SOME STUDIES ON THE STRATIGRAPHY AND SEDIMENTATION OF THE TRIAS OF THE WESTERN HIGHLANDS AND HEBRIDES, SCOTLAND

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SOME STUDIES ON THE STRATIGRAPHY AND SEDIMENTATION OF THE TRIAS OF THE WESTERN HIGHLANDS AND HEBRIDES, SCOTLAND.

by

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VOLUME I : TEXT

PREFACE

Academic Career

I first matriculated in the University of St. Andrews in October 1958 and in 1962 obtained a Second Class Honours B.Sc. degree in Geology. The same year I enrolled as a research student to study the stratigraphy and sedimentation of the Trias in northwest Scotland under the supervision of Dr. A.R. MacGregor. The results of my research are embodied in this thesis.

Certificate of Originality

I certify that this thesis is my own composition and is based on research carried out by me in the Department of Geology, University of St. Andrews, between 1962 and 1965. It has not previously been submitted for a higher degree.

....

Supervisor's Certificate

I certify that Martin John Brodie Lowe has pursued a course of research under my supervision and has fulfilled the requirements of Ordinance 16 (University of St. Andrews). He is qualified to submit this thesis in application for the degree of Doctor of Philosophy.

....

ABSTRACT

Sediments referred to the Trias outcrop at intervals over a distance of 105 miles (157 kms) along the northwestern seaboard of Scotland. A detailed description is given of the field occurrences and successions, and the stratigraphy is revised. Important red sediments in Wester Ross, previously mapped as Trias, are shown to be Torridonian and their significance is discussed.

The Trias is very variable in thickness, ranging from negligible to over 300 m (1000 ft). Lithological units show rapid lateral variation, and it is impossible to draw detailed comparisons between successions in different areas.

The sediments mainly consist of conglomerates and sandstones which are composed of materials derived from formations known in the area at the present time. The study of textures and sedimentary structures shows that the sediments are fluviatile. Piedmont deposits and sediments which accumulated in an environment intermediate between piedmont and valley-flat are common; true valley-flat deposits also occur, represented by thin fine-grained sandstones and siltstones. Concretionary limestones occur throughout the area, except in one locality, and are interpreted as pedocals.

The sediments probably accumulated in a series of partially isolated basins. Sedimentation was influenced early on by a chain of upland areas consisting of a sequence of Torridonian and Cambro-Ordovician sediments which extended from Loch Broom to Iona, west of the present outcrop of the Moine Thrust. Source areas to the east became dominant later. The climate was probably hot and semi-arid, with seasonal rainfall.

CONTENTS

CHAPTER I

INTRODUCTION

I INTRODUCTION

Rocks referred to the Trias have been mapped in Scotland by the Geological Survey in the Annan Basin, Dumfriesshire, on the Island of Arran, in the Elgin and Lossiemouth district, and in numerous outcrops scattered along the western seaboard and Inner Hebrides which are the subject of this investigation.

The Triassic age assigned to these beds is mainly based on their stratigraphical position : they lie conformably beneath proven Rhaetic strata and overlie a variety of older formations, the youngest of which is the Carboniferous. From this evidence it is reasonable to refer the beds to the New Red Sandstone, while the discovery of branchiopods of probable Keuper age at the top of the succession on the island of Rhum (Bailey 1944) suggests by lithological correlation that the other outcrops are also Trias. Rather tenuous comparisons may also be made with the Moray beds whose Triassic age has been fixed by their reptilian fauna (Westoll 1951, Walker 1961).

The beds consist mainly of conglomerates, grits and sandstones, with subordinate concretionary limestones, and occur at intervals over a distance of 105 miles (157 kms) along the west coast and islands; other outcrops mapped by the Geological Survey as Trias but re-interpreted in this study, occur up to 11 miles (19 kms) further north.

In the south of the area, the Trias is found well exposed and in a very fresh condition in the west of Mull at Gribun, and comprises the major part of the island of Inchkenneth one mile off-shore from Gribun. In the southeast of Mull the Trias again appears, but is considerably affected by Tertiary igneous intrusions. In Morvern, the Trias can be traced from the cliffs at Inninmore Bay up to the head of Loch Aline, then inland at intervals to Loch Arienas and Loch Teacuis, and finally to a thin development beneath the basalt caps of Beinn na h-Uamha, Beinn Iadain and Beinn Ithearlan. On the Ardnamurchan peninsula there are scattered outcrops of Trias, again much intruded by Tertiary dykes and cone sheets but little altered. Patches of Trias occur on the northwest coast of Rhum, on the Sleat peninsula of Skye, and on the Skye shore of the Sound of Soay at An Leac, while in Central Skye it flanks a broad syncline which extends from Broadford to Loch Slapin. Further patches occur on the southwest side of Loch Sligachan and on the north tip of Scalpay, while the Trias is also represented at the south end of Raasay and on a small headland at the southeast corner of that island. Returning to the mainland, Triassic strata cover a moderate area in the immediate vicinity of Applecross village, and outcrop in patches at Redpoint and Big Sand (Gairloch), at Camas Mor (north end of the Gairloch peninsula) and the southeast end of the Isle of Ewe in Loch Ewe. Finally, it comprises a poorly exposed strip extending northeastwards across the neck of land between Loch Ewe and Gruinard Bay. On the shore of Gruinard Bay it is well exposed and more thickly developed than elsewhere in the Western Highlands.

In addition to these outcrops, the Geological Survey has interpreted further exposures as being of Trias age. There are patches of red conglomerates and sandstones which occur at Rubha Reidh and Loch a Ceann

Carnaich north of Gairloch, at Badluarach on Little Loch Broom, and near Achiltibuie in Coigach. These beds require a re-interpretation, and it will be shown that they belong to the Torridonian and not to the Trias. For convenience they will be referred to as the 'Pseudo-Trias'.

A summary of the distribution of outcrops is given in Map 1.

<u>Purpose of the study</u>: No detailed work has yet been done on the Trias of this area. The mapping has been done by different people working at different times and some of it requires revision. No single geologist has studied all the Trias outcrops and attempted a correlation.

It is the purpose of this study to :-

1. map the rocks in more detail,
2. revise their stratigraphy,
3. attempt correlations between outcrops,
4. describe and classify the sediments,
5. investigate the sedimentary environment,

and 6. attempt a palaeogeographical reconstruction of the area in Triassic times.

In addition, field and laboratory evidence will be presented to show that the Pseudo-Trias belongs to the Torridonian.

<u>General method</u>: Field mapping was done mainly on a scale of 6 inches to 1 mile. Considerable use was made of aerial photographs, much of the mapping being done directly onto photographs in the field, using an overlay of ethulon (giving a scale of 6 inches to 1 mile in most cases). Maps made on photographs have been reconstructed on Ordnance Survey 6 inch maps to eliminate photographic distortion. Where very

scattered outcrops or poorly exposed rocks were being mapped a 1 inch to 1 mile scale was used, while occasionally a much larger scale was employed when more local detail was required.

Selection of specimens collected in the field was designed to give a representative coverage of both the geographical and stratigraphical distribution of rock types (see list of specimens, Table 1). Detailed local collections were made for investigation of particular topics. Laboratory studies of specimens involved the investigation of the mineralogy, grain-size distribution and textures of the sediments.

Measures and terms used: The metric scale is normally used in microscopic rock descriptions, and is becoming widely used in the description and classification of sedimentary structures and other field observations. The metric scale is used throughout this study, although distances in the field area are given in the British scale with the metric equivalent in brackets. In the measurement of successions, the British scale equivalent is often given in brackets for comparison with earlier work.

In the field description of clastic sediments the terms suggested by Wentworth (1922) are generally followed. These may be readily determined in the field by inspection with a hand lens and metal metric rule. The terms are as follows :-

Particle size	Wentworth (1922)			This study: field description.
>256 mm	Boulder			Boulder
256 - 64 mm	Cobble	"Roundstone"	"Pebble" or	Cobble
64 - 4 mm	Pebble	(N.R.C.)		Pebble

Particle size	Wentworth (1922)	This study: field description
4 - 2 mm	Granule	Grit
2 - 1 mm	Very coarse sand	Coarse sand
1 - $\frac{1}{2}$ mm	Coarse sand	
$\frac{1}{2}$ - $\frac{1}{4}$ mm	Medium sand	Medium sand
$\frac{1}{4}$ mm	Fine sand, silt and clay	Fine sand, silt and clay

"Pebble" is used as a general term to cover all particles larger than 4 mm, and can therefore be taken to include the pebble, cobble and boulder grades of Wentworth. This is the same as the "roundstone" grade recommended by the National Research Council's Committee on Sedimentation (quoted in Pettijohn 1957, p. 19, Table 5).

In the field description of conglomerates, pebble types are recorded in their estimated order of abundance.

Other terms:

Conglomerate: bed with > 50% pebbles

Pebbly sandstone/grit: bed with up to 50% pebbles

Fabric element: any component of a rock that behaves as a single unit with respect to an applied force (Fairbairn 1949, p. 3). In field descriptions of the conglomerates, the term covers the larger phenoclasts contained in them (pebbles, cobbles, boulders). In the laboratory study of sandstones the 'fabric elements' referred to are sand grains.

Fabric: "The spatial arrangement and orientation of fabric elements". (Potter and Pettijohn 1963, p. 23).

Cornstone: Concretionary limestone developed in fine-grained clastic sediment (Buckland 1821, p. 512). The term is extended here to include calcareous concretions in coarser sediments and also those developed at the surface of the basement rocks beneath the Trias.

Quantitative terms of stratification: the classification of McKee and Weir (1953) is followed :

Stratification	Cross-stratification	Thickness	Splitting property
BEDS: Very thick-bedded	X-BEDS: Very thickly cross-bedded	120 cm	Massive
Thick-bedded	Thickly cross-bedded	120–60 cm	Blocky
Thin-bedded	Thinly cross-bedded	60– 5 cm	Slabby
Very thin-bedded	Very thinly cross-bedded	5– 1 cm	Flaggy
LAMINAE: Laminated	X-LAMINAE: Cross-laminated	1 cm – 2 mm	Shaly (claystone siltstone) Platy (sandstone limestone)
Thinly laminated	Thinly cross laminated	<2 mm	Papery

Colours: Field descriptions of colours refer to fresh surfaces unless otherwise stated. The Geological Society of America's Rock-Color Chart (1963) was used in the laboratory to provide colour indicates for the main sediment groups.

Estimation of thicknesses: Where a thick series of sediments is exposed dipping along a coast section (e.g. Isle of Ewe and Gruinard Bay), the thickness has been estimated by taking a large number of dip readings and then constructing an accurate section drawn to scale, from which the thickness may be measured. The apparent dip in the line of section may be quickly obtained from the true dip by using a plot on a lower hemisphere stereographic net.

Place names are given as indicated on the 6 inch and 1 inch Ordnance Survey maps. The one exception is 'Badluarach'. The O.S. maps give the spelling as 'Badluchrach' which has been taken from the older Gaelic, but the local people use the modern anglicised spelling which is followed here. Most of the Gaelic place names are descriptive of local topography and certain words are very common. Some of the words that occur in place names referred to in this study are given below.

Glossary of Gaelic words:

abhainn	river	iolach	shout
allt	stream	iolair	eagle
ath	ford	leac	slab, flag-stone
ban	white	leacann	side of a hill
bagh	bay	lurg	shank, shaft, leg
beinn	hill, mountain	monadh	hill, mountain
brist	break	mor,mhor	great
calman	pigeon	muileann	mill
camus	bay	oir	border, edge (? coast)
carn	heap of stones	port	port, harbour
carnach	stony ground	reidh	smooth
ceann	head	riabhach	brindled, greyish
cnoc	hillock	ruadh	red
creag	rock	sgeir	reef or rock
cridhe	heart	sgurr	pointed hill
cruinn	round	sgairt	big shout
dearg	red	slabhag	core of a horn
droman	little prominence	sloc	pit, hollow
dubh	black	sron	nose
dunan	dunghill	stac	large precipitous rock
eilean	island	strath	plain, vale
gualainn	shoulder	teangadh	tongue
inch (from 'innis')	island	uaimh	cave

References to published works are presented as indicated in the <u>World List of Scientific Periodicals.</u>

In stratigraphical successions given in the text, the following symbols are used.

Conformable sequence.

Conformable non-sequence.

Unconformity.

CHAPTER II

HISTORY OF PREVIOUS WORK

II HISTORY OF PREVIOUS WORK

The first important study of the geology of the Western Highlands of Scotland was made by John Macculloch. "The indefatigable and sagacious Macculloch" was responsible for the first Government Geological Survey of Scotland, being appointed as geologist to the Trigonometrical Survey of Scotland in 1814, and commissioned for a regular Survey in 1826. His early work was devoted to the Western Isles of Scotland and the Isle of Man, and was published in three volumes in 1819.

Macculloch recorded several occurrences of strata now referred to the Trias. He gave a full description of the Western Mull outcrops at Gribun and Inchkenneth, with a fine account of the unconformity of the Gribun conglomerates and sandstones on the "primary strata" of the district, but although he followed secondary strata across to Morvern, he apparently missed the Trias there. He did not see it on Rhum, but on Skye he recorded a "calcareous conglomerate.............probably situated between the sandstone (Lias) and the limestone (Durness)". In Raasay he grouped the Torridonian and Trias together as "red sandstone". At Gruinard Bay ('Loch Greinord') he was impressed by the important unconformity between the "vertical and irregular...........primary sandstone" (Torridonian) and the "nearly horizontal.........red secondary beds" (Trias), and there he recorded the "only undoubted occurrence of the English "Red Marl" in northwest Scotland". In his 'General Map of the Western Isles' (Vol. III, p. 63) he showed the Torridonian as 'Primary Sandstone' and the sandstones and conglomerates of Inchkenneth, Gribun (Trias), Kerrera and

Oban (Old Red Sandstone) grouped together as "secondary red sandstone" along with the Trias and Old Red Sandstone of Arran.

Sedgwick and Murchison (1834, 1835) discussed the red sandstone and conglomerate series of Sutherland and Ross-shire, making several important references to the Trias. They gave a detailed description of the succession at Gruinard Bay, comparing the beds with those underlying the Lias in Skye and Applecross, which was an advance on Macculloch's work. They suggested that the beds ".....might represent the new red sandstone of England in its most characteristic form" (1835, p. 156).

Another Highland geologist at work during the middle part of the nineteenth century was Nicol, whose famous controversy with Sedgwick and Murchison need not concern us here. His Guide to the Geology of Scotland (1844) contains sections on the Western Highlands and Islands which appear to be based largely on the work of earlier geologists, particularly Macculloch (some of his text figures are almost identical to certain figures in Macculloch's Volume III.) However, he did undertake some revision and gave a short description of the Trias at Gruinard Bay (Sand and Udrigill) which he compared with similar beds beneath the Lias in Skye (following Sedgwick and Murchison). He also described the Mull Trias sandstones at Inchkenneth and Gribun, but did not correlate them with any strata elsewhere, apart from recording a similar formation in southeast Mull. In 1858 he published a comprehensive account of the 'Newer Red Sandstone' of Gruinard Bay, which was a considerable advance on the earlier descriptions of that locality. He interpreted changes in the source area of the beds from changes in the pebble content through the succession (an early exercise in palaeogeographical reconstruction) and suggested that we may regard "....the portion (of the New Red Sandstone) that is now seen as a fragment of what is may once have been".

A. Geikie, in a paper published in 1858, referred to a "Limestone Breccia" in Strath, Skye, which is clearly the "calcareous conglomerate" of Macculloch. He described its thickness and outcrop.

From 1869 to 1872 Bryce did field mapping in Raasay, publishing his results in 1873. He thought that the Trias there was Rhaetic, but offered no palaeontological evidence, his reason being "........because the rocks are conformable to the overlying Lias" (p. 355).

In 1870 John Judd started fieldwork in Scotland (Mull and Morvern). He was concerned mainly with the secondary rocks which he described in three papers; the most relevant to this study is the third, <u>The Strata of the Western Coasts and Islands</u>, which was published in 1878. Judd, a great admirer of Macculloch, was a geologist of at least equal industry and perception, and these three papers comprise a most important contribution to Scottish geology. He surveyed the Western Highlands and Islands in considerable detail, frequently recording and describing the Trias which he included in his 'Poikilitic' ["Trias and (Permian?)"], although in 1873 he had already referred beds in Moray and East Sutherland specifically to the Trias. Besides describing known outcrops of Trias in greater detail and proposing some ideas about their depositional environment, he also made several new discoveries of outcrops, including those of Morvern and Ardnamurchan, and re-interpreted the Raasay beds. In each instance he gave details of successions and estimated thickness, some of which were so accurate that they have been hardly improved upon by the Geological Survey in later years. He noted that the Trias in southeast Mull was much metamorphosed and frequently bleached. In conclusion, he suggested that not only were the present isolated outcrops of Poikilitic of the Western Highlands joined, but also the series in Antrim, Sutherland and Elgin were connected so that the formation was once very much more extensive.

Meanwhile, in 1876 the West Highland Trias made its first appearance as such on a geological map. The Geological Survey map shows the Trias at Gruinard Bay; most of the other outcrops of the western seaboard are too small to be shown, but Inchkenneth appears as Cretaceous (presumably following Judd who was mistaken in thinking that it occurred there). Trias outcrops were again included in the Geological Survey map of 1892 where the Gruinard Bay outcrops appear extended, but some confusion with the Torridonian there has occurred. Inchkenneth remained "Cretaceous".

In the last twenty years of the nineteenth century the Geological Survey turned its attention in earnest to the Northwest Highlands. The survey of the northwest area was started in 1882 and great advances were made from 1883-1886 by the team of Peach, Horne, Clough and Hinxman, with the later addition of Gunn. Although most attention was concentrated on the structure of the area, it was during this period that the great tracts of Lewisian Gneiss and Torridonian Sandstone of Wester Ross were surveyed;

at this time too the Trias (and Pseudo-Trias) must have been mapped although it received no published mention until it was described in the Northern Highlands handbook of 1936. Outcrops of the Wester Ross Trias and Pseudo-Trias are shown on the original Six Inch field maps, however, and appear on the One Inch maps published from them.

From 1892-93 another Survey officer, H.B. Woodward, mapped the southern (Mesozoic) part of the Island of Raasay; later workers on Raasay were mainly concerned with iron ore, oil shale, and Jurassic faunas, so that the present knowledge of the Raasay Trias is based completely on Woodward's mapping. After completing his work on Raasay, Woodward mapped the Mesozoic strata in Applecross and then went to Central Skye in 1896 to continue mapping that had been started by Alfred Harker in Strath. In 1899 he suggested that the Rhaetic might be represented above the Trias there. In 1900 he was replaced by C.B. Wedd who completed the mapping of the Strath Syncline and in 1901 discovered the Trias at Sconser (Loch Sligachan).

Meanwhile in 1898, while on a yachting cruise round Skye, the Director General of the Geological Survey, A. Geikie, had discovered the outcrops of Trias at An Leac and at the north tip of Scalpay. In 1902 Harker, working on Rhum, discovered the Trias there, but unfortunately interpreted it incorrectly as a "crush zone", failing to recognise it as a sedimentary deposit. His work was published in 1908 in the Memoir on the Small Isles of Inverness-shire. In 1896 C.T. Clough mapped the Sleat peninsula of Skye, and in 1898 (and 1899) he worked on the Skye shore of the Sound of Soay, his descriptions of the Trias there being published in the Memoir on Sheet 70 (1904).

By 1907 the Survey was at work in Mull, where Bailey was revising Judd's work in the southeast of the island. Between then and 1909 he mapped the Mesozoic strata including the Trias, and worked out the structure of the folds which have curved axes, similar to those mapped by Wedd in Central Skye. At the same time H.B. Maufe was working in Morvern where, in 1909, he described Triassic cornstones in an important note in the 'Summary of Progress' for that year, comparing them with kankar deposits of India and Africa. In 1910 G.W. Lee mapped the Trias on the south side of the Glais Bheinn plateau in Morvern. In the same year the Memoir on Sheet 71 (Glenelg, Central Skye and part of Raasay) was published, containing an account of the Trias in those areas.

