure 43.

N.W. S.E. N.W. S.E.

Near-upright fold of which the crest has been removed by erosion. N.W. side of Port Mooar.
Figure 44.

East limb of fold showing shallow-dipping fracture cleavage which is unrelated to folds axial plane.
Figure 45.

West.

East.

"Intermediate fold" on Gob ny Garvain.

Figure 46.

Overturned Folds.

Younger folds related to the fracture cleavage are more common than those above described. They occur throughout the area mapped. On the north-western side of the island their axial planes are inclined at about I5-20 degrees to north-west (parallel to the fracture cleavage) and the short limbs face north-west which is the closure direction of the anticlines. On the opposite side of the island these directions are reversed and the short limbs again face away from the central zone, towards the south-east, in which direction the anticlines close.

Fig.47 is a view, looking south, of the overturned folds exposed south of Traie ny Uainaigue. It shows the south-east facing short limb and inclination of the axial planes which are parallel to the fracture cleavage. Fig.48 shows folds at Gob ny Strona, Maughold Head, the axial planes of which are only gently inclined, and since it is likely that these beds young north-west the anticlines are overturned towards the north-west (landwards). The height of the section is about 80 feet. Fig.49 is a view of folds of this generation in the Agneash Grits above Maughold Head. Fig.50 shows this type of fold in a quarry in banded beds above the coastal cliffs near Stack Mooar. The relative position of the folds long and short limb are visible in the photograph. Fig.5I shows similar folds in the flaggy beds exposed in the quarry at Ballajora, Maughold, where occasional current-bedding indicates that the younger beds lie to north-west,and that the succession is right way up.

Fig.52 shows the lower limb of a recumbent fold (recumbent syncline if beds assumed right way up) exposed south of Gob ny Cally.The incompetent behaviour of greywacke bands is well shown. The axial plane is parallel to the shallow-dipping fracture cleavage.This fold seems to be resting on a thrust-plane dipping south-east at a low angle (5 degrees), since though the beds above and below this plane are of a similar lithology,individual bands cannot be matched.The folds general appearance is similar to the fold south of Maughold Head described by Lamplugh (Memoir p32).

Fig.53 is an enlargement of a microscope slide which illustrates a specimen of a fold (468) which occurs on Ballastowell, and is a typical example of the generation which are related to the fracture cleavage.This structure lies truly parallel to the folds axial plane in the area of the section.The micas lie parallel to the bedding unless dragged by the fracture cleavage.

Fig.54 (slide II69) illustrates a fold of this generation which occurs in banded strata in Glen Mooar.The gritty bands show small-scale brecciation and in places are regularly stepped-up along the planes of fracture cleavage (left centre of photograph). The incompetent argillaceous bands are thickened in the axial region.The micaceous folia lie parallel to the bedding and are puckered into a series of small folds and displacements by the fracture cleavage.

Slide IOI7 represents a fold in banded beds on the Snaefell railway, below the Bungalow Hotel. The oriented specimen clearly shows the shallow north-west inclination of the axial plane and parallel fracture cleavage. The fold has a plunge at a low angle to north-east and if the beds are regarded as younging to north-west, as the evidence suggests, it is an overturned anticline. Thin beds in either limb are regularly stepped-up towards the axis of the fold by the fracture cleavage.

I488 is a specimen of a fold which occurs in unbrecciated, thinly banded beds which are interbedded with the breccia exposed in Sulby Glen. The folds axial plane is parallel to the gently dipping fracture cleavage and is inclined at about 25 degrees to north-west.

Specimen I622 was obtained below the road past Snaefell to Tholt-c-will and shows a fold of this generation. The fracture cleavage is parallel to the axial plane and is inclined at about 30 degrees north-north-cast but is less strongly developed than is often the case. A narrow vein of sericite crosses the bedding at a low angle. It is involved in some of the microfolds shown by the bedding but since it is not broken in passing from one band to the next bedding-plane slip has not occured, though the vein does show a certain amount of curvature which is possibly to be attributed to plastic flow of the containing material. Specimen I643 illustrates a similar fold.

Slide I430 illustrates a specimen obtained in the feeder system to Glen Auldyn and shows a small fold in thinly banded slate. The micas lie parallel to the axial plane of this fold but are arranged in thin folia separated by areas composed of tiny quartz crystals or cryptocrystalline material. The appearance is more like an extreme gradation of shear cleavage than true flow or slaty cleavage. This cleavage is inclined at 25 degrees to north-cast and therefore lies about parallel to the common inclination of the fracture cleavage. Fracture cleavage however is also present, and post-dates the shear cleavage which it puckers and displaces. It is inclined at a low angle to south. If the shear cleavage developed at the expense of a fracture cleavage some displacement of bands, clearly related to it would be expected, but the only displacements have been caused by the fracture cleavage. To link either of these structures with the regional cleavages is difficult, but possibly the mica parallelism was acquired during the early movements and subsequent folding gave it its present low inclination. The shallow dip of the fracture cleavage may be due to local causes which are unknown.

A quarry on the left bank of the tributary to the stream flowing past Block Eary just above its junction with Glen Mooar exposes thinly banded slate with a strong north-west plunging lineation, to which the plunge of a small fold is parallel (specimen 2II0). The axial plane of the fold is inclined at I5 degrees to north-west. The fold has an amplitude of 20mm. It seems typical of the overturned folds which are related to the fracture cleavage but the north-west plunge is unusual.

A specimen of a fold in thinly banded slate obtained in the East Baldwin (I958) has a distinctive,cylindroidal crest.The plunge is to north-north-east at a low angle (5 degrees) and the axial plane and parallel fracture cleavage are inclined to west-north-west at 30 degrees.

Sharp folds (axial angle 80 degrees),are exposed in the thinly banded slate at Glen Mooar (see fig.55).They are of the zig zag,or chevron type (Sherbon Hills[I]) and it appears that rotation about knick-planes has occured.The beds are contorted at the axis.The platy minerals lie parallel to the bedding and the fold post-dates the early movements.

South of Ramsey there is a fold in the flow-cleavage.The axial plane is parallel to the fracture cleavage and has a dip to north-west at 5 degrees and a plunge at IO degrees in the unusual direction of north-west.Thin bedding crosses the fold and is lost to view before the exact nature of its geometric form is exposed.Since the flow-cleavage lies parallel to bedding except in the axial planes of folds which date from the early movements,it seems likely that a fold which formed during these movements has been refolded,the region exposed evidently being that of its axial plane.The whole structure is no doubt similar to the re-folded anticline seen in Traie Curn (see p.99).

I.Sherbon Hills,E. op cit I953 p.88

A specimen of a fold obtained in Ballure Glen is of particular interest since it displays two fracture cleavages in addition to the flow-cleavage which lies parallel to the bedding. Fig.56 shows an enlargement of the thin section and the two fracture cleavages referred to are clearly shown. One is near parallel to the axial plane of the fold and the earlier fracture cleavage is itself folded though its axis is shifted relative to that of the bedding.On the left of the figure the early fracture cleavage displaces the bedding along minute slips.The latest, axial-plane fracture cleavage, similarly displaces both bedding and early fracture cleavage.The flow-cleavage lies parallel to the bedding and therefore the movements in which the early and late fracture cleavages developed both post-date those in which the flow-cleavage formed,so that there is evidence for three distinct movements:- I) Flow-cleavage producing movements. 2) Early fracture cleavage producing movements. 3) Late fracture cleavage producing movements. The second fracture cleavage is parallel to the regional,gently inclined,fracture cleavage.

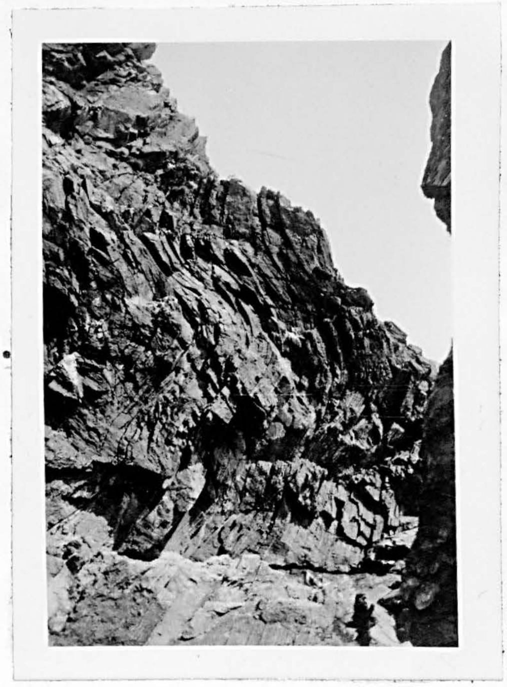
E.

W.

Folds south of Traie ny Uainaigue showing overthrust to south-east. Fracture cleavage parallel to axial planes.

Figure 47.

W.



E.

Folds at Gob ny Strona, Maughold Head. Height about 80 feet.

Figure 48.

W.

E.

Fold in Agneash Grits, Maughold Head, which is related to gently inclined fracture cleavage.

Figure 49.

W.  E.

Folds near Stack Mooar, south of Ramsey.
Figure 50.

W.  E.

Folds in quarry at Ballajora.

Figure 5I.

E.  W.

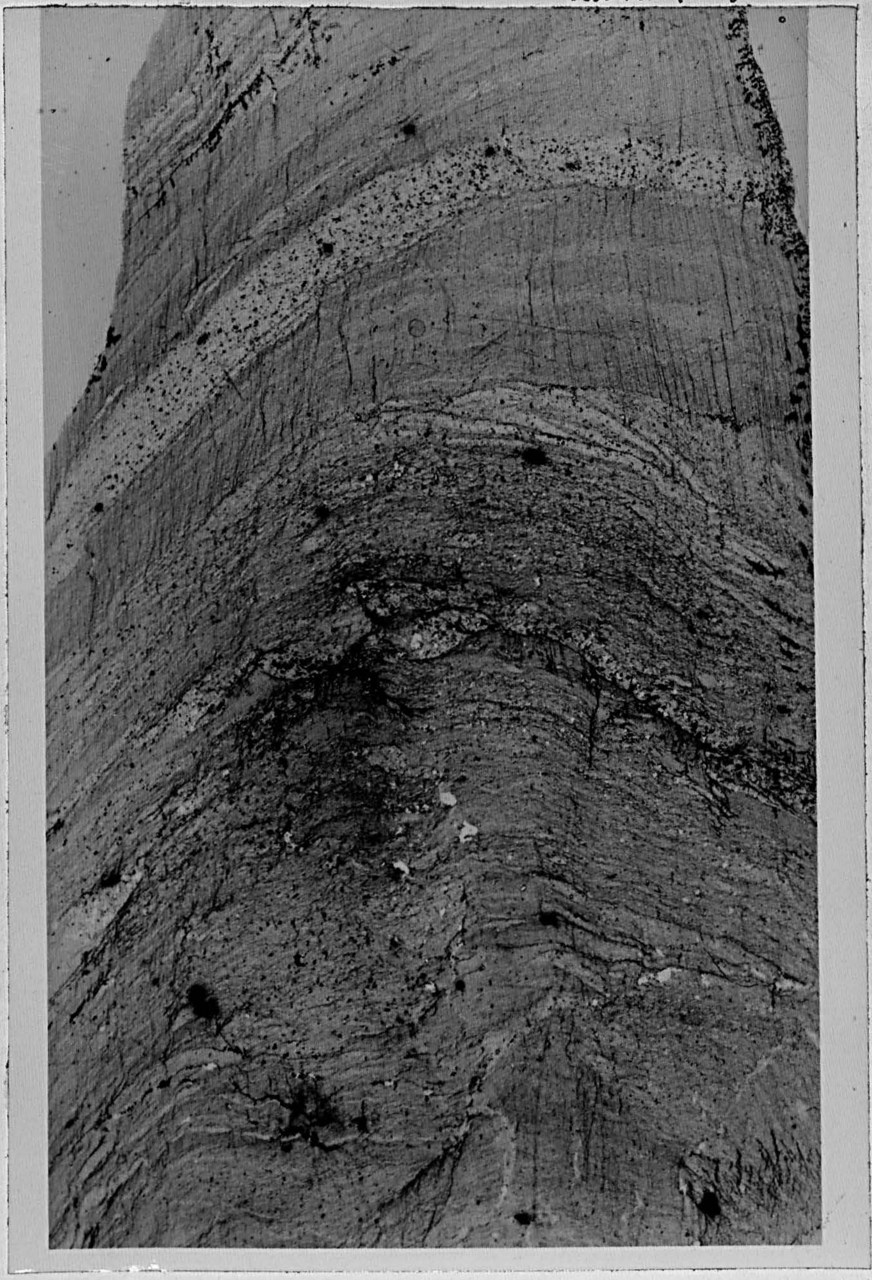
Recumbent fold at Gob ny Cally, observer facing south.

Figure 52.

320/50 S.W.

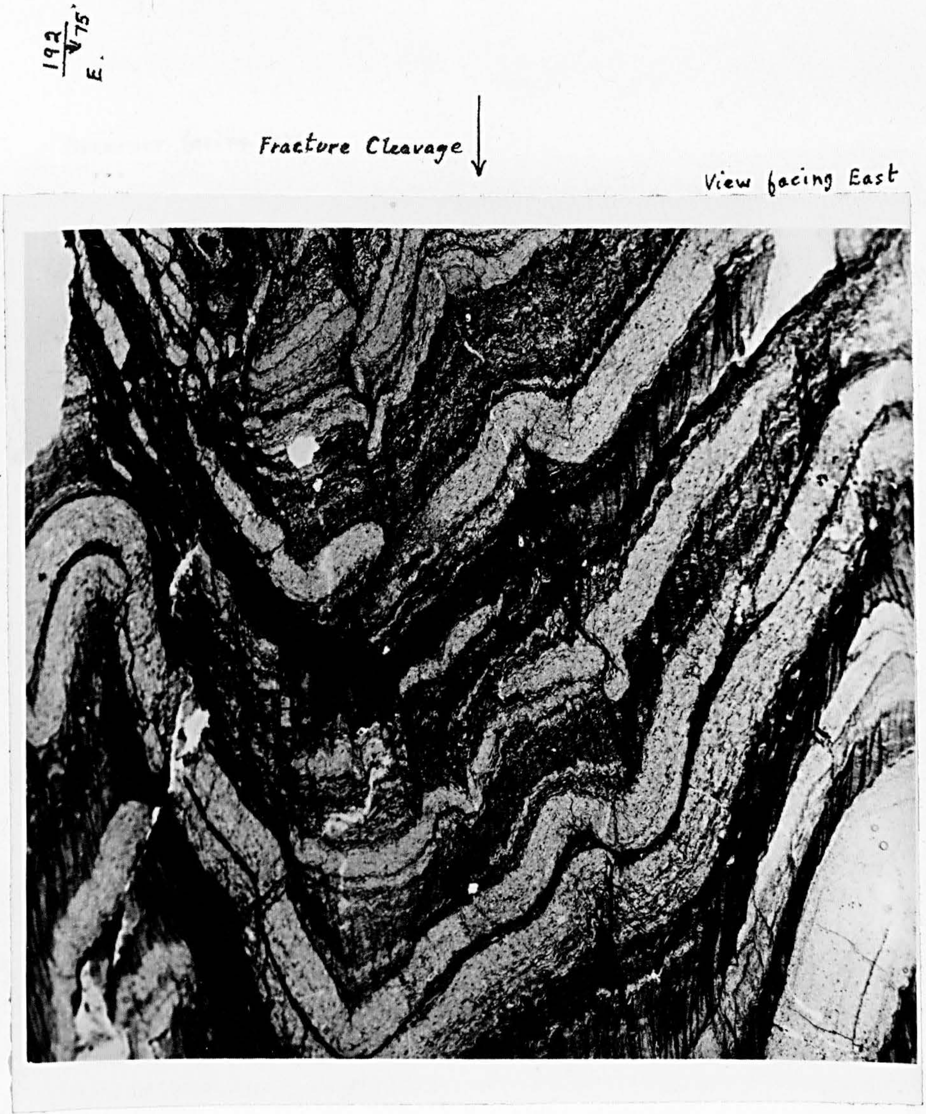
Fracture cleavage

Observer facing N.E.



Actual size: 6.3 cm by 3.2 cm.

Enlargement of slide 468 - Fold on Ballastowell.

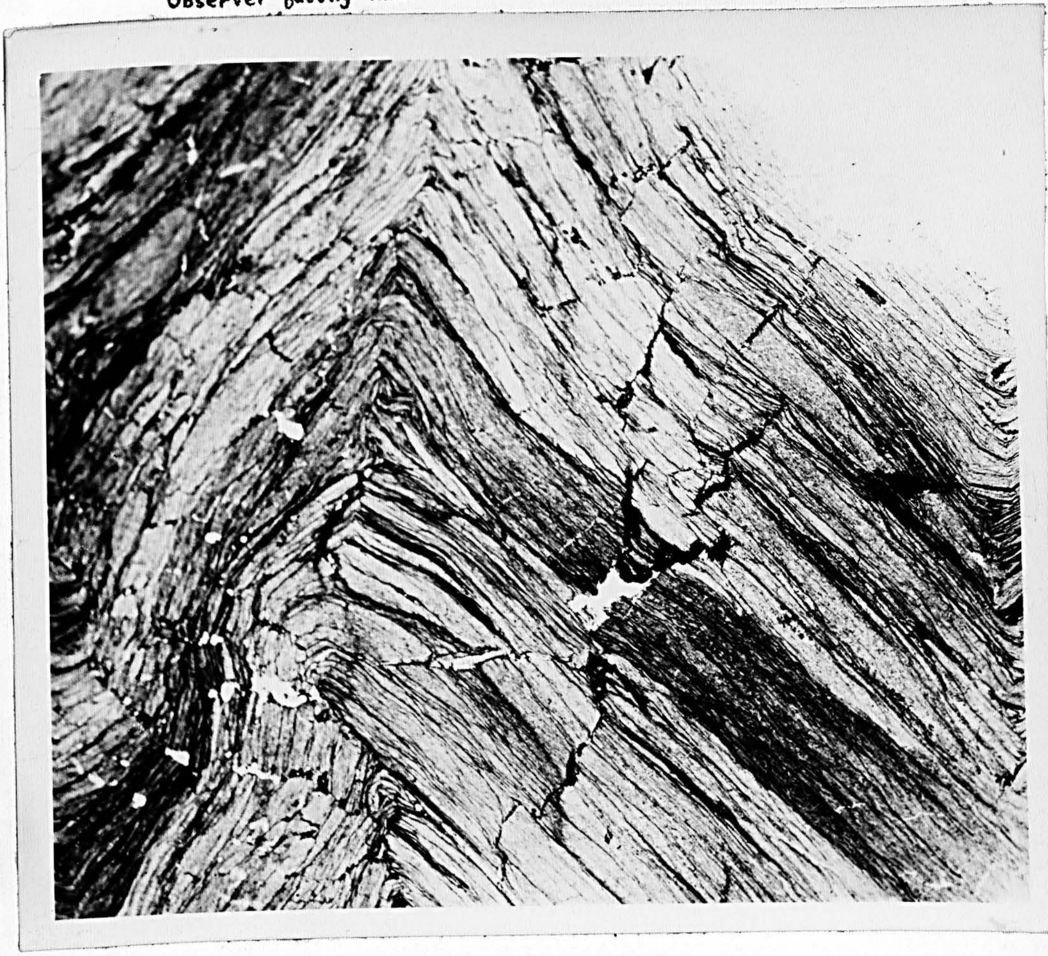


Actual size: 3.8cm by 3.Icm.
Enlargement of slide II69.Fold at Glen Mooar.

Figure 54.

045 V 80° S.E.

Observer facing N.W.

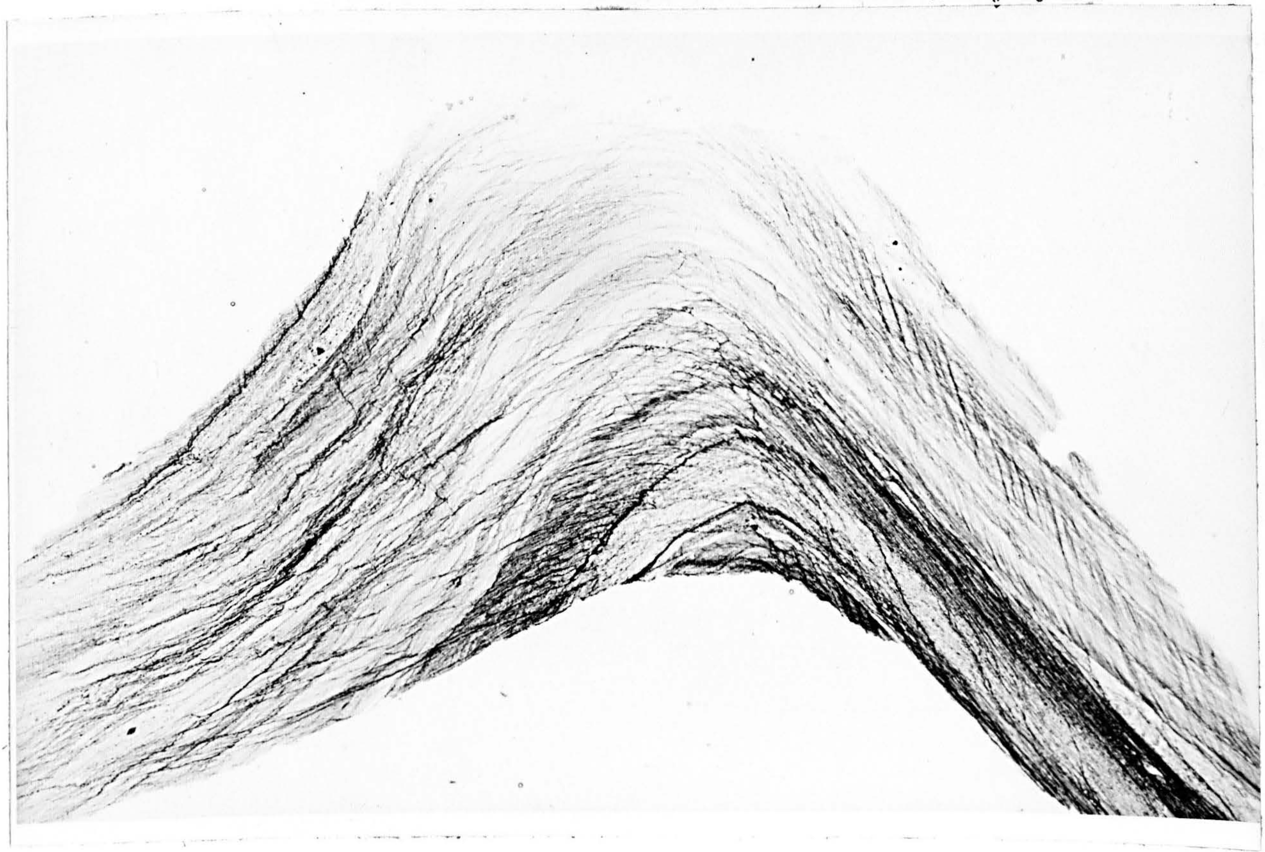


Actual size:2.8cm by 2.5cm.

Enlargement of slide II67.Chevron folds at Glen Mooar.

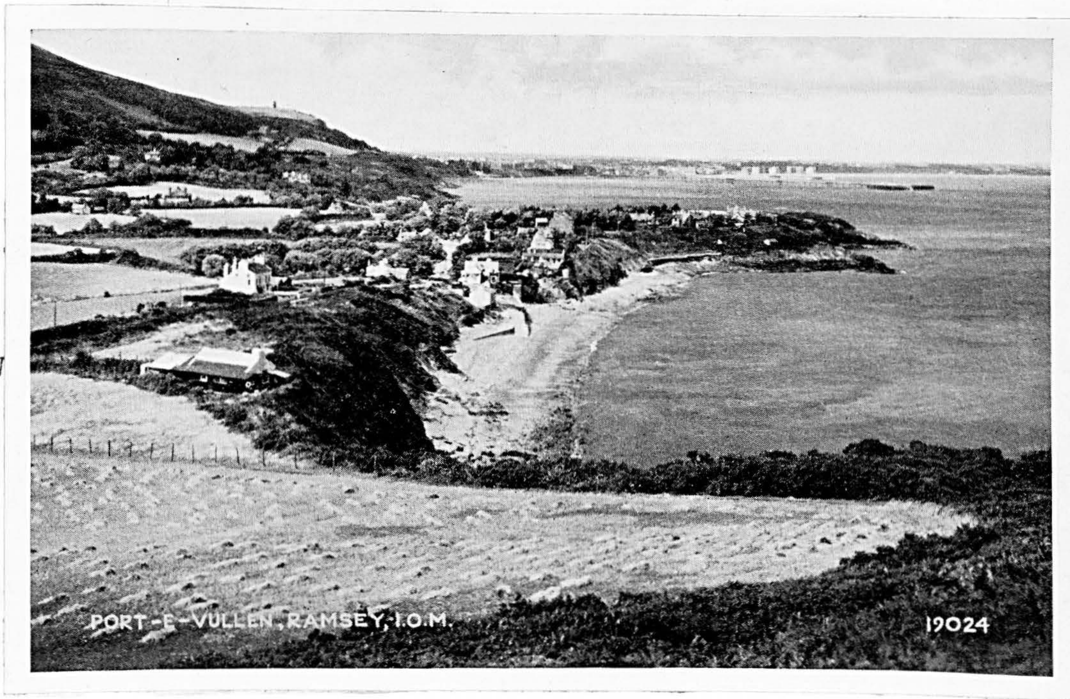
Figure 55.

View facing East.



Actual size: 5.5cm by 3.0cm.
Specimen of fold from Ballure Glen, Ramsey to show two fracture cleavages. One (the latest) is parallel to the folds axial plane - see in particular the right hand side of the figure. The earlier fracture cleavage has been folded - see left hand side of figure in particular. Note displacement of cleavage axis relative to that of bedding. Enlargement of slide 39.

Figure 56.

W  E.

Port-e Mwyllin.

Figure 57.

N.  S.W

Port Lewaigue.

Figure 58.

Cleavages.

Flow-cleavage.

Flow- or slaty cleavage forms the earliest planes of parting in the Manx Slates. It has a dip of about 55-60 degrees to north-west on the north-western side of the island and a similar amount of dip to south-east on the south-castern side of the island. It is probably vertical in the central zone (structural axis-see p.I34). Flow-cleavage has been shown to develop on the plane normal to the axis of greatest shortening of the strain ellipsoid by reference to deformed oolites - Cloos[I], and ovoid spots and concretions - Harker[2]. Mead[3] states that rock should deform first by "intergranular plasticity" and he thus explains the absence of cleavage in certain folded strata such as the Claremont Formation in California. He maintains that the capacity to deform in this way becomes reduced as folding proceeds, and is replaced by "interatomic plasticity" in the later stages. The amount of the first type of adjustment which a series can undergo is dependent on factors affecting the rate of consolidation such as the presence of arenaceous beds interstratified in the layers of shale, since these facilitate escape of contained water. In the Isle of Man no folds have been seen in which cleavage is lacking, and it is concluded that compaction must

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I. Cloos, E. "Oolite Deformation in the South Mountain Fold, Maryland" Bull. Geol. Soc. Am. I947.
2. Harker, A. "Metamorphism" pI53. I952 Methuen.
3. Mead, W. J. op cit I940

have passed beyond the stage at which intergranular plasticity could operate,and recrystallisation,with consequent development of flow-cleavage occured from the start of folding.Van Hise[I] maintains that slaty cleavage develops in a "zone of flowage" but strain-slip cleavage forms in a "zone of fracture" when the rocks are less deeply buried,and similar views are expressed by Harker[2]. Among others,Leith[3] and Harker maintain that recrystallisation is dominant over rotation of platy minerals in the development of flow-cleavage.Since dependent on weaker molecular attraction (Leith) parting occurs with equal facility along "any arbitrarilly chosen plane parallel with the direction of mineral orientation" (Sherbon Hills[4]).

Fracture cleavage.

Fracture cleavage is strongly developed in the Manx Slates,and is in many areas the most prominent "s" surface. Dips measured on fracture cleavage were the basis for the early view that the structure of the area is a simple anticline.From the greater part of the north-west and south-east of the island oriented specimens confirm the presence of fracture cleavage to a greater or lesser degree,and indicate that it maintains a general north-west inclination at about 25-30 degrees on the north-western side of the island and a

I.Van Hise,C.R. op cit I896.
2.Harker,A. op cit.
3.Leith,C.K. "Rock Cleavage" U.S.G.S.Bull.239 I905 pI-I53.
4.Sherbon Hills,E. op cit. pI08.

south-eastern dip at a similar amount, on the opposite side of the structural axis. It has a shallow inclination in the axial belt.

Fracture cleavage differs from flow-cleavage in that parting is dependent on definite planes of shear, between which there is no particular tendency to part parallel to these planes. In the Manx Slates the surfaces of parting are very closely spaced but in thin section the fissility can be seen to be due to distinct surfaces along which fracturing takes place. Mead[I] states that a slate or schist is less "interatomically plastic" than the parent rock and that when deformation continues beyond the limit to this kind of relief, further yielding takes place along surfaces of shear failure. Shearing develops on the circular sections of the strain-ellipsoid, and therefore from the theoretical point of view, planes of fracture in two intersecting directions should be expected, but in the Manx rocks one set only has developed, thereby agreeing with what is common experience from other areas. Turner[2] points out that in practice the other set of surfaces is usually present but is not conspicuous and therefore in general, the problem is one of "unequal slip upon several sets of surfaces". Various explanations have been

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I. Mead, C.J. op cit.
2. Turner, F.J. "Mineralogical and Structural Evolution of the Metamorphic Rocks" I950 pI75 Geol. Soc. Am. Memoir 30.

suggested for this and Becker[I] proposed that the two sets of shear planes rotate at different speeds. Fracture cleavage is formed parallel to one set and flow-cleavage parallel to the other. Sander[2] maintains that pre-existing planes of weakness exert a dominating influence over the development of slip surfaces even though they be considerably inclined to the planes of maximum shear. Schmidt[3] points out that extraneous factors may influence the resistance to movement which may be less in one direction than the other. Turner[4] amplifies this idea and suggests that a resistant mass of granite, for example, may thus exert a dominating influence, whereas overfolding in the opposite direction may provide ready relief and hence facilitate development of the one dominant fracture cleavage.

Movement along the fracture cleavage planes has not been constantly in the same relative sense and while it sometimes remains the same for a short distance, on adjacent planes it is usual to find that this is reversed, so that the two motions compensate one-another. Wright[5] describes a similar cleavage from Colonsay which he describes as an "alternating strain-slip" and which he states is similar to cases mentioned by Heim and Harker. He goes on to show how it is oriented in the

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I. Becker, G. "Experiments on Schistosity and Slaty Cleavage" U.S.G.S. Bull. I904 No. 24I.
2. Sander, B. "Gefugekunde der Gesteine" Vienna Springer. I930.
3. Schmidt, W. "Tektonik und Verformungslehre" I932 Borntraeger, Berlin.
4. Turner, F.J. op cit.
5. Wright, W.B. "The two earth-movements of Colonsay" Q.J.G.S. I908 Vol.64 p297-3I2.

plane normal to the maximum pressure where,as pointed out by Harker,there is no shearing component and where accordingly no motion should occur in rock made up of laminae of uniform strength.In Colonsay however,as in the Isle of Man, the rocks are far from uniform but the compensatory motions on the cleavage may produce no net movement.

Shear cleavage.

Shear cleavage has been recognised by Mead[I] .He distinguishes it from fracture cleavage by reference to the film of platy minerals which lie parallel to the shear planes.Leith[2] regards this as one of the incidental results of the rubbing together along these planes.Mead states that the mica may either have developed by recrystallisation or by shearing along the new planes.He states that it is most likely to either lie parallel to earlier foliation or to cross it at a large angle.Both Sherbon Hills[3] and Mead maintain that shear cleavage is a phenomena of rock flowage rather than fracture,but that it is not a consequence of homogenous plastic yielding since the deformation is accomplished by shear along parallel surfaces where however "interatomic adjustment" or recrystallisation but not fracture,occurs.

In the northern part of the Manx Slates fracture cleavage is invariably strongly developed and causes intense puckering

I.Mead,C.J. op cit
2.Leith,C.K. op cit
3.Sherbon Hills,E. op cit

of the earlier flow-cleavage and is generally to be regarded as shear cleavage rather than true fracture cleavage.When closely spaced this structure tends to obliterate pre-existing flow-cleavage and Broughton[I] believes that it can be transitional between fracture and flow cleavage.Where the shearing out of micas in the new direction has been most intense,it is evident that had the structure developed much further no trace of earlier flow cleavage would have remained.In the south central part of the Manx Slates recrystallisation has been more prolonged and more intense than in their northern part.At Archallagan the dominant "s" surface is a gently inclined schistosity.Its low inclination suggests a correspondence with the fracture or shear cleavage of the axial belt in the northern part of the island. Slides from specimens which surround Archallagan show that the fracture cleavage becomes less intense as the recrystallisation intensifies and this suggests that the schistosity developed via the sequence fracture cleavage-shear cleavage-schistosity,as suggested by Broughton.To the south of the Foxdale granite the recrystallisation has been less extreme and in slide I892 for example,though garnets and cordierite are present,lines of dark inclusions occur which possibly represent healed fracture cleavage.This has a dip of about IO degrees to south-east and

I.Broughton,J.G. "An example of the development of cleavages" J.of Geol.I946 LIV No.I pI-IS.

therefore agrees with the regional pattern of the fracture or shear cleavage.On South Barrule and farther to the south-west towards The Stacks cleavage dips at about 20 degrees to north-west.Microscopically fracture cleavage can be seen to be quite lacking and the gently dipping cleavage is a flow cleavage.Its inclination agrees with the regional pattern of the fracture or shear cleavage and it seems probable that it formed in the same period of movements as did this cleavage.

<u>Steeply inclined fracture cleavage.</u>

In addition to the dominant fracture cleavage an earlier one also exists.In Port Mooar there are near upright folds to the axial planes of which an early fracture cleavage is parallel (see p.I08).A steeply dipping fracture cleavage has been found in slides from specimens from other parts of the island,and so far as present evidence goes it seems most common in the region of the structural axis.

Slide 465 is a specimen from a fold from Ballastowell the axial plane of which is steeply inclined and parallel to a fracture cleavage which dips steeply south-west.Slide I695 from a specimen from the feeder to Snaefell River displays a fracture cleavage inclined at 55 degrees to east-north-east and which differs markedly from the dip of the regional fracture cleavage. Slide I696 from the same stream also shows a steep cleavage but the dominant cleavage in this case dips at only I0 degrees to south-east.In the stream-bed between Snaefell and Beinn-y Phott there are strong cross-cutting lineations,and in places two cleavages are well seen. In slide I586 the regional fracture cleavage post-dates a steeply inclined fracture cleavage (inclined at 60 degrees south-east).The relationship is similar in I842 where there is shearing which pre-dates the regional fracture cleavage.The shear planes are inclined at 80 degrees south-east.

Slide I956 (Injebreck),displays a fracture cleavage inclined at 75 degrees to west.Slide 2253 (West Baldwin) shows two cleavages.One dips to east-south-east at 60 degrees and the other dips at only I5 degrees to south-east.To the south of the Central Valley slide 2I84 from Slieu Chiarns and 222I from Garey Mooar also display a steeply dipping fracture cleavage.

It is possible that the steep fracture cleavage identified in these slides is correlatable with the steeply dipping cleavage seen at Port Mooar (where "Intermediate Folds" have been described).

Two slides at right angles to one another,were made from specimen I630 (stream between Snaefell and Beinn-y Phott).The shallow-dipping regional fracture cleavage is dragged by later, steeply dipping shear planes.This is the only case in which shearing which post-dates the regional fracture cleavage has been observed.

Flow cleavage was the earliest structure to develop. It was followed by the development of a less conspicuous fracture cleavage;later there was a widespread development of shallow dipping fracture or shear cleavage which is generally the latest structure present but shearing which post-dates this is also represented (slide I630).

West. East.

Stream-bed south of Snaefell and north of Beinn-y Phott. To show double cleavage.

Figure 59.

Regional Structure. (see Map 2)

The general dip of both bedding and fracture cleavage is north-westwards on the north-western side of the island and south-eastwards on the opposite side,as reported by the earliest workers and confirmed in detail by Lamplugh.On the east coast the change in dip of the fracture cleavage from north-west to south-east takes place at Port Mooar.As the axis is approached from either north-west or south-east there is a gradual reduction in the inclination of the fracture cleavage until it has very shallow dips (IO degrees).The axis of cleavage-dip reversal runs inland south-west from Port Mooar.Oriented specimens from this axis confirm the shallow dips on fracture cleavage.

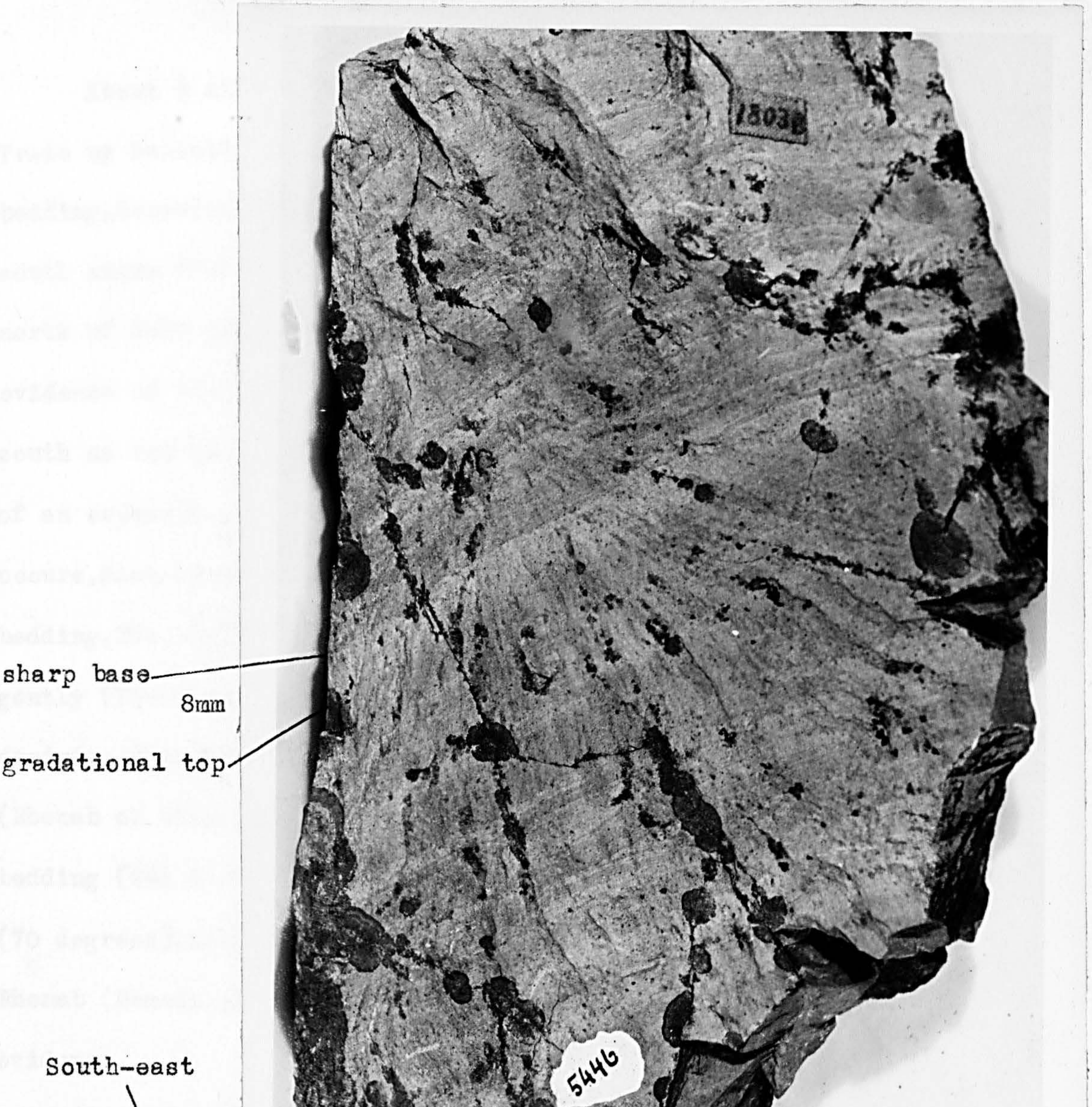
On the east coast the reversal of bedding-plane dip occurs a few hundred yards south-east of Port Mooar in the region north of Traie ny Uainaigue.The axis of reversal of dip direction (structural axis) of the bedding thus lies south-east of the similar cleavage axis in this region.At Traie ny Uainaigue there is a series of isoclinal folds,the axial planes of which are inclined south-eastwards at about 55-60 degrees and to the south of which,in the short space of IOO-I5O yards,the dips on bedding are predominantly to south-east at steep angles.To the north of Traie ny Uainaigue there is good right-way-up current bedding.This gradually becomes less satisfactory and at

Traie ny Uainaigue current-bedding is virtually absent, but grading appears in certain bands, in units 10-15mm thick or less, and becomes more common to the south. This indicates that the beds are right way up with younger strata to south-east (see fig.60). The beds thus display a normal sequence on both south-eastern and north-western sides of the structural axis. About $2\frac{1}{4}$ miles south-west of Port Mooar, the Corrany area is in the region of reversal of dip of both cleavage and bedding. Low dips are common on the cleavage but farther north-west the angle of inclination becomes greater. Dips on bedding are variable in both direction and amount but farther north-west the dip is generally steep and to north-west.

The change in bedding-plane dip is most clearly seen on the coast near Traie ny Uainaigue. This change occurs when the axis of an anticlinorium is crossed. The folds constituting this anticlinorium belong to the earliest generation and therefore the most important structural change which affects the bedding developed in the flow-cleavage producing movements. The north-western side of the anticlinorium, from youngest to oldest, consists of Cronk Sumark Slate, Sulby Flags, Barrule Slates, banded strata, and Lonan Flags. These have predominant north-westerly dips. South-east dipping Lonan Flags occupy almost the whole of the opposite limb. Higher divisions are not exposed although they are perhaps partly represented in the south of the island at Langness and at Port Greenough where graded, right-way-up, banded slates occur. This suggests that the anticlinorium extends to the south of the island and that these beds are the south-east dipping equivalents of the banded slates exposed on the north-western side of the structural axis. The south-east dipping flags at Douglas and Laxey are also right-way-up (current bedding).

It is significant that the other two major structural features that have been recognised in Manx geology - the Clay Head-Douglas syncline and the Sky Hill-Gob y Volley-Kirchmichael syncline are also unrelated to the fracture cleavage (see pI45) and date from the same period of movements as the isoclinal folds of Traie ny Uainaigue; it thus seems that the earliest movements exerted a controlling structural influence while the later were unable to do more than effect local modifications of the broad underlying features.

Lamplugh disagrees with the earlier workers in his structural interpretation since he concludes that the Manx Slates as a whole form a synclinorium whereas Cumming and Ward, for example, regarded the structure as a simple anticline (Memoir p30 & pII7). The evidence from current bedding and grading now available in the north-western part of the island supports the general order of succession which Lamplugh based upon this interpretation but whether this supports his other conclusions such as the postulated correlation of the Lonan Flags with the Niarbyl Flags is doubtful, though further evidence is required before a definite conclusion is reached.



Graded bedding - south of Traie ny Uainaigue. At the locality from which this specimen was obtained the beds are near vertical but the graded bedding indicates the younger rocks to outcrop in a south-easterly direction.

Figure 60.

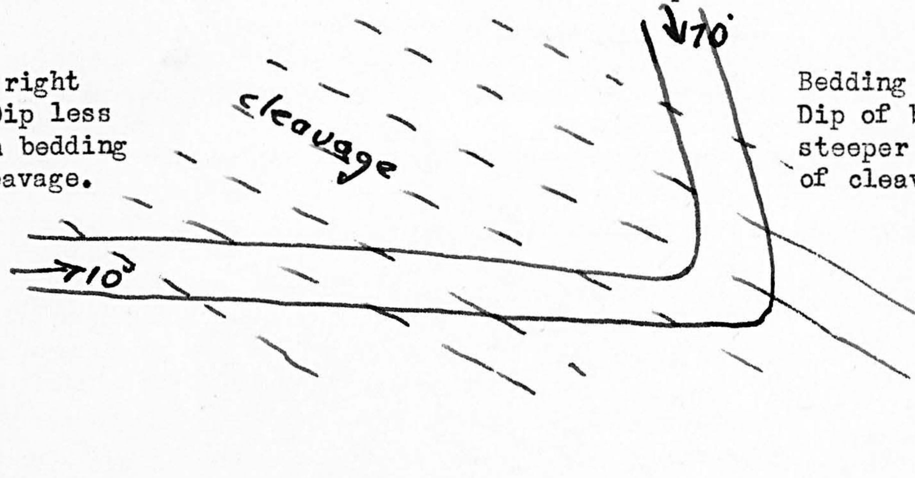
Port Cornah Syncline. (see Map 2)

About $\frac{1}{2}$ mile north of Port Cornah in the small inlet of Traie ny Halsall the beds show right way up graded and current bedding. Occasional way-up evidence found along the coast to the south shows that the sequence remains normal to about 450 yards north of Port Cornah. There current bedding is inverted. Similar evidence of inversion was observed at frequent intervals as far south as Gob ny Cally, where there is probably a fault, since south of an exposure gap 30-40 yards wide a different type of flags occurs, more homogenous than to the north, and without current bedding. The right way up beds south of Traie ny Halsall dip gently (I5-20 degrees). Flaggy beds exposed in the stream draining down to Cornah and in the parallel stream to the south (Rhenab or Glen Mona), also show poor right way up current bedding (944 & 962). The inverted strata of Port Cornah dip steeply (70 degrees). Lamplugh linked these beds with those exposed along Rhenab (Memoir pI44) but this is inconsistent with the way up evidence.

Fracture cleavage dips regularly at about 25 degrees throughout this area and is thus steeper than the shallow dipping upright beds, but is less steep than the inverted strata.

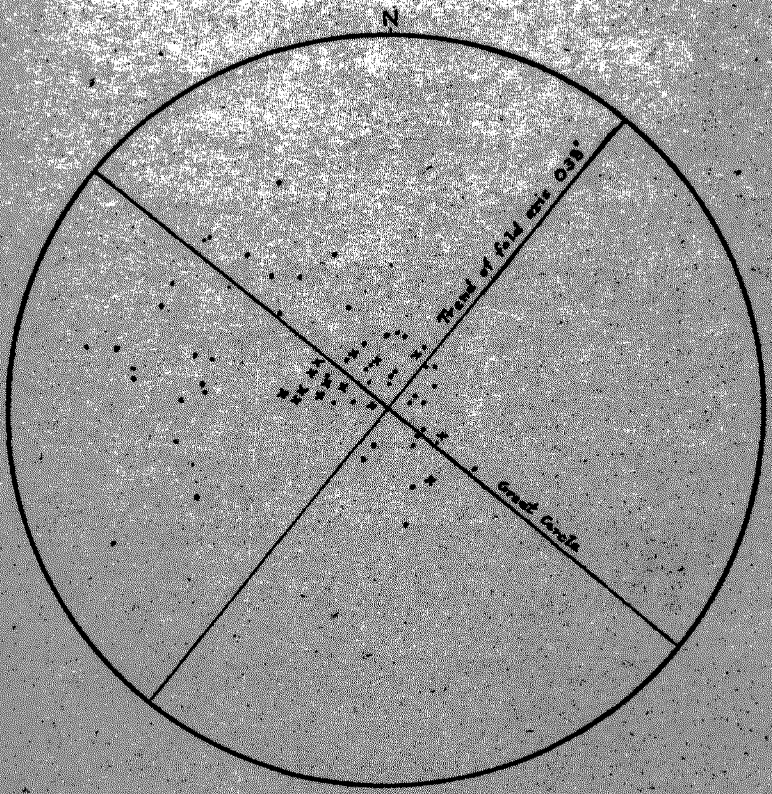
On the coast between the normal and inverted beds a great many loose blocks obscure the exposures and the possibility of concealed faults in this area has to be considered, but the facts as outlined above, appear broadly explainable on the assumption of an overturned syncline closing to the south-east and formed during the movements in which the fracture cleavage developed. On this hypothesis the overturned strata of the Gob ny Cally - Port Cornah area represent the steeply dipping upper limb of the syncline and the slightly inclined upright beds of Traie ny Halsall - Rhenab and the parallel stream to the north, the flat-lying, lower limb of the fold. It is also probable that the strata exposed in the streams draining down to Ballig farther west owe their shallow dips to the continuation of the lower limb of the same structure, but these may have been affected by the intrusion of the Dhoon granite, though if so, it is curious that dips are towards the granite instead of in the more usual reverse direction. On the assumption that the fold originated during the fracture cleavage producing movements the relationship between this cleavage and both the overturned and upright beds, at once becomes clear, for as shown in the diagram, this is a consequence of its parallelism to the folds axial plane.

Bedding right way up. Dip less steep on bedding than cleavage.



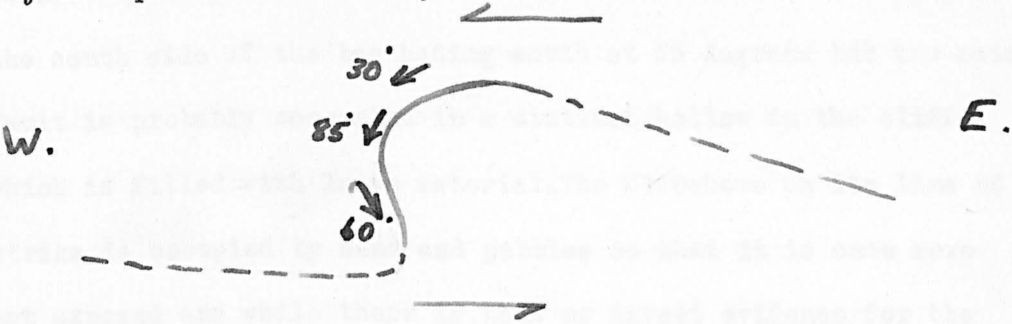
Bedding inverted. Dip of beds steeper than that of cleavage.

Trend of Axis of Port Cornah Syncline (Plunge zero).



- Poles to bedding.
+ Poles to fracture cleavage.

The plunge, as determined stereographically, is zero and the trend is north-east - south-west. This agrees with the trend of the minor folds to the south of Port Cornah which however have a gentle plunge to the south-west. These indicate steeply inclined overthrust to south-east which agrees with the outward movement to be expected from the trough of the major syncline. Drag folding possibly occurs in the landward regions but clearly defined crests and troughs are not exposed; in a series of exposures between the union of streams and the coast there is a systematic change in direction and amount of dip which may be explained in this way.