During 1913 G.V. Wilson completed the mapping of the Loch Buie (southeast Mull) area, finding only one outcrop of pre-Jurassic rocks which he tentatively assigned to the Trias. Lee was in Skye and Raasay working out the Jurassic succession in more detail : he found no evidence of Rhaetic strata on Raasay. In 1914 K.A. Campbell collected plant remains from the Morvern Carboniferous, establishing a minimum altitude for the possible base of the overlying Trias there.

The 1914-18 war interrupted the Geological Survey's mapping of the West Highlands. By 1915 only Wilson was left in the field : he confirmed Judd's earlier mapping of the Tobermory district in northeast Mull, including the presence of small outcrops of Trias beneath the Tertiary lavas.

Work recommenced in 1920, when Bailey mapped the sediments at Gribun and Inchkenneth; with the assistance of Manson who measured the sections and made fossil collections, he was responsible for working out the stratigraphy there, including Moine, Trias, Rhaetic, Cretaceous and Tertiary rocks. They described an important series of stream sections through the Wilderness to Uamha nan Calman, where the Lias appears above the Trias. The same year J.E. Richey began an examination of the secondary rocks in Ardnamurchan, and in 1922 Lee confirmed Judd's recognition of the Trias there.

In 1923 the mapping of the western seaboard was largely completed and no further work was done in that area until 1930 when Richey and others returned to work on the Moine schists of Ardnamurchan and Moidart. During this interval two important Memoirs were published, containing descriptions of Triassic strata. They are : The Pre-Tertiary Geology of Mull, Loch Aline and Oban (1925); and The Geology of Staffa, Iona and Western Mull (1925). The description of the Trias in the latter is 'reprinted with little change' from the former. Earlier, in 1920, The Mesozoic Rocks of Applecross, Raasay and Northeast Skye had been published containing descriptions of the Trias in those areas.

The next investigation of Triassic rocks in the Western Highlands was made by J.F. Scott whose report on a general survey of the geology and physiography of Morvern was published in 1928. He gave fairly detailed descriptions of the known outcrops of Trias in Morvern and recorded some small new ones. Unfortunately some of his thicknesses are inaccurate, but it is a useful paper as a general guide to the area. In 1932 Lee and

Pringle published a summary of the Scottish Mesozoic rocks which included the West Highland Trias but added nothing new to its study. In 1934, Macgregor and Manson, mapping for the Geological Survey, revised the position of the Carboniferous-Trias junction at Inninmore Bay, on palaeontological evidence.

During the Second World War, in 1943, Bailey visited Rhum for four days which he spent revising the tectonics as interpreted by Harker. He also showed that Harker's "crush zone" is in fact a succession of Triassic strata. He described a succession of about 200 feet, publishing his results in 1944.

Finally, in a recent investigation of the permanent magnetisation of the Torridonian sandstone, Irving and Runcorn (1958) used pebbles of Torridonian sandstone in Trias and Pseudo-Trias (believed by them to be Trias) conglomerates of Wester Ross to test the stability of magnetisation of the Torridonian sediments. They found magnetisation directions of the pebbles to be random.

CHAPTER III

STRATIGRAPHY

III STRATIGRAPHY

A. TRIAS

1. WESTERN MULL

The Trias is well exposed for 5½ miles (9 km) along the southeast side of Loch na Keal, extending from Samalan Island to Uamh nan Calman. It consists mainly of conglomerates with subordinate grits and sandstones, while frequent cornstone beds occur. The outcrops lie a little west of the Mull Tertiary dyke swarm, so only a few dykes occur and the beds are preserved in a fresh condition.

Magnificent exposures occur in the cliffs on the western side of Inchkenneth, a small island just under a mile (1.5 kms) long which lies a mile off the Mull shore. Over 60 metres (200 ft) of succession can be traced eastwards across the island, but the top is not present. On the Mull shore at Gribun the Trias again occurs, while in a stream section at Balmeanach much of the succession from basal Moine to overlying Rhaetic is exposed. The Trias can be traced southwestwards for a further 4 miles (6.5 kms), being exposed in a series of stream sections.

a. Inchkenneth and Samalan Islands.

On Inchkenneth the Trias dips gently east so that the basal beds are exposed on the west side of the island. The actual base of the formation is exposed at low tide beneath "The Humpies", a group of low craggy knolls on the peninsula south of Bagh an Iollaich. There the basal Moine appears as red-brown, evenly-bedded metasediments which have been variously referred to by the Geological Survey (Bailey, in Lee and Bailey 1925) as "gneisses". "granulites" or "arkose-gneisses". The Moine again appears on the north side of Bagh an Iollaich, where it rises steeply in the cliffs to 15 m above sea level, returning to sea level at the northeast corner of the island, providing an uneven base to the Trias.

The Trias succession on Inchkenneth has three divisions (Map 3):

3. Chapel Beds.	Grey, buff or greenish sediments. Conglomerate at the base passing upwards into calcareous grits with conglomeratic patches and a prominent cornstone horizon	35 m
2. Iollaich Beds.	Brick-red sandstones and conglomerates, with thin cornstones towards the top	9.5 m
3. Humpies Conglomerate.	Basal red-brown conglomerate	c. 15 m variable.

1. Humpies Conglomerate: Mainly conglomerate and breccia with a coarse gritty calcareous matrix and containing coarse-grained sandstone and grit lenses that are sometimes indistinctly cross-bedded (Fig. 1). About half of the pebbles in these beds are angular fragments of Moine granulite which have been derived directly from the basement rock. In addition, rather less angular fragments of limestone, orthoquartzite, red sandstone and red granite are prominent, while pebbles of chert, granodiorite, pink porphyry and felsite also occur. The arkose-gneiss fragments are the largest, many falling in the boulder grade (up to 92 cms measured); the limestones, sandstones and igneous fragments fall mainly within the cobble and pebble grades. Imbricate structure is sometimes present, and occasional calcareous segregations occur as impersistent bands and nodules (cornstones). Apart from the grit lenses

which are thin-bedded or thinly cross-bedded, the beds are thick or very thick-bedded, forming most of the western faces of The Humpies (Fig. 2). The top is uneven, indicating a small degree of intraformational erosion (Fig. 3).

2. Iollaich Beds: A brick-red conglomerate occurs at the base, containing abundant pebbles of arkose-gneiss but virtually no other types. Occasional limestone fragments appear not far from the base, and the conglomerate soon gives way to coarse-grained feldspathic sandstones and grits which contain several irregular horizons of conglomerate, each about 0.3 m thick. Towards the top occasional beds of rubbly cornstone occur, veined with sand, and pebbles of vein quartz, red sandstone, limestone and chert are present. Tabular pebbles are imbricated, and the sandstones, grits and finer-grained conglomerates are cross-bedded in parts (Fig. 4). Pebbles are smaller than those in the Humpies Conglomerate. Only occasional arkose-gneiss fragments were recorded within the boulder grade, other pebbles all falling in the cobble or pebble grades. The Iollaich Beds cap the Humpies Conglomerate in The Humpies, and re-appear faulted up into the top of the cliffs north of Bàgh an Iollaich from where they can be traced round part of the north side of the island.

3. Chapel Beds: This is the thickest and most widely represented of the three divisions. At the base 18 m (60 ft) of pale grey conglomerates and pebbly calcareous grits occur, containing pebbles of vein quartz and quartzite with some mica-schist. Other rock types, so

prominent in the lower beds, are absent here. A bed of rather sandy cornstone follows, forming a prominent feature in the low cliffs beneath the chapel (Fig. 5). It is somewhat variable, but is generally about 5 metres thick, and shows a marked upward increase in carbonate content, being very sandy in the lower half. Overlying the cornstone are 12 m of grey calcareous quartzose grits and sandstones containing quartzose pebble bands 0.2 to 1.0 m thick. Some of the beds show grading from a pebble bed at the base through grit to a medium-grained sandstone within 2.5 m; scattered nodules of cornstone are sometimes developed at the top of the sandstone. (Fig. 6). Some of the sandstones are buff or pinkish in colour, and may be thinly cross-bedded. Conglomerates overlying cornstones often contain scattered pebbles of cornstone.

The top of these beds is not present on Inchkenneth, but pale buff calcareous sandstones and cornstones that comprise Samalan Island, a little more than half a mile (1.0 km) down dip to the northeast, may represent a higher part of the succession.

The off-shore reefs of Sgeir Leathan, Sgeir na Laimhrige Moire and Maol an Domhnaich are all composed of pale calcareous sandstones and grits with some development of cornstones, and may be referred to the Chapel Beds.

Judd (1873 and 1878) described fossiliferous Cretaceous strata in Inchkenneth, but he was apparently misled by erratic boulders. He also recorded "........some irregular beds and veins of gypsum" which were not seen in this investigation.

An attempt was made to compare the succession as described above from the south side of the island with that on the north side, across the fault (see Map 3). The three divisions were still clearly distinguishable, but specific variations within the Chapel Beds could not be traced across the island. The thick cornstone bed thins northwards giving an impersistent horizon along the north coast. It seems that within the three divisions beds tend to die out laterally, being replaced by otherswithin a small distance, so that the finer details of the lithological variations in the succession given above are only valid locally.

A general view of part of the island is given in Fig. 7.

b. <u>Gribun</u>.

Coastal exposures of the Trias extend southwards from Rudha Baile na h-Airde to Eilean Dubh Cruinn, both on the shore and in low cliffs. Above the cliffs there is a prominent raised beach running from Balnahard to Balmeanach, cut into the Trias at 12-15 m (40-50 ft) above sea level : inland exposures are limited by raised beach deposits, but one important stream section occurs at Balmeanach (Allt na Teangaidh).

1. Coast section: Here the Trias has a slight northerly dip, so that the highest beds may be examined at Rudha Baile na h-Airde and sediments rest with marked unconformity on an uneven surface of Moine metasediments (Fig. 8). The unconformity rises southwards into the cliffs which become higher, so that at Mackinnon's Cave cliffs of Moine have a height of 18 m (60 ft) and are capped by Trias (Fig. 10). The base of the Trias is characterised by a development of cornstone which veins and replaces

the underlying arkose-gneiss along joints and bedding planes to depths of up to one metre (Fig. 9).

The three divisions recognised in Inchkenneth are not quite so distinct here, but certain important general features remain. Using the Inchkenneth nomenclature for the divisions, the following criteria hold good in both localities:

3. Chapel Beds: Mostly pale coloured sediments (buffs and greys). Contain a prominent cornstone horizon. Sandstones and grits are abundant and quartzose. Thin quartzose conglomerates, with some scattered cornstone pebbles occur. Cosmopolitan pebbles and arkose-gneiss are rare or absent : mostly vein quartz and quartzite occur.

2. Iollaich Beds: Pink or reddish colours. Conglomerates and grits. A few cosmopolitan pebbles, but Moine arkose-gneiss strongly predominates.

1. Humpies Conglomerate: A coarse conglomerate of angular Moine fragments occurs at the extreme base, followed by a conglomerate containing cosmopolitan pebbles. Colours are chocolate-brown or red-brown.

At Gribun, the 'cosmopolitan pebbles' include limestone (and dolomite), orthoquartzite, red sandstone, quartz-mica-schist, metaquartzite, chert, red granite, granophyre, pink porphyry, felsite, vein quartz, and a few pebbles of mica-trap which have probably been derived from sheets that intrude the Moine at Eilean Dubh Cruinn, believed to be of Old Red Sandstone age (Bailey, in Lee and Bailey 1925, pp.54-55). Blocks of Moine reach a maximum diameter of 60 cms; limestone pebbles are moderately rounded and are commonly of cobble grade while other rock types are generally smaller (pebble grade) and angular. At Rudha Baile na h-Airde there is a widespread development of cornstone which is correlated with the main horizon of the Inchkenneth Chapel Beds (Fig. 5a). The thicknesses at Gribun are:

3.	Chapel Beds	24 m
2.	Iollaich Beds	5 m
1.	Humpies Conglomerate	c. 5 m variable

Total thickness: 34 m (112 ft). (See Figs. 11,12 and 13).

2. Allt na Teangaidh:

Here the Moine surface has risen cutting out the Humpies Conglomerate, so that the base of the section occurs in Iollaich Beds which are typically represented as conglomerates containing a predominance of Moine fragments. These are followed by a gap, after which Chapel Beds are exposed, near Balmeanach farm, consisting of pale buff and greenish calcareous sandstones and grits with quartzose pebble beds, and a bed of cornstone 3 m thick which may probably be correlated with the cornstone at Rudha Baile na h-Airde (3.5 m) and Inchkenneth Chapel (5 m). At the top of the Chapel Beds one metre of conglomerate occurs, containing vein quartz pebbles in a yellow calcareous study matrix; this is overlain conformably by dark grey sandy limestones containing a shelly fauna, including Pteria contorta, alternating with subordinate yellow sandstones. Manson collected a fauna of marine lamellibranchs from the Pteria beds (Lee and Bailey 1925, p. 73) which fixes their Rhaetic age; Arkell (1933) suggested more specifically that they might be referred to Westbury Beds.

The total thickness of the Trias is 37 m (125 ft).

In a distributary of Allt na Teangaidh, just south of Balmeanach farm, there is a small exposure of pale Trias conglomerate containing vein quartz pebbles. The Rhaetic is not seen, but $\frac{1}{3}$ mile (0.5 km) to the southwest, above Mackinnon's Cave, shelly limestones and rusty sandstones with indistinct carbonaceous remains outcrop beneath a prominent sill (Fig. 10) : these are referred to the Rhaetic.

c. <u>The Wilderness.</u>

Southwest from Mackinnon's Cave the landscape is dominated by two features: 1. sea cliffs of Moine arkose-gneiss (30-60 m) high,

and 2. cliffs of Tertiary lavas set back $\frac{1}{4}$ mile (0.3 km) from the coast.

In between these two features there is a steep slope largely composed of grass and heather covered scree, beneath which Mesozoic and Tertiary sediments occur, extending southwestwards for nearly 3 miles (4.6 km) from Mackinnon's Cave. Strictly speaking 'The Wilderness' is only the last $1\frac{1}{2}$ miles, but for the purposes of this description it will be taken to cover the whole strip.

Despite the thick scree cover, five stream sections expose the sediments at convenient intervals through The Wilderness, while beyond a fault downthrowing to the south, the Trias is exposed on the shore at Uamh nan Calman, its most westerly occurrence in Mull.

The five stream sections, with distances from Mackinnon's Cave, are :-

1. Ath Dearg .... $\frac{1}{3}$ mile (0.5 km)
2. Sloc nam Ban .... $\frac{5}{6}$ mile (1.4 km)

3. An Dubh Allt .... 1 miles (1.9 km)

4. Allt na Leacainn .... 1 miles (3.0 km)

5. Lurg Bhriste-Chridhe .... 2¼ miles (3.7 km)

The coastal exposure at Uamh nan Calman is 2 miles (4.6 km) from Mackinnon's Cave. The localities are given in Map 2 and the sections summarised in Fig. 151.

1. Ath Dearg: 27 m (90 ft) of Trias is exposed in a waterfall. It rests on the Moine, the actual base being in an inaccessible part of the fall, but viewed from a distance there seems to be a cornstone development veining the Moine. A few feet above the base, on the lip of the lower part of the fall, a barytes vein occurs. It is rather brecciated and is veined with thin streaks of greenish sand. It is about 2 m thick, and is the only occurrence of barytes encountered in the whole investigation.

There follows a succession of pale buff or greenish pebbly grits and conglomerates, containing four cornstone horizons (Fig. 14). The grits and conglomerates contain sub-rounded pebbles of vein quartz and quartzite, but little else. The cornstones are mottled red and green in colour and appear to be internally brecciated. Some show traces of oolitic structure. They are developed above grits, and vary in thickness from 6 m to 0.5 m. Each cornstone tends to be rather variable in thickness, having an indistinct gradational base and an erosional top, the overlying clastic sediments containing a few detrital fragments of cornstone.

At the top, beneath a prominent sill, there occurs 23 cms of a soft yellow sandstone containing carbonaceous traces. This is identical with the sandstone beneath the sill above Mackinnon's Cave and may therefore be taken as Rhaetic. The succession is partly repeated by an inconspicuous low-angle fault above the sill.

2. Sloc nam Ban: Here the Trias is poorly exposed. At the base, pale grits and conglomerates overlie the Moine, the actual unconformity being obscured by a sill. Pebbles are mainly vein quartz and quartzite, although at the extreme base some angular fragments of Moine arkose-gneiss occur. There is an uneven development of cornstone in the grit. Less than 1.5 m of sediment are exposed before the stream is choked by talus for 13.5 m, above which a pale brown cornstone appears. After a further gap of 2 m the following succession was measured:

1.2 m	Coarse gritty sandstone containing rounded quartz pebbles.
1.7 m	'Remanie' rubble of silicified chalk fragments in a coarse quartzose gritty matrix.
0.75 m	Grey-green rather micaceous silts.
1.0 m	Pale greyish grit with occasional pebbles of silicified chalk, passing downwards without a noticeable junction into
0.6 m	Conglomerate, containing subrounded and rounded vein quartz pebbles.

Bailey (in Lee and Bailey 1925, p. 72) suggested that the grey-green micaceous silts might be Rhaetic, but the new exposure of chalk pebbles occurring in the top of the underlying beds proves both the silt and the conglomerate beneath it to be post-Cretaceous (i.e. Tertiary).

No Rhaetic beds are exposed, but comparison with the Ath Dearg section suggests that if present they lie within the gap between the cornstone and the Tertiary conglomerate, which is reasonable. The discovery of Rhaetic beds in An Dubh Allt (see below) makes it likely that the Rhaetic is represented here as well, giving the Trias a maximum thickness of about 15 m (50 ft).

3. An Dubh Allt (Coireachan Gorma): The base of the Trias is well exposed, with 2 m of cornstone containing angular blocks of Moine overlying the Moine itself which is veined by cornstone to a depth of 2 m *in situ*. A gap of 3 m follows, and above this the following succession was measured:

0.6 m	Rusty sandstones containing carbonaceous fragments interbedded with dark grey calcareous siltstones containing *Pteria contorta*.
1.2 m	Sill
0.3 m	Rusty sandstones containing obscure carbonaceous remains.
1.5 m	Green, buff, yellow and red flaggy sandstones.
4.6 m	Hard pale grey quartzose and micaceous coarse sandstones, with uneven quartzose pebble bed at the top.

The discovery of *Pteria contorta* dates the calcareous siltstones and associated sandstones as Rhaetic; the pebble bed probably marks the top of the Trias, giving a total thickness of 12 m (40 ft).

200 yards southwest of this section, the Moine surface rises close to the base of the Tertiary lavas, which overlie the sediments throughout Western Mull. In the gap there is a small outcrop of Trias conglomerate, containing vein quartz pebbles and a few fragments of Moine. Its estimated maximum thickness is 3 m (10 ft).

4. Allt na Leacainn (besides Ton Dubh-sgairt): The lower part of the succession above the Moine is not exposed so that the position of the base has to be estimated. Above the gap there are greenish and grey quartzose sandstones, grits and conglomerates, with two prominent cornstone beds measuring 8 m and 1.2 m in thickness. Nodules of cornstone which weather orange of yellow occur in the

gritty beds and detrital fragments of cornstone are seen in the conglomerates. Pebbles are mainly vein quartz, but a little Moine arkose-gneiss is present. The thickness of the Trias here is not less than 27 m (90 ft).

5. Lurg Bhriste-chridhe: Approximately 30 m (100 ft) of Trias is patchily exposed in this stream. The base is exposed showing the usual cornstone association with the Moine, and the lower 22 m consists of cornstones alternating with pale greenish coarse-grained sandstones containing occasional vein quartz pebbles. The upper 8 m is comprised of greenish pebbly calcareous grits and conglomerates containing a predominance of subrounded vein quartz pebbles; a little arkose-gneiss is also present.