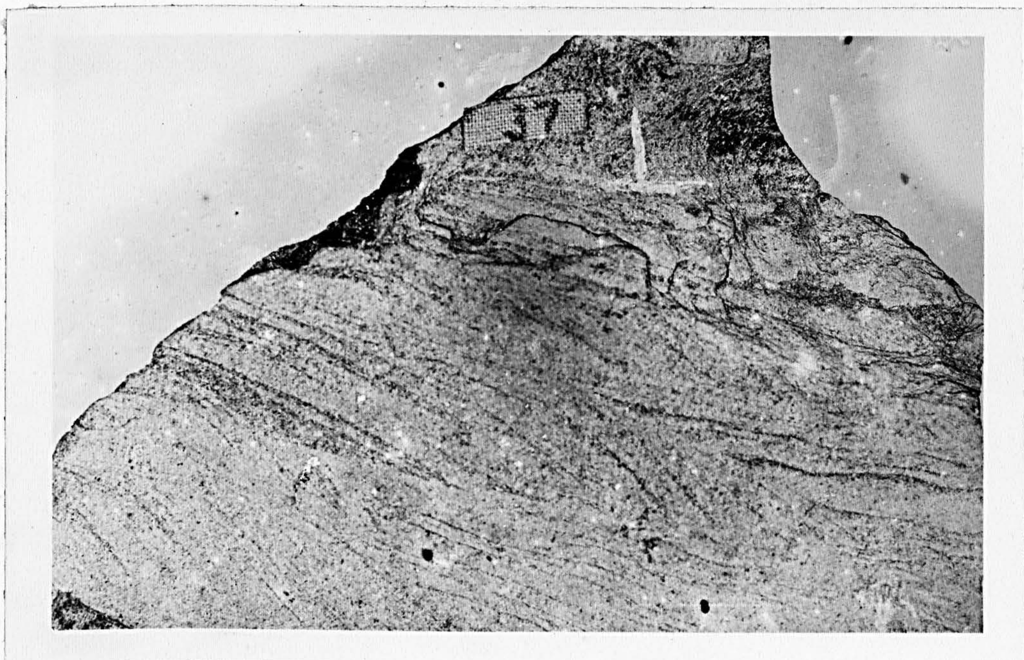
As shown in the diagram, upright beds with a landward dip of 30 degrees occur in the first exposures but a short distance to the west other outcrops show this to have increased in amount to 85 degrees and farther west again the beds are inverted and dip eastwards. The dotted line shows the hypothetical continuation of the strata in the form of a drag fold related to the movements to be expected on the upright limb of the major fold. Changes of dip are sometimes due to faulting as is well seen in Rhenab at the western end of the glen near the cottage by the roadside.

The beds to the north of Traie ny Halsall do not appear to be involved in the fold since though they young to south-east,which would place them on the folds flat lying limb,the dips are steep and sometimes vertical.Furthermore,folds related to the fracture cleavage which occur south of Traie ny Uainaigue,indicate drag movements with overthrusting to south-east if regarded as drag folds,and this is in the opposite sense to that which would have been expected on the lower limb of the syncline.It therefore seems highly probable that a fault of some magnitude reaches the coast at Traie ny Halsall and by facilitating erosion is doubtless indirectly responsible for the inlet.Two small faults outcrop on the south side of the bay hading south at 55 degrees but the main fault is probably concealed in a distinct hollow in the cliffs which is filled with loose material.The foreshore on its line of strike is occupied by sand and pebbles so that it is once more not exposed and while there is thus no direct evidence for the relative direction or type of movement it seems that this may be of a hinge or rotational nature.This conclusion is reached by a consideration of the fracture cleavage which dips in the same direction and at about the same amount,in the rocks to the north as in those believed affected by the syncline.The suggested sense of movement and direction of outcrop of newer beds in the Port Cornah syncline are the same as those on the north-west side of the island but since the dips of both bedding and cleavage are to south-east,and not north-west,the need for rotation becomes evident.

The fact that the dip of the fracture cleavage remains constant in direction and amount both to north and south of the postulated hinge fault is curious,since it implies that rotation described exactly the correct angle and then ceased. However,if one postulates that the fold developed during the flow-cleavage producing movements the relationship of the fracture cleavage to the upright and inverted beds becomes coincidental.Furthermore the form of the fold as drawn in scale section is more similar to folds which developed in the fracture cleavage movements than in the flow cleavage movements since the latter are often sharp crested.

Lamplugh remarked that there was something "peculiar in the structure and composition of these rocks" (pI44 Memoir) but the postulated syncline seems to account for many of the "peculiarities" of the region such as the bedding-cleavage relations in the inverted and upright beds,the flat dips of Rhenab and inversion of Port Cornah together with the change in amount of dip,and it seems reasonable to accept its existence tentatively,at least.

Bedding dips into specimen away from observer



Actual size: 7cm by 8.2cm.
Inverted current bedding - north side of inlet at Port Cornah.

Figure 6I.

<u>Sky Hill - Gob y Volley - Kirkmichael Syncline.</u> (see Map I)

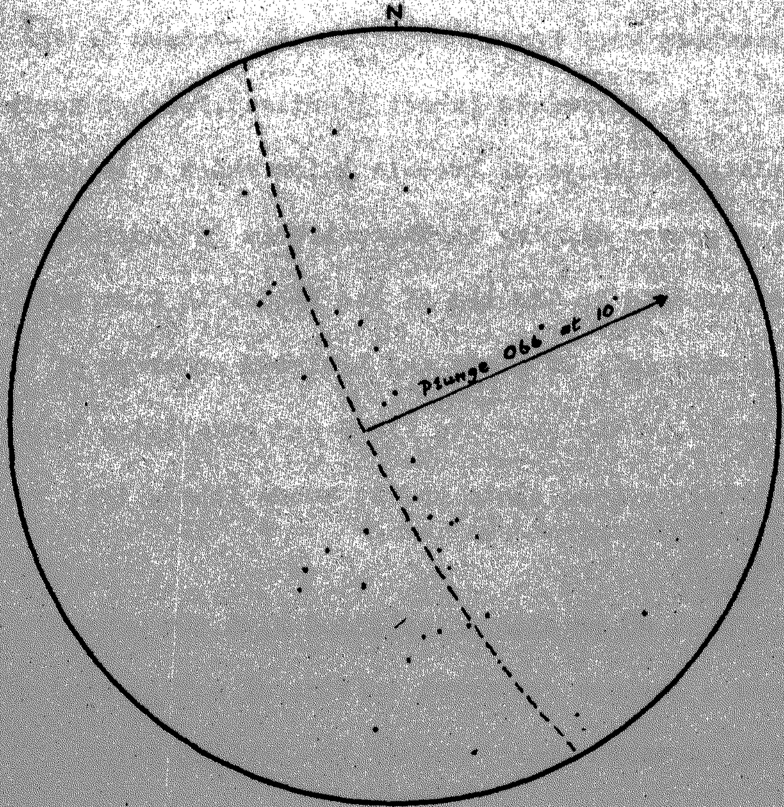
The bands crossed as one ascends the northern slopes of Sky Hill are, breccia, slate, breccia (interbedded with a thin zone of graded sediments - see fig. I4), and flags. Dips are to south-east but as the band of flags is crossed, which is exposed on the flatter ground of the summit of the hill, the dip reverses to north-west. This suggests that the flags lie in the trough of a sharp syncline. South of the band of flags, breccia (in contact with the flags), and slate are exposed. The succession is therefore similar to that which outcrops on the northern slope of Sky Hill and farther south isolated outcrops of breccia surrounded by slate, perhaps represent upfolds of the lowest horizon of breccia seen to the north. Dips are lower to the south and the bands accordingly have wider outcrops.

The deduced order of succession (see p85) indicates that the beds to the south of the synclinal trough are right way up but way-up evidence has not been found in this locality (slides 49I, 5I8). The south-east dipping sediments interbedded with the breccia on the northern slopes of Sky Hill show right way up graded bedding (fig. I4).

On the western part of Sky Hill the strike shows a systematic change and swings round to form the nose-shaped form characteristic of a plunging fold and the whole succession is closed in this manner east of the small gully draining down to Churchtown,known as Glionney Killey,where the next exposures are situated.In this gully the outcrops are of slate interbedded with occasional thin bands of grit.A dip of 30 degrees to south-east was obtained.To the west isolated outcrops of breccia occur west of Glen Tramman and in the upper part of the stream draining down to Glenduff.Elsewhere very homogenous slate is exposed to the west of Sky Hill as far as Narradale (about I½ miles).Farther south there are small isolated outcrops of breccia below which a better exposed band of flags occurs dipping north-west.This is underlain by a band of breccia exposed in the bed of the feeder to Glen Auldyn below Skyhill farm.A wide belt of slate and isolated outcrops of breccia lie to the south.To the east the flags and underlying breccia pass abruptly into thinly bedded slate and it seems likely that the junction is faulted.

The small exposures of breccia interbedded with the most southerly exposed slate perhaps represent infolds of a thin band of breccia.The ascending sequence (below termed the Skyhill farm succession) up to the flags - breccia,slate,breccia,flags - is therefore the same as that exposed on Sky Hill.This in conjunction with the faulted eastern margin, suggests that the Skyhill farm succession may represent the downthrown continuation of the southern limb of the Sky Hill syncline.Hence the fault which breaks the eastern continuation of the Skyhill farm succession may be continued northwards to affect the western continuation of the Sky Hill succession.

Plunge of Sky Hill - Gob y Volley Syncline.



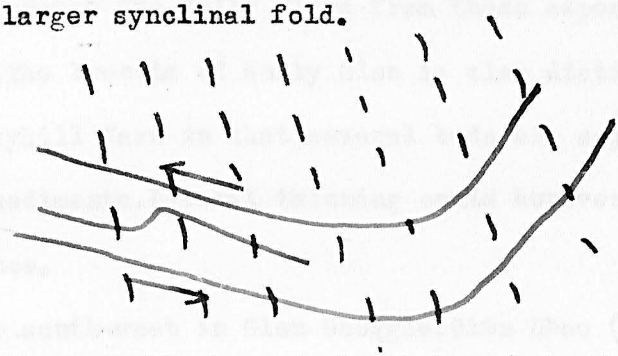
· Poles to bedding.
- - - Great Circle.

The slate and breccia exposed to the west of Sky Hill will on this interpretation, be younger beds than any exposed on Sky Hill itself. This postulated fault also facilitates the interpretation of the distribution of metamorphic minerals. Biotite occurs on Sky Hill but is absent west of the postulated fault. This biotite is north of its general regional limit and its presence may be explained by the apparent lateral shift to the north of beds within the biotite isograd. Conversely, the presence of biotite in beds of the Sky Hill and Skyhill farm successions gives additional support to the correlation based on lithology. The absence of biotite in specimens from the west of the postulated northward extension of the fault is confirmatory evidence for its continuation (e.g. slides 3I0,543A,528A,I536). The probable slight north-west inclination of the axial plane of the fold suggests overthrust to south-east. This agrees with the movement direction indicated in this area for folds developed during the movements in which the flow-cleavage formed.

South-east dipping flags reappear on Gob y Volley to the west, approximately where one would anticipate flags to occur if allowance is made for the effect of the fault and the stereographically determined I0 degrees eastward plunge of the fold. Way-up evidence is poorly developed at Gob y Volley but indistinct current-bedding indicates that the beds are right way up. Lamplugh records the south-eastern dips at this locality (Memoir pI32-3) but interprets them as due to the rocks "under the shelter of the grit masses... (yielding)...

less readily than elsewhere to the compressive force which established the isoclinal arrangement of the folded strata" - a view which is highly unlikely since flags dipping north-west occur only a short distance to the south.These flags outcrop on Mount Karrin on the strike of the similar,north-west dipping current-bedded flags exposed to the north of the breccia in Sulby Glen.The beds of breccia are not continued to the western side of the valley where the flags rest directly on slate.Slate underlies the breccia of the eastern side of the glen and it is probable that the absence of the breccia to the west is due to the lenticular nature of the deposit which dies out.

Westwards the strike of the flags on Gob y Volley swings round to north-north-east suggesting that the plunge of the fold leads to closure of the outcrop.The exposures in the upper reaches of Glen Shoggle to the west,are of slate and therefore this affords some confirmation for the suggested closure of the band of flags to the east of this locality.The south-east dipping Gob y Volley flags may be the continuation of the north-westerly inclined Mount Karrin flags.Slate lies above the flags of both Mount Karrin and Gob y Volley and this slate is succeeded by a thin zone of flags in the trough of the syncline.In the road section in Sulby Glen between Daleveitch and Ballacuberagh,the north-west dipping limb of these flags is folded into an isoclinal anticline (axial plane inclined steeply north-west). This fold suggests overthrust to south-east as would be expected on the assumption of drag along the southern limb of the larger synclinal fold.



These flags strike towards Cronk Sumark to the east. Coarse bands of greywacke dipping south-east, are exposed at the very base of this hill and these possibly represent the topmost beds of the flags. The eastward projection of the north-west dipping flags is unsatisfactory since slate outcrops on the line of strike. The slate exposed in the Glentramman and Glionney Killey district above the Skyhill farm succession is separated from the slate overlying the Gob y Volley and Mount Karrin flags in Sulby Glen by breccia exposed in the Narradale streams. The absence of this breccia to east and west may be due to the lenticular nature of the breccia or to faulting. Some additional confirmation for the intervention of faults is afforded by the apparent displacement of the axis of the syncline. If this axis is projected east-north-east from the area of Gob y Volley along its line of strike it arrives in the Sky Hill district shifted a few hundred yards north of the axis on Sky Hill.

The westward continuation of the Skyhill farm succession is not clear. In this succession flags are underlain by breccia as in

Sulby Glen,but slate and breccia in the stream to the east of Narradale separates the Sulby Flags from those exposed below Skyhill farm.The breccia of Sulby Glen is also distinct from that below Skyhill farm in that several beds are separated by undisturbed sediments.Lateral thinning could however explain this difference.

Farther south-west in Glen Shoggle,Glen Dhoo (now known as Ballaugh Glen),and Glen Wyllin,south-east dipping slate is exposed. In each case the dip is reversed a short distance to the south-east thereby suggesting the continuation of the syncline to the west coast of the island.The trough of the syncline is displaced to the south of where seen at Gob y Volley.This probably indicates faulting.

This syncline therefore extends for a total distance of about 8 miles and occupies,what in pre-glacial times was the northern coast.It is thus similar,both for its position relative to the original northern coast and for its length,to the east coast syncline,reported as early as I880 by Clifton Ward[I],which extends south from Clay Head to the region of St.Anne's Head south of Douglas. This syncline is described in detail by Lamplugh (Memoir pI5I-I55) who reports that "the axis of the synclinal trough runs roughly parallel to the coast and is never more than a few hundred yards inland".It is also evident that this structure pre-dates the fracture cleavage as does the Gob y Volley - Sky Hill syncline since Lamplugh continues that

I.Clifton Ward,J. "Notes on the Geology of the Isle of Man" Geol.Mag.Vol 7 I880 pI-9.

"the south-east cleavage is not affected by the reversal of bedding" but the presence of later folds relatable to the fracture cleavage is implied when he states that "the minor plications of the limbs of the folds are often so arranged that their axial planes are parallel to the cleavage." (Memoir pI52).

Mechanics of Folding.

In the north-east of the island the earliest generation of folds have steeply inclined axial planes.They dip at about 55-60 degrees to south-east on the south-east side of the island,and have a similar amount of dip to north-west on the north-west side of the island.The flow-cleavage (to which the axial planes are parallel) appears vertical in the axial region of the island.The steep limb of the folds faces the structural axis from both sides.

Flow-cleavage is stated to form parallel to the "ab" plane of the strain ellipsoid and "is perpendicular to the resultant of compressional stresses" (Mead [I]).Since these folds have axial-plane flow-cleavage it suggests compression normal to their trend in a general north-west - south-east direction.The inclination of the axial planes suggests that a couple was superimposed on the compression and Billings [2] proposes that this may be brought about by a reduction in the intensity of compression at lower crustal levels so that the uppermost layers move more,causing asymmetry and overturning of the folds.In the Isle of Man the overthrust implied was towards the axial region from both sides.

As described above (pI08) there are near-upright folds in Port Mooar with a wide-spaced axial plane fracture cleavage.This cleavage may be correlated with a similar steeply inclined fracture cleavage in

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I.Mead,W.J. op cit I940
2.Billings,M.P. "Structural Geology" Prentice-Hall. I942.

other parts of the island. The flow cleavage pre-dates these folds which are themselves earlier than the regional, shallow-dipping, fracture cleavage. They are evidently intermediate in age to the major movements but their steeply inclined axial planes link them with the early folding. It is possible that they developed at a late stage in the movements which produced the early folds. The axial planes of the intermediate folds are inclined to south-east on the south-eastern side of Port Mooar and to the north-west at the western end of the inlet so that the change in inclination occurs to the north of the point where the corresponding reversal affects the axial planes of the early, flow-cleavage folds. However, it is at Port Mooar that the axial planes of the overturned folds reverse their inclination and it seems likely that the underlying cause for this already exercised an important effect on the structures of the island when the intermediate folds were formed.

The latest important folding in the Isle of Man produced overturned folds with axial planes parallel to the gently inclined regional fracture cleavage. In contrast to the folds of the first movements the short limbs of these folds face away from the structural axis. This suggests that overthrust was to north-west on the north-western side of the island and to south-east on the south-eastern side of the island. The suggested movements are therefore in opposite senses for the earliest and latest folds.

The fracture cleavage generally has a shallow inclination and this suggests vertically directed force. This cleavage shows a tendency to flatten in the axial region (dips of about IO degrees are common) and this may imply late-stage upward movements in which the cleavage functioned as the dominant "s" planes and produced a regional "bending fold". Sherbon Hills[I] points out that this will cause an increase of the surface area and that "stretching may take place by flowage from the anticlinal crest towards the limbs of the fold, giving a supratenuous fold, or by normal faulting". If flowage from the axial region in the Isle of Man had occured the movement directions of the overturned folds related to the fracture cleavage would be explained.

This idea has a number of proponents who explain large-scale folding such as that of the Alps and Jura mountains by assuming vertical uplift with gravitational sliding away from the uplifted zone, with the production of thrust faults and overfolds. Jeffreys[2] maintains that under high pressure and temperature, rocks will undergo strain by "continuous distortion" and material will flow from an elevated tract to the low ground in front (the foreland) and will itself be overridden by a later developing fold. He suggests that this may account for the superposed nappes of the Alps. Bull[3] remarks that it has been found impossible experimentally, or by any mechanical scheme, to initiate folding at the centre of a trough of

I. Sherbon Hills, E. op cit I953 p90
2. Jeffreys, H. "Earthquakes and Mountains" Methuen London I935 pI53
3. Bull, A.J. "The Compression of a Sheet" Proc. G.A. I943 Vol. 54 pI85-I89

sediments,as occured in the formation of the Alps,by the application of a force from outside.He goes on to suggest that the Jura Mountains resulted from northward sliding of the rocks on the north side of the Alps.He quotes Buxtorf[I] who showed that the Jura folds are superficial and concludes from this that the salt horizons of the Muschelkalk which are not folded (though the basement is shortened by thrust faulting) "played the part of a lubricant" on which the sliding took place.This principle is put forward by Haarmann[2] and Van Bemmelen[3]. Bain[4] describes flowage folds in marble and suggests that flowage from the rising element of Appalachia towards the sinking Appalachian geosyncline may explain many features of Appalachian tectonics.It is pointed out by Nevin[5] that "each actively developing fold apparently acts,more or less,as a buffer" with the result that the lateral transmission of thrust over long distances by beds acting in the manner of a strut is not possible, since folding would occur near the source of pressure and die out progressively away from this.Therefore "simultaneous flexuring over a wide area (requires)....the transmission of force through the more rigid basement".Sherbon Hills[6] declares that it is the "invocation of a force (gravity) that affects every particle of a rock mass and does not require the transmission of stress by the deforming rocks themselves that perhaps appeals most in the

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I.Buxtorf,A. I9I6.
2.Haarmann,H. "Die Oszillations Theorie" Stuttgart I930.
3.Van Bemmelen,R.W. "The Geology of Indonesia" Vol.IA The Hague I949.
4.Bain,G.W. "Flowage Folding" Am.J.Sci.I93I Vol.5,22 p50I-530.
5.Nevin,C.M. op cit p57.
6.Sherbon Hills,E. op cit p66.

theory of gravitational tectonics". Longwell[I] however, calculates the angle of slope that would be required to enable the downslope component of gravity to overcome the frictional resistance and concludes that the energy provided would be too low. Daly postulated the shearing of higher zones over a subcrust of glassy basalt which would offer negligible frictional resistance to the sliding mass. This suggestion seems to remove many of the arguments proposed by Longwell against the hypothesis of gravitational tectonics in general. It seems likely that folding may result from gravitational sliding, provided a lower zone exists which has a very low frictional resistance against the overlying rocks on which the sliding can take place. In the Isle of Man, if the late-stage folds are to be explained in this way some underlying horizon ought to be present on which the mass sliding occured. This horizon may have been a plastic granite (see p2I8).

I. Longwell, C.R. "The Mechanics of Orogony" Am.J.Sci. Vol.243A 1945 p4I7-47.

Succession of Movements.

The movements in which the cleavages developed occured in a definite sequence and this may now be summarised:

I. Isoclinal folding occured with the development of flow-cleavage.

2. Near-upright folds and a patchily distributed, steeply inclined, fracture cleavage developed.

3. The regional fracture cleavage developed which dips at low angles to north-west on the north-western side of the island and to south-east on the south-eastern side.

Lamplugh recognised a similar though not identical sequence. This was:

"I. Consolidation of the sediments, accompanied by feeble disturbance of the bedding.

2. Acute folding, leading to fluxion-movement along the bedding planes, and in its later stages to extensive displacement in every part of the series, with the development of strain-slip and brecciation in certain areas.

3. Relief from extreme strain, and intrusion of the older basic dykes, and segregation of the older quartz veins.

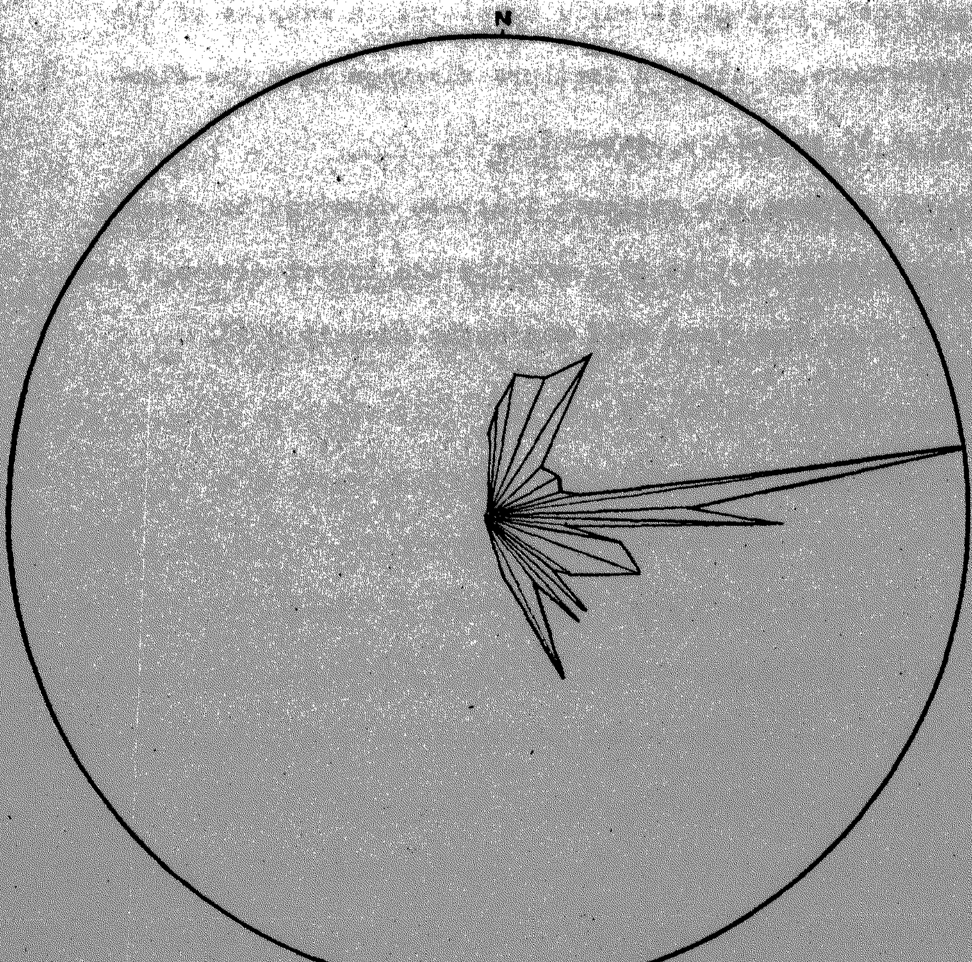
4. Renewed pressure on the folded mass, causing the local development of close-set planes of fissility or shear-cleavage through the further compression of the rock material. Sericitic mica frequently developed on the planes of movement, along with other and more considerable metamorphic effects in certain tracts. The intrusion of the granitic

rocks seems to have taken place at about the close of this stage.
5.After a short interval of comparative quiescence,the stresses again renewed,especially on the flanks of the island,acting in the same direction as before,but with less intensity,producing incipient cleavage in the finer grained strata,but with little shearing except along definite planes of weakness.The granitic dyke rocks suffered deformation during this stage.
6.Post-lower-Carboniferous disturbances,producing much local complication in the Carboniferous rocks but with no recognisable effect except normal faulting in the older strata". (Memoir p71-72).

Lamplugh attributes the breccias and early folds to the same movements but in my view the breccias formed contemporaneously with sedimentation and pre-date the early tectonic folds.A notable difference between Lamplugh's scheme and that now proposed concerns stage 4 of his movements.He states that "the interior portion of a block of slate surrounded by shear-planes may possess a structure indistinguishable from 'ultimate cleavage' but (this) passes insensibly at the margins into well-marked 'shear cleavage' or 'fissility', without change of direction".To my knowledge there is no fracture cleavage which merges into the flow-cleavage.The only possibility is that Lamplugh refers to occasional planes of bedding-plane slip which are parallel to the flow-cleavage.This impression is evidently erroneous since he illustrates the shear cleavage as crossing the fragments in the breccia at an angle which more nearly corresponds with the regional fracture cleavage than the flow-cleavage (Memoir p63). The same difficulty is met with if an attempt is made to correlate this cleavage with the cleavage of stage 2 of my scheme and in any case, the steeply inclined fracture cleavage of my stage 2 has not been recognised as strongly developed in samples of the breccia. Furthermore, my stage 2 fracture cleavage cuts the flow-cleavage which it therefore post-dates.

Lamplugh assigns the regional fracture cleavage to stage 5 and correctly states that it is generally the latest cleavage and post-dates earlier important fold movements (Memoir p85).

200 bearings on Faults in North-east of Isle of Man.



5 degree interval.

Faults.

Faults in the Isle of Man cause numerous clefts in the coastal exposures. The most common trends are north-north-east, approximately east-west, and north-west. In the northern part of the island the majority hade at a high angle but some low angle thrusts have been seen, and Lamplugh (memoir p87) also refers to displacements of this type. It seems likely that faulting occured during three periods - Caledonian, Hercynian, and Tertiary. The thrusts and north-east strike faults are probably of Caledonian age, the north-south, east-west faults (which are associated with the mineralisation) are probably Hercynian, and the north-west faults Tertiary. Anderson[I] draws attention to the inadvisability of grouping fractures as of a particular age on account of a correspondence in strike between faults and the structural pattern of that age but himself concludes that north-west trending normal faults are common in the Tertiary.