6. Uamh nan Calman: A fault occurring at this point downthrows to the south so that the Trias outcrops on the shore and in a sea cliff. The lowest beds are exposed in intertidal reefs where a cornstone is seen, overlain by a conglomerate containing pebbles of Moine arkose-gneiss, quartzite and vein quartz. The base is not exposed. Exposures re-appear in the cliff above the beach. There white and greenish coarse to medium-grained sandstones and grits containing yellow weathering cornstone nodules interdigitate with conglomerates containing subrounded vein quartz pebbles and also a little quartzite and Moine arkose-gneiss. The sandstones and grits are thinly cross-bedded in parts. Pyrites is commonly developed as a matrix.

At the top, 2 m of cornstone developed in a pale greenish grit is overlain with disconformity (Grabau 1905) by a 'cementstone' band (35 cms exposed). The 'cementstones' were considered by Bailey (in Bailey and Anderson 1925, p. 47) to be of Liassic type, although they are unfossiliferous. Lias cementstones carrying conspicuous pyrites are found in landslipped material further along the shore : the pyritisation of the sediments may therefore be taken as post-Liassic.

Taking the Rhaetic as a marker horizon, there is very little correlation between the Wilderness sections in the Trias. Interdigitation is rife, beds tending to pass rapidly into others when traced laterally. The Humpies Conglomerate is cut out by the rising Moine surface north of the Wilderness; the colour, lithology and pebble content of the Wilderness Trias indicate that it may all be referred to the Chapel Beds, the Moine cutting out the Iollach beds as it rises southwards, although it carries with it a characteristic veneer of cornstones and associated scattered angular fragments of arkose-gneiss. Stratigraphical considerations show that the southward thinning of the Trias is due entirely to the presence of a hill of Moine. At Ton Dubh-sgairt and beyond, the Trias thickens rapidly again.

2. SOUTHEAST MULL

The Trias is fairly widespread, occurring at Craignure Bay, Duart Bay, Loch Don and Loch Spelve. The outcrops are close to the Tertiary igneous complex of Central Mull and are considerably affected by it. Two main factors are involved : 1. Intrusion by dykes and cone sheets.

The outcrops at Loch Don are the least disturbed, while the heaviest intrusion occurs at Rudha Riabach on Loch Spelve. Faulting associated with intrusions makes successions and thickness difficult to work out.

2. Pneumatolysis: The Mesozoic strata lie within the zone of pneumatolysis of the Central Mull complex which has produced considerable alteration of the sediments; in some cases almost complete recrystallisation has taken place, while in many of the sediments original textures are blurred or obliterated. Albite and epidote are commonly developed. The Loch Don area is again the least affected, but a specimen collected as Trias grit at Duart Bay looks like an acid igneous rock in thin section (Fig. 59).

Nearly all the Trias sediments are bleached by a combination of the two effects. They are difficult to interpret in this area, which has proved the least rewarding of the areas studied.

a. <u>Craignure and Duart</u>

The Trias is seen at both ends of Craignure Bay. At Port na Luinge a conglomerate containing vein quartz pebbles is in contact with psammitic Moine gneiss in the core of a small anticline; fragments of Moine also occur in the rock. At Java Point the conglomerate is overlain by Tertiary lavas and on the southwest side of the embayment it dips inland beneath Lias sandstones. At the southeast end of the bay Trias conglomerates are seen, folded and intruded. The main features of the succession may be unravelled: the base is not exposed, but the lowest beds contain fragments of Moine psammitic gneiss indicating that it may not be far below. Some mica-schist (pelitic Moine) also occurs, but vein quartz predominates throughout the succession, with subordinate quartzite. On the southern limb of an anticline a sequence 52 m (170 ft) thick was measured (Fig. 152.). It consists mainly of coarse quartz pebble conglomerates interbedded with quartzose grits and coarse-grained sandstones which also contain quartz pebbles. The conglomerates are very thick-bedded and sometimes contain thinly to very thinly cross-bedded lenses of coarse-grained sandstone (Fig. 15). Pebbles are up to 8 cms in diameter. The grits and sandstones are thin to very thin-bedded, the sandstone beds only occurring at the very top of the succession. The beds are overlain by pale unfossiliferous crystalline limestones referred to the Lias on account of obscure remains of *Gryphaea* and *Lima* that occur higher up (Lee,in Lee and Bailey 1925,p. 80).

Southeast of Craignure the feature Druim Mor is composed of Trias grits and conglomerates which are exposed at intervals along the western slopes.

On the southeast side of Camus Mor, a tidal inlet off Duart Bay, a patch of shattered calcareous sandstones and an outcrop of conglomerate and grit with vein quartz pebbles occur : the grit and conglomerate have been considerably altered (Fig. 59).

A small faulted wedge of Mesozoic strata occurs at Achnacroish, 1/3 mile (0.5 km) southwest of Duart House. The Trias is represented by coarse quartz pebble conglomerates and finer gritty beds.

These exposures are heavily intruded by dykes and cone sheets, particularly at Craignure Bay. All the sediments have been bleached to a white or pale grey colour.

b. Loch Don

The best exposures occur along the eastern limb of the Loch Don anticline which runs due south for 2 miles (3.2 km) from the head of Loch Don. Along the west side of the loch there are conglomerates containing vein quartz and quartzite pebbles in a calcareous sandy matrix with honeycombe weathering, alternating in places with calcareous pebbly grits and sandstones. The conglomerates are thin to very thick-bedded and are occasionally thinly cross-bedded (Fig. 16). Quartzose pebbles are up to 15 cms in diameter : other pebble types present are red sandstone, red granite, mica-schist and purple jasper, mostly in the range 2 - 6 cms.

Between 1 and 1½ miles (1.5 to 2.5 kms) along the eastern limb of the anticline the Trias is seen to overlie Old Red Sandstone lavas and underlie muddy limestones and calcareous sandstones of the Lias; its thickness there is 4.6 m (15 ft). It consists of a conglomerate containing a variety of pebbles including vein-quartz, limestone, quartzite, red sandstone, porphyry, jasper, and a few fine-grained dark rocks which may be Old Red Sandstone basalt. The pebbles are fairly well-sorted and small, being in the range 0.5 to 1 cm. Thus there is a southerly reduction in pebble size. The matrix is mainly carbonate, but contains angular nodules of chert about 1 cm in diameter.

These beds are little altered, and are the most significant examples of the Trias sediments in Southeast Mull.

c. Loch Spelve

Trias conglomerates and grits with local breccias comprise most of the northeast side of Loch Spelve where they are intricately entangled amongst dykes and cone sheets, and are also intruded by gabbro and granophyre. No attempt was made to map these intrusions or work out their intimate relationship with the Trias : this has already been well done by the Geological Survey (Sheet 44). The intrusions tend to be resistant to weathering and stand out above hollows where patchy outcrops of Trias are sometimes exposed. There are fairly good exposures on the shore at Fellonmore and Rudh Iain'Ic Ailein. Inland, on the slopes south of Abhuinn an t-Stratha Bhain (An t-Sleagach) and on the shoulder of Cruach Ardura thick woods reduce the exposures. In Abhuinn an t-Stratha Bhain itself there are only a few outcrops of coarse quartzose sandstone.

From Strathcoil at the north end of the outcrops down to Rudha Riabach the sediments are predominently pebbly quartzose grits and quartz pebble conglomerates. Pebbles are mainly 0.5 to 5 cms in diameter, and are mostly vein quartz with subordinate quartzite. South of Rudha Riabach, along the shore by Fellonmore and Rudh Iain'Ic Ailein, the sediments become coarser grained, with conglomerates containing well rounded pebbles of quartzite which fall in the cobble and boulder grades. They are commonly 15 - 20 cms in diameter and reach a maximum of 33 cms. A few well rounded cobbles of granite are also present. The conglomerates are very thick-bedded and alternate with grits and sandstones.

The base of the beds occurs at Balure cemetry, $1\frac{1}{2}$ miles (2.5 km) southwest of Rudha Riabach, where a coarse angular breccia contains fragments of the local Moine psammitic gneiss on which the Trias rests.

At Kinlochspelve there is a small outlier of Trias in contact with the Moine and overlain by Tertiary lavas. It consists of pale conglomerate and grit with vein quartz pebbles which occasionally reach cobble size, but with very little Moine gneiss.

All the Loch Spelve Trias sediments are bleached, giving pale grey or white colours. Many of the quartzite pebbles are spotted with little dark patches : these are seen in thin section to be aggregates of epidote crystals which are probably a product of Tertiary pneumatolysis.

It is quite impossible to estimate the thickness of the Trias in this area. The dips of the beds are generally moderate to steep (20° to 60°) although round Rudha Riabach they reach 70° to 90°, which implies a fairly large thickness. However, there is considerable faulting associated with the intrusions and many of the beds may be repeated. On the shore below Cnoc Carrach, ¼ mile (0.5 km) northwest of Rudha Riabach, there is a 9 m sequence of steeply dipping purple micaceous silts alternating with grey limestones. Although there is no fossil evidence, the lithology of the beds strongly suggests that they belong to the Lower Lias (Broadford Beds). Black nodular shales and micaceous sandstones exposed in a stream 300 yards further northeast may also be Lower Lias. These previously unrecorded outcrops provide strong evidence that the Trias in this area has a top present, and the total thickness may not be so very great as Bailey thought (Lee and Bailey, 1925, p. 68).

3. NORTHEAST MULL

Exposures of rocks referred to the Trias are limited to two localities on the coast south of Tobermory. In both cases the sediments outcrop beneath Tertiary lavas.

a. Mull shore opposite Calve Island. At the southeast end of the narrows between Calve Island and Mull, on the Mull shore, pale calcareous muds with cornstones and soft pale quartzose sandstone bands occur dipping at 7° due north. They have a prominent honeycombe weathering. No pebbles were recorded.

b. Shore beneath Gualann Dubh. Here there are two exposures of horizontal calcareous sandstones and unevenly weathering cornstones, veined with grit which infills cracks (Fig. 17). Occasional small rounded quartz pebbles are present.

These beds closely resemble the Chapel Beds of Western Mull, and it is reasonable to follow Judd (1878) and Wilson (Summary of Progress for 1915) in referring them to the Trias.

4. MORVERN

The Trias has the largest areal extent of the Mesozoic rocks in Morvern. Outcrops extend 9 miles (14.5 km) inland from Inninmore Bay to Beinn Ithearlan. It is thickest at Inninmore (27 m), dwindling inland to almost nothing in places. It rests unconformably, but with no discordance of dip, on Upper Carboniferous sediments at Inninmore, while from Kinlochaline northwards it is underlain by pelitic and psammitic Moine gneisses.

It is generally overlain by the Lias, although at Larachbeg it underlies Rhaetic shales and in Beinn Iadain and neighbouring peaks it is immediately overlain by Cretaceous strata. In Coire Slabhaig it appears to be capped by Tertiary lavas, but more probably it is faulted against them.

The sediments are not much intruded and appear generally in a fresh unaltered condition. They resemble the Western Mull facies, consisting of red conglomerates with subordinate grits and frequent beds of pale cornstone.

a. Inninmore Bay and Coire Slabhaig

Mesozoic strata are exposed at intervals from Ardtornish round Rudha an t-Sassunaich and along steep slopes beneath Tertiary lava crags to the east end of Inninmore Bay where they are faulted against the Moine in Dearg Allt. The Trias is represented eastwards from Rudha an t-Sassunaich.

A section through the thickest part of the Morvern Trias is obtained in the burn 300 yards east of the Quarry Burn, just west of the landslip. It was originally measured by Lee in 1910, and the stratigraphy revised by Campbell (Summary of Progress for 1914) and Macgregor and Manson (1934). It was recorded by Lee (in Lee and Bailey 1925, p. 66) where the section given adds up to approximately 230 feet : this total has been misprinted as 320 feet and the mistake repeated in the table on page 2, and again by Scott (1928, p. 160) and Richey and Thomas (1930, p. 33). The Trias overlies Carboniferous sediments which are yellow quartz pebble conglomerates and quartzose grits and sandstones which contain thin beds of purple shale which yield Carboniferous plant remains.

The stream section was measured upwards from the highest plant bed, giving the following result:

Bed Thickness		Description of Bed	Stratigraphical Horizon
Metres	Feet		
3.0	10	Intercalculations of shelly limestone and shales.	No diagnostic fossils
0.6	2	Medium-grained yellow sandstone.	LIAS
0.45	$1\frac{1}{2}$	Red, green and grey shale with sandstone nodules.	*obtusum* zone (Pabba Beds)
3.0	10	Gap	
3.0	10	Red, purple and green mottled fine-grained sandstones.	
0.6	2	White calcareous pebbly coarse-grained sandstone.	
3.7	12	Red coarse to medium-grained sandstone with some cornstone nodules in the upper third.	
0.6	2	White calcareous pebbly coarse-grained sandstone, greenish in parts.	
1.5	5	Red coarse to medium-grained sandstone with some cornstone nodules in the upper half.	
3.0	10	Red coarse to medium-grained sandstones with cornstone nodules throughout.	TRIAS
3.0	10	Pale cornstone bed.	(25 m/83ft +)
7.5	25	Brick-red fine-grained micaceous sandstone with cornstone nodules in the upper part, coalescing upwards into the cornstone bed; the top is gradational.	
2.1 (variable)	7	Breccia of angular fragments of psammitic Moine and vein quartz in red gritty matrix.	
7.5	25	Coarse yellow quartzose sandstones, gritty in parts, with scattered vein quartz pebbles and iron-rich nodules.	CARBONIFEROUS
2.75	9	Intercalations of coarse to medium-grained sandstone with purple micaceous sandy shale containing plant remains.	

The base of the Trias is drawn in the same position as Macgregor and Manson put it (<u>Summary of Progress</u> for 1934, pp. 76 and 79), for the following reasons :

1. Beds immediately below this horizon are of a different lithology from those above, and compare closely with proven Carboniferous beds lower in the section.

2. The breccia marks a change in sedimentation and is the lowest bed with red colouration.

The shale above the gap was referred by MacLennan (1953, p. 453) to the top of the <u>obtusum</u> zone of the Lias so that the overlying shale-limestone sequence, although resembling Broadford Bed facies, must belong to the Pabba Beds or younger. The gap between the <u>obtusum</u> shale and the topmost exposures of the Trias is likely to contain lower beds of the <u>obtusum</u> zone which is fairly thickly represented elsewhere in Morvern, so that the top of the Trias may not lie much above the bottom of the gap. The absence of the <u>birchi</u> zone and of Broadford Beds, unless due to non-deposition, indicates some erosion in Liassic times (MacLennan 1953, p. 454). This could have removed part of the top of the Trias as well as lower beds of the Lias, but the effect was probably slight and cannot be estimated. It is reasonable to give the thickness of the Trias as a little over 25 metres.

Traced eastwards the sedimentary succession is lost beneath the landslip, but re-appears on the slopes of Aoineadh Mhor, above Inninmore cottage, where the Trias is represented by a 3 m crag of cornstone veined with chalcedony, and traces of soft red and white pebbly grits.

Westwards, just across the Quarry Burn fault which downthrows about 45 m to the west, there are outcrops of cornstone along the overgrown path beneath Braigh Rudha an t-Sassunaich. These sometimes show a prominent oolitic structure, and bands of chalcedony are common. Below the path there are scattered exposures of gritty and pebbly cornstone, with pebbles of vein quartz and a little arkose-gneiss and mica-schist.

At Rudha an t-Sassunaich there is a fine exposure of cornstone at sea level, 4.8 m thick. A coarse conglomerate underlies the cornstone, containing imbricated pebbles of vein quartz and psammitic Moine, and occasionally some red granite. The cornstone is nodular in the lower half, but the upper half is very compact; it is traversed by numerous thin veins of chalcedony which usually occur parallel to the bedding. West of this point the Trias is truncated by another fault.

In Coire Slabhaig on the north side of Glais Bheinn which rises above Innimmore Bay, a few outcrops of pale conglomerate and breccia are seen almost in contact with the psammitic Moine there. Cornstones are well developed and contain many bands and nodules of pink and blue chalcedony. The conglomerate contains mainly vein quartz and Moine pebbles, the latter reaching 60 cms in diameter. The Moine is veined by cornstone in places. Lee (in Lee and Bailey 1925, p. 67) and Scott (1928, p. 161) have estimated the thickness of the Trias here as at least 40 feet; exposures now available suggest a rather smaller thickness, probably nearer 6 m (20 ft). The occurrence of Trias 900 feet above sea level, when 1¼ miles (2.0 km) to the south it is no higher than 400 feet, cannot be explained by the attitude of the beds, which dip very gently northwards. Instead, the presence of a fault is indicated. The Geological Survey's Sheet 44 shows the line of a possible fault running southeastwards round the foot of the Glais Bheinn crags, in Coire Slabhaig. It is likely that this fault exists in that position, and so the Trias in Coire Slabhaig is in fact faulted against and not overlain by the Glais Bheinn lavas.

b. Kinlochaline

At Kinlochaline House, 5 m of horizontally bedded pebbly grits and coarse red micaceous sandstones are in contact with micaceous pelitic Moine, and are overlain by red grits with scattered cornstone nodules passing up into a bed of cream-coloured cornstone 4.6 m thick. To the north, the six stream exposures of Scott (1928, p. 161) are now choked with talus, but at Larachbeg a brick-red highly micaceous sandstone overlies the Moine, which is again micaceous. The base is fairly even, and the Moine is stained red to a depth of 0.5 m below the contact. The Trias is incompletely exposed, but the general order of succession is :

Bed thickness		Description of Bed	Stratigraphical Horizon
Metres	Feet		
0.32-0.35	1	Grey shales containing abundant plant fragments and lamellibranchs and including a thin band of grit.	? RHAETIC
3.0	10	Pale calcareous coarse-grained quartzose sandstones and grits containing vein quartz pebbles. Fine-grained sandstone towards the top.	
4.8	15	Variegated green and cream pebbly grits and conglomerates. Pebbles are mostly rounded vein quartz; some psammitic Moine.	TRIAS (32 m/105 ft)

Bed thickness		Description of Bed	Stratigraphical Horizon
Metres	Feet		
24.0	80	Coarse red micaceous sandstones and grits, with conglomerate bands. Includes two beds of cornstone developed in gritty sandstone.	
		Micaceous pelitic schists	MOINE

The possible Rhaetic beds were first investigated by Scott (1928, p. 165) who recorded non-marine lamellibranchs and plant-fragments. The plant fragments are identified as Pagiophyllum peregrinum (Lind. and Hutt.) which was described by Seward (1904) from the Lower Lias of England, while the lamellibranchs are "Ostrea", indicating a marine rather than a non-marine environment for the beds.

South of Achranich, 150 yards east of the boathouse, there is an overgrown disused quarry where Judd (1878) recorded finding imperfect casts of bivalve shells (Cyrena ?). There 10.5 m of quartzose sandstones and pebbly grits occur, with a thick-bedded conglomerate at the base containing quartz pebbles. Just below the conglomerate there is a grit containing flakes and pellets of purple coloured shale identical to that of the Carboniferous at Inninmore. In places the shale has weathered out leaving organic-like casts which may have been taken by Judd to be shell casts. No organic traces were found in this investigation, apart from indefinite traces of possible plant fragments in the shales. In the quarry the rock is badly weathered, and may be examined in a fresher condition in the re-facing of Ardtornish Towers, which was taken from this quarry.

Judd referred this exposure to his 'Poikilitic' and it has since been mapped by the Geological Survey (Sheet 44) as Trias. However, in lithology the rocks closely resemble the sediments of the Carboniferous succession at Inninmore, while the presence of Carboniferous-type shale fragments at the base further suggests that the beds are Carboniferous and not Trias, and indeed nowhere else in the Morvern area (or in most of the other areas) is the base of the Trias represented by pale quartzose beds, red beds being typical. Favourable comparisons are made below between a sandstone specimen from these beds (Ka 3) and one from the Inninmore Carboniferous (In 22), and therefore the beds are correlated with those occurring immediately below the Trias at Inninmore (see p. 39).