Proceeding south from Ramsey, Barrule Slates, Banded Beds, Quartzites (Agneash Grits), and Lonan Flags are exposed in order. Barrule Slates outcrop on the south-west strike of both the Agneash Grits and Banded Beds and it is likely that the south-west continuation of the succession is faulted. The same sequence outcrops to the south of where it would have occured had its strike been continued without interruption.

Quartzites, of similar appearance to those seen at Maughold Head,

I. Anderson, E. M. "The Dynamics of Faulting" Oliver and Boyd.

reappear at Corrany.Their north-east continuation appears to be faulted since there are banded beds in the stream on their line of strike.To the south-west of Corrany banded slates lie on the strike of the quartzites and it again seems necessary to infer a fault to separate the quartzites from the westerly exposures.Hence it appears possible that the main fault divides into two branches north of Corrany (see map).

To the south there is a belt of quartzites of the same lithological type which extends from Slieau Ouyr south-west to Creg Agneash,and Cronk y Vaare;to the north-east this quartzite strikes towards the Dhoon granite and the streams draining down to Ballig where flaggy strata is exposed.It therefore seems likely that to the north-east the quartzites are bounded by a fault.This is possibly the same fault as that which terminated the Corrany quartzites to the south-west and this may therefore represent the displaced portion of the Creg Agneash belt (see map).

The structural axis (see pI34) is displaced relatively south, as are the beds, and this is further evidence which supports the conclusion that the south-west continuation of the sequence exposed in the coastal region south of Ramsey is faulted.

The precise position of these faults is generally not clear and topography gives little help.Low ground does occur between North Barrule and Ballagilley and this possibly indicates the course of the fault in this region.The low ground followed by the main road south of Corrany possibly indicates the course of the fault to the south.

The sequence exposed on Sky Hill is repeated south of Skyhill farm and it is possible that these beds represent the faulted continuation of those exposed on Sky Hill (see pI46).

The rocks south of Traie ny Halsall are probably separated from those to the north by a rotational fault (see pI42).The position of the landward continuation of this fault is not clear but the evidence indicates the need for a fault approximately where indicated on the map.

There are numerous fissures in the coastal cliffs south of Ramsey which probably contain faults but nothing can be inferred regarding their throw or direction of movement since in general they produce no apparent effect upon the rock-type exposed.An exception occurs south of Ramsey,I50 yards east of the commencement of rock outcrops,where as reported by Lamplugh,breccia is bounded by parallel faults the most northerly of which is inclined at 45 degrees to north-west.

To the south banded slate is exposed as far as Port Lewaigue, where on the north side of the bay,a narrow band of lighter slate is contained between parallel faults.Thin bands of dark slate are contained in the igneous rock of Tableland Point.In some cases the slate appears to be contained between parallel faults,some of which as suggested by Lamplugh (Memoir p123),may be continuations of those seen in Port Lewaigue. Haematite staining is common in association with many of the small faults in Port-e Mwyllin and on some of these the amount of lateral movement was estimated from the displacement of a sequence of bands of greywacke and slate. In one case this amounted to 6 feet and in another to 20 feet.The east side of the fault had in each case been displaced relatively to the south-east.

The depth of the side gully draining down from Park Lewellyn to the stream flowing east to Corrany suggests that it may coincide with a fault.This is perhaps continued to the south where there is a parallel gully which joins the main stream almost opposite the former one.This suggestion is in part born out as there is iron-staining towards the head of both gully's where the rock is decomposed.Further iron-staining occurs farther west in the main stream.

Lamplugh (Memoir p145) suggests that there may be a fault along the northern branch of the Snaefell River,since the rock both in the stream-bed and in the underground workings of the mine is considerably shattered; this may be the case,as the stream flows through a narrow, steep-walled channel quite different to that of the main stream.If this is so it has no apparent effect on the rock-types exposed.

The beds on either side of the gully in which the East Baldwin has its source have a different amount of dip.This suggests that the stream coincides with a fault.The channel is also narrower and steeper-walled than that of the main valley.

Joints. (see I inch map "Structures")

Vertical joints in the Isle of Man follow two principal directions. These are north-west - south-east, and north-east - south-west. The former group are cross, or "ac" joints and trend about normal to the strike of the fold axes. According to Turner[I] they are "almost universal in deformed rocks". The other set intersect these at about 90 degrees and are longitudinal, lying parallel to the regional strike. The relationship to Caledonian trends suggests that a Caledonian stress-system exerted a controlling influence over their development.

Lineation. (see I inch map "Structures")

The dominant lineation in the Manx Slates trends north-east - south-west and is Caledonian in trend. The north-east - south-west lineation includes the strike of both minor and major folds and the intersection of cleavages and bedding. A lineation at right angles to this is also common. It is confined to a faint crinkling which affects all visible "s" surfaces and has therefore been produced at a late stage in the movements.

The trend of the fold axes averages north-east - south-west but in detail it shows a regular change from east-north-east - west-south-west in the north-eastern part of the island to north-north-east - south-south-west in the centre of the island. The angle of plunge is low and averages from I0-20 degrees but the early folds related to the flow-cleavage occasionally plunge at steeper angles of up to 35 degrees.

I. Turner, F.J. op cit I948 pI82.

The folds do not show a systematic change in direction of plunge such as would indicate a culmination or depression.On the information available at present both the earliest and latest folds follow the arcuate trend mentioned above which according to the generally accepted scheme corresponds to the "b" fabric axis.This axis therefore occupies the same spatial position for both sets of folds but the "a" and "c" axes exchange positions; "a" is vertical during the early movements but lies in the gently inclined fracture cleavage during the later movements.The late-stage north-west lineation is therefore an "a" lineation comparable to the vertical one frequently described as affecting flow-cleavage (Anderson [I]).In the areas where breccia is exposed the most striking lineation is that caused by the stretched fragments which show a strongly marked orientation parallel to the "b" axis.

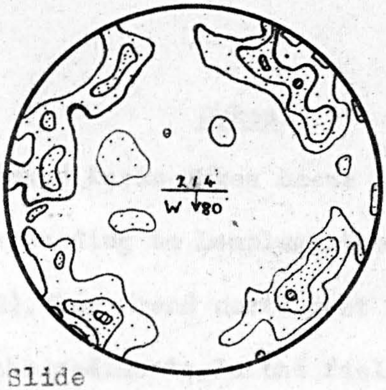
Petrofabric Diagrams.

I866	Diagram parallel to N.E.-S.W. trend;normal to N.W.-S.E. lineation.	I.
I87I	" " " " " " "	I.
I892	" " " " " " "	2.
I695	" " " " " " "	3.
III5	" " " " " " "	3.
774B	Diagram normal to N.E.-S.W. lineation.	3.

I.Staurolite-Kyanite subfacies.
2.Cordierite-anthophyllite subfacies.
3.Biotite-chlorite subfacies. 774B near outer limit of zone.

I.Anderson,E.M. "On Lineation and Petrofabric Structure etc." Q.J.G.S. I948 p99-I32 CIV Pt.I.

Slide I87I-Archallagan.
200 Poles.



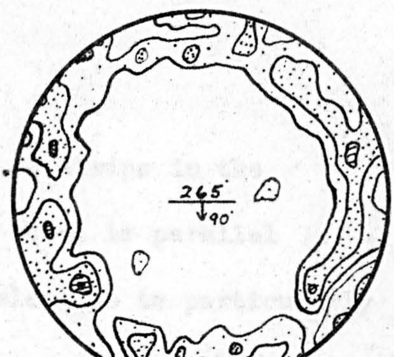
Slide I866-Archallagan.
200 Poles.

Slide
I892.Quarry 200 ft.S.W.
of Foxdale Granite.

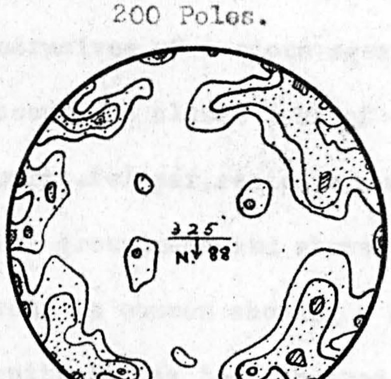
350
Poles.

Slide I695.N. tributary to
Snaefell River.

200
Poles.



Slide 774B.Sulby Glen.
200 Poles.



Slide III5.Port Mooar.
200 Poles.

Diagrams of Quartz "C" Axes.

Over 6%
4%-6%
2%-4%
I%-2%

% Concentration of Poles.

Dykes.

Metamorphosed basic dykes occur throughout the Manx Slates Series though, according to Lamplugh, their concentration varies (Memoir p298-99). They trend north-east to south-west parallel to the strike of the sediments. In the field they appear green and show a greater or lesser amount of cleavage depending on their age with relation to the movements.

Pre-Flow-cleavage Dykes.

The oldest dykes are often sheared out as strips in the sediments and are crossed by a flow-cleavage which is parallel to the bedding in the enclosing strata. This cleavage is particularly well seen where the surface is polished by the sea, as on the coast south of Ramsey in Port Lewaigue and Port-e Mwyllin where the intersecting intrusives of various ages described by Lamplugh (Memoir p3I9) occur. The oldest dyke of the set is pale in colour and contains quartz, felspar, sericite, and chlorite and large amounts of calcite in the groundmass and shows a well developed strain-slip cleavage. Leucoxene is common showing a skeletal development at the expense of ilmenite; it has been sheared parallel to the schistosity. The dyke of intermediate age is chiefly composed of calcite with smaller amounts of chlorite and muscovite showing strong parallel orientation; fracture cleavage is also well developed. This rock, like that which it cuts, is intersected by both flow and fracture cleavage. Dykes cut by both flow and fracture cleavage are common and it seems that the flow-cleavage producing movements were preceded by an early period of magmatism. Among these EI960 south of Port Erin, EI979 Calf of Sound, E2828 Foxdale, E2428 Glen Auldyn, E2I92 West Folieu, E2I94 Port Lewaigue, E2407 Block Eary, E2402 Tholt-c-Will, and E2388 stream east of Bungalow Hotel, Snaefell, may be mentioned as good examples. Chlorite is almost invariably present. The crystals show mutual parallelism and wind round porphyritic constituents such as plagioclase felspar. Calcite is present to a greater or lesser extent and leucoxene is fairly common;- the mineral assemblage being typical of low-grade metamorphism of basic igneous rocks. It is likely that the majority of dykes intruded during this early magmatic phase were dolerites or closely allied rock-types.

Post Flow-cleavage, Pre-Fracture cleavage, Basic dykes.

Dykes cut by the fracture cleavage but with no strong mineral orientation are quite common. Hence it is likely that a further phase of basic igneous activity occured after the earliest folding but prior to the movements in which the fracture cleavage developed.

In the field, the fracture cleavage can often be followed from the sediments into the dykes where it is usually wider spaced but inclined at a similar, though sometimes steeper angle. Dykes of this group are EI95I Port Erin, E2098 Barnell, Kirk Patrick, E2003 near Fleshwick, E2390 Kerroo Mooar, Sulby, E2I34 Cronkbane between Kirkmichael and St.Johns,E2I29 Lhargee Ruy,Greeba,E2480 Traie ny Uainaigue, and E2389 Block Eary stream north of Snaefell.In mineralogy they are similar to the above mentioned dykes but any mineral orientation is due to drag by the fracture cleavage.The mineral assemblage is again characteristic of low-grade metamorphism and it is noteworthy that in certain ones,recrystallisation has outlasted shearing.This was noted by Watts in his petrographic descriptions (e.g. E2388, E2828,Memoir p309-3I0).The amount of shear shown by these rocks varies but this may be in part due to the position in the dyke from which the specimen was obtained,for as Lamplugh noted (Memoir p298) the shearing is sometimes more intense at the margin than in the interior and this is particularly the case with the broader,more massive dykes.

Post-cleavage Basic Dykes.

There are unsheared dykes which were probably intruded after folding had ceased.Among these E2922 is of interest since it intersects the previously mentioned intrusions at Port-e Mwyllin. This rock is considerably altered and much of the felspar is pseudomorphed by sericite but EI945 and E2II4 from Port St. Mary, in which shearing is also lacking,are less decomposed and in particular E2II4 has a doleritic appearance.It thus seems likely that basic dykes which post-date Caledonian folding are represented in the Manx Slates.

Microgranite Dykes.

Dykes of microgranite are confined to the axial region in the Isle of Man (Memoir pII4,299,3II). They are pre-fracture cleavage in date (see fig.62) and sometimes cut the basic intrusions. Microgranite dykes occur which contain characteristic minerals (e.g. garnet). Lamplugh attributed these minerals to metamorphism, but since they occur at places in the biotite zone outside the garnet isograd the more probable explanation is that the garnets were assimilated by the dykes from garnetiferous rocks below in the manner attributed to the garnet-bearing rocks of the Borrowdale volcanics- Walker[I] .E2420 probably gained its characteristic group of minerals (garnet,epidote,etc.) by a similar process of contamination and while of the "greenstone type" the amount of shearing (fracture cleavage only) suggests it may have been intruded at about the same time,or rather earlier,than the microgranites.

Lamplugh concluded that the microgranites were not only younger than the "greenstones" but were the youngest Pre-Carboniferous intrusions in the island (Memoir p3I8). This view is not,in my opinion,warranted since uncleaved basic rocks (dolerites) occur and the only evidence of movement shown by many of the lamprophyres is a flexing of the micaceous minerals.

I. Walker,E.E. "Garnet-bearing rocks of the Borrowdale Volcanic Series" Q.J.G.S. I904 p70-I04.

Lamprophyres.

The Manx lamprophyres show a good deal of mineralogical variability both as regards their primary constituents and also in the amount of alteration which they have undergone.From the petrographic point of view they fall into two groups characterised either by the presence of hornblende or biotite,but as pointed out by Watts "no sharp lines of division" exist and "it is possible to obtain gradations between almost any two types" (Memoir p300). Characteristically the ferro-magnesium constituents form the phenocrysts while the felspars are confined to the groundmass. The rocks are frequently highly altered and epidote,chlorite, and calcite,are freely developed forming the matrix together with saussuritised and sericitised felspar.Actinolite and sometimes tremolite form "tails" to the hornblende which often shows a partial change from brown to green and the latter an alteration into chlorite which is also widespread at the expense of biotite. Apatite is an abundant accessory as lath-like crystals.

Just as gradations exist in the mineralogical composition of the rocks,so do they exist in the amount of shearing to which they have been subjected and while in some,planes of movement are at once apparent,others show only a slight flexing of the micas perhaps produced by the method of intrusion.Specimens of all types may be found which show these features and there seems to have been no definite order of intrusion,or gradational sequence in the petrological variety being formed at a given time with respect to the movements.There is similarly no correspondence between the amount of shearing and the degree of alteration.

Slides EI8I4,EI8II,and EI94I, from Langness are unsheared and but slightly altered.Slides EI970 Dalby beach,Balnalargy, EI8I5 Langness,EI964 south side of Niarbyl,and E2II7 Glen Meay are also unsheared but the degree of alteration is greater.

The amount of alteration shown by mineralogically similar lamprophyres is also variable.EI8I0 Langness and E2504 Port Groudle, are hornblende-mica lamprophyres but EI8I0 shows the greatest development of chlorite.

It seems likely that the intrusion of lamprophyres continued over a period and those which are unsheared are the youngest members of the suite which post-date the movements.

Sequence of Magmatic Episodes.

Attempts to correlate a definite magmatic sequence with various stages of tectonic evolution have been made by Stille[I], Umbgrove[2],and Rittmann[3],and the conclusion is that in general there is an early phase of basic igneous action,followed by folding and the formation of synkinematic acid batholiths.There are post-tectonic eruptions of andesite and a final late phase, of basic magmatic activity.

In the Isle of Man the scheme is of general validity but

I.Stille,H.I939,I940.
2.Umbgrove,J.H.F. "The Pulse of the Earth" Nijhoff I947 p77.
3.Rittmann,A. "Zur thermodynamik der Orogenese" Geol.Rundschau 33 I942.

breaks down in detail. Basic magmatism is represented by the early dolerites which pre-date both flow and fracture cleavage. A dyke of this suite cuts the acidic intrusion of "Lhergydho-type" in Port-e Mwyllin (see p3I7-3I9 Memoir). This relationship therefore indicates that there was early acidic magmatic activity. This is at variance with the predicted sequence of igneous events. The granitic intrusions however, are syntectonic and agree with the above scheme. The Manx lamprophyres formed at about the same time as the granitic rocks but their intrusion outlasted the movements since some are uncleaved. Post-tectonic basic intrusion may be represented by the uncleaved dolerites. The small amount of volcanic material in the Manx Slates is andesitic in character. It is highly cleaved and therefore not post-tectonic as the deduced magmatic sequence would require.

Correlation with Dykes Elsewhere.

According to Richey[I], Arenig dykes occur in the Southern Uplands and Ayrshire region of Scotland. They are lenticular, and have been involved in intense isoclinal folding, and trend parallel to the fold axes. In these respects they resemble the earliest dykes in the Isle of Man. The distribution of Caledonian dykes (Lwr.O.R.S.) is also reviewed by Richey. He records the presence of lamprophyres and microdiorites and it seems possible that the later dykes in the Isle of Man may belong to this period.

I. Richey, J.E. "The Dykes of Scotland" Trans. Edin. Geol. Soc. I3, Pt.4 I939 pI.

Richey states that a particular trend is characteristic of the three main regions where these dykes occur.It is north-north-east in the Grampians,east-west to the north-west of the Great Glen fault,and north-east and north-west in the Southern Uplands and Lake District where two sets are present.In North Wales only the north-west set is represented.The north-east trend of the dykes in the Isle of Man thus corresponds with those of the Grampians,Southern Uplands,and Lake District,but differs from the latter district in that the north-west trending dykes seem to be absent.

<u>Order of Intrusion of Dykes.</u>

I. Felsite of "Lhergydho-type".

2. Sheared "greenstones"
   - a)Affected by flow-cleavage.
   - b)Affected only by fracture cleavage.

3. Foxdale and Dhoon microgranites - sheared but less so than 2b - see Memoir p298.

4. Lamprophyres - some sheared but others unsheared.

5. Unsheared "greenstones".

West

East

Cliffs at Traie ny Uainaigue
cut by dyke simulating a sill.

Figure 62.

Economic Deposits.

Description and Distribution of Ores.

Considerable economic importance was attached to the ore minerals (sulphides of Ag-Pb,and Zn) in the Isle of Man during the 19th century.Zinc was important at Laxey but was hardly represented at Foxdale (Memoir p493).These two places were the centres of the mining industry though small amounts of ore,of little commercial importance,have been found in most parts of the Manx Slates Series.

The most productive areas are in close proximity to granite but Lamplugh does not attribute the mineralisation to the intrusives since at Foxdale the igneous rock itself is intersected by the ore-bearing lode and at Laxey the lode cuts a dyke springing from the granite.This does not necessarily mean that no relationship exists between the granite and ores.In Cornwall for example,the ores are stated to be clearly associated with the granite[1],although the veins cut through both granite and slate.Lamplugh acknowledges the underlying control of the structural axis of the slates over the distribution of the Manx ores since he remarks that "most of the metalliferous veins of the island" are distributed along the axial region (Memoir p522).

The deposits occur in well-defined crystal lined veins or cavities with a matrix of quartz or calcite (Memoir p520) associated

1. Dunham,K.C. "Age Relations of Epigenetic Mineral Deposits of Britain" Trans.Geol.Soc.Glasgow Vol.XXI Pt.III 1952.

with pyrites and chalybite; the description suggests deposition under mesothermal conditions.

The lodes have a north-south or east-west trend, but apart from Foxdale where the main lode trends east-west, all the more productive deposits are in north-south fractures (Memoir p487). These fractures are thus independent of the north-east - south-west Caledonian strike of the Manx Slates which form the country rock.

Effect of Country Rock on Lode.

It is stated (Memoir p49I) that the lead ore shows a tendency to be richer in silver where the vein cuts slate compared to where granite forms the country rock of the same lode. The country rock has been described as influencing the nature of the lode elsewhere (e.g. Cornwall - Dewey[I]).

Age of Mineralisation.

Finlayson[2] concluded that metalliferous ores were largely of Hercynian age in the British Isles and the north-south, east-west trend of the lodes in the Isle of Man suggests such an age. Lamplugh however reports cases in which the north-west trending olivine-dolerite dykes, supposedly Tertiary, are intersected by the mineral veins (Memoir p488-9I, 5I4-I5) or are associated with ore in positions which he maintains "it could not have occupied before or during the

I. Dewey, "Mineral Zones of Cornwall" Proc.G.A. I925.
2. Finlayson, A.M. "The Metallogeny of the British Isles" Q.J.G.S. LXVI p28I-328, I9I0.

injection of the molten matter" (Memoir p489).He also cites an instance in which copper pyrites occurs in a vein in the Carboniferous basement conglomerate at Langness (Memoir p488,538).While he believes that it is "likely that the deep-seated channels which permitted the upward egress of the molten rock may also have served,at a somewhat later stage of the same period of thermal activity,as conduits for the vapours and waters which supplied the crystalline infilling to the re-opened fissures" he also recognises that "it does not follow, (however),that the whole of the Manx metalliferous veins are of this age" (Memoir p489).While he does not make a definite statement he appears to favour a Tertiary age for the metalliferous infillings since he quotes from J.G.Goodchild, who was an exponent of this view, and other authors who support the contention that mineralisation occurs "in association with the intrusion of igneous rocks" (Memoir p490) which were evidently the olivine-dolerites.However,he cautiously adds that "some additional factor in the local conditions" is required for the whole explanation.Dunham[I] shows that there is no satisfactory relationship between the British olivine-dolerite dykes of Tertiary age and mineralisation,and gives reasons for believing that residual waters from hydrothermal ore deposition may persist in depth to cause metallogenesis at epochs much later than their time of primary origin, and he suggests that this may explain local anomalies in the time of mineralisation in certain regions and may possibly explain the cases when mineral veins appear to post-date the Tertiary dykes.

I.Dunham,K.C. op cit.

Nature of the Vein-filled Fractures.

The distribution of stress throughout the British Isles during the Hercynian orogeny has been considered from the theoretical point of view by Anderson[I] who concludes that transcurrent faulting was general, in response to a north-south pressure system. He states that the explanation assumes a contemporaneous origin for the north-south and east-west fractures which, as they are supposedly transcurrent faults, should be vertical. In Cornwall the mineral veins are not vertical and north hading lodes have been faulted by those hading south and Dewey concludes that these are younger. He also quotes Maclaren according to whom the mineral content of the two series differs so that contemporaneity is unlikely. The mineralisation also differs in veins which intersect at right angles in the Skiddaw Slates (see Rastall[2]). The Manx mineral veins are not vertical and the north-south and east-west fractures are not contemporaneous. Some difference in the type of mineralisation in nearby veins at Foxdale is referred to by Captain Kitto (Memoir p503).

Lamplugh regards the east-west fractures at Foxdale as having undergone horizontal movement (horizontal slickensides are mentioned Memoir p487) but at Laxey they are regarded as "true normal faults" (Memoir p52I). In the Snaefell mine it is stated by Lamplugh (p527)

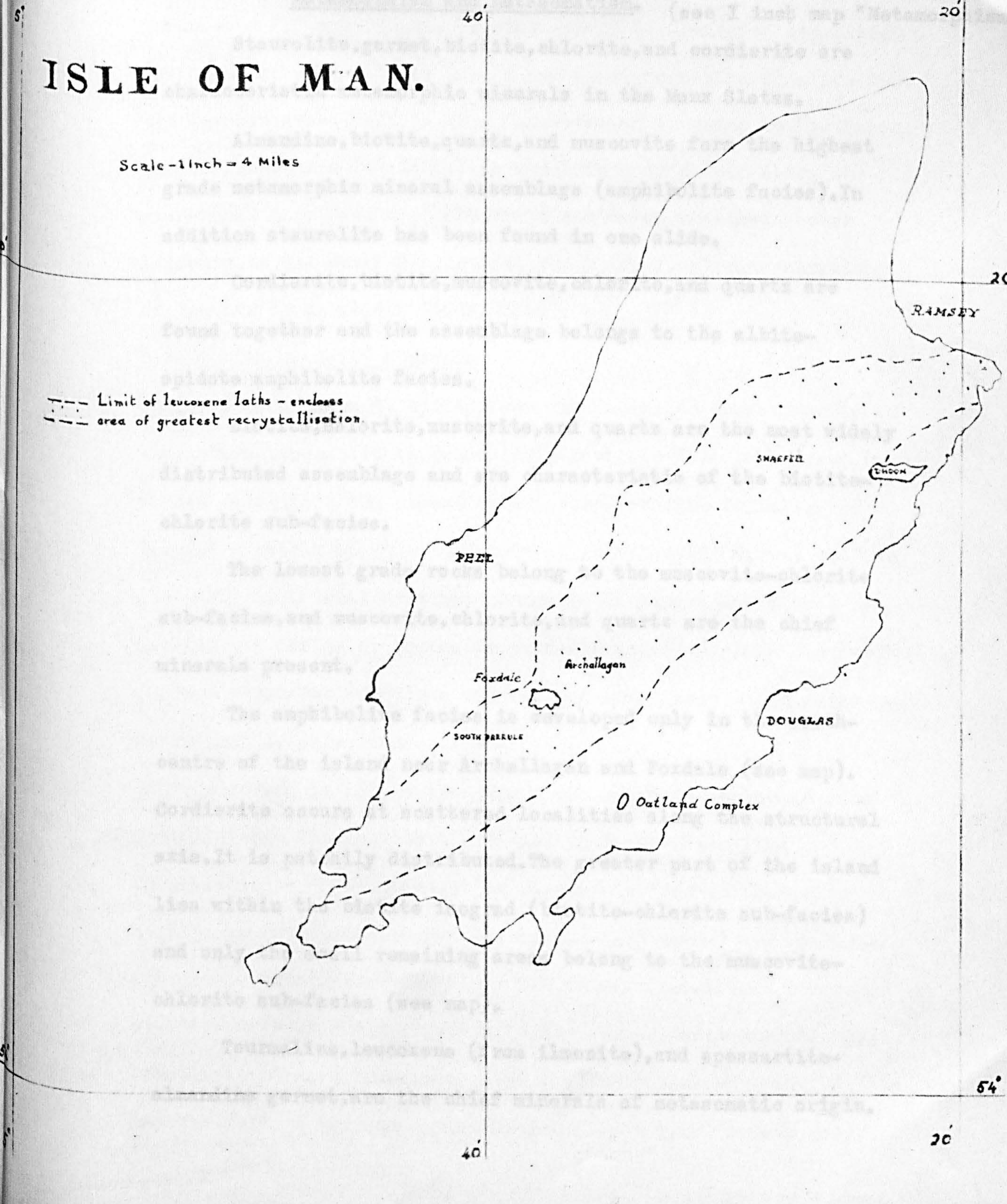
I. Anderson, E.M. op cit.
2. Rastall, R.H. "The ore-deposits of the Skiddaw District" Proc. Yorks. Geol. Soc. Vol. 24 I938-4I p328-343.

that "the striae on some faces (are) vertical,and on others horizontal or inclined" and he concludes (p52I) that movement "has probably been oblique".According to Anderson normal faults hading in one direction should theoretically be accompanied by a complementary set with parallel strike but opposite hade.