These beds are overlain by coarse reddish sandstones and grits containing cornstone horizons, which are similar to the basal Trias at Kinlochaline House and Larachbeg; they outcrop south of Achranich, while in the stream at Achranich bridge they are close to the Moine, indicating that the Moine surface has risen about 12 m eastwards from the head of the loch, cutting out the Carboniferous. Quartzose grits and sandstones again comprise the upper part of the succession which is overlain by fine-grained shelly sandstone referred by Lee (in Lee and Bailey 1925, pp. 73-74) to the Rhaetic.

c. Morvern Hinterland

The Trias is very poorly exposed northwards from Larachbeg owing to forestry plantations. At Loch Arienas, below the Little Bonnet of Lorne, the basal conglomerate is seen containing local Moine fragments, quartz and mica, above quartzo-feldspathic psammitic Moine gneiss which is intricately veined with cornstone.

In Allt an Aoinidh Mhoire, 3.2 kms (2 miles) to the northwest, at the localities indicated by Scott (1928, pp. 162-163), psammitic Moine gneiss is veined by cornstone, above which a 5 m (16 ft) succession of greenish and reddish grits and cornstones is exposed. At a lower horizon, in a tributary, the base of the Trias is marked by a breccia of Moine fragments, but there is little evidence of cornstone development. As Scott has pointed out (1928, pp. 162-163), these two exposures illustrate the transgressive nature of the Trias on the Moine : the Moine surface rises 15 m (50 ft) in ¼ mile (0.5 km).

On the southwest shore of Loch Teacuis, at Ard na Tiobairt, there is a very spectacular development of cornstone in the Moine, extending to a depth of 3 m beneath the unconformity (Figs. 18 and 19). Above this there is at least 2.5 m of sandy cornstone passing into coarse pebbly grits and conglomerates containing subrounded pebbles of vein quartz and quartzite, with rather more angular Moine fragments.

Finally, thin patches of Trias are present beneath the lava caps of three prominent peaks north of Loch Teacuis. On Beinn Ithearlan pale cornstone outcrops on the northeast slopes, below the basalt, while on the north side of Beinn Iadain, in Coire Riabach, the succession is :

	Lava	TERTIARY
1.5 m	Silicified chalk	
3.0 m	White sandstone	CRETACEOUS
0.6 - 0.9 m	Green and grey shelly sandstone (Cenomanian Greensand)	
0.3 - 0.6 m	Cornstone	TRIAS
	Micaceous pelitic gneiss	MOINE

On the south side of the same hill, above Lon Beinn Iadain, the cornstones are again seen in intimate association with the Moine. These are overlain by Cenomanian Greensand after a slight gap, in which Scott (1928, p. 166) found Liassic strata.

On the northeast side of Beinn na h-Uamha a few feet of cornstone are poorly exposed; on the south side the Cretaceous lies directly on the Moine.

5. ARDNAMURCHAN

The Trias is thinly represented in scattered outcrops between Mingary in the south and Ockle in the north of the peninsula. It rests on Moine gneiss and is overlain by Lias limestones referred to the Broadford Beds (Lee, in Richey and Thomas 1930, p. 37). The Mesozoic rocks are distributed around the fringe of the Ardnamurchan Tertiary intrusion complex and are intruded by a very large number of dykes and cone sheets. However, unlike the Mull complex, the Ardnamurchan intrusions include very little acid material so that there are no pneumatolytic effects. Although entangled amongst intrusions, the sediments are fresh and largely unaltered.

a. Mingary

Below Mingary pier, cornstones containing occasional pebbles of vein quartz and local psammitic Moine underlie 1.8 m (6 ft) of medium-grained white sandstone which dip at 18° south below Lower Lias limestone. On the south side of the road the cornstones are repeated, containing chalcedony in bands up to 2.5 cm thick. They have replaced grits which were originally thinly to very thinly cross-bedded : a 45 cm unit still retains the original structure preserved in cornstone. Between these and Port an t-Salainn there are a few more patches of cornstone, and the basal Moine is permeated by cornstone at the unconformity. (See detailed map of Richey, in Richey and Thomas 1930, Fig. 23 p. 174).

At Rudha a Mhile there is a 6 m (20 ft) succession of Trias between the Moine and the Lias. There is much intrusion and some faulting, and a revision of Richey's map (Richey and Thomas 1930, Fig. 25 p. 177) shows that nowhere is the Trias succession obtained complete (Map 7). The succession can be reconstructed thus :

	Limestones and shales	LIAS
1.8 m (6 ft)	White medium to fine-grained sandstone, slightly uneven at base	? RHAETIC
6 m (20ft)	Red pebbly grits and sandstones, containing pebbles of vein quartz and psammitic Moine, the latter particularly near the base. Two beds of pink and white cornstone are developed in the sandstones	TRIAS
	Psammitic gneiss	MOINE

The top of the Moine is permeated by cornstone. The white sandstone has been included by Richey (1930, p. 35) in the Lias. However, along with its equivalent at Mingary pier it may be comparable with the Rhaetic sandstone east of Loch Aline in Morvern (see above, p. 44). Its slightly uneven base suggests that it is post-Trias.

At Sgeir nan Eun the base of the Trias is in contact with the Moine in cliffs below a raised beach. Cornstones are prominent, veining the Moine to a depth of 0.5 m beneath the unconformity. A patchy breccia of Moine fragments also occurs. The Trias is overlain by Lias limestones with 0.3 to 0.6 m of hard white sandstone (? Rhaetic) at the base. The undulating

Moine surface causes the Trias to vary in thickness from 3 to 5 m (10 - 16 ft).

b. Ben Hiant and Loch Mudle.

A thin breccia of Moine fragments (5 to 8 cms) and rounded vein quartz pebbles, with a little red grit and occasional cornstones, occurs in three poor stream exposures on the southeast face of Ben Hiant. It is overlain by Lias and Tertiary sediments.

2 miles (4.8 km) north, on the second bend of the steam flowing from Lochan na Gruagaich into Loch Mudle, about one metre of purple cornstone is exposed in contact with the Moine but hardly penetrating it. It is sandy and buff coloured in parts, and terminated upwards by a sill. According to Simpson (in Richey and Thomas 1930, pp. 35-36) the Trias is not found east of this point in Ardnamurchan, Tertiary lavas resting directly on the Moine or with a thin base of Tertiary sediments.

c. Swordle.

The Trias is exposed in a number of outcrops which are scattered among the intrusions to the north and west of Swordle, between the Moine and Lias. The best and most typical exposure occurs near the mouth of Allt Ockle, above the east bank of the stream, where 6 m (20 ft) of red and purple breccia, conglomerate and grit overlie an uneven surface of psammitic Moine gneiss. A well developed cornstone at the base penetrates the Moine to a depth of one metre, along joints and foliation planes. The basal cornstone is 60 cms thick and contains angular fragments of the local Moine. Above this the conglomerates contain pebbles mostly in the diameter range 3 to

25 cms which are composed of Moine and a little vein quartz. Cornstone occurs throughout : in the conglomerates it is developed as irregular patches but in the grits there is a tendency towards a vertical development in pipe-like bodies. The section is terminated by a cone sheet which has bleached the top one metre of sediment.

6. RHUM

On the northwest coast, along the slopes of Monadh Dubh, Trias sediments occur over an area of about 1.3 square kms. The beds lie unconformably on Torridonian sandstones, the junction being almost continuously exposed as a roughly semi-circular outcrop extending from A Mharagach in the north, swinging half a mile (0.8 kms) inland, and returning to the coast at a prominent headland half a mile north of the mouth of Glen Shellesder. The beds are truncated to the northwest by sea cliffs which make most of the coastal exposures inaccessible.

The base is marked everywhere by a cornstone. Permeation of the underlying Torridonian occurs to a depth of 2 m, being commonly one metre. In places, replacement <u>in situ</u> is so intense that the true base of the Trias is difficult to determine (Figs. 21 and 22). Torridonian sedimentary structures such as convolute bedding may be preserved in the cornstone. There usually follows a bed of white cornstone above the Moine, being 1.7 to 2.7 m ($5\frac{1}{2}$ to 9 ft) thick, which is also present round almost the entire periphery of the outcrop. The cornstones are particularly well seen for one mile (1.6 km) along the summit of a prominent ridge marking the southern boundary of the Trias outcrop above Glen Shellesder.

Overlying the cornstone there is a conglomerate containing rather angular pebbles of Torridonian sandstone alone, set in a red gritty matrix of small sandstone fragments and quartz grains. Scattered nodules of cornstone are developed in the grits and in places they coalesce into distinct beds, as in the first stream south of A' Mharagach where five distinct cornstone horizons occur, each with nodular cornstones in grit, overlying conglomerate and progressively coalescing upwards into a cornstone bed which in turn is followed by another conglomerate with an erosional base. In the cliffs at the southwest end of the outcrop the maximum thickness of this bed is 10-5 m; inland it thins to a few feet.

The next conglomerate has Torridonian sandstone as the predominant pebble type, with a few pebbles of Durness limestone, orthoquartzite and some re-worked cornstone. It is 38 m (125 ft) thick in the cliffs, but also thins inland.

Above the conglomerates there is a bed of quartzose sandstone, overlain by a fossiliferous succession of buff weathering sandstones, and dark grey sandy limestones and siltstones. This is best exposed in the second stream south of A' Mharagach where a 21 m succession is fairly well exposed. The beds are closely similar in lithology to the Rhaetic of Western Mull. From material collected by Bailey (1944, pp. 172-173) from the highest bed, Euestheria minuta auctorum has been identified which proves the deposits to be either Keuper or Rhaetic. However, C.P. Chatwin (in Bailey 1944, p. 173) recorded that "The small size of the specimens and their association with ostracods suggests T.R. Jones's var. brodeina.

of Rhaetic age; but in the only two specimens which show reticulate ornament between the ridges, the number and size of meshes are more in accord with forms from the Keuper". Other fossils recorded include ostracods (? Darwinula), an impression of a fish tooth and a few isolated palaeoniscid scales.

Although Bailey did not record fossils from below the highest bed, the whole succession of 21 m is fossiliferous. The lowest beds are sandy, containing obscure fragmentary carbonaceous plant remains up to 1.5 cms in length. In the upper 10 m there are beds of fine-grained grey calcareous sandstone containing abundant rather obscure remains of fish teeth and scales, tiny shells, and carbonaceous remains.

Chatwin's fossil identifications could almost equally well suggest a Rhaetic age for these beds, which seems more likely in view of their lithological similarity to the Mull Rhaetic. No other beds of this nature occur in the Trias of the area studied, and they certainly represent a change in depositional environment. The beds beneath pass upwards without an obvious break in deposition into the fossiliferous beds, and so their age may still be reasonably taken as probable Keuper and certain Trias.

Although the complete succession cannot be measured at one single point, a generalised succession with maximum thickness is as follows :

21 m (70 ft)	Sandstones and bedded sandy limestones alternating with siltstones and shaly partings. Fossiliferous.	? RHAETIC PASSAGE BEDS
38 m (123ft)	Conglomerates containing Torridonian sandstone, Durness limestone, quartzite and detrital cornstone pebbles. Sandstone at the top.	TRIAS

10.5 m (35 ft)	Conglomerates containing only Torridonian sandstone pebbles, some cornstone developed.
1.7 - 2.8 m ($5\frac{1}{2}$ - 9 ft)	Cornstones
	Torridonian

Total thickness is > 73 m (240 ft). This compares closely with Harker's result (1908, pp. 15-16).

7. ISLE OF SKYE

Mesozoic rocks are widespread in Skye, particularly in the centre and northeast of the island. Wherever the base is seen, the lowest beds are Triassic: thus the Trias occurs below Jurassic strata at Strath (between Broadford and Lochs Eishort and Slapin), on the south side of Loch Sligachan, and on the Sound of Soay (An Leac). Isolated outcrops with no overlying sediments also occur in Sleat.

a. <u>An Leac</u>

On the north side of the Sound of Soay, immediately to the east of Allt na Meacnaish, there is a small promontary composed of coarse Trias conglomerates alternating with cornstones. These are overlain by younger Mesozoic strata and by a Tertiary basalt sheet. The base of the Trias is not seen.

A little to the east, the basalt sheet descends below sea level, but 100 yards beyond An Leac 6 m of conglomerate is exposed between the basalt and the Torridonian sandstone on which it is seen to rest. Further east, the basalt is in direct contact with the Torridonian, but 9 m of conglomerate then re-appears, rising to the top of the cliff where it is hidden by scree, one-third of a mile (0.5 kms) east of An Leac. Younger Mesozoic strata are not seen in this section, apart from some inaccessible sandstones and shales exposed high in the cliff.

The conglomerate at An Leac is composed mainly of Durness limestone and dolomite pebbles set in a calcareous matrix, contrasting with the conglomerates to the east which contain little limestone, the pebbles being mostly Torridonian sandstone and grit set in a red gritty matrix with calcite cement.

The succession at An Leac is :

	Basalt	TERTIARY
2.8-3.0 m (9-10 ft)	Pale grey unfossiliferous limestone.	?LIAS/PASSAGE BEDS
1.1 m (3½ ft)	Fine-grained very thin-bedded white sandstone with dark partings. Cross-laminated in parts.	
0.5 m (1 ft)	Grey siltstones with pyrite cement.	?
2.4 m (8 ft)	Conglomerate and sandstone with shale partings. Contains wood fragments; also angular chert pebbles and re-worked cornstone.	?RHAETIC PASSAGE BEDS (9.4 m/30½ ft)
5.5 m (18 ft)	GAP	
1.0 m (3 ft)	Conglomerate (as above).	
4.2 m (14 ft)	Conglomerate with pebbles of limestone and red sandstone. A little chert, but no wood or re-worked cornstone.	TRIAS
11.3 m (37½ ft)	Four conglomerate - cornstone 'cycles'.	15.5 m/51½ ft
	Torridonian	

Although the Torridonian base is not seen, it may be assumed to be close because 1. it occurs above sea level only 100 yards to the east and 2. there is a sudden increase in abundance of Torridonian pebbles in the lower part of the lowest exposed conglomerate.

The junction between the Trias and suggested Rhaetic passage beds is not distinct. The highest Trias conglomerate is composed almost entirely of limestone pebbles set in a gritty calcareous matrix (limestone conglomerate). The overlying conglomerate is finer-grained and pebbles tend to be rather more angular; limestone fragments are still abundant and there are also many angular pieces of chert. Many of the limestone fragments are re-worked cornstone. This slight lithological change can be defined within 3-5 cms, but after 30 cms large fragments of wood appear and continue scattered throughout the bed. The wood is preserved as lignite, the fragments varying in length from 10 to 48 cms. They lie in the bedding plane and show no preferred orientation. Above the gap the beds become finer-grained, being yellow calcareous quartzose grits and sandstones, with conglomeratic patches. Lignite fragments up to 90 cms in length occur and appear at two distinct horizons. Pebbles of limestone and chert are abundant.

The lignite has been examined by A.C. Seward (in Clough 1904, p. 9) and identified as coniferous wood, (possibly Araucarioxylon ?).

Higher beds at An Leac are unfossiliferous and cannot be referred with certainty to the Lias, although 650 yards west these beds are overlain by limestones and shales with Gryphaea sp.

The most interesting feature of the Trias succession is the alternation of conglomerate and cornstone. In each 'cycle', conglomerate at the base is followed by cornstone with a gradational junction. The top of the cornstone is uneven, the overlying conglomerate having an erosional base and containing detrital fragments of re-worked cornstone (Figs. 23,24). The cornstones contain abundant thin bands of chalcedony which are developed parallel to the bedding.

Pebbles in the conglomerates become smaller upwards through the succession. In the lowest bed, pebbles of Torridonian sandstones are up to 25 cms in diameter, while the pebbles generally range from 6 to 16 cms. Apart from in the lowest bed there is very little Torridonian material present, limestone and orthoquartzite predominating, with a little subordinate vein quartz and chert.

Taking the top of the Trias as indicated above, the total thickness at An Leac is more than 15.5 m (50 ft), thinning eastwards to 9 m (30 ft) which may be attributed to a rising Torridonian surface which is accompanied by the presence of red sandstone pebbles in the conglomerates.

b. Strath.

In Central Skye the Trias outcrops on both limbs of a syncline which runs south from Broadford and then curves westwards through 90° to Rudha Suisnish. Although disjointed by faulting, the outcrops are otherwise continuous for 3 miles (4.8 kms). Scattered exposures also occur around the anticline to the northwest of the Strath Syncline, and between Skulamus and Ob Lusa. The Trias is overlain everywhere by Broadford Beds except at Heast and Allt a Mhuilinn where passage beds of possible Rhaetic age intervene. The Trias overlies a thrust complex of Torridonian and Cambro-Ordovician sediments, resting on the Torridonian everywhere except at the extreme southwest end of the outcrops where Cambrian quartzite and Durness Limestone form the base.

The general succession is :

	Shelly limestone and shales.	L.LIAS (Broadford Beds)
4.6-6.0 m (15-20ft)	Coarse quartzose sandstones and grits.	
0-15 m (0-50ft)	Conglomerates	TRIAS
	Torridonian	

The total thickness varies from 4.6 to 15 m (15 to 50 ft).

Along the southeast limb of the syncline between Skulamus and Heast the Trias consists mainly of quartzose sandstones and grits containing vein quartz and quartzite pebbles. The basal conglomerate is little seen but is thinly exposed at intervals; at Skulamus it contains abundant pebbles of vein quartz, quartzite and mica-schist, but southwards the pebbles are mostly of Torridonian sandstone. The total thickness of the Trias here is 4.6 m thickening southwestwards to Heast where it is 10-12 m, including red and green micaceous shaly and papery calcareous micaceous siltstones at the top which are not represented elsewhere in Skye. They are overlain by Passage Beds and Lower Lias strata, the succession being :

	Alternations of shelly limestone and shale with <u>Liostrea irregularis</u>.	L.LIAS (Broadford Beds)
2.1 m (7 ft)	Limestone overlain by shale, siltstones and fine-grained sandstones with obscure plant remains.	? RHAETIC PASSAGE BEDS
1.5 m (5 ft)	Red and green micaceous siltstones.	
9.2 m (30ft)	Quartzose grits and coarse-grained sandstones.	TRIAS
3.0 m (10ft)	Conglomerate with some cornstone in the matrix.	
	Torridonian	

The Trias is faulted up into the hillside above Heast where there is a very coarse conglomerate containing abundant pebbles of Durness limestone, some orthoquartzite and chert, and a little Torridonian sandstone in parts.

The pebbles are set in a coarse gritty matrix with abundant calcite cement. The rock is so highly calcareous that it commonly exhibits the characteristic clint and grike weathering of limestones. Its pale colour and characteristic weathering make it readily distinguishable from a distance in the field. It is very similar to the main part of the conglomerate at An Leac, and will be referred to as 'limestone conglomerate'; it is common in the Strath Syncline (Figs. 25 and 26).

Along the southeast face of Beinn a'Chairn, 4.6 m of Trias limestone conglomerate extends southwestwards for fully one mile (1.6 km) to Tòrr Mòr where it is truncated by a fault. It overlies the Torridonian and is overlain by 4.6 m of pale thin-bedded quartzose grits and sandstones which are sometimes thinly cross-bedded. The conglomerate thins slightly southwestwards while the grits are reduced to 3.0 m at Tòrr Mòr. The sandstones and grits are overlain by shelly limestones and shales (Broadford Beds) with a thin conglomerate at the base containing pebbles of dark compact limestone and pale re-worked cornstone, with complete and broken lamellibranch and gastropod shells, which can probably be referred to the base of the Lias.