The Manx mineral veins are steeply inclined but rarely vertical and show dips of 70-80 degrees in either direction. Thus for those for which information is provided in the Memoir, IO have an east-west trend 6 of which hade south and 4 hade north, and I9 have an approximately north-south trend of which I2 hade east and 7 west.

It seems likely that as Lamplugh suggested these fractures are normal faults.The east-west fractures post-date those of north-south trend (Memoir p503,5I3) and according to theory this requires the least pressure to have changed in position from east-west during the formation of the north-south fractures to north-south.The theory requires maximum pressure throughout to have been vertical and this may indicate a considerable weight of overburden.Normal faults,like dykes are regarded as a tensional feature and their infilling with vein-stuff is therefore readily explained.

The location of the mineralised belt along the north-east - south-west structural axis suggests that Caledonian causes exerted a controlling influence over the formation and distribution of the ores but the north-south,east-west trend of the veins,indicates the establishment of a Hercynian stress system.This determined the local trend of the vein-filled fractures but did not influence the regional distribution of the mineral concentrates.


ISLE OF MAN.
Scale - 1 inch = 4 Miles
Limit of leucoxene laths - encloses area of greatest recrystallisation.
RAMSEY
SNAEFELL
PEEL
Archallagan
Foxdale
SOUTH BARRULE
DOUGLAS
O Oatland Complex
40
40
20
20'
20
54°
5'

Metamorphism and Metasomatism. (see I inch map "Metamorphism")

Staurolite,garnet,biotite,chlorite,and cordierite are characteristic metamorphic minerals in the Manx Slates.

Almandine,biotite,quartz,and muscovite form the highest grade metamorphic mineral assemblage (amphibolite facies).In addition staurolite has been found in one slide.

Cordierite,biotite,muscovite,chlorite,and quartz are found together and the assemblage belongs to the albite-epidote amphibolite facies.

Biotite,chlorite,muscovite,and quartz are the most widely distributed assemblage and are characteristic of the biotite-chlorite sub-facies.

The lowest grade rocks belong to the muscovite-chlorite sub-facies,and muscovite,chlorite,and quartz are the chief minerals present.

The amphibolite facies is developed only in the south-centre of the island near Archallagan and Foxdale (see map). Cordierite occurs at scattered localities along the structural axis.It is patchily distributed.The greater part of the island lies within the biotite isograd (biotite-chlorite sub-facies) and only the small remaining areas belong to the muscovite-chlorite sub-facies (see map).

Tourmaline,leucoxene (from ilmenite),and spessartite-almandine garnet,are the chief minerals of metasomatic origin.

Tourmaline (of metasomatic origin) occurs at scattered localities which in the south of the island are never more than $2\frac{1}{4}$ miles from the Foxdale granite. It is also concentrated in veins in the Dhoon granite. Leucoxene (as laths) is ubiquitous in a belt along the structural axis (see map). Spessartite-almandine garnet occurs patchily in the Snaefell district. There are local concentrations of apatite (e.g. slides I553D, E2889).

Description of Chief Minerals.

Chlorite is present in slides from all facies. It is frequently an alteration product. It is generally pleochroic from pale green to almost colourless and occasionally shows lamellar twinning. The largest crystals of chlorite occur at Archallagan (0.3mm) but generally individual crystals cannot be distinguished. Within the amphibolite facies it occurs as randomly oriented, platy porphyroblasts (0.5mm) which are sometimes twinned and which show pleochroism from colourless to pale green.

Biotite occurs in all facies except the muscovite-chlorite sub-facies. Within the amphibolite facies it forms plate-like porphyroblasts (0.5-I.0mm). It is pleochroic from colourless to dark brown (x-colourless, y-pale brown, z-dark brown) and contains pleochroic halos. Elsewhere along the structural axis it occurs as a felted mass of small crystals (0.05-0.06mm) which are pleochroic from light to dark brown. Away from the structural axis the biotite imparts only an aggregate pleochroism (light grey to dark grey, light green to mid-green) to the rock. The degree of preferred orientation is high and this imparts flow-cleavage to the rock (the other platy minerals are oriented parallel to the biotite and contribute to the flow-cleavage). The biotite is often partly replaced by chlorite.

Muscovite is best formed at Archallagan where the rock is a silvery schist. Along the remainder of the structural axis recrystallisation has been less intense but in places the rock is a silvery phyllite. At Archallagan the muscovite crystals attain a size of 0.5mm but elsewhere they are smaller (e.g. less than 0.03mm) and occur as a felted mass in the matrix. Where recrystallisation has been very slight white mica occurs as a sericitic aggregate.

Almandine occurs as hexagonal porphyroblasts which attain approximately 5mm in diameter (figs. 63,64). It is colourless in thin section but red or pink in hand specimen. There are all stages of replacement by chlorite which is often concentrated marginally. The chlorite is pleochroic from pale green to near colourless. It often contains pleochroic halos. The garnets commonly deflect the foliation forming augen in which interlocking aggregates of quartz are often concentrated. Some of the garnets contain small inclusions which are sometimes ordered and apparently represent former "s" planes. The inclusions are generally in parallel rows which however do not always conform to the existing planar structures in the rock.

Rarely, the inclusions show a spiral arrangement which suggests rotation of the porphyroblast during growth (e.g. slide E2669). Inclusions of quartz are common in the garnets and tourmaline is occasionally present.

Staurolite occurs as irregular shaped porphyroblasts (0.8mm) in slide E2669. It shows pleochroism from colourless to pale yellow (x-colourless, y-very pale yellow, z-pale or mid-yellow). The crystals are sieved with inclusions of quartz. Twinning is displayed by some of the staurolite (see fig.65). Not more than three crystals occur within the section.

Spessartite-almandine garnet porphyroblasts attain diameters of 5 - I0mm and occur as well shaped rhombicdodecahedra (fig.66). They are often partly chloritised but are sometimes quite fresh and unaltered. The chlorite differs from that which replaces the garnets at Archallagan in that it does not contain pleochroic halos. The garnets sometimes contain symmetrically arranged inclusions (slide I553D) which outline pyramids the apices of which are at the centre of the crystal while the bases of the pyramids are formed by the sides of the crystal. Harker [I] describes this arrangement of inclusions from Mn-garnets elsewhere. The fracture cleavage is deflected by the garnets which pre-date this structure. Leucoxene laths also post-date the garnets and project into pseudomorphed garnet crystals.

I. Harker, A. "Metamorphism" p44, I952, Methuen.

Chemistry of Garnets.

In view of the patchy distribution of the garnets in the Snaefell district and in the light of work by Goldschmidt[I],and others,colourimetric analyses were performed to determine the manganese content of the garnets.The results are set out in the accompanying table which for comparison also includes analyses of garnets from other areas.These results show a good deal of variability in the amount of MnO.

Only I609 (a specimen from the stream between Snaefell and Beinn-y Phott) would fall within the composition field of spessartite as given by Rankama and Sahama[2].They state that the MnO in spessartite varies from I5%-40%.All but those from near Foxdale could be regarded as spessartite-almandine.The amount of manganese which the garnets now contain is subject to the alteration which the sample has undergone and the sample which contains the highest percentage MnO is also the least altered specimen.

Specimen I553D displays a dark band,more garnetiferous,than the surrounding slate.Analyses of the dark band and surrounding slate show a higher percentage MnO in the dark band.While the amount is not large in either sample it is likely that the higher MnO-content explains the greater concentration of garnets.Turner[3] states that a high concentration of Mn in the sediment is not necessary to provide

I.Goldschmidt,V.M. "Die Injektionsmetamorphose im Stavanger-Gebiete" Vidensk.Skr.Mat.Naturv.Kl.,No.IO.

2.Rankama & Sahama "Geochemistry" Univ.Chicago Press I949 p64I.

3.Turner,F.J. op cit pI38 I948.

a high concentration of Mn in small garnets. Thus although the concentration of Mn in the sediments in I553D is not large it is likely that there was sufficient to allow the formation of Mn-garnets.

Isle of Man.

		% MnO	% Spessartite.
I553D	Quarry east of Bungalow Hotel, Snaefell - Garnets	4.379	I3.09
I553D	Dark garnetiferous band.	0.09I7	
I553D	Surrounding rock.	0.0I47	
I5I9	Snaefell railway.	I3.39	40.06
I559	Northern cliffs Snaefell.	5.994	I7.94
I609	Stream-bed south of Snaefell north of Beinn-y Phott.	I6.I7	48.4I
8I3	Snaefell railway.	I2.6I	29.22
3790	Foxdale	I.097	3.285
2252	Crosby quarry.	0.922	2.I38

Comparison Analyses.

Carrickmines, Co. Dublin.	I8.55
New Galloway.	I4.88
Grainsgill.	6.02
Odenwald.	I.90
Harlech.	38.04
Texas, Horse Mountain.	3I.77
Colorado.	29.48
Madagascar.	39.40
Virginia, U.S.A.	38.7
Connecticut.	37.2I
" " " " "	32.I8
California.	20.04

Cordierite has a maximum size of I - I.2mm within the aureole of the Foxdale granite (see fig.67,68).Elsewhere the largest cordierite crystals reach 0.6 - 0.8mm (figs.69,70,7I).The mineral occurs both as pseudomorphs and unaltered crystals. Within the aureole of the Foxdale granite the cordierite has been completely pinitised but it often shows its pseudo-hexagonal crystal form.Elsewhere it is often fresh or only partly altered.It sometimes shows twinning and its characteristic pseudo-hexagonal form but often has an irregular to oval outline.

The cordierite post-dates the flow-cleavage.Traces of this structure remain within the crystals in the form of minute inclusions which lie parallel to the flow-cleavage in the surrounding rock (e.g.figs.67,7I).It is earlier in date than the fracture cleavage (see fig.7I) which is often deflected by, or continues for short distances within,the boundaries of the cordierites.

In slide I963 it is interesting that some of the thin veins of quartz which cut the xenoblasts are themselves broken by the fracture cleavage indicating that they post-date the formation of the cordierite and pre-date the fracture cleavage.

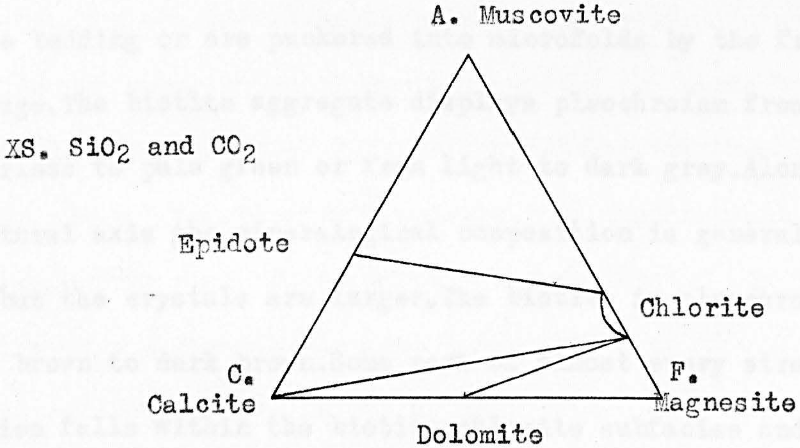
The cordierite which occurs some distance from the Foxdale granite aureole is often little altered but in slide I985,Injebreck, there are irregular to rectangular pseudomorphs which are crowded with small dark inclusions the arrangement of which indicates rotation of the crystals.It is likely that these pseudomorphs were originally cordierite.

Tourmaline occurs as green,lath-like crystals which when the mineral is abundant,can be distinguished in hand specimen with the aid of a lens.It shows pleochroism from light to mid-green (x-near colourless,z-medium green) in section and sometimes displays a bluish core surrounded by a green border (e.g.slide I9I6).When most abundant tourmaline is practically the sole constituent of the rock (e.g. I895).It displays lath-like crystal form and sometimes occurs in wavering folia (e.g. E2084). Triangular sections are quite common and the minerals tendency to idiomorphism where it is of metasomatic origin contrasts with the irregular detrital form which it displays when present as an accessory - e.g. present throughout the Manx Slates.

Leucoxene occurs as plate-like crystals (maximum length about 2mm) at the expense of ilmenite which is not always entirely replaced. Its orientation is random and it post-dates the fracture and flow cleavage.

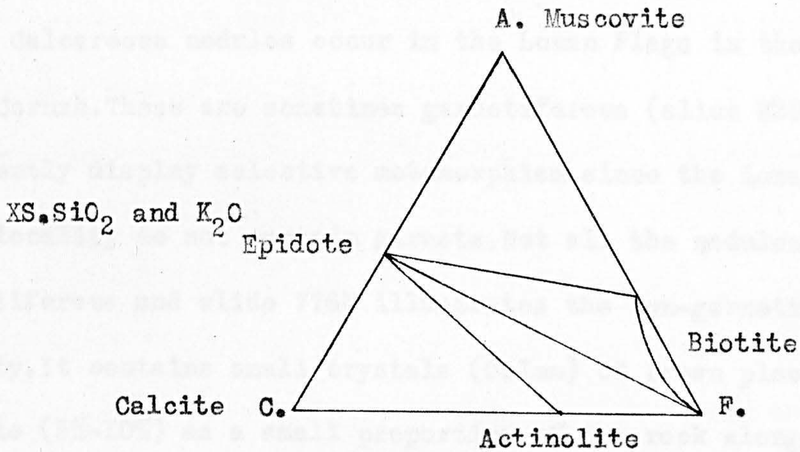
Characteristics of Facies.

Greenschist Facies.



Muscovite-chlorite subfacies.

Muscovite, chlorite, and quartz are the characteristic minerals in rocks which belong to this facies. The grain size is very small (see p89-description of slides from specimens obtained at Cronk Sumark).



Biotite-chlorite subfacies.

The greater part of the Manx Slates belong to this facies (see map). The recrystallisation varies and is greatest along the structural axis. Recrystallisation gradually fades towards the outer limits of the facies where it is not apparent in hand specimen. In the outer limits of the zone biotite, chlorite, and muscovite, form a felted mass of tiny crystals which lie parallel to the bedding or are puckered into microfolds by the fracture cleavage. The biotite aggregate displays pleochroism from near colourless to pale green or from light to dark grey. Along the structural axis the mineralogical composition is generally the same but the crystals are larger. The biotite is pleochroic from light brown to dark brown. Some part of almost every stratigraphic division falls within the biotite-chlorite subfacies and the proportions of biotite-chlorite and quartz-sericite vary according to the lithological type. Quartz and sericite preponderate in the light bands whereas biotite and chlorite are dominant in the dark bands.

Calcareous nodules occur in the Lonan Flags in the region of Port Cornah. These are sometimes garnetiferous (slide E25I0) and apparently display selective metamorphism since the Lonan Flags at this locality do not contain garnets. Not all the nodules are garnetiferous and slide 776N illustrates the non-garnetiferous variety. It contains small crystals (0.Imm) of brown pleochroic biotite (5%-I0%) as a small proportion of the rock along with a similar proportion of pale green, pleochroic chlorite (0.3mm). Epidote occurs and exhibits patchy, faint green pleochroism. Groups of interlocking quartz crystals,which sometimes contain tiny apatites,are surrounded by calcite (60%-70% of rock approximately). Laths of leucoxene are irregularly distributed across the section which is stained by limonite.Rutile occurs as an accessory.The mineral assemblage is characteristic of the biotite-chlorite subfacies to which the surrounding sediments belong but the greater proportion of calcite has allowed the free crystallisation of this mineral together with epidote thus distinguishing the assemblage from that of the Lonan Flags.As pointed out by Stainier[I] the apparent selective metamorphism of the nodules is similar to that seen in the Ardennes where the same phenomena is found on a larger scale.

There are patches of garnetiferous slate within the biotite-chlorite subfacies in the Snaefell district.These occur on Snaefell at the localities described by Lamplugh and in the bed of the stream between Snaefell and Beinn-y Phott where they have been found during the present work.

Mode of Occurrence of Spessartite-Almandine Garnet within the Biotite-Chlorite subfacies.

In all but two of the known occurrences the garnets are associated with veins of granular quartz.The veins enclose argillaceous patches which are of the order of I5cm across.These contain numerous garnets which average 5 - I0 mm in diameter,and

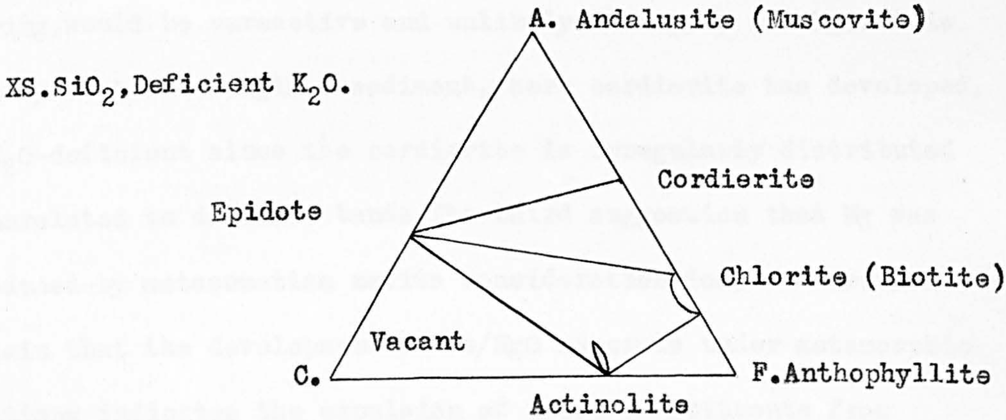
I.Stainier,X."Le Metamorphisme des Regions de Bastogne et de Vielsalm" Bull.de la Soc.Belge de Geol.Tom.XXXIX I929.

which are usually chloritised,but sometimes quite fresh and unaltered.

Approximately 900 yards west of the Bungalow Hotel up the Snaefell railway a patch of garnetiferous slate occurs.No connection appears to exist between the garnets and nearby quartz veins. The distribution of the garnets also seems unrelated to either bedding or cleavage.The patch of garnetiferous slate is about 4 feet wide.The concentration of garnets thins out by a rapid reduction in the size and numbers of the crystals and 3 feet from the edge of the garnetiferous area none can be found either microscopically or in hand specimen.Four slides confirmed these facts.In view of the association elsewhere of the garnets with quartz veins it is particularly interesting that a narrow vein of chlorite,quartz,and muscovite (see slide 8I6),not more than three feet from this garnetiferous slate,is quite barren of garnets as is the surrounding slate.

In the small quarry,previously described by Lamplugh,to the east of the Bungalow Hotel,garnets are to be found.Their distribution is once more distinctive and independent of quartz veins though influenced by the bedding since they are more abundant in I cm thick bands of dark grey slate than in the remainder of the rock.Specimen I553D was obtained at this quarry (see pI86).

Albite-Epidote Amphibolite Facies.



Actinolite-Epidote hornfels subfacies.

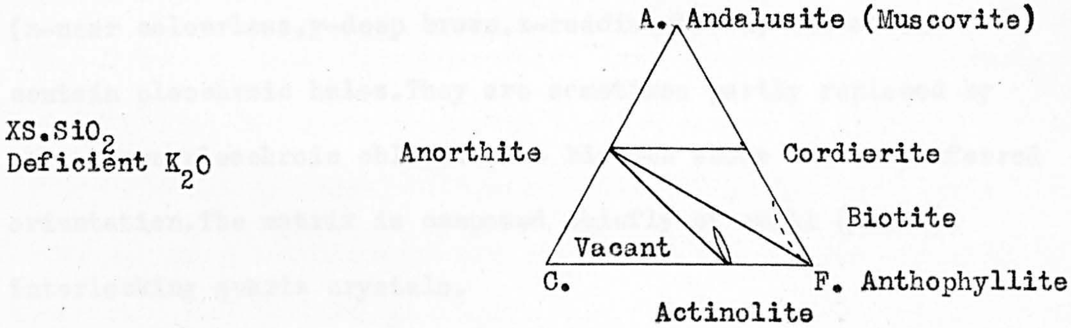
Within the biotite isograd patches of cordierite-bearing rocks occur.The mineral assemblage in these rocks,muscovite, chlorite,biotite,quartz,cordierite,is characteristic of the Albite-Epidote amphibolite facies.

Cordierite is often a Mg-rich mineral (Turner[I]).This element could be supplied from three sources:at the expense of pre-existing biotite;from the original rock if MgO had not been completely absorbed in the formation of biotite (e.g. if the original rock were deficient in K_2O);or by introduction from Mg-rich solutions.Cordierite commonly develops under conditions of low shearing-stress and Turner (p93) states that chemical

I.Turner,F.J. op cit I948 p79.

readjustment is very slow under thermal conditions so that there is no hornfelsic equivalent of the greenschist facies. The biotite-bearing assemblage, which formed under the influence of earlier shearing, would be unreactive and unlikely to supply the Mg. It is unlikely that the original sediment, where cordierite has developed, was K_2O-deficient since the cordierite is irregularly distributed and unrelated to definite bands. The third suggestion that Mg was introduced by metasomatism merits consideration. Some authorities maintain that the development of Fe/MgO minerals under metamorphic conditions indicates the expulsion of these constituents from elsewhere. This conclusion seems to meet with the fewest difficulties and in my opinion, is favoured, but the precise cause of the patchy distribution of the cordierite remains problematical.

Amphibolite Facies.



Cordierite-Anthophyllite subfacies.

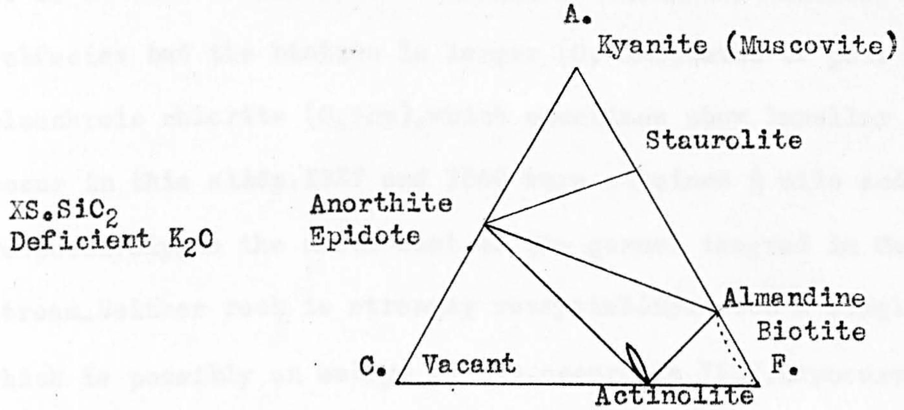
The development of this facies is strictly localised and only occurs within a few hundred feet of the Foxdale granite. It is illustrated by the following slides:

E2889. This slide shows a contact between the granite and surrounding hornfels. At the contact there are porphyroblasts (I.5mm) of colourless garnet but those farther from the contact (though in the same section) are smaller (0.4mm) and less well formed. Apatite enrichment has taken place within about Imm of the contact where this mineral comprises about 50% of the rock. The apatite occurs as uniaxial negative, anhedral crystals (0.08mm). Accessory amounts of apatite occur within the granite and within the hornfels situated farther from the contact. Tourmaline is enriched within a zone about Imm thick from the granite contact. It comprises about I0%-I5% of the rock within this zone but elsewhere, both in granite and hornfels, it is only an accessory constituent. There are platy porphyroblasts of biotite (0.75mm) which show pleochroism (x-near colourless, y-deep brown, z-reddish brown) and often contain pleochroic halos. They are sometimes partly replaced by pale green, pleochroic chlorite. The biotite shows little preferred orientation. The matrix is composed chiefly of small (0.Imm), interlocking quartz crystals.

I892. Small garnets (0.8mm) are present which are largely pseudomorphed by pale green, pleochroic chlorite (see fig. 64). Cordierite occurs as hexagonal porphyroblasts (Imm) now pseudomorphed by faint yellow-green pinite (see fig. 67). The cordierite has often partly assimilated the groundmass and the flow-cleavage can be traced within the margins of the crystals. There are randomly oriented crystals of pale green, pleochroic chlorite (0.3mm) which sometimes show lamellar twinning. They often contain pleochroic halos, in which respect they resemble the partly replaced biotite porphyroblasts of E2889. It appears possible that these crystals of chlorite were originally biotite porphyroblasts now completely replaced. The matrix consists of folia of chlorite and sericite and interlocking quartz crystals (0.12mm).

E2803. This slide contains similar pseudomorphed cordierite porphyroblasts (0.75mm) to those seen in slide 1892 (see fig.68). The matrix consists of alternating folia of muscovite (.06mm maximum size of laths) and small (0.05mm) quartz crystals and sericite. The muscovite folia are approximately 0.04mm wide, the quartz-sericite bands about 0.08mm wide. Brown sphene, as irregular crystals, is an abundant accessory.

Turner explains the presence of both almandine and cordierite in this facies by reference to the limited extent to which Mg and Fe may replace one another in these two minerals so that the two metals behave as independent components and not as the uni-component Mg/Fe which are mutually interchangeable.



Staurolite-Kyanite sub-facies.

There are few exposures for about $\frac{3}{4}$ mile to the north of the Foxdale granite but one small exposure indicates that the rock is not garnetiferous (see slide I887). $\frac{3}{4}$ mile to the north-north-east exposures of garnetiferous mica schist occur at Archallagan where the metamorphism in the Isle of Man reaches its highest grade. The metamorphism increases rapidly from all sides towards this locality and this increase is most clearly seen in the beds of the streams (Cooillingill and Glion Darragh) which drain northwards from Archallagan.

$\frac{1}{4}$ mile west of the garnet isograd (see map) recrystallisation is no more intense than is usual along the structural axis (see 2I85). A similar lack of intensification of metamorphism is shown by slide I887 which illustrates a specimen obtained $\frac{1}{2}$ mile south-west of the garnet isograd. Slide 2I8I, specimen obtained 5/6 mile east-south-east of the garnet isograd, is similar. Specimen I874 was obtained in Glion Darragh I/3 mile north of the garnet isograd. It is similar to rocks from elsewhere within the biotite-chlorite subfacies but the biotite is larger (0.4mm). Laths of pale green pleochroic chlorite (0.5mm), which sometimes show lamellar twinning, occur in this slide. I857 and I860 were obtained ½ mile and ¼ mile respectively, to the north-east of the garnet isograd in Cooillingill stream. Neither rock is strongly recrystallised but a single crystal, which is possibly an embryo garnet, occurs in I857. Exposures to the east, west, and south, of Archallagan are not sufficiently plentiful to allow the garnet isograd to be positioned more accurately than to within about ¼ mile. To the north, in Glion Darragh, exposures are nearly continuous and the isograd may be defined to within 50-I00 feet.

Survey slide E2669, western branch of Glion Darragh (Memoir pII2), contains staurolite (see fig.65). The occurence is evidently very localised since despite the preparation of several more slides from specimens obtained in the same area no further occurence of staurolite has been found.

The general microscopic appearance of these schists is of alternating folia of interlocking quartz crystals and parallel oriented platy minerals. The schistosity is deflected by hexagonal porphyroblasts of garnet which form augen. Quartz is often concentrated in the corners of the augen formed by the garnets. Plate-like crystals of brown, pleochroic biotite (0.75mm), with pleochroic halos, are of irregular distribution. Tourmaline, leucoxene, magnetite, sphene, and zircon form accessories.

Relation to Movements.

By reference to the most important cleavages in the rocks it is possible to distinguish definite phases in which certain characteristic new minerals appeared and hence to correlate stages in the metamorphism with the movement phases.

Muscovite-chlorite and Biotite-chlorite subfacies'.

The earliest movements led to sharp folding and the development of steeply inclined flow-cleavage. This is imparted to the rock by platy minerals such as chlorite, muscovite, and biotite which formed during these movements by recrystallisation. During this movement phase it is unlikely that the grade of metamorphism was anywhere advanced beyond the biotite-chlorite subfacies and in regions away from the structural axis towards both the south-east and north-west sides of the island very little mineralogical change took place. This stage of metamorphism is the most widespread and typical of the Manx Slates but in places it has been obscured by later metamorphism and metasomatism.

Spessartite-almandine garnets.

The fracture cleavage is deflected by these garnets and evidently they developed before this latest phase of movements. Their relationship to the flow-cleavage is less apparent. This cleavage generally stops short at the margins of the crystals and does not appear to flow around them (except where dragged into that relationship by the fracture cleavage), as would be the case if the cleavage post-dates the crystals. Therefore it is likely that the garnets post-date the early movements.

Albite-epidote amphibolite subfacies.

Cordierite occurs at scattered points along the structural axis and appears to have formed later than the biotite of the flow-cleavage movements since trails of inclusions lying parallel to the schistosity can frequently be traced across individual crystals (see figs.67,71). The planes of fracture cleavage either penetrate a short distance into the cordierite crystals or are deflected by them. The cordierite therefore formed prior to the movements in which the fracture cleavage developed.

Cordierite is listed by Harker[I] as a typical "antistress" mineral by virtue of its common development under conditions of low-grade, purely thermal metamorphism, but in Scotland it is also known to occur under "regional" conditions. Harker attributes its presence to deficient shearing-stress and emphasises that its occurrence is quite distinct from a second metamorphism. The "widespread and abundant" distribution of this cordierite contrasts with that in the Manx Slates which is patchy. It seems unlikely that maximum shearing-stress could prevail throughout the greater part of a series but have a reduced value at scattered localities. If the temperature of the rocks remained elevated after the reduction of shearing stress one would anticipate a general development of cordierite provided the rocks were, in general, of appropriate

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I. Harker, A. op cit 1952 p231.

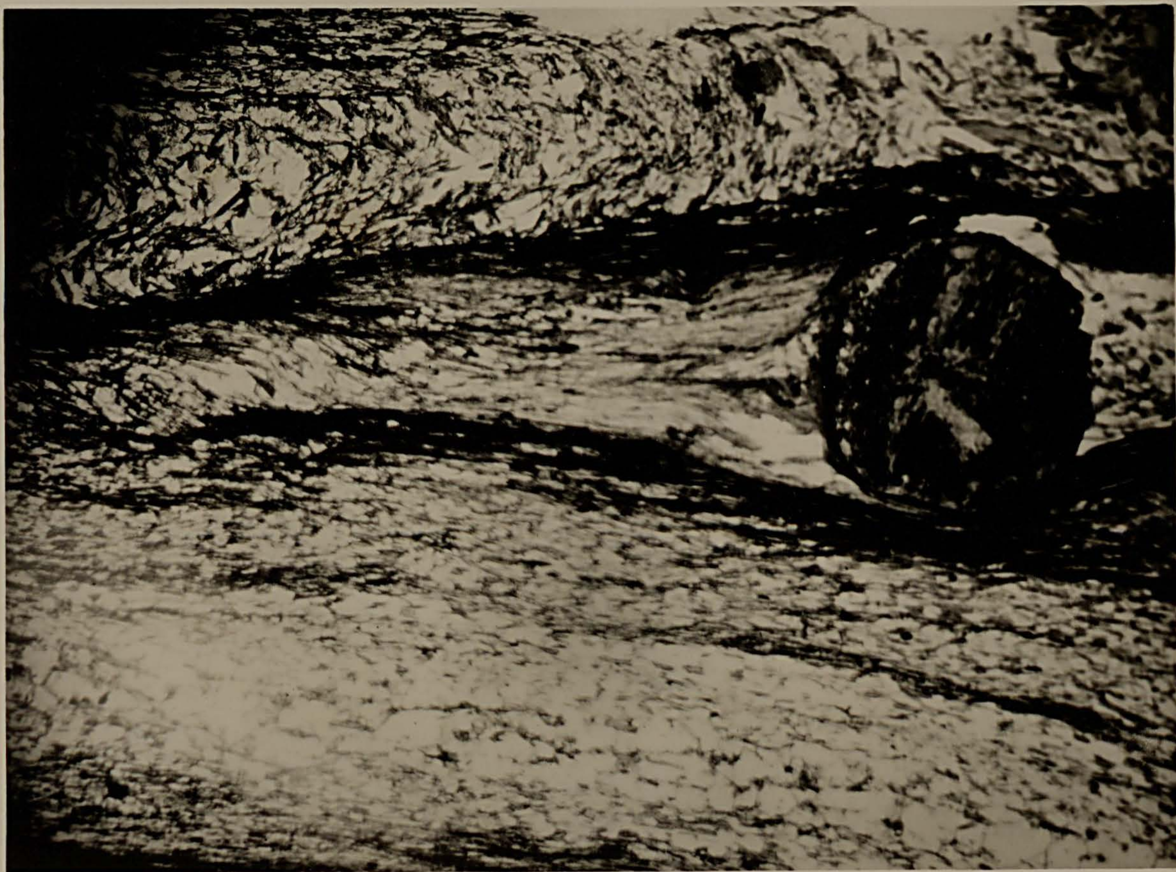
chemical composition. The Manx cordierite is patchily distributed but there is no evidence to suggest that this is dependent on changes in lithology such as might have caused the chemical composition to be patchy. The scattered development of cordierite may have been caused by the local introduction of appropriate elements required for its development (e.g. MgO possibly). There is no evidence (such as that provided by Harker) to support the view that shearing-stress was below its maximum value during the early movements and early metamorphism and therefore an introduction of say magnesium during the early movements would have been unlikely to lead to the development of cordierite. Hence it seems probable that the cordierite developed in response to the metasomatic introduction of certain elements (e.g. MgO) at a period when the early movements had finished or become reduced in intensity. It seems likely that the cordierite developed at a period of reduced stress between the major movements.

Amphibolite facies.

Fracture cleavage is present outside this facies but gradually becomes indistinct as the garnet isograd is approached (see map). It seems probable that recrystallisation outlasted the fracture cleavage producing movements.

265
N 80

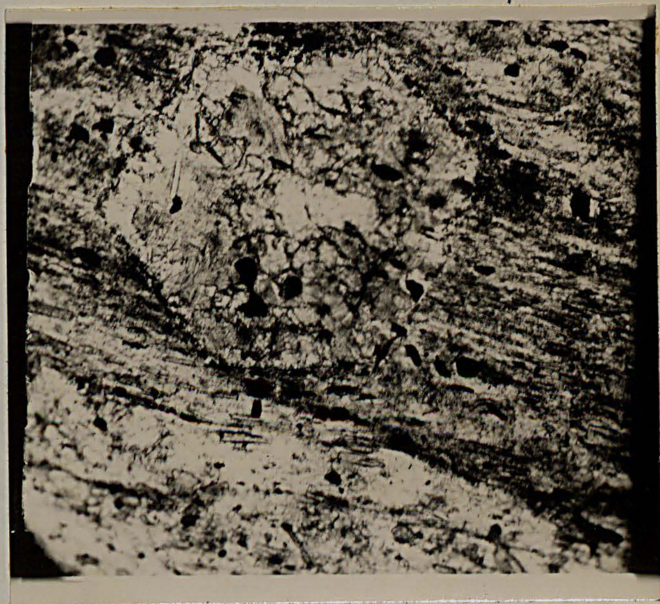
Observer facing North



Magnification by 26.
Slide I878, specimen from Glion Darragh. Garnet porphyroblast with augen structure and shearing.

Figure 63.

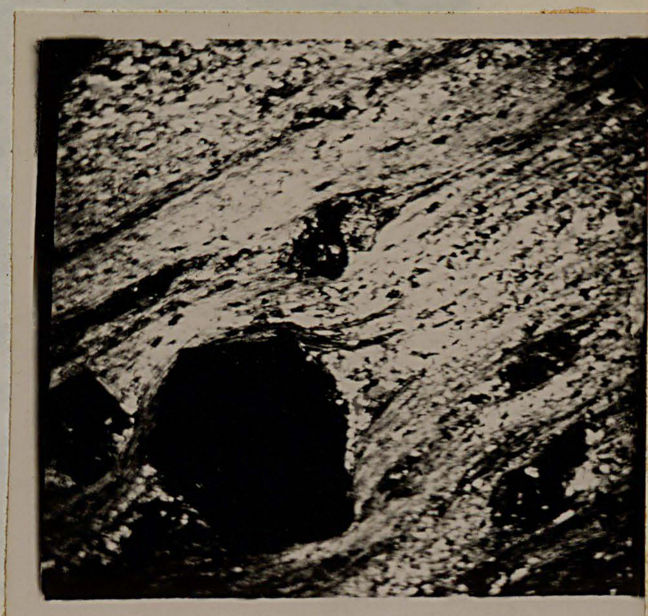
Observer faces West



S ∧ 80 / 218.

Magnification by 63.
Slide I892, specimen from quarry south of Foxdale granite - garnet porphyroblast.

Figure 64.



Magnification by II.
E2669, Glion Darragh, Archallagan. Garnet, staurolite, and biotite, porphyroblasts - staurolite showing twinning.

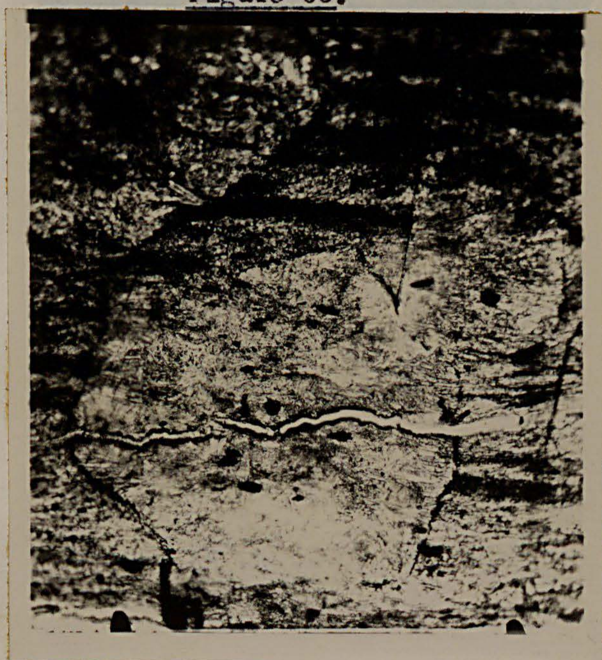
Figure 65.

E45°/160

Observer facing east.

Slide I529,specimen from south of Snaefell and north of Beinn-y Phott - stream-bed.Garnet porphyroblasts.

Figure 66.



S80/218

Magnification by 38. Observer facing West.

Slide I892,specimen from quarry south of Foxdale granite.Cordierite porphyroblasts.

Figure 67.

Magnification by 40
Slide E2803, Potts shaft, Foxdale. Cordierite porphyroblasts.

Figure 68.

Observer looking S.E.

046
↓70
S.E.

Magnification by I8. Crossed nicols.
Slide I36I, specimen from upper reaches Glen Auldyn, above fork near level on 6 inch map. Cordierite porphyroblasts showing pseudo-hexagonal form.

Figure 69.

Magnification by 35.
Slide I602,specimen from stream-bed between Snaefell and Beinn-y Phott above Lead Mine.Cordierite porphyroblasts.

Figure 70.

Magnification by 2I.
Slide I963,specimen from East Baldwin. Cordierite porphyroblasts.Note inclusions lying parallel to schistosity and deflection of fracture cleavage by oval-irregular Cordierite crystals.

Figure 7I.

Hydrothermal Effects.

Cause for Patchy distribution of Spessartite-almandine Garnet.

Under conditions of regional metamorphism as described by Barrow[I], Goldschmidt[2], Tilley[3], and others, garnet forms the index mineral for the next higher zone to that of biotite. It was found by Goldschmidt[4] that in the Stavanger district of Norway the order of appearance of biotite and garnet was reversed and garnet developed before biotite. This garnet was shown by him to be spessartite-almandine containing I2.28% MnO.

Turner[5], Phillips[6], Tilley[7], Williams[8], Woodland[9], Emerson[IO], Fermor[II], Kitson[I2], and Myashiro[I3] have also described the development of Mn-garnets under conditions of low-grade metamorphism. It has been shown (Turner) that a high concentration of Mn is not required to allow a considerable development of garnet. Garnetiferous quartz veins, evidently similar to those in the Snaefell district, have been described by Emmons[I4], and by Barth and Balk[I5].

It seems probable that Mn was introduced into the Manx Slates of the Snaefell district by certain of the quartz veins and this

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I. Barrow, G. Q.J.G.S. I893 XLIX p330-338. Proc.G.A. XXIII p274-290. I9I2.
2. Goldschmidt, V.M. Vidensk.Skr. I9I5.
3. Tilley, E.C. Min.Mag. XXI I926 p34-46.
4. Goldschmidt, V.M. Vidensk.Skr. I920 No.IO p48.
5. Turner, F.J. op cit I948 pI38.
6. Phillips I928 p550.
7. Tilley, E.C. I923 pI98
8. Williams I927 p36I.
9. Woodland, A.W. Q.J.G.S. I939 pI-32 XCV. Geol.Mag. I938 p366-82.
IO. Emerson, C.K. U.S.G.S. Bull. No.597 I9I7.
II. Fermor, Mem.Geol.Surv.India. XXXVII I909
I2. Kitson, Tr.Inst.Min.Met.Eng. Vol.LXXV I927 p372-84.
I3. Myashiro, A. Geochimica et Cosmochim.Acta I953.
I4. Emmons "Principles of Economic Geology" Mc.Graw Hill I9I8 p52.
I5. Barth and Balk Bull.Geol.Soc.Am. I936 Vol.47 p685-774.

allowed spessartite-almandine garnet to develop. Possibly the Mn was introduced by veins of only a certain age (quartz veins both pre-date and post-date the fracture cleavage) and this perhaps accounts for the absence of garnets from the majority of quartz veins.

Boron Metasomatism.

Tourmaline is concentrated in veins in the Dhoon granite and at localities in the south of the island which are never more than 2¼ miles from the Foxdale granite.

Lamplugh denied any relationship between the Foxdale granite and the tourmaline on the grounds that the tourmaline was too far from the intrusive for it to have been responsible.

Tourmalinisation, remote from any granite, has been described by Williams[I], Fearnsides[2], and Barth[3]. Many cases are known in which an unmistakeable relationship exists between tourmalinisation and granite. Such cases have been described by Teuscher[4], Dunn[5], and Harwood and Brammal at the Dartmoor granite. Barth[6] associates the tourmaline in the slightly metamorphosed rocks of Dutchess Co., New York, with the granitic intrusives; the presence of tourmaline in limestone and dolomite of this region is particularly important

I. Williams. Q.J.G.S. I927 LXXXIII p354-6.
2. Fearnsides. Rept. Brit. Assoc. I908 (I909) p704.
3. Barth and Balk op cit p792, I936.
4. Teuscher, E.O. Min. Pet. Mitt. 47, I936 p2II, 273.
5. Dunn, J.G.W. Econ. Geol. I922 Vol. I7 pI53.
6. Barth and Balk op cit.

since Goldschmidt and Peters[I] found only 0.0005% - 0.001% B_2O_3 in recent sedimentary carbonates. In Otago, Hutton[2] attributes the regionally distributed tourmaline to boron-carrying magmatic solutions even when the tourmaline occurs as much as 120 miles from any known outcrop of granite. In the more highly metamorphosed equivalents of these rocks tourmaline becomes increasingly abundant.

In the Manx Slates, when tourmaline is a major constituent of the rock, it seems justifiable to conclude that it is of metasomatic origin and is probably related to granite.

Elsewhere in the Manx Slates, tourmaline is a common accessory mineral. Read[3] believes that the ubiquitous presence of tourmaline in regionally metamorphosed rocks indicates the action of "emanations" through all grades. However, tourmaline is a common accessory mineral in such non-metamorphic rocks as those of the Weald[4] and this casts doubt on its metasomatic origin when present in small quantities in metamorphic rocks. Goldschmidt and Peters demonstrated the presence of 0.I% B_2O_3 in argillaceous marine sediments. On metamorphism this would, according to Turner[5], be sufficient to account for minor amounts of tourmaline in the rock.

The accessory amounts of tourmaline in the Manx Slates are likely to have been an original constituent of the sediments as the crystals often display detrital form.

I. Goldschmidt and Peters. Zur Chemie des Bors, Nachr. Ger. Wiss. Gottingen, Mat-Phys. K.I. p403-407, 528-545.

refs. cont'd over/

Quartz Veins.

The quartz veins are not associated with the granites in Lamplugh's view.He concludes "that they have been formed in crevices by infiltration and segregation under the influence of thermal waters" (Memoir p320).The relationship of the veins to the surrounding sediments does often suggest infiltration rather than injection "along continuous fissures like the dykes" since in many cases the sediment is impregnated and assimilated by the vein.This however does not prove that they are not of granitic parentage.

Stainier[I] compares the metamorphism in the Ardennes with that in the Isle of Man and discusses the significance of the quartz veins.He concludes that the veins are of eruptive origin. Harker[2],Lomas[3],and Simmons[4],associate the Manx quartz veins with the granites.They regard them as a final acidic residue of the granitic magma.

I.Stainier,X op cit I929.
2.Harker,A."The Grainsgill Greisen" Q.J.G.S. pI39.tli.
3.Lomas,J. "Quartz Dykes near Foxdale" Geol.Mag.I903 p34.
4.Simmons,W.C."The Granite mass of Foxdale,Isle of Man,etc."Geol.Mag. I9II p345-352.

refs.cont'd.

2.Hutton,C.O."The significance of tourmaline in the Otago,schists" Roy.Soc.New Zealand Trans. Vol.68 Pt.4 I939 p599-602.
3.Read,H.H. "Met.and Igneous Action" Sect.C, Brit.Assoc.I940.
4.Allen,P."Wealden Petrology;Top Ashdown pebble bed and top Ashdown sandstone" Q.J.G.S. I949
5.Turner,F.J. op cit pI27.

Turner and Verhoogen[I] state that in the uppermost zones of the crust "quartzose veins of hydrothermal origin are abundant and represent the only material contribution expelled from the magmas congealing in the depths beneath". In my opinion this is the most likely conclusion and the Manx quartz veins are likely to have been introduced by hydrothermal solutions which were probably of granitic parentage.

Causes of Metamorphism.

a) Regional.

i) Lamplugh's Views.

Lamplugh attributes the metamorphism to "differential movements" but admits that the granites may "have played their part in raising the temperature of the rock-mass and bringing it nearer to the critical stage".

The development of new minerals (e.g. garnet on Snaefell and tourmaline south of South Barrule) in the vicinity of quartz veins is attributed to "increased crushing and friction developed along the junction of soft and hard masses".

Recrystallisation is stated to be "chiefly prevalent in the banded strata of transitional type which lie between the Barrule Slates and the Grits".

He suggests that there is a relation between the distribution

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I. Turner & Verhoogen "Igneous and Metamorphic Petrology" McGraw Hill 195I p306.

of the breccias and metamorphism with respect to the structural axis.

He states that "it is noteworthy that the greatest degree of alteration is attained where the planes of dominant 'shear cleavage' are flat or nearly so".

ii)Discussion of Lamplugh's views.

The association of new minerals with quartz veins indicates that these minerals are of hydrothermal origin.

The present work indicates no greater degree of recrystallisation in banded strata than in homogenous slates.

The origin of the breccias is unlikely to have any relationship to the metamorphism and in any case there is no real comparison between the distribution of the breccias and metamorphism.

The most widespread metamorphism pre-dates the fracture cleavage which has a shallow dip along the structural axis. The more intense recrystallisation at Foxdale and Archallagan appears to have outlasted the fracture cleavage producing movements. The fracture cleavage probably has no direct bearing upon the causes for Manx metamorphism.

iii)Discussion of Current postulates as to the Causes of Regional Metamorphism and their application to Manx metamorphism.

Turner[I] lists five principal mechanisms which are currently put forward either individually, or in combination, to explain regional metamorphism. These are: regional invasion by granitic magma; regional

I. Turner, F.J. op cit 1948 p283-284.

deformation under tangential stress;deformation under vertical load resulting from deep burial;static recrystallisation under high temperature due to deep burial;and regional invasion by chemically active solutions.

Of these,static recrystallisation at high temperature can be at once dismissed as a cause of Manx metamorphism as this occurred during intense folding;since the widespread development of biotite apparently coincided with the first phase of movements which appear to have occurred under lateral compression,deformation and metamorphism under vertical load can also be ruled out.The coincidence of the first phase of metamorphism with the early movements at first sight seems to support the view that the movements caused the metamorphism but as metamorphism dies out towards the north-west and south-east,where these movements were no less intense than in the metamorphic region,the conclusion is not supported.

The Lonan Flags exposed to the south-east of the metamorphic belt are the oldest rocks of the Manx Slates Series (see p85) whereas the Cronk Sumark Slates and Sulby Flags,to the north-west of the metamorphic belt,are the youngest beds of the series. Therefore it is not possible to explain the difference in metamorphic grade,as between the south-east and north-west coasts and the axial region,as due to an insulating effect dependent on thicker sedimentary cover.

While the conclusion that deformation exerts a catalytic effect on metamorphic reaction is not questioned, in the Manx Slates, some other agency in addition seems required to explain the development and distribution of new minerals.

Stainier[I] has postulated that a granitic batholith underlies the axial region and that the Foxdale and Dhoon granites are apophyses of the deeper granite.

Many French geologists' correlate the style of contact with the depth at which granite occurs, believing that those at the centre of a wide belt of alteration formed in situ, while those with a narrow aureole were intrusives which rose from their place of formation, to present cross-cutting relations to the country rock.

If the postulated granite, beneath the Manx Slates, is assumed to approach most closely to the surface below the axial belt the difference in the degree of metamorphism between that belt and the north-west and south-east districts of the island may be explained. In my opinion this view meets with the fewest difficulties as an explanation for the distribution of Manx metamorphism.

b)Localised high-grade metamorphism.

i)Lamplugh's View.

Granite of Foxdale type was found in the shaft of the Old Cornelly lead mine, Archallagan, at a depth of 300-400 feet (Memoir pIII). Lamplugh does not attribute the metamorphism in the Archallagan region to the heating effect of this granite on the grounds that

I. Stainier, X. op cit 1929.

comparable metamorphism is lacking in the sediments which surround the Foxdale granite itself. The metamorphism at Foxdale differs in kind, but not degree, from that at Archallagan (see pI94, I97).

ii) Alternative to Lamplugh's view.

Brindley[I] reports that hornfels occurs near the contact of the Leinster granite and as isolated patches within the massif, but away from the contact the hornfels passes into mica-schist, which constitutes the main rock-type of the aureole. This again merges into slate farther out. Brindley considers that the schist and hornfels are strictly contemporaneous, the schist having developed under intense paracrystalline deformation within the granitic aureole, the whole of which represented a mobile or plastic envelope to the igneous body. Contact metamorphism took place hand in hand with the intrusive movements.

This explanation is not exactly applicable to the metamorphic high in the Foxdale-Archallagan district of the Isle of Man since no gradual outward passage from hornfels into schist occurs in the rock surrounding the granite but it suggests an explanation which may fit the facts of the case.