In the northwest limb of the syncline the rocks are similar. Immediately south of Broadford, in Allt a Mhuilinn, the basal Trias conglomerate contains pebbles of red sandstone, quartzite and vein quartz, with a little limestone, mica-schist, chert and jasper, set in a gritty calcareous matrix. Some bands packed with limestone pebbles occur. Overlying the conglomerate are pale quartzose grits and coarse to medium-grained sandstones. To the south of Cnoc na Cubhaig the conglomerate contains pebbles of limestone, red arkosic sandstone, quartzite and vein quartz. Little is seen of the higher beds there, although there are a few patchy exposures of badly weathered medium-grained sandstone. Scattered outcrops of quartzose gritty sandstones can be followed southwards to Loch Buidhe where there is a very fine development of the limestone conglomerate, containing limestone blocks up to 17 cms in diameter, and extending for 1½ miles (2.5 kms) round the north side of Beinn a Chairn. Along this part of the outcrop the quartzose grits and sandstones are not developed, but within the limestone conglomerate a 0.6 m band of medium to fine-grained red sandstone can be followed for almost the full 1½ miles southwestwards from Loch Buidhe. There is much orthoquartzite in the rock as well as limestone, and a few pebbles of red Torridonian sandstone occasionally occur.

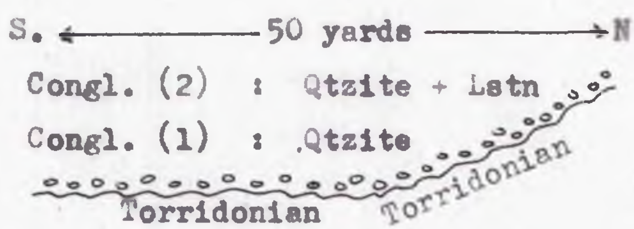
To the west, the northwest limb is displaced southwards by faulting below Beinn a Mheadhoinn, down the valley of Allt na Pairte. On the east side of the stream 15 m of coarse conglomerate occurs. The Geological Survey map (Sheet 71) shows this overlain by Lias, which is not the case : the conglomerate is intruded by granophyre on two sides and faulted on the other two. At the base it contains large blocks of quartzite (up to 35 cms) and a little limestone (up to 12 cms). The matrix is gritty and contains cornstone concretions which increase in abundance upwards. Limestone fragments become commoner upwards (up to 16 cms maximum diameter) so that the rock grades into a limestone conglomerate in the upper part.

On the other side of the stream, which follows a fault, the conglomerate is seen overlying Torridonian sandstones. The succession is :

	Granophyre sill	
9.2 m (30 ft)	Conglomerate with abundant limestone and quartzite pebbles	(2)
4.6 m (15 ft)	Conglomerate packed with angular quartzite pebbles; angular Torridonian fragments in basal 0.6 m (2 ft)	(1)
	Torridonian	

The conglomerate is banked against a rising surface of Torridonian. The second conglomerate contains a few scattered fragments of red sandstone where the Torridonian base rises against it.

Thus we have :-



= Torridonian pebbles

Northwards the outcrops are disturbed by repeated faulting and intrusion by a granophyre sheet. The Torridonian base is twice seen again, overlain by limestone conglomerate with a very fine-grained red muddy matrix (Fig. 60c). Fossiliferous limestone pebbles were collected from the conglomerate at this locality, on the slopes of Beinn a Mheadhoinn.

On the north side of Glen Boreraig the limestone conglomerate is again very well developed. It is about 9.2 m (30 ft) thick at the eastern end of the outcrop, thinning to nothing at the western end where it is overlapped by the Lias 1 mile (1.6 kms) west of the summit of Beinn a Mheadhoinn. Although in the west it overlies quartzite and then limestone instead of Torridonian, the pebble content remains virtually constant. Where the conglomerate is in actual contact with a quartzite basement the quartzite pebble content is very much lower than at Allt na Pairte where it overlies Torridonian (see above). Limestone pebbles with fossils were also collected at this locality.

North of Suardal, on the northwest limb of the neighbouring anticline, limestone conglomerate occurs again. It is poorly exposed and is overlain by pale pebbly quartzose grits and sandstones. Across the axis of the anticline there is a conglomerate containing vein quartz and quartzite pebbles, with angular red sandstone fragments at the base and a gritty matrix. The thickness of the Trias here does not exceed 3.0m (10 ft).

The outcrops between Skulamus and Lusa are of conglomerate. The best exposure is below Ashaig Bridge where a well developed basal cornstone heavily veins the Torridonian to a depth of 3 m <u>in situ</u>. Above this there is a conglomerate with a soft red gritty matrix enclosing pebbles of Torridonian alone. These are mostly rounded, although the larger ones (15-25 cm) are rather more angular.

The distribution of pebble sizes in the conglomerates is dealt with quantitatively below (pp.213-214 and Figs.140-142).

The areal distribution of the limestone conglomerates and the pale quartzose grits and sandstones is summarised in Fig. 141 They overlap in only a small part of the area.

c. <u>Loch Sligachan</u>

On the northern slopes of Glamaig, on the southeast side of Loch

Sligachan, a highly faulted patch of Mesozoic strata occurs over an area of about one square mile (2.5 sq. kms). The Trias occurs thinly between the underlying Torridonian sandstones and grits and overlying shelly Lias limestones and shales, with possible Rhaetic beds at the base of the Lias (Woodward, in Peach et al 1910, p. 96).

At the east end of the exposures the Trias consists of conglomerate containing pebbles of Torridonian sandstone, quartzite, limestone, vein quartz and a little acid gneiss (Lewisian) and mica-schist. This is overlain by bright red fine-grained sandstones and siltstones containing scattered rounded limestone and vein quartz pebbles. Further west the conglomerates are not seen, but bright-red rather micaceous calcareous siltstones and clays with a few scattered pebbles occur. In the southwest, a few reddish cornstones are developed in the fine-grained sediment.

The total thickness of the Trias does not exceed 15 m (50 ft).

d. Sleat.

Half a mile (0.8 km) north of Tarskavaig Bay there is a small outlier of Trias resting on Torridonian shales and grits. At the base there is a striking development of cornstone which veins the underlying shales to a depth of 3.0 m. The cornstone tends to be best developed along bedding and joint planes, but it has also developed across the bedding. The Torridonian has a purple stain at the Trias base and for several yards around the outlier, where the Trias has been stripped off.

The cornstone is overlain by conglomerate which contains abundant pebbles of orthoquartzite, including blocks of "pipe rock", (up to 25 cms maximum diameter), and limestone, Torridonian sandstone grit and shale, and a few pieces of chert. The matrix is red or brown calcareous grit and fairly well developed cornstone concretions also occur. The thickness present is 9.2 m (30 ft).

Clough (in Peach, Horne *et al* 1910, p. 93) has recorded similar conglomerates on Sgeir Fhada and Sgeir Biodaig at the entrance to Tarskavaig Bay.

North of Rudh an Iasgaich a thin veneer of conglomerate is exposed in scattered outcrops between Moine schists and Tertiary basalt sheets.

The Sleat outliers are heavily intruded by the Skye Tertiary dyke swarm.

8. SCALPAY

At Rudh a Chinn Mhoir, the northeast tip of the island, there is a small patch of Trias overlying Torridonian sandstone. There is no geological top to the Trias, although loose blocks of Lias limestone occur locally. The succession is :

15 m (50 ft)	Coarse very thick-bedded conglomerates containing well-rounded cobbles of Torridonian sandstone, Durness limestone, orthoquartzite, vein quartz, mica-schist and acid gneiss. Coarse gritty matrix with some irregular cornstone concretions.
9.2 m (30 ft)	Brick-red grits and coarse-grained flaggy sandstones with abundant cornstone concretions and several bands of conglomerate containing pebbles as above.
	Torridonian

There is a disconformity at the base so that in places it is difficult to distinguish the basal Trias from the slightly weathered top of the Torridonian; slight irregularities in the Torridonian surface help to make the disconformity recognisable. This locality is rather unusual in having sandstones at the base instead of the more normal conglomerates (Fig. 27). The same situation holds at Eyre on Raasay (see below).

Eilean Leac na Gainimh, a small island which is attached to Scalpay at low tide, is composed of 9.2 m (30 ft) of coarse conglomerates similar to those of the upper half of the main outcrop. A fault intervenes between them. Among the orthoquartzite pebbles, two blocks of "pipe rock" were found. No fossil shells were found in the limestone pebbles, but two specimens of a sponge-like form were collected (Fig. 49). The conglomerate has a coarse gritty matrix which is thinly to very thinly cross-bedded in parts; the matrix may be well indurated (pebbles sliced clean through by jointing) or rather crumbly. Pebbles of red sandstone, limestone and quartzite are up to 25 to 30 cms in maximum diameter, somewhat larger than in the main outcrop where they are up to 15 to 20 cms, being mostly 5 to 8 cms (Fig. 28).

9. RAASAY

On the Island of Raasay a very fine succession of Mesozoic rocks has been preserved beneath Tertiary lavas and sills. They are in a fresh condition and comprise half of the southern part of the island. The Trias appears at the base : at Eyre (the southern tip of the island) and at Rudha na Leac on the east coast. Its base is not seen at Rudha na Leac, but at Eyre it overlies the Torridonian. It is overlain at both localities by Broadford Beds.

a. Eyre

Outcrops of Trias extend from Rudha na Cloiche to South Fearns, the best exposures being in the cliffs behind the houses at Eyre. It is faulted against and intruded by granophyre in the west, and overlain by Lias in the east. The Trias dips from 16° to 21° to the northwest, and the underlying Torridonian has a similar dip so that there a disconformity instead of an angular unconformity at the base, as on Scalpay.

At Rudha na Cloiche, red Trias sandstones and grits, with subordinate red silts and clays occur 15 m (50 ft) above sea level, and there is a small outcrop of conglomerate on the beach halfway between the point and Raasay pier. Eastwards, the base rises round the lower slopes of Suisnish Hill to Eyre Burn, where the succession is repeated across a fault, the base appearing a little above sea level at Eyre, and again ascending northeastwards, seen in a strike section.

The complete succession is not seen anywhere. The lowest beds are best exposed in the Eyre cliffs where the succession is :

10.5 m (35 ft)	Coarse conglomerate containing rounded pebbles of Torridonian sandstone, orthoquartzite, vein quartz, Durness limestone and mica-schist.
7.0 m (24 ft)	Brick red and white soft coarse to medium-grained sandstones containing scattered pebbles of vein quartz and quartzite with a little Torridonian. Cornstone concretions developed in the upper half as impersistent bands up to 15-25 cms thick.
0.5 m (1½ ft)	Pebble bed with soft sandy matrix. Subangular and subrounded pebbles of quartzite, vein quartz and a little Torridonian.
c.1.0 m (3½ft) variable	Soft gritty coarse-grained purple sandstone.
	Torridonian

The basal sandstone closely resembles the Torridonian sandstone itself, but has a calcite cement. It may be the product of winnowing of a weathered Torridonian surface and is of particular interest because it does seem in fact to be a re-worked arkose, which is rare both in recent and fossil sediments. The same applies to the base of the Scalpay succession which lies only one mile (1.5 kms) across Caol Mor from Eyre.

Eastwards the precise base is not exposed, but the 7 m sandstone with cornstones resolves into distinct divisions with increased cornstone development. Due north of the lighthouse four beds of sandstone grade up into cornstone bearing horizons. Each cornstone has a well-defined top, the next sandstone having a slightly erosional and sometimes conglomeratic base. The sandstones range from 25 cms to more than 3 m in thickness and the cornstones 38 to 65 cms.

The 'sandstone-with-cornstones' also continues northeastwards, while the overlying conglomerate is well developed everywhere. In the Eyre Burn the upper parts of the conglomerate are seen to contain thinly cross-bedded lenses of pale buff or pink grits and coarse to medium-grained sandstones.

Overlying 'passage beds' (calcareous sandstones and dark shales) were doubtfully assigned to the Rhaetic by Woodward, but Lee found the evidence inconclusive, including them at the base of the Lias (see the Survey's clean copy Six Inch map of South Raasay, and Lee and Pringle 1932, p. 170).

The general succession in South Raasay is :

Shelly limestones and shales. Calcareous sandstones and dark shales at the base	L.LIAS (Broadford Beds)

18-21 m (60-70 ft)	Conglomerates with some lenses of grit and sandstone towards the top.	
7 m (24 ft)	Sandstone with scattered development of cornstones resolving into distinct beds northeastwards.	TRIAS
0.5 m ($1\frac{1}{2}$ ft)	Pebble bed with sandy matrix .	
c. 1 m ($3\frac{1}{2}$ ft) variable	Soft purple and red sandstone .	
	Torridonian	

Total Trias thickness : c. 28 m (95 ft).

b. Rudha na Leac

A section through 40 m of Trias is exposed on this headland. The base lies beneath the low water mark, but abundant pebbles of Torridonian sandstone in the lowest exposed conglomerate suggest that the base is Torridonian and should occur not far below. The top is covered by beach deposits and a grassy slope, but above the gap typical shelly limestones and shales of the Broadford Beds follow. The sediments are much intruded by thin basic Tertiary dykes and sills, but are fortunately little altered. No faulting occurs within the section, although it is faulted out to the south.

The succession (Fig. 152) consists of brick-red sandstones interbedded with conglomerates. The sandstones are thicker than the conglomerates, while each of the main conglomerate beds gives way laterally to more sandy lithology in a northerly direction,

Cornstones are commonly developed within the sandstones; in one case they form a distinct series of 'sandstone-with-cornstone' profiles, the cornstones having sharp erosional tops and grading downwards into sandstone. (Fig. 29 and Frontispiece).

The conglomerates frequently contain very thinly cross-bedded lenses of coarse to medium-grained sandstone. Patches of cornstone tend to develop in the sandstones but are infrequent in the conglomerates themselves. Pebbles in the conglomerates consist of Torridonian sandstone and grit, limestone, orthoquartzite, metaquartzite, vein quartz, mica-schist and chert. Torridonian pebbles are dominant near the base, but Durness limestone becomes more frequent upwards. In the highest beds vein quartz and quartzite are dominant. In the limestone pebbles siliceous remains of tiny rod-like organisms are common, while the second conglomerate bed yielded pebbles of fossiliferous limestone.

Sandstones become more frequent upwards through the succession. The cement is calcite throughout.

10. APPLECROSS

$7\frac{1}{2}$ miles (12 kms) northeast of Rudha an Leac the Trias is again seen on the mainland coast at Applecross village. It has a fairly large areal extent, stretching for 3 miles (4.8 kms) from River Applecross to Camusteel, but it is rather poorly exposed, much being obscured by a thick cover of drift. It overlies Torridonian and underlies Liassic strata. The Mesozoic rocks are terminated to the east by a combination of two fault systems (not hitherto recognised) which downthrows them against the Torridonian. A small outlier of Trias remains perched 76 m (250 ft) above the rest, east of the faulting.

South of Milton the Trias is thin (c. 4.5 m). The base is well exposed on the shore there, and its position can be followed south for $\frac{3}{4}$ mile

(1 km). At the base there is a development of cornstone veining the Torridonian to a depth of 23 cms, particularly along bedding planes. The unconformity is slightly angular and the Torridonian surface is rather uneven. 0.5 m of conglomerate follows, containing mainly Torridonian pebbles but with some subangular and subrounded pebbles of vein quartz and orthoquartzite, and also some Durness limestone. This is overlain by coarse grit containing pebbles of the same rock types, Torridonian sandstone again being dominant. These grits have a soft sandy matrix and some well defined cornstone horizons. Pebbles average 1-3 cms in diameter, but may be up to 13-15 cm. In places the unevenness of the Torridonian surface has imparted a depositional dip to the conglomerates and grits above.

The conglomerate is better developed ½ mile (0.8 km) southeast of Loch a Mhuilinn where a crag above the road exposes a red sandstone with cornstone at the top, overlain by a 2 m exposure of coarse conglomerate and grit containing a predominance of orthoquartzite pebbles, with limestone, red sandstone and vein quartz in addition. Most of the pebbles are subrounded. 350 yards to the north, overlying beds are exposed in a small scarp : three to four beds of rubbly cornstone with thin chalcedony bands are developed in 3.5 m of red gritty sandstone. Due east, across the fault, the small outlier of Trias is composed of red clays, and cornstones developed in red gritty sandstone, the total thickness being about 6 m.

The Trias also occurs in a shallow corrie on the northwest side of Meall Loch a Chota, where it dips beneath the Lias along the roadside. Three stream sections there expose the higher beds of the succession which are red clays containing cornstones and some impersistent pebble beds up to 55 cm thick. The greatest exposed thickness measured is 3 m. More conglomerates occur beneath, pebbles being rather angular fragments of quartzite and limestone with a little red sandstone, set in a red gritty matrix which is rather calcareous, with some cornstone. There are also smaller fragments of vein quartz. Pebbles have been heavily fractured parallel to local jointing, but the fractures are not evident in the surrounding matrix. Pebbles range up to 10-12 cms.

The second of these stream exposes the junction with the Lias, in a low bank south of the road, just opposite the disused lime kiln. The section is :

	Limestones : pale, light grey weathering. Nodular towards the base with a buff sandy matrix.	LIAS
3-4.6 m (10-15ft)	Purple, green and grey laminated micaceous siltstones with 'lens and flaser' bedding, containing limestone nodules (2-10 cms) in the top 55 cms : sparse at first, becoming more frequent upwards.	?RHAETIC
	Red and green variegated micaceous siltstones.	TRIAS

This section has already been published, including details of higher Lias beds, by Lee (1920, p. 7), Lee and Pringle (1932, p. 173) and Hallam (1959, p. 171). In each case the ?Rhaetic as given above has been included as Triassic "sandy shales" or "sandy marls". It is shown below (pp. 202-203) that the ?Rhaetic beds are probably marine, and therefore are unlikely to be Trias.

600 yards north of this point, in the bank of the third (most easterly) stream, badly weathered beds were dug out with a spade to reveal the following succession:

1.5 m	Soft badly weathered limestone, grey when fresh.	LIAS
0.3 m	Blue-grey, non-micaceous clay.	
0.6 m	Purple clay with green micaceous patches.	?RHAETIC
0.9 m	Red-brown and patchy green micaceous clays.	TRIAS

Northwards, the Trias is not exposed, but conglomerates are seen in Allt Mor and Abhuinn an Stratha Bhan (River Applecross). In the latter river the succession is:

3 m Coarse conglomerate with pebbles of limestone, red sandstone, quartzite and vein quartz.

2 m Brick-red coarse-grained sandstone containing scattered vein quartz pebbles. Uneven cornstone with vertical development occurs in the upper 0.6 m.

The Trias therefore appears to thicken northwards and eastwards from Milton, and a generalised succession for its maximum development may be as follows:

	Purple siltstones	?RHAETIC (not present at Milton)
c.1.5 m (5 ft)	Red and green micaceous siltstones.	
c.7.5 m (25 ft)	Brick-red sandstones containing cornstones and with subordinate clays, alternating with conglomerate at the base.	TRIAS
	Torridonian	

The total thickness is unlikely to exceed 9 metres.

11. REDPOINT

On the coast below raised beach deposits at Redpoint clachan a small outlier of Trias sediments unconformably overlies the Torridonian. Conglomerates, red grits and coarse to medium-grained sandstones predominate. The sandstones contain scattered discrete calcareous nodules which weather out as spherical bodies, but do not coalesce into beds of cornstone.

The basal Torridonian is little affected by carbonate permeation, and is overlain at the south end of the outcrop by 3.7 m of coarse grit containing lenses of conglomerate and scattered pebbles. The matrix is carbonate and the lowest 0.6 m is nodular, without pebbles. In the pebble beds Durness limestone and orthoquartzite (up to 25-30 cms diameter) predominate over arkosic sandstone and grit pebbles (15-25 cms). There is a little vein quartz and occasional small pebbles of jasper and pink felsite.

In the centre of the outcrops these beds are overlain by a soft orange-red calcareous sandstone which appears to be well-sorted and has a suggestion of dune bedding, although this is not clear. The sandstone is intercalated with conglomerate containing pebbles of limestone, quartzite, red sandstone, some chert and jasper and a little acid gneiss and mica-schist. The limestones are mostly grey and compact, but there are also bedded pink and cream coloured varieties. Pebble sizes range up to 10 to 30 cms (i.e. up to cobbles and boulders). These beds are 3 to 4.6 m (10-15 ft) thick. Loose blocks on top suggest that more conglomerate may follow.

The total exposed thickness is only 8 to 9 m (26-30 ft).

The outcrop of the Torridonian surface suggests that these beds were deposited in a shallow hollow in the Torridonian landscape.

12. GAIRLOCH, BIG SAND.

On the north side of Loch Gairloch Trias strata are inferred to cover an area of ½ sq mile (1.3 sq kms) above the Torridonian. Most of this is covered with drift, raised beach deposits and blown sand, but a strike section of ½ mile (0.8 kms) is exposed along the River Sand.

The dominant rock type is a soft brick-red coarse-grained sandstone which is gritty in parts and contains scattered pebbles and conglomeratic bands. It is well exposed in the river bank just north of the road bridge where it is faulted against the Torridonian, while across the fault to the south the basal unconformity is exposed.

Further downstream the unconformity descends so that beds occur that are lower in the Trias succession. Again soft coarse-grained brick-red sandstones and grits predominate, but some bands of conglomerate occur in lenses, the thickest being 3 m. Pebbles in the sandstone are of vein quartz and quartzite, with a little red sandstone, while the conglomerates contain pebbles of up to 30 cms (boulder grade) of orthoquartzite, with smaller pebbles (cobble to pebble grade) of grey and pink limestone, mica-schist, a little red Torridonian sandstone and some vein quartz. The matrix of the conglomerate is soft red-purple gritty sandstone.

The 3 m conglomerate exhibits a change from the base, where the above assortment of rock types occurs, to the top, where it is finer-grained with 1-5 cm pebbles of vein quartz and quartzite but no Torridonian or limestone. Within the bed are intercalated 5 to 10 cm bands of brick-red sandstone, which are very thin-bedded with uneven bases and flat tops; the well exposed upper bedding plane of one of these shows parting lineation (see pp.198-202 and Fig. 46).

South of Little Sand farm the base is again exposed, where 2.1 m (7 ft) of grit and conglomerate containing orthoquartzite and Torridonian sandstone pebbles (up to cobble grade) overlie the Torridonian with slight angular unconformity.

The Trias is banked against a Torridonian surface which slopes gently uphill to the north, and the most complete succession is :

>3 m (10 ft)	Soft brick-red coarse-grained sandstones with scattered pebble beds.
3 m (10 ft)	Soft brick-red coarse-grained sandstones intercalated with coarse conglomerates and grits.
2.1 m (7 ft)	Conglomerate with a gritty matrix
	Torridonian

The total exposed thickness does not exceed 9 m (30 ft).

13. CAMAS MOR

8 miles (2.4 kms) north of Big Sand, on the east side of Camus Mor, a small outlier of Trias occurs above the Torridonian, downfaulted against the northeast side of the Loch Maree Fault (see p. 103). The succession is:

>6 m (20 ft)	Brick-red and chocolate-brown conglomerates and grits. Pebbles as below.
0.6-15 m (2-5ft) variable	Brick-red gritty sandstones with cornstone almost absent. Scattered pebbles of Torridonian and orthoquartzite.
5.2 m (17 ft)	Red grit overlying 0.6 m very coarse conglomerate containing pebbles of Torridonian and orthoquartzite up to 30 cms in diameter, alternating with and lensing into cross-bedded sandstones.
0.1.5 m (0-4½ft)	Brick-red gritty cross-bedded sandstone. Patchy cornstone in upper half. Locally, where it abuts against the Torridonian, pebbles of red sandstone and grit occur alone. Elsewhere there are scattered pebbles of limestone and quartzite.

4.6 m (15 ft) . Coarse conglomerate. Rounded pebbles (up to cobble and boulder grade : 45 cms maximum, mostly 23-30 cms) of Torridonian and quartzite in a gritty matrix. Intercalations of coarse-grained sandstone lenses, vaguely cross-bedded. Some limestone fragments in the upper half.

6.5 m (22 ft) Coarse conglomerate. Rounded and subrounded pebbles of Torridonian and orthoquartzite (up to cobble and boulder grade : boulders mostly 23-30 cms; others 5-13 cms). Matrix is coarse red and gritty containing granules of the same material as the pebbles.

Torridonian

The conglomerates are thick to very thick-bedded; the sandstones are thin-bedded and thinly cross-bedded in parts (Fig. 30).

Upwards through the succession quartzite pebbles become more abundant while Torridonian pebbles become smaller. The Torridonian surface rises at the north end of the outcrop, so that the lowest 12 m (40 ft) of the succession is banked against it.

The total thickness is at least 25 m (83 ft).

14. THE AULTBEA STRIP

The most northerly occurrence of the Trias in the west of Scotland is at Udrigle on the western coast of Gruinard Bay, where it is preserved in a faulted wedge extending for nearly one mile (1.6 kms) along the shore, overlying the Torridonian. After a small interval it appears again at Laide, at the northeast end of a downfaulted graben-like strip of Mesozoic rocks one mile wide, which may extend southwestwards for 4½ miles (7.2 kms) to Aultbea. The Trias also appears on the Isle of Ewe.

The rocks in the faulted strip are poorly exposed beneath a thick cover of drift and peat. The Trias is well seen on the coast at Laide, but the overlying Lias is restricted to a small patch of limestone at Sand. Inland across the neck of the peninsula and on the east side of Loch Ewe there are no exposures. Recent extensive excavations in connection with the installation of oil tanks have only uncovered Torridonian bedrock on the southeast side of the graben; within it, the drift cover is too thick.

On the Isle of Ewe the Trias is well exposed along the shore at the southeastern end of the island.

a. <u>Isle of Ewe</u>

At Na h-Uamhagan, west of Gualann Mhor, a thick succession of Trias sediments is exposed, unconformably overlying the Torridonian.

An angular breccia occurs at the base with a soft reddish calcareous matrix. Cornstone penetrates the Torridonian for up to 30 cms along joints and bedding planes. Above the breccia there is a thick sequence of rapidly alternating conglomerates, grits and sandstones which also lens and grade into each other laterally. The sandstone is coarse-grained and brick-red, and occurs in about equal proportions to the conglomerate which contains subrounded pebbles and cobble of Torridonian sandstone, orthoquartzite and grey and pink Durness limestone.

Cornstones only occur in the upper part of the succession, where they are developed at the tops of beds of brick-red gritty sandstones which rapidly alternate with thin pebble beds containing the same pebble varieties as lower in the succession. The ideal sequence in each bed is:

conglomerate ⟶ grit ⟶ coarse sandstone ⟶ coarse to medium sandstone with cornstone developed at the top

The conglomerate at the base is often missing. The top of the cornstone is sharp, the next sequence having an erosional base.

On the west coast, a little north of Gualann Mhor, there are two exposures of pink and buff sandstones and grits containing thin pebble beds. Pebbles are small and rather angular, consisting of arkosic sandstone, quartzite and limestone, with some smaller angular vein quartz pebbles. These beds probably represent a higher part of the succession.

The beds generally dip at 20° - 30° E.S.E. along the coast, and the general succession is as follows:

?	Pink and buff sandstones and grits with pebble beds.
60 m (200ft)	Brick-red sandstones, sometimes with conglomerates at the base of the beds, with cornstones developed along the upper bedding planes. (Conglomerate > Sandstone).
110 m (360ft)	Rapid alternations of conglomerate and brick-red sandstone. No cornstone. (Conglomerate = Sandstone).
7.5 m (25 ft)	Breccia of Torridonian fragments in carbonate cement.
	Torridonian

The total thickness is more than 180 m (590 ft).

b. Laide and Udrigle

From just north of the Laide fishing station to Sron a Chuirn Deirg a thick succession is exposed at intervals along the shore, the upper beds being truncated by an important fault at Poll an Eoin Mor.

The base is very well exposed, with Trias breccias covering an uneven surface of steeply dipping Torridonian sandstones; these pass up into repeated units of conglomerate and pebbly grit, each grading up into coarse brick-red sandstones. Pebbles become less abundant upwards apart from a bed of conglomerate near Udrigle House, and halfway along the section cornstones begin to occur as developments in the upper parts of the sandstones.

The conglomerates and cornstones have fairly well defined distributions (see Map 13).

At Sron a Chuirn Deirg the higher beds are pebbly grits grading up into coarse-grained micaceous sandstones and containing some thin lenses of conglomerate. The grits are red or white, the sandstones are soft and bright orange or brick-red in colour, being mottled green in patches. Pebbles are mainly of vein quartz and quartzite, but some red sandstone, limestone and mica-schist occur.

The conglomerate-grit-sandstone graded units that comprise the bulk of the succession vary in thickness from 0.6 to 7.4 m (2 to 24 ft). The grits and conglomerates have slightly uneven erosional bases which may contain fragments of reworked cornstone if there is a cornstone bed beneath. The cornstone beds probably became more rapidly indurated than the sediments in which they were developed, because there is no trace of reworked Trias sandstone which was probably poorly indurated and readily disaggregated. In the highest beds there are some horizons of mud flake pseudo-conglomerate, thin flakes of purple and brick-red shale and siltstone occurring in the bedding planes. The sandstones are sometimes very thinly cross-bedded, but this is generally rather ill-defined.

The succession is given in Fig. 152 . By the method outlined above (p. 7) it is estimated to be over 276 m (900 ft) thick which compares closely with Judd's calculation (1878, p. 690).

The main divisions are:

>135 m (450 ft)	Grits and sandstones, predominantly orange and brick-red in colour, containing scattered pebble beds and occasional lenses of conglomerate. Patchy irregular development of cornstone at the tops of sandstone beds.
102 m (240 ft)	Repeated units of conglomerate and grit with sandstone tops. Cornstones are developed in sandstone occurring in the upper 47 m (160 ft).
51 m (70 ft)	Breccia with a calcareous gritty matrix; seen in contact with the basement throughout. A little cornstone developed at the unconformity.

Torridonian

The point north of the fishing station is composed of the basal Torridonian sandstone, but immediately to the southeast, at Am Fiaclachan, more Trias sediments are downfaulted against the Torridonian. Here an angular breccia of red sandstone and orthquartzite fragments is overlain by red coarse-grained sandstones intercalated with calcareous grits and conglomerates. In the higher sandstones near the jetty cornstone is developed in the tops of the beds, becoming more abundant upwards.

These beds are overlain by one of the coarsest conglomerates of the whole area studied : large angular boulders of Torridonian sandstone (up to 50 cms maximum diameter) and grey Durness limestone (up to 28 cms) with some orthoquartzite (up to 33 cms) lie embedded in a coarse pebbly and red gritty matrix which has an abundant calcite cement.

A little beyond the waterfall, 300 yards south of the fishing station, another fault occurs, downthrowing soft brick-red coarse-grained pebbly sandstones against the conglomerate. These have a low dip, and can be followed round the shore beneath the ruined chapel, where they occur as distinct units, with conglomerate at the base of each and occasional thin red muds developed at the top. Mud flake pseudo-conglomerates and mud cracks occur (Figs 45 a&b).

Beach debris intervenes southeastwards until at Leac Dubh, on the southeast margin of the graben, the succession is again exposed beneath a thick cover of drift and raised beach deposits. Here shaly micaceous siltstones exposed on the beach have well developed cornstones developed in them at the base of the cliff, the cornstone being fairly homogeneous and occurring as rolls and nodules up to 30 cms thick. Within the siltstones are bands of compact well-sorted very thin-bedded pale buff fine-grained sandstone with parting lineation (Figs.46 a&b). Some occur infilling channels in the siltstone, being very thinly cross-bedded. Above the cornstones are coarse-grained sandstones and grits with an uneven base, containing a little detrital cornstone near the base and some irregular nodules developed within the beds, which are thick to very thick-bedded and separated by partings of purple siltstone. They are greenish, buff or grey in colour, with pinkish patches, and are at least 12 m (40 ft) thick.

A little south of Leac Dubh there is a small exposure of Lias limestone; no evidence of faulting was found in between, so the Leac Dubh sandstones are probably the uppermost Trias beds.

It is difficult to correlate the beds south of the fault at Am Fiaclachan with those of the main section. Judd (1878, p. 671 Fig. 1) drew a section showing the structure, in which certain correlations are implicit. However, the Am Fiaclachan fault is missing, and the east end of the section is rather misleading.

The angular breccia at Am Fiaclachan may be near the base, but the position of the very coarse conglomerate at the waterfall is not clear, although it is likely to be in the lower part of the succession. The brick-red pebbly sandstones in the cliffs and below the chapel at Laide can probably be correlated with those at Sron a Chuirn Deirg, while the beds at Leac Dubh clearly represent the highest part of the succession.

Adding the beds at Leac Dubh to the top of the main section, we get a thickness of Trias sediments at Gruinard Bay of 300 m, or close on 1000 feet, which is its thickest development in the Western Highlands.

15. SUMMARY

a. Stratigraphical position

1. Base: There is not a great variety of rocks underlying the Trias. In Mull, Morvern, Ardnamurchan and the south of Sleat the Trias lies on a Moine basement, except for two places in Morvern where Upper Carboniferous sediments come in between. On Skye the Torridonian forms the base of the Trias except in one locality where there is Cambrian orthoquartzite and limestone and in the south of Sleat mentioned above. The Torridonian also occurs at the base in Rhum, Scalpay, Raasay, Applecross and Wester Ross.

2. Top: In places where the Trias is complete, the top has been drawn at the junction with marine passage beds of Rhaetic or uncertain age, or with the Lias. Passage beds are patchily and unevenly developed in the area. In Western Mull they are well developed and are of undoubted

Rhaetic age. In Morvern, the shelly sandstones of Loch Aline contain a lamellibranch fauna known in the Rhaetic deposits of Wales, and although the shells do not have the zonal value of _Pteria contorta_, it is reasonable to refer the beds to the Rhaetic (Lee and Pringle 1932, pp. 169-170). By virtue of their position, the shales at Larachbeg nearby are also likely to be Rhaetic. In Ardnamurchan it is suggested that a 2 m sandstone at the top of the Trias may be correlated with the Loch Aline Rhaetic sandstone by its lithology (p. 47). The Rhum passage beds are definitely Keuper or Rhaetic and are taken as Rhaetic in this study (see p. 51).

The age of the passage beds at An Leac cannot be fixed definitely, but as on Rhum the top of the Trias is drawn at the appearance of wood fragments. In Strath, passage beds are only patchily developed. The sequence of shales, siltstones and calcareous sandstones at Heast is fairly similar to the Rhaetic of Western Mull and to a lesser extent to the Larachbeg Rhaetic, while the presence of plant remains again suggests climatic change . The limestones and shales of the overlying Lias are unfossiliferous for the first 3 m, above which _Liostrea irregularis_ appears. Hallam (1959) did not find Lias zones beneath _angulata_? and _bucklandi_ in Strath : the lowest fossiliferous beds of the Heast Lias are likely to represent one of these, with the unfossiliferous beds below possibly included with them. The passage beds beneath could then possibly represent the _planorbis_ zone or pre-_planorbis_ beds, although they have more lithological affinity with the Rhaetic.

In Raasay, possible passage beds were included by Lee in the base of the Lias (see p. 65) where the lowest zones recorded by Hallam (1959, pp. 172-173) are <u>angulata</u>? and <u>bucklandi</u>. The evidence both here and at Loch Sligachan is very inconclusive, and it is probably most reasonable to assign the passage beds in these localities to the Hettangian stage of the Lias.

The passage beds in Applecross have been referred to the Trias by earlier workers (see p. 69), but evidence presented below suggests that they are marine sediments. At the top limestone nodules are developed which coalesce into an unfossiliferous limestone bed 1 m thick which is overlain by fossiliferous sandy shales with sandstones and sandy limestones which Hallam (1959, pp. 170-171) assigned to the <u>planorbis</u> zone of the Lower Lias. Thus the passage beds and unfossiliferous limestones span the Rhaetic and pre-<u>planorbis</u> beds if present : therefore the passage beds are probably Rhaetic.

Where passage beds are not developed, the Lias overlies the Trias directly, with various zones at the base. This occurs in one part of Western Mull (Uamh nan Calman), Southeast Mull, part of Morvern, parts of Skye (Strath), possibly on Raasay, part of Applecross, and probably at Gruinard Bay.

Summary of beds overlying the Trias:

Western Mull:	Rhaetic everywhere except at Uamh nan Calman (undefined Lias).
Morvern:	Rhaetic at Loch Aline; Inninmore Bay : Lias with <u>obtusum</u> zone (MacLennan 1953, p. 453) above a slight gap.
Ardnamurchan:	Rhaetic? (Mingary) (overlain by <u>planorbis</u>? zone : Richey and Thomas 1930, pp. 37-38); north coast : Lower Sinemurian or Hettangian (op. cit. p. 40).

Rhum:	Rhaetic.
Skye:	Rhaetic? (possibly pre-<u>planorbis</u> Lias) in patches. Elsewhere : <u>angulata</u>? and <u>bucklandi</u> (Trueman 1942, p. 206, and Hallam 1959, pp. 174-177).
Raasay:	<u>angulata</u>? and <u>bucklandi</u> Lias zones (Hallam 1959, pp.172-173).
Applecross:	Rhaetic (near the lime kiln), <u>angulata</u>? (Milton).
Laide:	Doubtful, possibly Sinemurian (Phemister 1960, p. 87).

3. Age: The identification of fossils collected by Bailey (1944) from the top of the beds on Rhum has indicated a Keuper or Rhaetic age for the upper parts of the succession there. However, it is suggested above (p. 51) that the fossiliferous sequence is more likely to be Rhaetic than Keuper. It is still reasonable to refer the succession of conglomerates and sandstones lying conformably beneath these beds to the Trias, and probably to the Keuper. In Western Mull a similar succession conformably underlies proven Rhaetic strata, and may also be referred to the Trias. By comparison with these two successions outcrops of the same lithology in a similar stratigraphical position may also be of Trias age.

It is unlikely that Trias conditions could have persisted into the Rhaetic or Lias, because of the climatic change which is marked by the appearance of plant fragments in the passage beds and the disappearance of cornstones (see also Chapter X). Hallam (1959) described the loss of the lower zones of the Lias in the Skye area as accompanying a southward thinning of the Lower Broadford Beds, which he suggested were deposited in a region of variable topography, with parts of the higher ground in the southwest of Strath. This compares closely with the early Trias topography (pp. 59,214) and explains the local loss above the Trias of the lowest zones (Fig. 143).

In Morvern the absence of the Broadford Beds and part of the Pabbay Beds from beneath the upper parts of the <u>obtusum</u> zone at Inninmore has been interpreted by MacLennan (1953, p. 454) as indicating intra-Lias erosion, between the Broadford Beds and the <u>birchi</u> and <u>obtusum</u> zones, unless it is simply due to non-deposition. She postulated an unstable basin of sedimentation in the Morvern area during Mesozoic times.

b. <u>Rock types</u>

1. Conglomerates. These comprise more than half of the Trias succession almost everywhere, being particularly abundant in the lower parts. They are thick to very thick-bedded, occasionally thinly cross-bedded, and sometimes exhibit imbricate structure. There is a wide variety of pebble types and a few varieties occur almost throughout the outcrops (Table 3). At the base, pebbles tend to reflect the local pre-Trias geology. The distribution of pebble types is discussed in more detail below (pp. 212-215). The matrix is usually grit or medium to coarse-grained sandstone, with an abundant calcite matrix; it generally comprises about 10 to 30% of the rock.