If the rocks exposed at Archallagan were subjected to shearing movements while the rock surrounding the Foxdale granite was in some

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I. Brindley, J.C. "Metamorphic aureole at the northern end of the Leinster granite" I8th Session Int. Geol. Cong. I948, p27-28. The Geology of E. Ireland.

way protected the development of schist at Archallagan and hornfels at Foxdale would be a natural consequence. No information is at present available as to the direction from which the granite was intruded or as to whether the Foxdale and Old Cornelly granites are directly connected but it seems possible that the Cornelly granite underwent either more intense, or more protracted, movements than the Foxdale granite and hence exerted a greater shearing effect upon the overlying sediments. It may be that the difference is connected with the different relative positions of the sediments at the two places; at Foxdale they lie at the same structural level as the granite while the roof has been removed by erosion but at Old Cornelly the schist lies 300-400 feet above the intrusion towards which its greatest intrusive force may have been directed.

In any event and in view of the inadequacy of other explanations, it seems to me, most reasonable to attribute the local high-grade metamorphism of this region to the heating effect of the granite.

Summary of Evidence in favour of the postulate that a buried granite underlies the Axial Belt.

I)Metamorphism.

The distribution of regional metamorphism may be explained if one assumes that the postulated granite is closest to the surface beneath the axial belt.

2)Metasomatism.

a)Boron metasomatism,leading to tourmalinisation,is commonly associated with granite.The tourmaline is often some distance from visible granite outcrops ($2\frac{1}{4}$ miles) but it is distributed along the axial belt beneath which the postulated granite extends.

b)The distribution of leucoxene laths is strikingly associated with the axial belt (see map).

c)Mn-metasomatism occurs along the axial belt (e.g. Snaefell garnets).

d)Cordierite is patchily distributed along the axial belt (possibly due to Mg-metasomatism).

e)Apatite is patchily concentrated along the axial belt (e.g. slide I553D).

f)"Basic elements" have been stated to become concentrated adjacent to regions undergoing "granitisation".Such a process occuring in depth beneath the axial belt,may have expelled Ti,Mn, Mg,and P, giving rise to metasomatism.

g)Retrograde changes of the chief metamorphic minerals to

OH-bearing pseudomorphs indicate late-stage hydrothermal activity such as is a common accompaniment of the final phase of granitic activity.

h)The lamprophyre dykes show late-stage deuteric effects. It is possible that the solutions which caused these effects were of granitic parentage.

3)<u>Intrusions</u>.

a)The microgranite dykes are confined to the axial belt.

b)The granitic intrusions (Foxdale and Dhoon granites) are on, or near the axial belt - the Oatland igneous mass is however an exception. They are perhaps apophyses of the more deeply buried granite.

4)<u>Mineralisation</u>.

a)The economic mineral deposits occur in north-south, east-west fractures which are distributed along the axial belt. Ore deposits are often associated with plutonic rocks and the axial-belt distribution of the ores may indicate the existence of an underlying granite.

5)<u>Structures</u>.

a)The fracture cleavage folds are overturned away from the structural axis. Plastic granite may have provided a surface of low frictional resistance on which outward sliding under gravity could occur e.g. "gravity tectonics".

b)The fracture cleavage forms an anticline and the dips flatten in the axial region. The structure resembles a regional "bending fold" (Sherbon Hills) in which fracture cleavage acted as the dominant "s" planes. This fold perhaps developed in response to the vertically directed force of the granite. This regional doming would cause tension in the axial belt and it is to this belt that the micrograninte dykes are confined (see 3a).

Summary of Events in the Geological History of the Manx Slates.

I) Sedimentation; "creep" resulted in small-scale disturbance of the bedding and later, submarine slides produced breccias.

2) Pre-cleavage intrusions:- "Lhergydho felsite" and early basic dykes.

3) North-west - south-east compression produced folds slightly overturned towards the structural axis and "inverted fan" flow-cleavage. Widespread, low-grade metamorphism.

4) Early fracture cleavage and near-upright folds formed (e.g. Port Mooar). These probably developed in the closing phase of 3.

5) Relaxation of compression. Intrusion of second suite of basic dykes. Microgranites intruded in the axial region along with larger plutonic masses. Establishment of vertical forces. Cordierite developed due to the continuation of metamorphism or metasomatism after relaxation of stress.

6) Vertically directed forces became dominant. Folds overturned away from structural axis. Regional fracture cleavage developed. In late phases this functioned as the dominant structural planes and formed a gentle anticline.

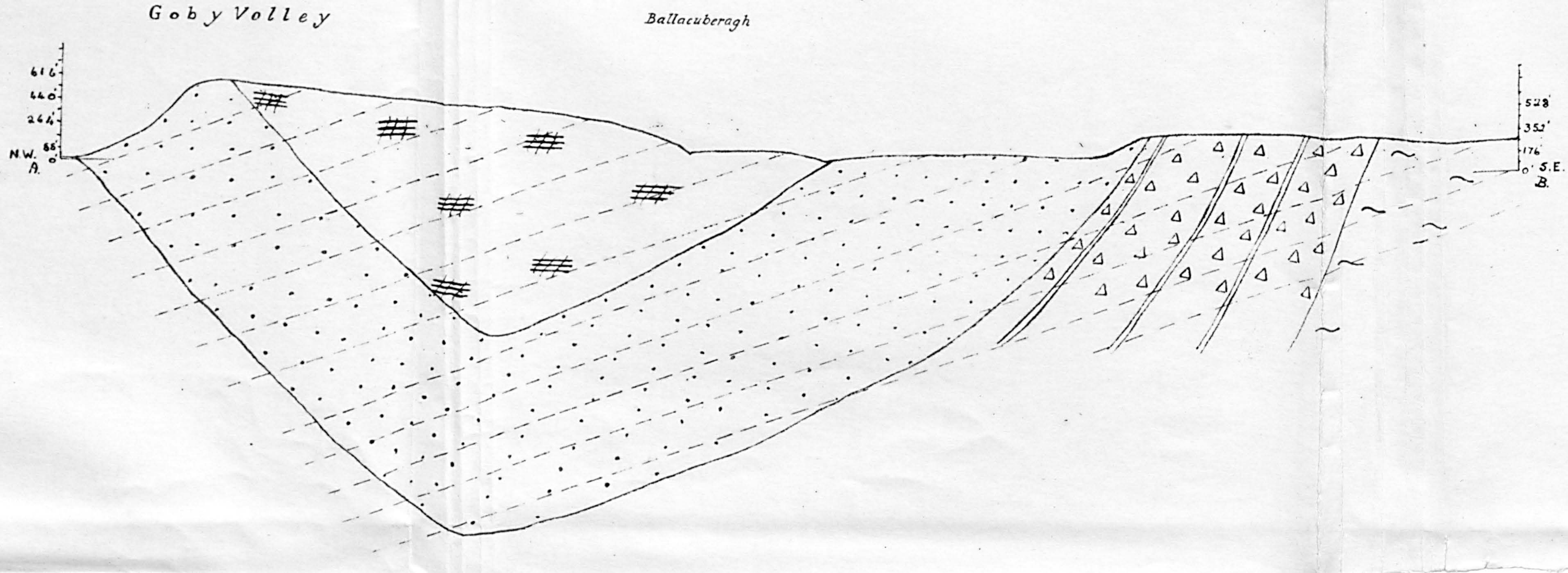
7) Metamorphism outlasted the movements at Archallagan and healed the fracture cleavage.

8) Faulting, jointing, and late lineation.

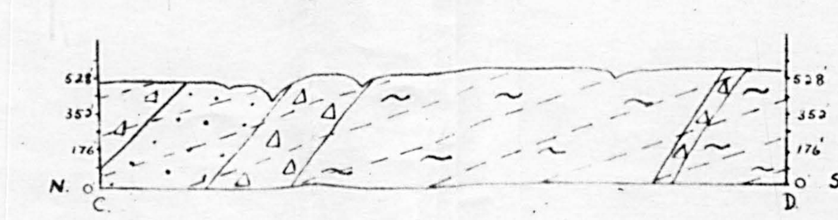
9) Hercynian stress system established forming north-south and east-west fractures filled by economic deposits.

IO) Tertiary (?) olivine-dolerite dykes intruded.

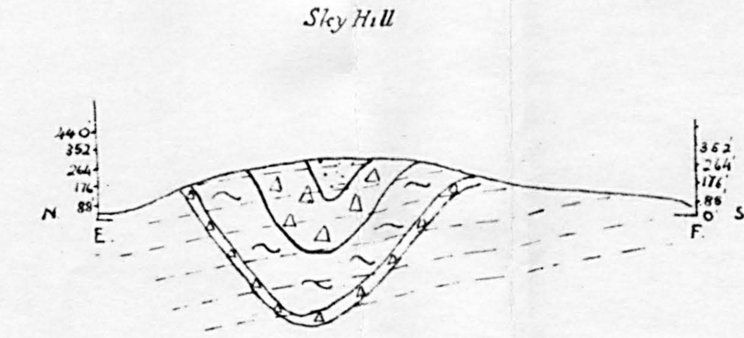
GOB Y VOLLEY SYNCLINE.

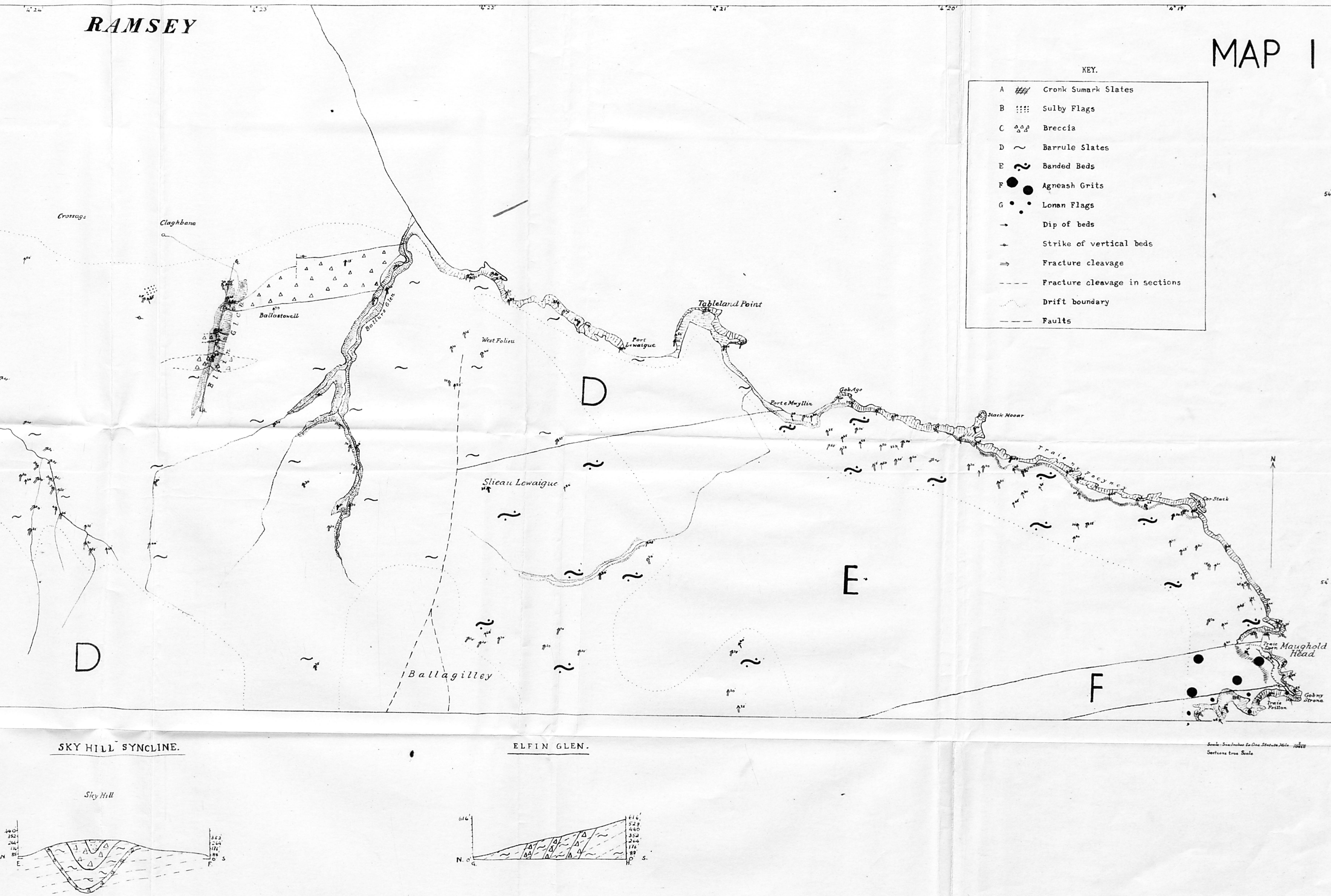


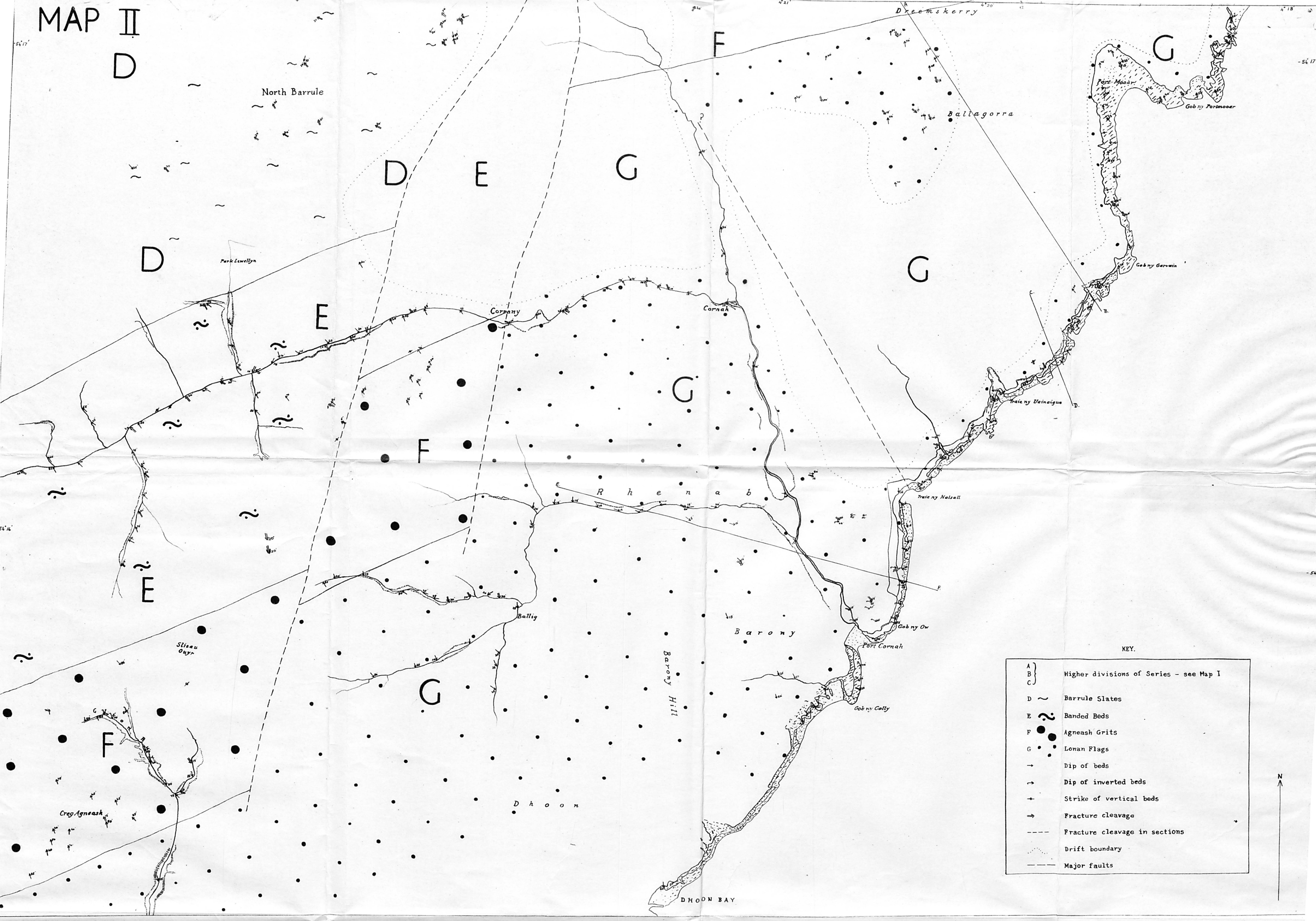
SKY HILL FARM SUCCESSION.

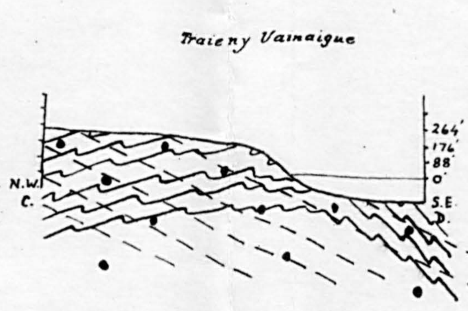


SKY HILL SYNCLINE.

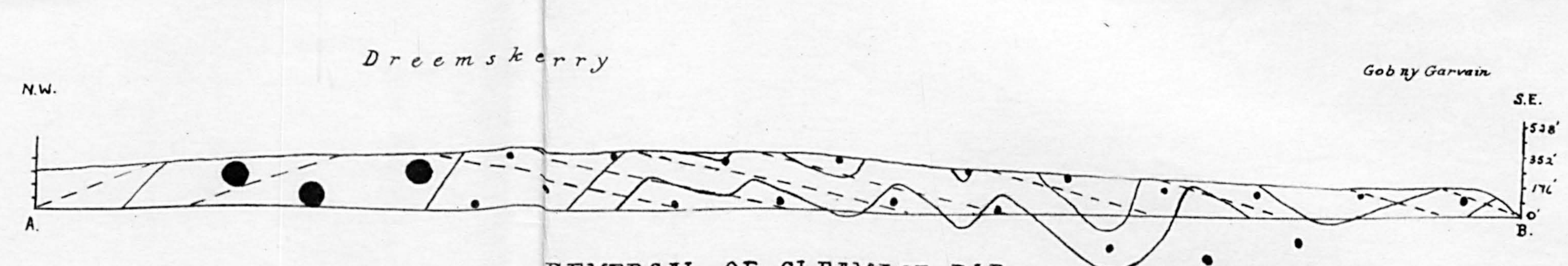



MAP I
RAMSEY
KEY.
A Cronk Sumark Slates
B Sulby Flags
C Breccia
D Barrule Slates
E Banded Beds
F Agneash Grits
G Lonan Flags
Dip of beds
Strike of vertical beds
Fracture cleavage
Fracture cleavage in sections
Drift boundary
Faults
Crossags
Claghbane
Ballastowell
Ballure Glen
West Folieu
Tableland Point
Port Lewaigue
Port e Mwyllin
Gob Age
Stack Mooar
Slieau Lewaigue
Ballagilley
Maughold Head
Gob ny Strona
D
E
F
SKY HILL SYNCLINE.
Sky Hill
ELFIN GLEN.
N
S
Sections true Scale

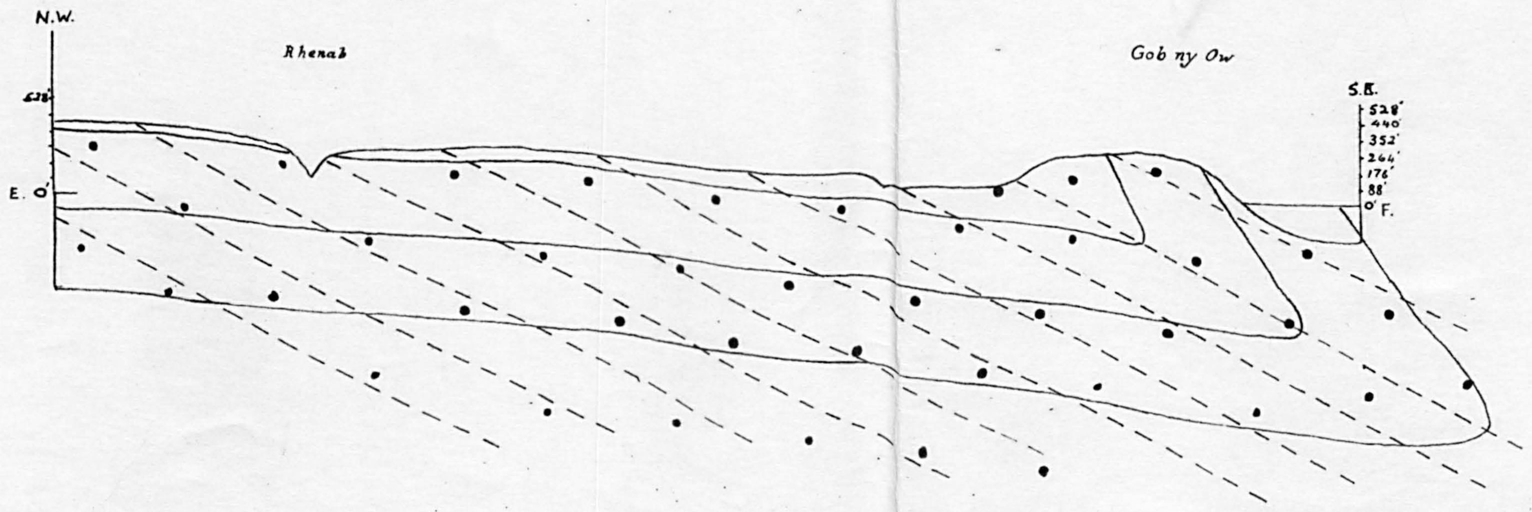




REVERSAL OF BEDDING.



REVERSAL OF CLEAVAGE DIP.

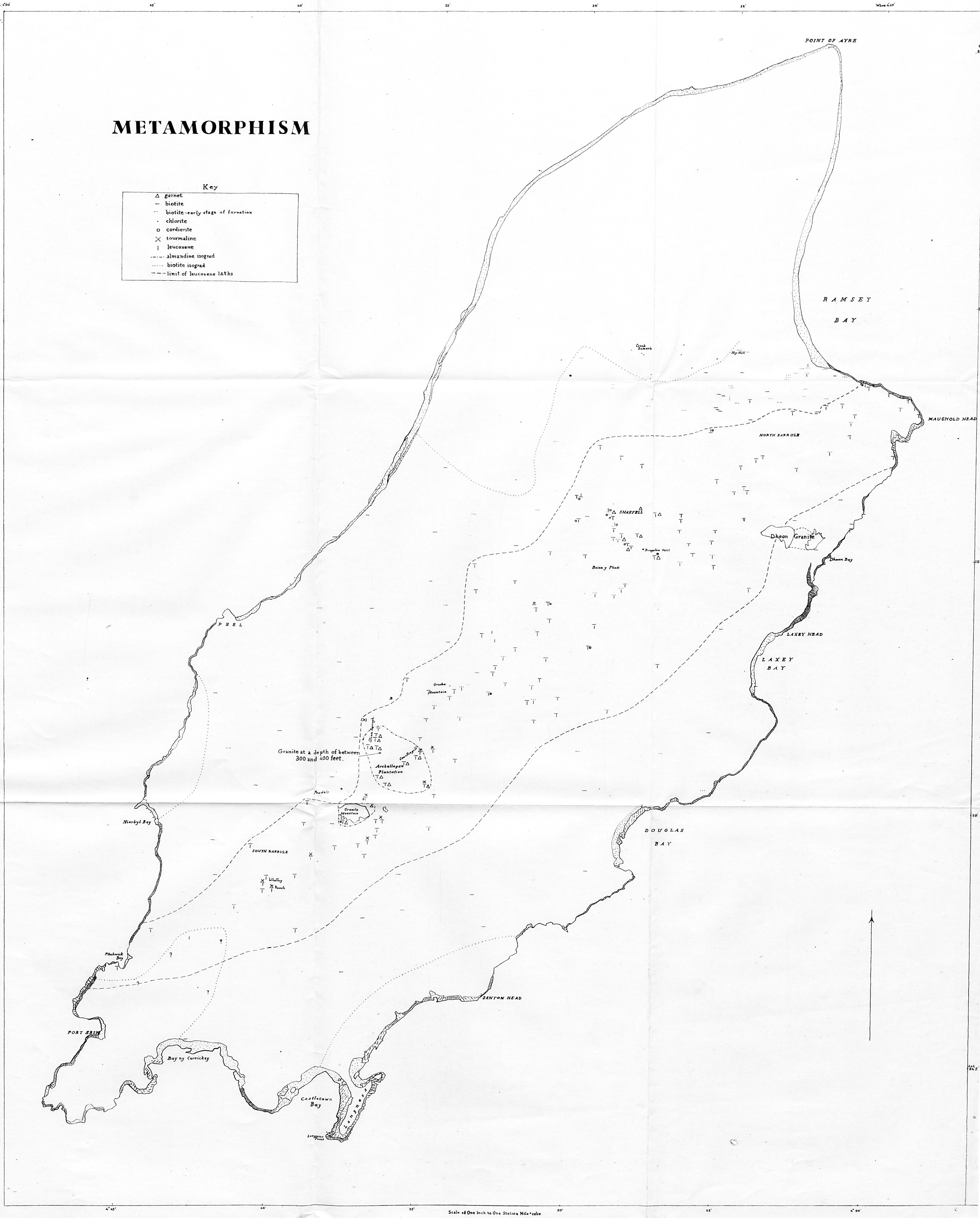


PORT CORNAH SYNCLINE.