2. Sandstones and grits. These are rather less abundant than the conglomerates. In the lower parts of the successions they usually occur as cross-bedded lenses in the conglomerates, but in the upper parts they are thin to very thin-bedded, often being intercalated with pebble bands. They are usually calcite cemented. Three main varieties can be distinguished in the field:

a. Feldspathic. These are usually reddish in colour, and tend to occur in the lower parts of the successions, particularly as lenses in the conglomerates. Although freak occurrences at the base of the succession on Scalpay and Raasay are difficult to distinguish from the weathered Torridonian beneath, they are usually quite distinct from the Torridonian arkoses, being fairly soft, calcareous, and less feldspathic. Colours are lighter too.

b. Quartzose. These are always pale coloured, and occur in the upper parts of the successions.

c. So-called "marls". In earlier descriptions of the West Highland Trias "marls" have been mentioned frequently. The brick-red sediments that have been given this name, are in fact very soft calcareous medium-grained sandstones. They are particularly prominent in the successions of Raasay, Applecross, Gairloch and Gruinard Bay. The mechanical size analysis of three specimens is described in Chapter VI , and the results given in Table 4a.

3. Siltstones. These are rare. Red and green micaceous flaggy siltstones occur at the top of the Trias succession at Heast, and high in the succession at Gruinard Bay. A mechanical size analysis for the latter is also given below.

4. Calcareous clays. These are true "marls" or"marlstones" (Pettijohn 1957, p. 369) and are very rare. They occur as a matrix in parts of the limestone conglomerate in the Strath Syncline and the conglomerate in south Raasay and are slightly better developed in thin beds at Loch Sligachan and Applecross.

5. Cornstones. These are very common in the Trias. Apart from their development at the basal unconformity, they are most common in the

upper parts of the successions where they form distinct beds; they also sometimes occur as nodules in the matrix of conglomerates. They are described more fully in Chapter VII .

c. Correlation and thicknesses

In attempting correlations the only reliable marker horizon is the base of the Rhaetic or other passage beds, and to a lesser extent the Lower Lias. Lithological components of most of the successions described above are not persistent when traced laterally. In Western Mull the three distinct divisions set up on Inchkenneth are still recognisable on the Mull mainland, but they are lost in Southeast Mull and Morvern. In Central Skye the division of the succession into basal conglomerates and upper grits and sandstones is only valid locally in the north and east part of the Strath Syncline : in the southwest of the Syncline conglomerate comprises the whole succession, and the two divisions give way laterally to each other. There is no trace of these divisions in Scalpay and Raasay, although a rough correlation may be made between the successions on either side of Caol Mor. The successions at Isle of Ewe and Laide are fairly closely comparable, although the upper beds are missing at Isle of Ewe. Many of the other isolated outcrops are little more than patches of conglomerate clinging to a Torridonian or Moine surface.

However, the main features of the successions which are fairly generally shown when the Trias is complete are:

1. Conglomerate at the base. Local rocks predominate in the pebbles, and cornstones are often developed at the basal unconformity.

2. Conglomerates predominate in the lower parts of the succession, accompanied by feldspathic sandstones and grits.
3. Quartzose sandstones occur in the upper parts of the succession.
4. Cornstones occur throughout, but are more common in the upper parts.

Thicknesses vary considerably, and in the southern and central parts of the area this appears to be caused by unevenness in the pre-Trias landscape. In Wester Ross the outliers at Redpoint, Gairloch and Camas Mor are incomplete, while at Isle of Ewe (also incomplete) and Gruinard Bay relatively enormous thicknesses of sediment are present.

Successions with thicknesses and attempted correlations are summarised in Figs. 151,152 .

B. PSEUDO-TRIAS

In Wester Ross the Geological Survey has mapped certain outcrops of red conglomerate as Trias (Map 12). However, these beds show several important differences from the sediments described above, and detailed mapping shows that they cannot be post-Torridonian.

1. RUBHA REIDH AND LOCH A CEANN CARNAICH

a. Rubha Reidh

On the coast 150 yards south of the lighthouse, coarse red conglomerates lie with marked unconformity on Torridonian sandstones (Fig. 31). They are banked against a slope that rises steeply eastwards, up to 200 ft above sea level. There in a crag at the roadside they are not so coarse and are evenly bedded in units 60 - 90 cms thick. These units weather differentially so that pebbles stand out slightly from the matrix. They are interbedded with 8-23 cm units of very hard deep red arkosic sandstone and evenly-weathering conglomerate which requires close inspection of a fresh surface to distinguish it from the sandstone. (Fig. 31a).

The coarse conglomerate contains boulders of Torridonian sandstone up to 1.5 m in diameter. These are embedded in a hard bright red gritty matrix (comprising 10-15% of the rock) and the bedding is massive. The thick-bedded conglomerates at the roadside contain pebbles of arkosic sandstone up to 30 cms in diameter; in the evenly-weathering thin-bedded conglomerates the pebbles seldom exceed 15 cms. The matrix is a very hard red arkosic medium to fine-grained sandstone and the pebbles are almost identical to the matrix so that it can be difficult to recognise pebbles at first glance in some of the hand specimens. The thin-bedded sandstones are also medium to fine-grained and arkosic, and some are internally laminated. They contain a few thin ($<$ 0.5 cms) bands of opaque ore.

The stream immediately to the south follows a shatter zone 6 m wide, to the south of which beds are slightly downfaulted : these have all been mapped by the Geological Survey as Torridonian, the beds described above being interpreted as Trias.

However, in the south wall of the gully cut by the sea at the mouth of the stream, the conglomerate again occurs at sea level. It is interbedded with sandstones in a 15 m sequence which <u>underlies</u> beds mapped by the Geological Survey as Torridonian.

The succession is :

-	Thin-bedded arkosic sandstones and grits containing scattered angular fragments of red arkosic sandstone. Pebbles of vein quartz and a little quartzite become commoner upwards, the beds passing into typical Torridonian sediments : very hard red arkosic sandstones with convolute bedding and thin partings of bright-red fine-grained micaceous sandstone.
4.0 m	Thin-bedded conglomerates containing pebbles of arkosic sandstone in a matrix of arkosic sandstone. Bedding is even, 30 to 60 cms thick.
5.8 m	Alternations of arkosic sandstone units (30-135 cms) and pebbly grits and conglomerates (60-150 cms). Sandstones are very hard, medium to fine-grained. Pebbles are of arkosic sandstone. All bedding is very even.
4.5 m	Thick-bedded conglomerate (part of a single unit). Fabric elements consist entirely of subangular arkosic sandstone blocks up to 60-90 cms in diameter. Ill-sorted.

Sea Level.

The unconformity may be fairly close beneath.

North of the fault the conglomerate can be traced inland for ½ mile and the position of the unconformity noted at intervals. The unconformity is angular, beds above it usually having a lower dip than those below which assists the mapping of the scattered inland outcrops. (Map 14).

On the north coast, ½ mile (0.8 km) east of the lighthouse, the unconformity is again very impressive, coarse conglomerates being banked against a steep surface of thin to thick-bedded Torridonian sandstones. The fabric elements consist entirely ~~to~~ of medium to fine-grained arkosic sandstone, in boulders up to 15 m in maximum diameter. The matrix is medium to fine-grained bright-red arkosic sandstone. (Fig. 32).

The conglomerate continues eastwards in steep sea cliffs. Here on the Geological Survey's Six Inch map the "Trias" conglomerate is recorded as "clinging to the cliffs" : in fact it is bedded in the cliff.

It is also seen in high sea stacks, where it is difficult to distinguish from sandstone beds from a distance. In one stack (next to Stac Buidhe) which is attached to the shore, the conglomerate can be followed right round the base, and is overlain by evenly thin to thick-bedded arkosic sandstones and a thick dark ore band (not accessible for measurement) which is again seen in the mainland cliff and can be used as a marker horizon for working out faulting.

In the mainland cliff the coarse massive basal conglomerate is overlain by evenly thin-bedded medium-grained chocolate and red-brown arkosic sandstones which contain scattered pebbles of red arkosic sandstone and are 10-15 m thick. They include the dark ore band which is consistently 25-30 cms thick and is split up within itself by several thin bands of arkosic sandstone. It contains mainly specularite (α haematite) and magnetite.

Evenly thick to thin-bedded conglomerates follow which are smooth-weathering in parts. They form a horizon 6 m thick, thinning eastwards to 4.5 m, which can be followed eastwards in the cliffs to the fault at Camus an Fhraoich.

Mapping was not continued east of this fault, but conglomerates interbedded with sandstones were noted in the cliffs on the south side Camas Mor.

The field evidence at Rubha Reidh indicates that the red conglomerates cannot possibly belong to the Trias. They occur stratigraphically within the Torridonian, comprising an intraformational Torridonian conglomerate.

The impressive unconformity marks an important pause in Torridonian sedimentation which has not been previously recognised in this area.

b. Loch a Ceann Carnaich

Similar rocks are exposed on the lower slopes of An Cuaidh, in the woods above Loch a Ceann Carnaich. No basal unconformity is exposed, but for 500 ft up the hillside above the loch sandstones and conglomerates are seen at intervals. The lower conglomerates are massive, but near the top of the wood there are thin-bedded alternations of conglomerate and medium-grained sandstone. The conglomerates have smoothly-weathered surfaces and are difficult to distinguish from sandstones without careful examination of fresh faces. Conglomerate predominates over sandstone.

In a small face near the top of the south end of the wood, smoothly weathering and differentially weathering conglomerates alternate. The fabric elements consist almost entirely of medium to fine-grained red or bright red arkosic sandstones; a few scattered pebbles of quartzite and deep red jasper also occur. The matrix is hard medium-grained sandstone, which in some beds is slightly softer than the pebbles, giving the differential weathering effect.

2. BADLUARACH

On the southwest side of the mouth of Little Loch Broom, red conglomerates are exposed in a coast section extending for one mile (1.6 kms) from Leac an Ime to Uamh an Oir. A little to the south they again occur at two fine inland exposures at Carn Dearg Ailein and Carn Dearg na h-Uamha.

At Uamh an Oir the unconformity is well exposed, and above it is a thick massive conglomerate with sandstone and pebbly grit fragments set in a bright red matrix of arkosic sandstone and grit (Fig. 33). Boulders are up to 4.6 m in diameter. In addition to arkosic sediments, fabric elements also include a few scattered pebbles of vein quartz, gneiss and quartzite. The matrix has pale oval or circular reduction spots (up to 2.5 cm) with green centres (up to 0.5 cm). Westwards, the conglomerate is faulted up into a knoll 50 ft above sea level.

Torridonian sandstones beneath the unconformity are exposed eastwards along the shore for 340 yards, and then the unconformity reappears. There the older Torridonian dips west at 21°, while the Pseudo-Trias is banked against a 75° slope and dips east at 22°. The Pseudo-Trias has a diachronous facies boundary, coarse conglomerates at the surface of the unconformity giving way upwards and laterally eastwards to grits and sandstones within a distance of 1 to 2 m. When corrected for the dip of the Pseudo-Trias, the plane of the unconformity dips at 50° east.

The sandstone units into which the conglomerates and grits grade are evenly thin to thick-bedded. They contain some beds of smoothly weathering conglomerate. The fabric elements are again composed of medium to fine-grained red arkosic sandstone, with a similar matrix of hard red sandstone.

The overlying beds comprise the cliffs beneath Cnoc na h-Iolaire, where they are inaccessible but appear from a distance to be evenly thin to thick-bedded and chocolate brown in colour. Sandstones and grits with conglomeratic beds of Torridonian sandstone pebbles occur at Stac Cas a Bhruic, where trough-bedding is very well developed in the sandstones.

There the beds are folded into a gentle syncline and anticline, with two small axial faults. The beds continue to Leac an Ime with little variation, being mainly medium-grained chocolate coloured sandstones containing occasional pebbles of red sandstone.

At Leac an Ime an erosional contact marks the base of overlying coarse massive conglomerates. These contain pebbles cobbles and boulders of arkosic sandstone, and there are a few rare pebbles of quartzite. The base of these conglomerates also occurs in a low knoll 200 yards to the west, and again at the very top of Cnoc nah-Iolaire.

The basal unconformity is so steep that the erosional contact overlaps it to the south, where there are two fine exposures of the base of the Pseudo-Trias. At Carn Dearg Ailean the plane of unconformity and the Pseudo-Trias dip eastwards at 45°. Beneath it, the older Torridonian dips at 13° to the northeast, while above it there is 6 m of massive conglomerate overlain by 20 m of thick to very thick-bedded conglomerates and sandstones. 600 yards (0.6 km) to the south the unconformity is again exposed beneath Carn Dearg na h-Uamha. A fault must occur between here and the previous locality, because the plane of unconformity and the Pseudo-Trias dip at 45° to the north, the older Torridonian dipping 22° northwest. The Pseudo-Trias consists of 10-12 m of very thick-bedded conglomerates containing Torridonian sandstone fragments up to 1.5 m in diameter, and occasional pebbles of Lewisian gneiss near the base.

Both the Pseudo-Trias and the older Torridonian of this area are heavily jointed, and are intruded by a 'swarm' of clastic dykes which contain medium-grained arkosic sandstone. Shearing has occurred along the unconformity at Carn Dearg na h-Uamha off-setting two clastic dykes there 35 cms and 40 cms to the west above the unconformity. A description of these dykes and a discussion of their significance is given in Appendix II.

The relationship of the dips of the Pseudo-Trias to the unconformity indicate a pre-Pseudo-Trias landscape of older Torridonian rocks having a slope dipping 50^{o} east just west of Cnoc na h-Iolaire, with a horizontal (peneplaned) surface at a higher altitude to the south.

The close similarity between the lithology and field relationships of these beds and the Rubha Reidh conglomerates and sandstones, strongly suggests that they are of the same age, i.e. Torridonian. Part of the beds along the coast, between the basal unconformity and the erosive contact, have in fact been mapped as Torridonian by the Geological Survey, although the conglomerates at Leac an Ime, Uamh an Oir and inland were referred to the Trias.

3. ACHILTIBUIE (COIGACH).

Around Rubha an Dunan the Geological Survey has marked several outcrops of Trias : at Port Mhaire, on the tip of the point, and south of Achlochan.

At Port Mhaire there is a coarse conglomerate faulted against Lewisian gneiss. It contains large boulders of fine-grained red arkosic sandstone, several of which are 2 m in diameter, the largest measuring 7.5 x 6 m. The matrix is coarse to medium-grained red arkosic sandstone comprising 10-15% of the rock. A few small pebbles of migmatitic gneiss are present. 400 yards south a conglomerate with pebbles and cobbles of red sandstone and some gneiss is exposed in a low crag above the beach.

South and southwest of Achlochan exposures of conglomerate occur along 400 yards of the coast. They overlie fine-grained red Torridonian sandstones and siltstones with marked unconformity, burying a steep rugged ancient landscape which projects through the conglomerate at two points. The conglomerate contains pebbles, cobbles and boulders of hard red fine-grained sandstone, up to 4 x 3 m in size, the largest measured having a maximum diameter of 8 m. These are mostly subangular, although some are subrounded, and are set in a matrix of coarse to medium-grained red sandstone which is gritty in parts and comprises 15-20% of the rock. The sandstone shows a tendency to be bedded, and is sometimes 'domed up' over large boulders. A few pebbles of gneiss are also present.

The conglomerates are overlain by at least 2.5 m of hard purple grits and coarse-grained sandstones which alternate with bright-red thinly laminated micaceous sandstones and siltstones containing some thin paler bands of grit. The purple grit is evenly bedded in units 5-20 cms thick and the red sandstone units are 0-20 cms thick, being cut out in places by the grit. ½ mile (0.4 km) southeast of Achlochan there are grey micaceous siltstones and shales which, assuming no faulting, are stratigraphically above the conglomerate; they are typical of Diabaig Group sediments of the type area. The conglomerate is cut by a single thin clastic dyke containing fine-grained red arkosic sandstone.

The conglomerate at Port Mhaire has been described by Gracie (1964, pp. 92-93) who compared it with the 'sedimentary breccio-conglomerate facies' developed in the Torridonian beside Enard Bay at Cnoc Mor an Rudha Bhig, on the north side of the Coigach peninsula. There he recognised one important intraformational unconformity and two marked erosional contacts within the Torridonian. The 'sedimentary breccio-conglomerate facies' is developed above the unconformity, and he suggested that it formed as a rock-slide on a steep lubricated surface. He did not record that this outcrop had been previously mapped as Trias, nor did he described the 'Trias' outcrops south of Achlochan.

At the extreme tip of Rudha an Dunan and also immediately west of Cnoc na Croiche two further outcrops previously mapped as Trias occur. These are angular breccias of Lewisian gneiss set in a gritty matrix. They appear to underlie the older Torridonian conglomerate and contain no Torridonian fragments. They can probably be assigned to the Torridonian, and certainly are not Trias.

4. SIGNIFICANCE

The field evidence given above shows that the red conglomerates at Rudha Reidh and Achiltibuie are of Torridonian age, while those at Badluarach are closely comparable. Further evidence is given below, confirming that they are not Trias.

Gracie was the first to recognise that there is an angular unconformity of regional extent within the Diabaig Group of the Torridonian in the Coigach area. It is now clear that such an unconformity not only occurs at Enard Bay and beneath Port Mhaire, but also at Achlochan, Badluarach and Rubha Reidh. This indicates an important pause in Torridonian sedimentation which was probably accompanied by a considerable time lapse.

Torridonian rocks which the Geological Survey mapped as Diabaig at Stoer and below the unconformity at Coigach, must be considerably older than those in the Diabaig type area. It is now reasonable to divide the Torridonian further into:

1. "Older Torridonian" : rocks beneath the unconformity.
2. "Younger Torridonian" : the true Diabaig + Applecross + Aultbea Groups.

However, the ages of the sedimentary boulder conglomerates may not be the same in the four localities : at Loch a Ceann Carnaich and Badluarach the occurrence of sedimentary quartzite pebbles (Fig. 72 d) suggests an Applecross age (see Peach <u>et al</u> 1910, p. 274), while the Achiltibuie (overlain by Diabaig-type sediments) and Rubha Reidh beds are probably Diabaig.

Irving and Runcorn (1958) studied the permanent magnetisation of the three divisions of the Torridonian. The Torridonian sandstone is very suitable for palaeomagnetic work, and they were able to ascertain the directions of natural remnant magnetisation of a representative selection of specimens collected over a wide area (1958, Fig. 1, p. 85). In the Aultbea and Applecross groups they found that the magnetisation is along a N.W. negative/S.E. positive axis, but in the "Diabaig" group at Achiltibuie they discovered a change from uniform N.W. magnetisation in the "basal red sandstones" to N.W.- directions in the "overlying flagstones" (1958, p. 87). The map of sampling sites and the nature of the sediments suggests that the samples were actually collected across the intra-formational unconformity at Achiltibuie. Thus the N.W.+ directions would refer to the Older Torridonian and the N.W.- directions to the true Diabaig beds. The time lapse indicated by the unconformity could account for the swing in the direction of magnetisation.

As a check for the stability of magnetisation of the Torridonian sediments, Irving and Runcorn measured the magnetisation of irregularly shaped pebbles of fine-grained Torridonian sandstone in conglomerate beds in Wester Ross, which they believed to be of New Red Sandstone age. The directions were found to be random, showing that the magnetisation of the Torridonian sandstones had become stabilised before New Red Sandstone times. However, while the conglomerates that they sampled at Isle of Ewe and Laide are Trias, the Rubha Reidh and Coigach conglomerates can now be shown to be of Torridonian age. Therefore the magnetisation became stable during Torridonian times, which makes Irving and Runcorn's work even more valid than they previously thought it to be.

It is not within the scope of this thesis to deal with the stratigraphy of the Torridonian in further detail. Future research should include a detailed revision of the stratigraphy, combined with more palaeo-magnetic work at crucial localities such as Coigach.

In the studies that follow, the properties of the Pseudo-Trias sediments are mentioned briefly in passing, and are summarised in Appendix I.