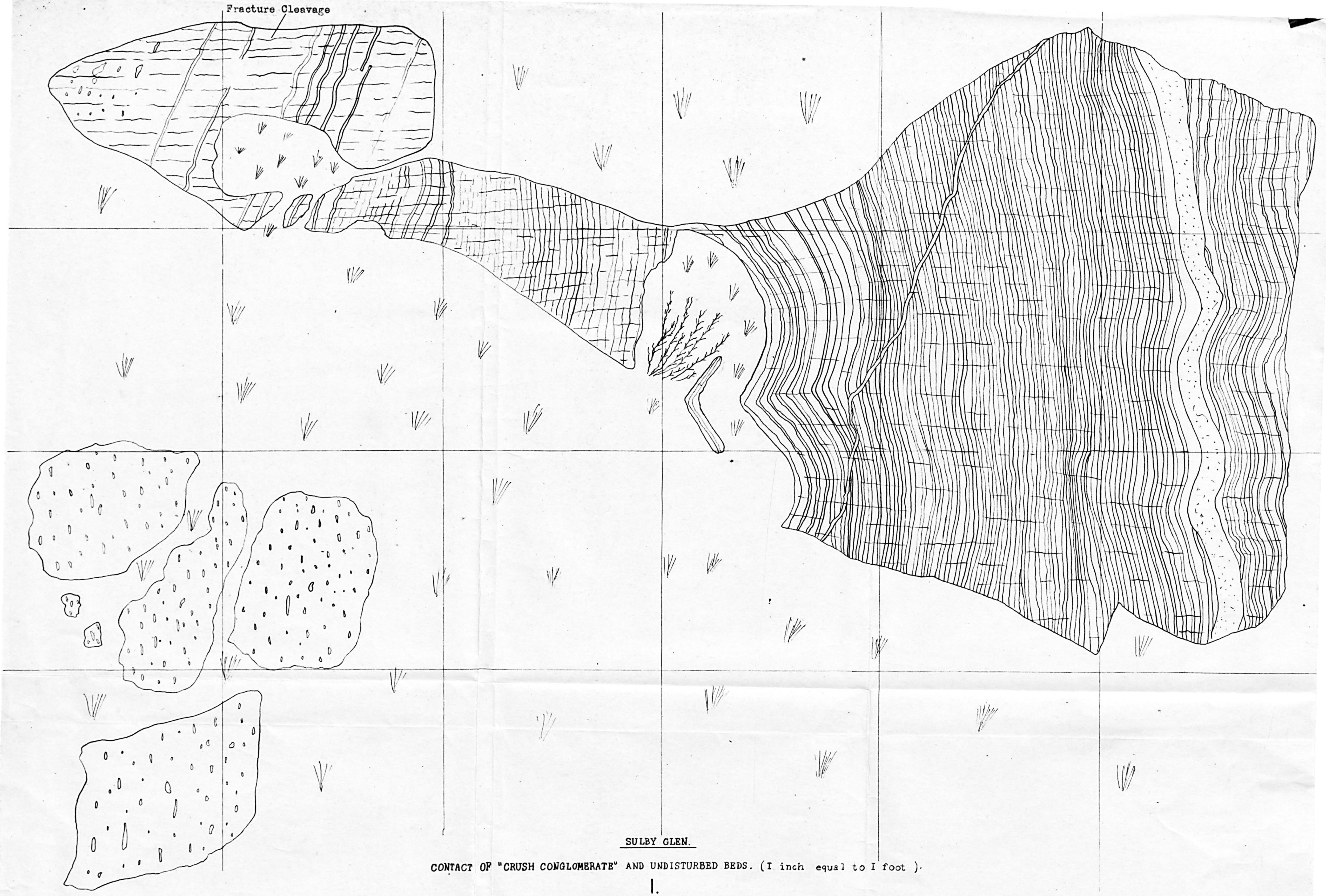
ISLE OF MAN.


STRUCTURES.
Key
Dip of beds
Dip of inverse beds
Strike of vertical beds
Fracture - cleavage
Plunge of fold
Lineation
Lineation of fragments of breccia
Joints
POINT OF AYRE
RAMSEY BAY
MAUGHOLD HEAD
Port Mooar
NORTH BARRULE
Kirkmichael
SNAEFELL
Port Cornah
Dhoon Bay
PEEL
Patrick
LAXEY BAY
Lonan
CLAY HEAD
Glen Maye
Dalby
Niarbyl Bay
Port Groudle
DOUGLAS BAY
SOUTH BARRULE
PORT ERIN
SANTON HEAD
Bay ny Carrickey
Castletown Bay
Calf Sound
Scale of One Inch to One Statute Mile

ISLE OF MAN.



Scale of One Inch to One Statute Mile



SULBY GLEN.

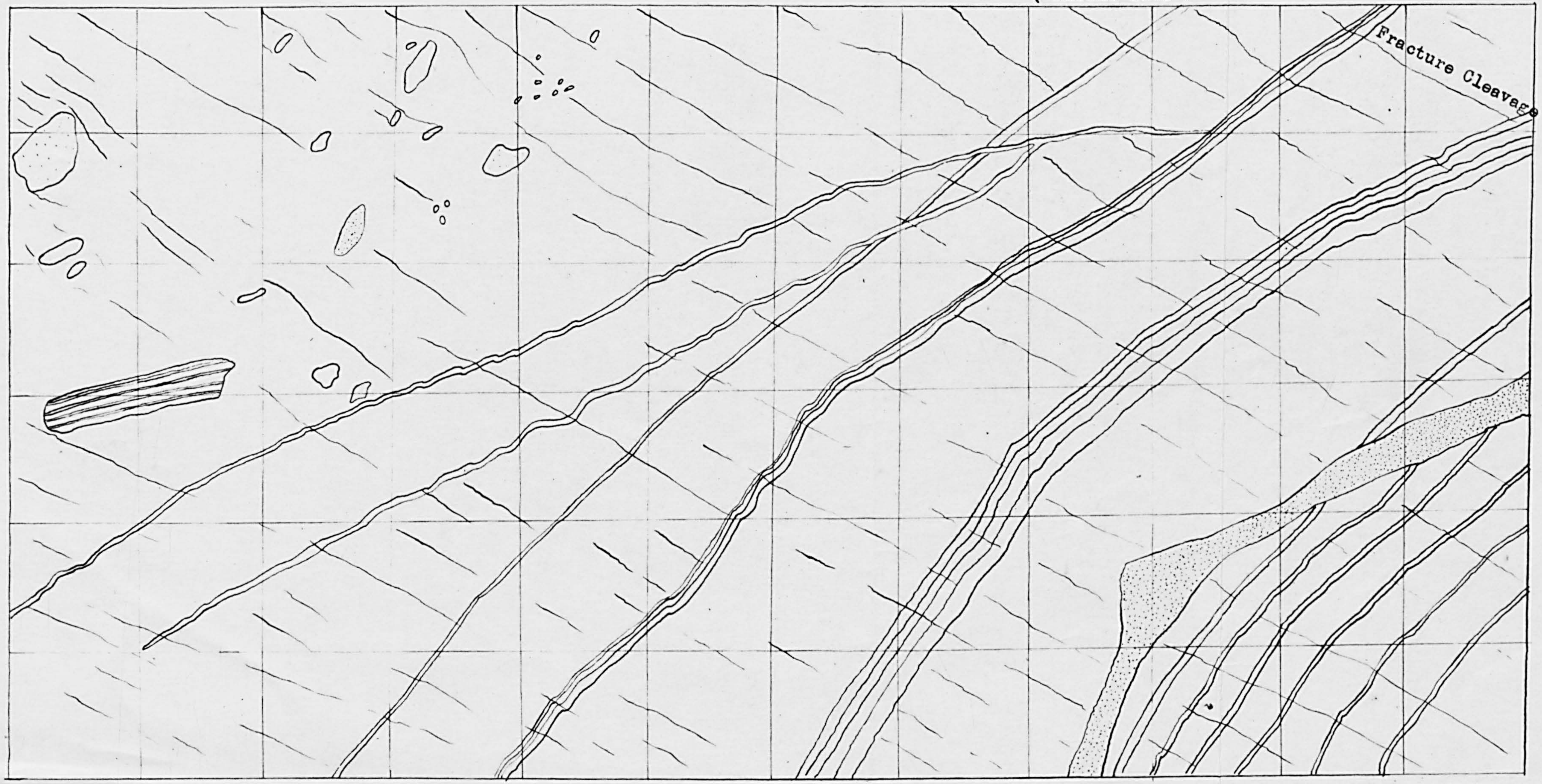
CONTACT OF "CRUSH CONGLOMERATE" AND UNDISTURBED BEDS. (I inch equal to I foot).

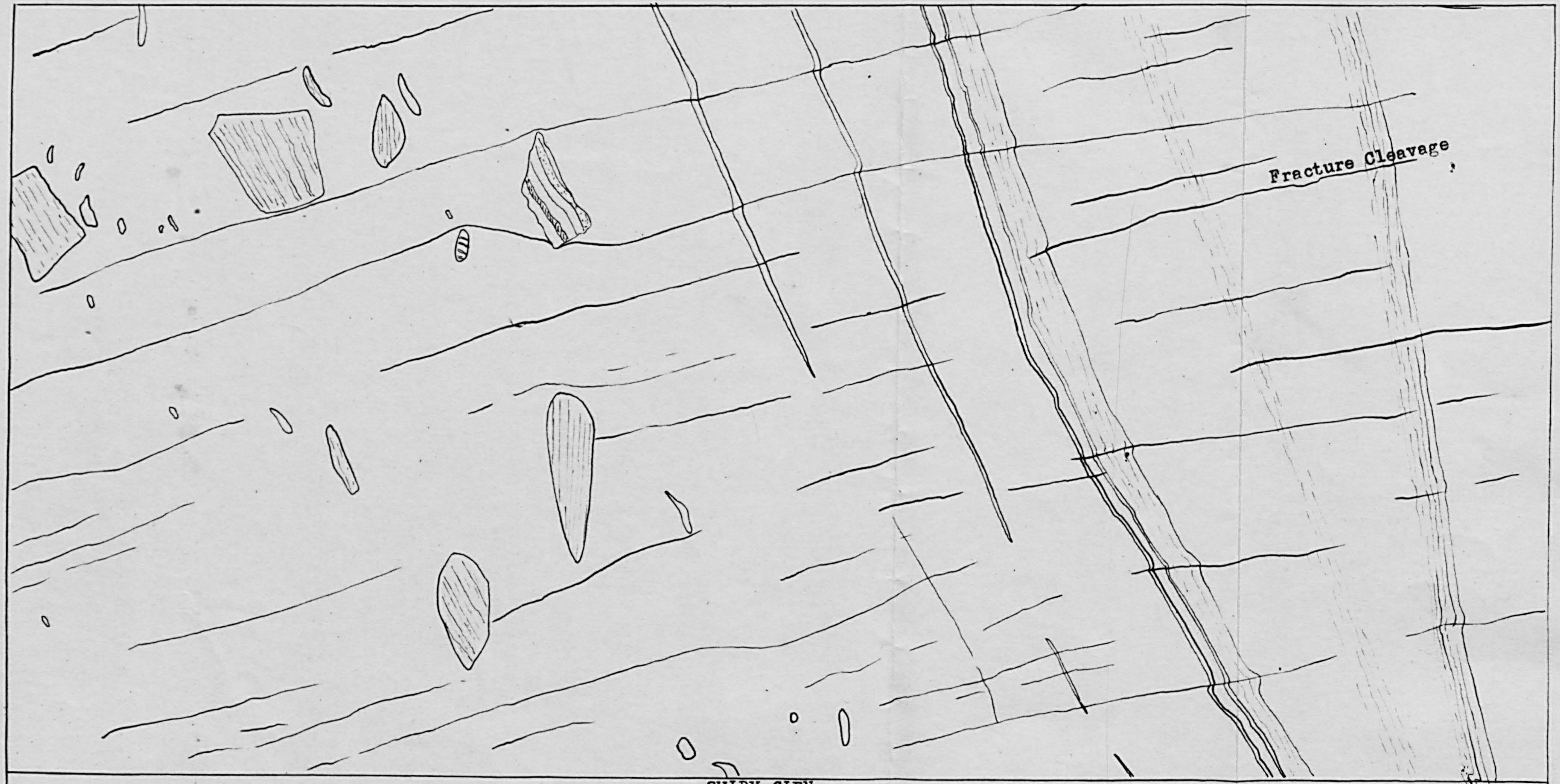
1.

SULBY GLEN.

CONTACT BETWEEN "CRUSH CONGLOMERATE" AND UNDISTURBED THINLY BANDED STRATA.

(Actual size)





SULBY GLEN

CONTACT BETWEEN " CRUSH CONGLOMERATE" AND UNDISTURBED THINLY BANDED STRATA.

3.

(Actual size)

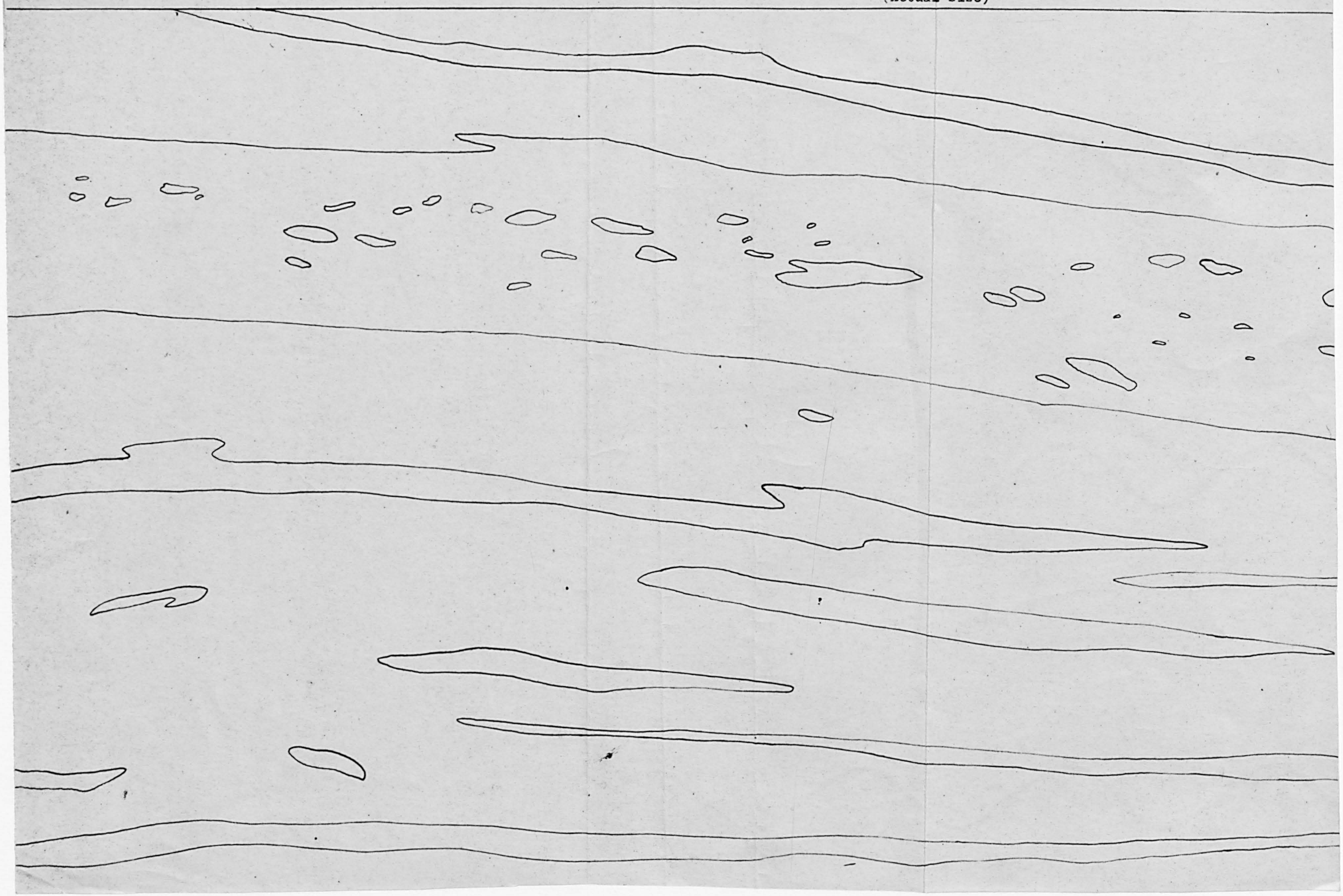
DRUIDALE (LOC 1501).

CONTACT BETWEEN BRECCIA AND RELATIVELY UNDISTURBED STRATA.
(Actual Size)

4.

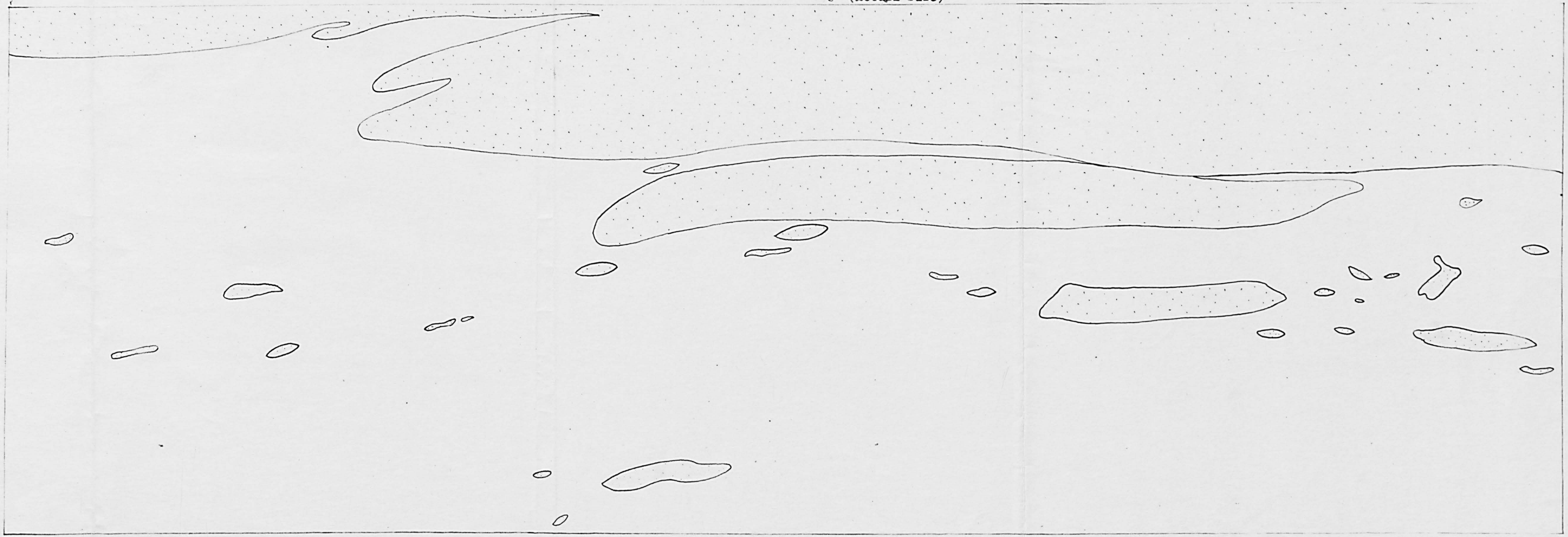
5. DRUIDALE.

BAND OF FRAGMENTS INTERBEDDED IN NON FRAGMENTED STRATA. (Actual Size)

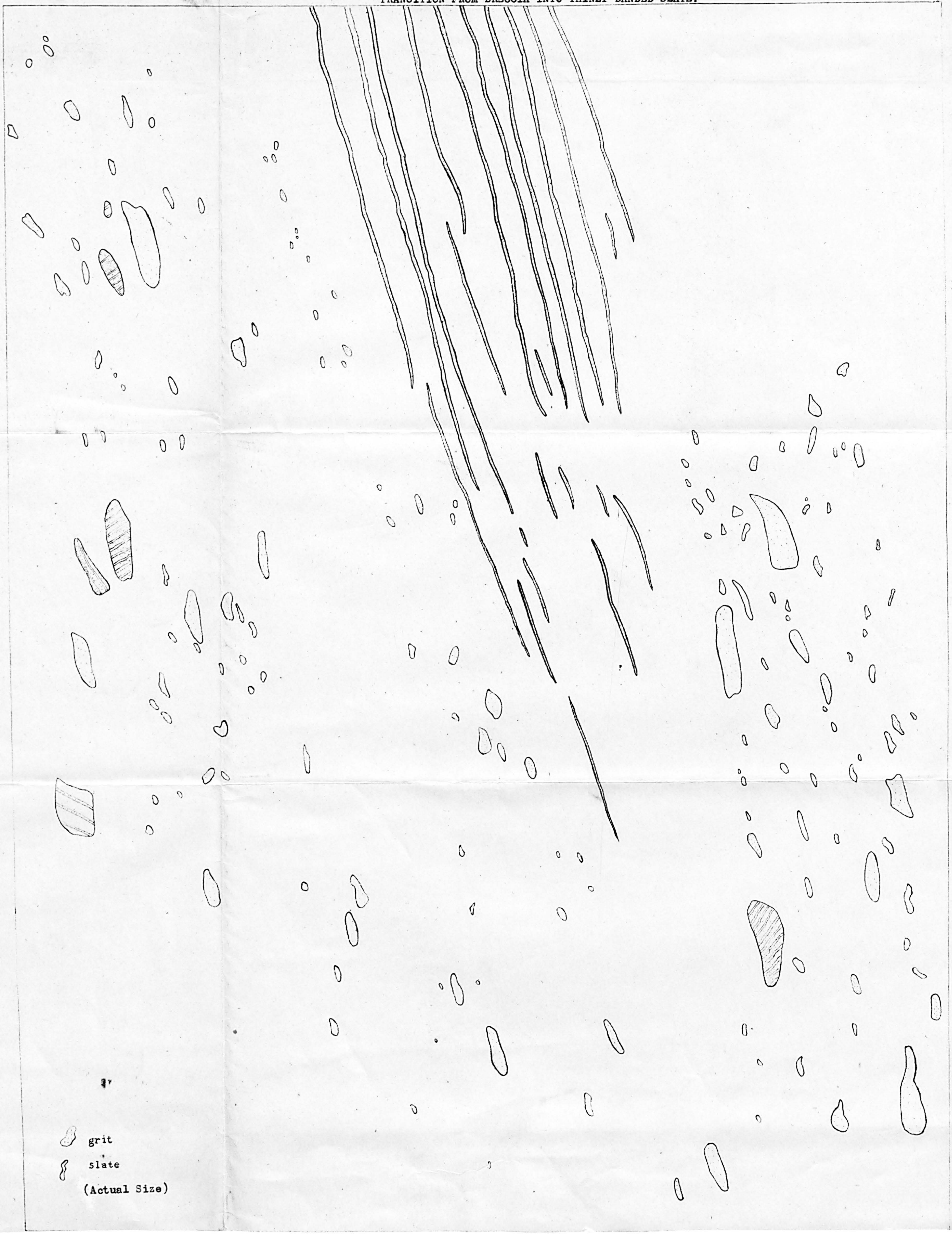


6. DRUIDALE. (locality 1520).

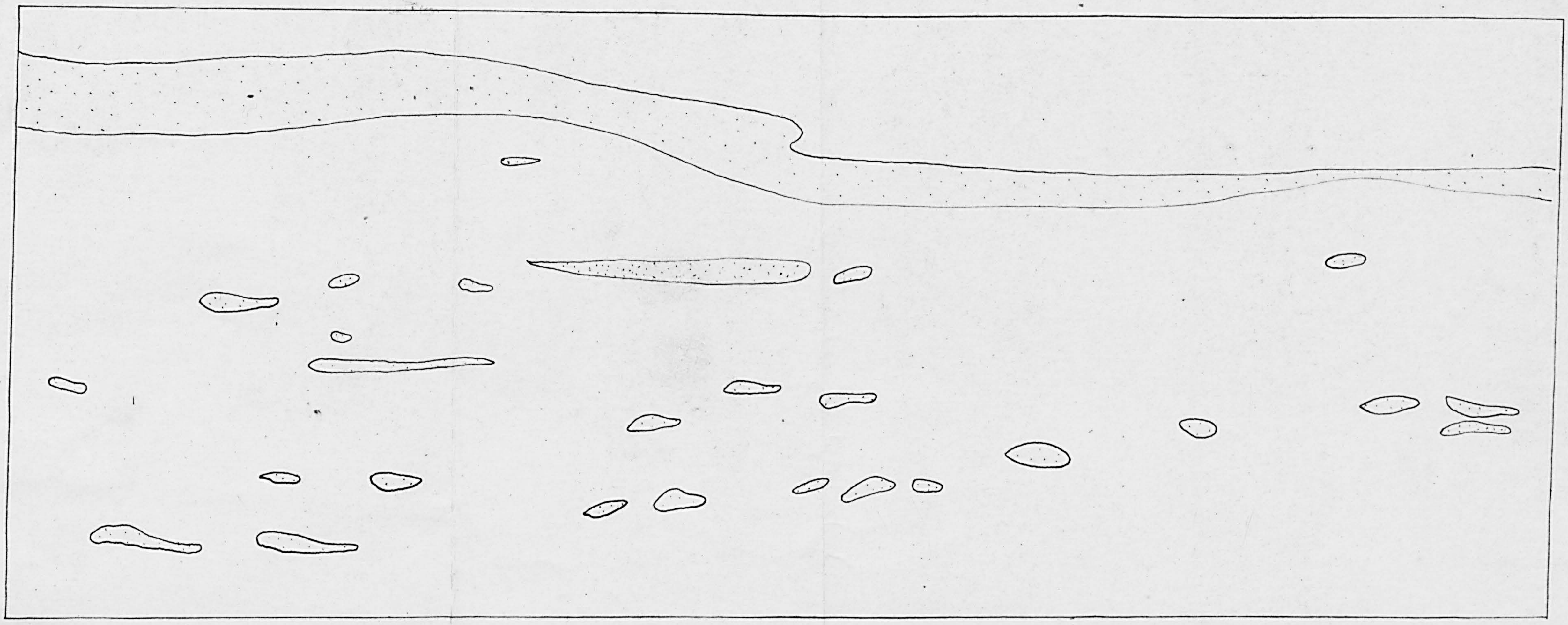
Contact between normal bedded rocks and breccia - to illustrate possible infolding. (Actual Size)



7. DRUIDALE (LOCALITY 1523).
TRANSITION FROM BRECCIA INTO THINLY BANDED SLATE.



FRAGMENTS ENCLOSED BY NORMAL STRATA. (Actual Size)
8.



STREAM BED SOUTH OF CREG AGNEASH (LOC. 1759).

STREAM BED SOUTH OF SNAEFELL (LOC.1532).

DEVELOPMENT OF FRAGMENTS RESEMBLING "CRUSH CONGLOMERATE" IN NORMAL BEDDED STRATA. (Actual Size)

9.