CHAPTER IV

STRUCTURE

IV STRUCTURE

A. FOLDS

Mesozoic strata are little folded in the Western Highlands and dips are generally low, with beds lying horizontal in many localities. Dips measured for the Trias generally vary between 10° and 20°, although in Southeast Mull they reach vertical in places.

A representative selection of 150 dip values taken over the entire Trias outcrops mapped gives an average of 17°. Excluding the unusually high values in Southeast Mull, the average is 13°.

Apart from tight folding at Craignure and gentle folding at Gruinard Bay, actual folds in the Trias and associated rocks were mapped in only two areas :

1. The Auchnacraig peninsula, Loch Don.
2. Strath, Skye.

1. The Auchnacraig peninsula

Here is represented part of a series of folds having arcuate axial traces which are concentric about the earlier of the two calderas of the Mull Tertiary volcano. The dominant structure in the peninsula is the Loch Don Anticline containing Dalradian limestones and phyllites in the core which are flanked successively by Old Red Sandstone volcanic rocks, Mesozoic sediments, and Tertiary lavas. The anticline is dislocated by a wrench fault set normal to the fold axis, south of which the anticline is resolved into two subsidiary folds.

The Trias is exposed along the eastern limb of the anticline, and also in small patches in the subsidiary folds to the south and in a complementary minor fold to the southwest. On the west flank of the anticline, however, Pabba Beds immediately overlie to O.R.S. lavas, cutting out both the Trias and the Broadford Beds which overlie the Trias in the eastern limb. Lee (in Lee and Bailey 1925, p. 68) suggested that part of this discontinuity may be due to faulting.

Detailed mapping by Cheeney (1962) has shown an angular discordance between the Tertiary lavas and the underlying Mesozoic beds. This suggests that two episodes of folding occurred: one before and one after the eruption of the Tertiary lavas. The discovery of a folding episode which occurred before the lavas were erupted may have some relevance to the mapping of the Trias in Western Mull if it has any regional extent. Only a slight unconformity was recognised at the base of the Tertiary there, but when it is being taken as the only stratigraphical marker horizon available the effects of an unconformity cannot be ignored. Therefore the thicknesses given in sections 151 (5) and 151 (6) can be taken only as minimum values, although they are probably fairly close to the true values.

2. Strath

The major structure involving Mesozoic strata is a syncline $1\frac{1}{2}$ miles (2.4 kms) broad, extending for 7 miles (11.2 kms) from Broadford to Rudha Suisnish. The fold axis has an arcuate trace centred on Beinn na Caillich, which is part of the eastern Red Hills Tertiary granite intrusion.

The Mesozoic rocks rest on thrust Torridonian and Cambro-Ordovician sediments. The thrusting is Caledonian and the folding of Tertiary age (Bailey 1939, p. 150), probably being a consequence of the intrusion of the Red Hills granite.

Folding in the Strath area makes an important contribution to this study by providing the only truly three-dimensional data of any of the Trias areas mapped. A scatter of outcrops is available over an area of 10 square miles (25 sq kms) which has assisted the reconstruction of the palaeogeography of the area.

B. FAULTS

Faulting has played a prominent role in the preservation of Mesozoic rocks in the West Highlands. Sediments which otherwise would have been eroded away have been preserved in blocks and wedges downfaulted into the basement rocks. Faults involved are usually high angle normal faults, with throws of up to 1000 ft and more. The most important of these are:

1. A N-S fault downthrowing Carboniferous and Mesozoic sediments against the Moine : east end of Inninmore Bay, Morvern.
2. The N.E. - S.W. Screapadal Fault downthrowing Mesozoic sediments against the Torridonian in Raasay.
3. A N.E. - S.W. fault along the River Applecross, downthrowing Mesozoic sediments against the Torridonian (possibly an off-set continuation of the Screapadal Fault), with an associated system of normal faults forming the southeast margin of the Mesozoic outcrop at Applecross.
4. The N.W. - S.E. Loch Maree Fault downthrowing the Trias to the northeast against the Torridonian at Camas Mor.
5. N.E. - S.W. faults downfaulting a graben of Mesozoic sediments into Aultbea Group sandstones of the Torridonian at Gruinard Bay.

In addition to these major faults, the Trias sediments are also affected by much minor faulting. In Mull, Morvern, Ardnamurchan, Skye and Raasay these are mostly late Tertiary normal faults of small throw with a N.W. or N.N.W. trend, indicating a relief of pressure both between N.E. and

S.W. and also along the fault lines connected with the Tertiary plutonic centres (Anderson 1942, p. 173). Such faults are particularly well-exhibited intersecting the Strath Syncline (Map 9), where most of them downthrow to the northeast.

Phemister (1960, p. 92) indicated that the main faults of the Northern Highlands have directions that bear little relation to their age. Both N.N.E. and N.W. directions have been lines of weakness in this part of the earth's crust since Archaen times, and there is evidence of movement at different geological periods along individual lines of weakness. Some faults have also moved in more than one way e.g. the Loch Maree Fault shows a horizontal displacement of 3 miles (4.8 kms) at Kinlochewe, as well as downthrowing to the southwest at Loch Maree (cf. the altitude of the base of the Torridonian on the Lewisian on either side of the Fault) and to the northeast at Camas Mor, giving a resultant 'hinge-like' movement. Such fault movements, if partly contemporaneous with the deposition of the Trias, could help to explain certain features of the Trias successions in Wester Ross (see Chapter X).

Jointing is common in the Trias sediments, and joints are often marked by conspicuous calcite veins (Figs. 37 and 38).

C. IGNEOUS INTRUSIONS

The Trias sediments are intruded by a variety of Tertiary igneous masses, the commonest of these being basic dykes of the four volcanic centres, particularly the swarms of Mull and Skye. Outcrops that do not lie on or near the strike of these swarms are generally the least intruded.

At Gruinard Bay, Isle of Ewe, Camas Mor, Big Sand (Gairloch), and Redpoint there are no intrusions in the Trias, and only two dykes, each 1.2 m thick, were mapped at Applecross. On Raasay the beds at Rudha na Leac are heavily intruded by dykes and sills, while at Eyre, on Scalpay, at Loch Sligachan, along the Strath Syncline and at An Leac dykes are common, striking N.N.W. to N.W. The Tarskavaig outlier lies in the thick of the Skye swarm and is very heavily intruded.

The Rhum swarm is not thick, but a few N.W. striking dykes intrude the Trias there. Morvern and Western Mull lie on opposite sides of the Mull swarm and are intruded by only a few basic dykes.

In Ardnamurchan and Southeast Mull heavy intrusion has occurred. There the sediments are intruded not only by dykes of the swarms, but also to an even greater extent by a wide variety of ring dykes and cone sheets associated with the volcanic centres.

In Ardnamurchan the Mesozoic sediments are intimately entangled amongst intrusions which are mostly quartz-dolerite cone sheets (Richey 1961, Plate VII) but are generally freshly preserved. Despite the intrusions, the thickness and stratigraphical position of the Trias can be quite accurately worked out.

In Southeast Mull however, as already noted (p. 32), the Mesozoic sediments fall within the zone of pneumatolysis surrounding the Mull volcano, and are considerably altered, apart from those near Loch Don. The sediments at Loch Spelve are even more intricately entangled amongst intrusions than those in Ardnamurchan, and everywhere except the Auchnacraig peninsula the Trias is intruded by both acid and basic cone sheets and basic dykes, as well as gabbros and granophyres. (See Survey Sheet 44, and Richey 1961, Plate IV).

However, apart from Southeast Mull, intrusions do not provide any great obstacle to the study of the Trias sediments of the Western Highlands.

Associated with the volcanic centres are thick lavas which have provided a protective covering for the softer sediments beneath. Areas where Mesozoic sediments particularly owe their preservation to overlying lavas are West and North Mull, Morvern, Rhum?, Skye and Raasay.

CHAPTER V

PETROGRAPHY

V PETROGRAPHY

INTRODUCTION

In this chapter the field distribution of pebbles in the conglomerates is summarised and petrographic descriptions are given of the various rock-types represented. Pebbles are compared with rocks from known formations which are believed to have provided their source.

The mineralogical content of the sandstones is investigated by modal analysis. The classification of the sandstones is based on the results of this analysis and petrographic descriptions are given of the two main sandstone classes and of some less typical sandstones.

A. CONGLOMERATES

1. FIELD ANALYSIS

The study of the petrography of conglomerates in the field involves the investigation in hand specimen of the pebbles of which they are composed. Some workers (e.g. Kelling 1961) have attempted a quantitative approach, but in order to obtain results that are statistically acceptable (Hasofer 1963, and Solomon 1963, see below, pp. 118-119) a prohibitively large area of outcrop must be analysed at any single locality.

In this investigation only a quantitative approach is attempted, although a distinction is made in the pebble distribution table (Table 3) between pebbles that are "commonly present" and those "sparsely present", these being purely descriptive terms. In Chapter III above, pebble types have been listed in their estimated order of abundance at each locality.

In the field, the following rock-types were identified as pebbles occurring in the Trias conglomerates, being tentatively assigned to the parent formations given in brackets: acid gneiss (Lewisian); arkose-gneiss, metaquartzite, quartz-mica-schist (Moine); red sandstone (Torridonian); orthoquartzite (Cambrian); limestone and dolomite (Durness Limestone); chert (Durness Limestone or unassigned); granite, granodiorite, porphyry and felsite (Old Red Sandstone igneous rocks); with vein quartz always present.

The regional distribution of these rock-types is given in Table 3 from which it can be seen that Torridonian sandstone and Cambro-Ordovician quartzite, limestone and chert are typically present in all the Trias conglomerates except those in Morvern and Ardnamurchan. Lewisian gneiss occurs only as infrequent pebbles in the central area, while Moine rocks appear to be represented spasmodically. Old Red Sandstone igneous rocks occur only in Mull (particularly in the west) and Morvern; the Pre-Cambrian igneous varieties were only recognised in thin section, and will be discussed below.

There is frequently a clear control of the pebble types by the local pre-Trias geology, particularly in the basal beds. Thus in Western Mull, abundant fragments in the basal Trias conglomerate can be clearly matched with the local Moine arkose-gneiss; in Morvern, the local psammitic and pelitic Moines comprise the bulk of the clastic debris; the Torridonian which underlies the Trias of Rhum, Skye, Scalpay, Raasay, Applecross and Wester Ross is well represented in the conglomerates in those areas, particularly near the base of the succession.

Reference has already been made to the limestone conglomerate occurring in Skye (pp. 56-57). This rock contains an abundance of limestone fragments which predominate over the other rock types, frequently comprising more than 50% of the pebbles in the conglomerate, which approaches the "calclithite" of Folk (1959). The matrix is often highly calcareous which, combined with the high content of limestone pebbles, causes the rock to weather typically into clints and grikes, producing an almost karst-like topography in places (Fig. 26). Typically associated with the limestone is orthoquartzite, which may also be present in some abundance, and chert, while vein quartz and Torridonian sandstone may occur to a lesser extent. Interstices between pebbles are filled with grit containing fragments of quartz, limestone and chert set in a calcareous matrix. The rock is usually pale cream or grey in colour, but sometimes (e.g. on the slopes of Beinn a Mheadhoin) a deep red muddy matrix occurs. The limestone conglomerate has a well-defined distribution in the Strath Syncline, which is shown in Fig.

Other conglomerates tend to be chocolate-brown to brick-red in colour, although quartzose pebble beds in the higher horizons are pale grey or buff. It is difficult to use a colour-chart accurately for defining the colour of a conglomerate, but roughly the colours vary from dark reddish brown 10 R 3/4 (e.g. Humpies Conglomerate) to light red 5 R 6/6 (e.g. Iollaich Beds), with the limestone conglomerates being medium light to medium grey N 5.5 (with a gritty matrix) or brownish grey 5 YR 4/1 (with a red mud matrix).

Conglomerate matrices are sandy or gritty with a carbonate cement, and appear to be comprised of the same materials as the pebbles. They are described under 'sandstones' below (Ik 3, Ik 7).

2. DESCRIPTION OF PEBBLES (See Figs. 53, 54, 55).

Acid gneiss: Medium to coarse-grained pink gneiss, containing abundant quartz and feldspar with accessory biotite. The feldspar is predominantly microcline, with subordinate acid plagioclase (oligoclase). The rock compares closely with descriptions of the acid varieties of Lewisian gneiss given by Teall (Raasay), Hinxman and Clough (Wester Ross), (in Peach et al. 1907).

"Exotic" igneous rocks: Rare fragments of felsite, silicified porphyry and jasper occur in the Raasay-Applecross area. These compare fairly closely with pebbles described by Teall (in Peach et al. 1907) from the Torridonian, which were assigned to a formation older than the Torridonian, of which they are now the only record. The felsites are occasionally spherulitic and are all heavily stained pink and red. The porphyries contain small quartz phenocrysts set in a matrix of fine granulo-chalcedony, while the jasper consists entirely of a fine-grained mosaic of chalcedony which is bright red in hand specimen. A comparison between a felsite pebble collected from the Trias of south Raasay and a pebble from the Applecross Group of the Torridonian in north Raasay is given in Fig. 53 a&b. These pebbles have probably been re-worked from the Torridonian.

Metamorphic rocks: a. "Arkose-gneiss": Metasediments commonly found in the southern part of the area are psammitic gneisses containing equigranular quartz and feldspar, with accessory biotite and some muscovite flakes, which usually have parallel alignment imparting a foliation to the rock. Feldspars comprise up to 20% of the rock, with potash varieties (orthoclase and microcline) predominating over plagioclase (andesine or oligoclase). Other accessories include garnet, epidote and opaque ores.

These pebbles can be matched exactly with the underlying Moine paragneiss in Mull, Morvern and Ardnamurchan. In Morvern, some of the gneiss are pelitic, with a very high content of mica, particularly biotite.

Not all the specimens contain enough feldspar to warrant the term 'arkosic' (Pettijohn 1954), but generally the tenor of feldspar is so high that the name "arkose-gneiss" as used by Bailey (see pp. 19-20) is quite appropriate. Most of the rocks have not been strongly metamorphosed, and original sedimentary textures are still apparent.

b. Metaquartzite and quartz-mica-schist: Quartzose metamorphic rocks were found at most localities. Although they are not so abundant as the arkose-gneiss in the southern part of the area they have a more widespread distribution, particularly in the upper parts of the successions.

The quartz usually occurs in a tessellate mosaic (Macgregor 1952, Pl. Vl, Fig. 1) with uniform extinction of quartz. Other specimens have sutured grain boundaries and undulose extinction of quartz, which are characteristic features of the Moine thrust belt and core schists of the Morar anticline (Macgregor 1952, Pl. Vl, Fig. 3). Optic axes of quartz grains sometimes show preferred orientation.

The metaquartzites are sometimes pure quartz mosaics, but more usually they contain accessory muscovite and biotite flakes with parallel orientation of long axes, and small amounts of potash and plagioclase feldspar which are equigranular with the quartz. In some, the mica is abundant enough to give the rock a prominent schistosity.

Arkosic sandstones: Red coarse to fine-grained sandstones and grits are present in most of the localities, medium-grained sandstone being the most common. They typically contain grains of quartz, potash feldspar and plagioclase with accessory micas and opaque ores, set in a matrix of ferric oxide and silica. The potash feldspars are microcline and orthoclase with some perthite, and the plagioclase feldspar is oligoclase. The feldspars are commonly stained red, which combined with the red dust in the matrix gives the rock its characteristic colour.

Both hand specimens and thin sections of pebbles can be matched with arkosic sandstones of the Torridonian Series of the West Highlands, as described by Peach et al (1907 : particularly Teall, p. 286), and observed by the writer in many localities. There is no doubt that the Torridonian provided the source for this material.

Orthoquartzite: These are equigranular, containing fairly well rounded quartz grains which are mostly in the diameter range 0.2 - 1.0 mm, with a few accessory flakes of muscovite and biotite and occasionally some opaque ore. Feldspar is often present, in grains of the same size as the quartz. It is represented by orthoclase and oligoclase but does not comprise more than 10-15% of the rock, being more commonly in the 5-10% range. Contacts between grains are sometimes sutured, but are more usually convexo-concave or planar. The cement is silica which is often developed in optical continuity with the quartz grains; thin films of opaque dust sometimes occur around the grains.

These pebbles compare well with the Basal Cambrian Quartzite of the Northwest Highlands (Peach <u>et al</u> 1907; Swett 1965). Swett found that the 'orthoquartzites' fell in Pettijohn's classification as follows (in order of decreasing abundance): orthoquartzite, subarkosic sandstone, arkosic sandstone. He found an increase in maturity from the base of his 'Lower member' (up to 25% feldspar, mostly about 10%) upwards into the "Pipe Rock" member' (0 to 7.7% feldspar). Therefore the pebbles may have been derived from rocks of the upper Lower member and from the "Pipe Rock" member.

Blocks of "pipe rock" contain "pipes" which measure 3-4 mm in diameter, being similar to the "small pipes" of sub-zone I (Peach <u>et al</u> 1907, pp. 366, 372-373).

<u>Limestone and dolomite:</u> A range of carbonate rocks is represented among the pebbles, many of which show evidence of diagenetic alteration. Limestones and dolomites cannot be placed in separate rock types because of the typical association of calcite and dolomite in these rocks. There is no satisfactory petrographic scheme for diagenetically altered carbonate rocks, but of the classifications suggested by Ham (1962), Folk's (1959, 1962) subdivision of limestone types is the most appropriate in this case.

The carbonate rocks include micrites, dismicrites, intramicrites, microsparites, intramicrosparites, oomicrites and pelmicrites, in that order of abundance. They show several phases of diagenesis, in which recrystallisation, dolomitisation and silicification (see below) are prominent. Algal laminations are sometimes present.

These rocks can all be matched with specimens described by Swett (1965) from the "Durness Carbonate formation" (formerly the "Calcareous Series" of the "Durness Limestone": Horne, in Peach <u>et al</u> 1907, pp. 365-366).

The source of the carbonate material has therefore been provided by this formation, but it is not possible to pick out any of the constituent limestone members as a particular source. The formation extends from Durness to Skye at the present day, and no doubt continued much further south in Trias times (see pp. 160-161).

Fossils in 'Durness Limestone' pebbles were collected by Woodward from the Trias conglomerate at Rudha na Leac on Raasay, and described by Lee (1920, p.9). They are: "<u>Dalmanella</u>?". <u>Hormotoma subangulata</u> Ulrich and Scofield, <u>Maclurea,</u> <u>Ophileta,</u> and a "rod-like organism".

In this investigation fossils were found in the carbonate pebbles on Raasay and also at two new localities in Central Skye. They include <u>Diparelasma</u>? (see Ulrich and Cooper 1938, p. 147 <u>et seq</u>.). (from Rudha na Leac), <u>Ectomaria</u> Koken (Moore 1960, p. I 291), <u>Lesueurilla</u> Koken (Moore 1960, p. I 192) and some sponge-like forms (Glen Boreraig), and an indistinct member of the Euomphalacese (Beinn a Mheadhoin). The gastropods and brachiopods are preserved in silica exhibiting "beekite" structure.

The sponge-like forms compare closely with those in an outcrop of the Strath Suardal limestone which strikes for ½ mile (0.8 km) along the hillside between Beinn and Dubhaich and the marble quarry at Kilchrist (Fig. 49a); the detailed structures in these specimens have been almost entirely destroyed by recrystallisation and it is not possible to identify them. In addition, thin siliceous rod-like remains were commonly found in carbonate pebbles throughout the outcrops from Mull to Wester Ross, being most abundant in Central Skye; they may represent tiny worm burrows.

The most probable source of the fossiliferous material is divisions V and Vl of the Durness Carbonate, which according to the Geological Survey (Peach, in Peach et al 1907, pp. 380-385) are the most fossiliferous.

The fossils are illustrated in Figs. 49-52.

Chert: Many are clearly silicified Durness Carbonates, in which original structures (ooliths, pellets, algal laminations) have been preserved in the replacing silica. Others are likely to be silicified homogeneous micrites and sparites. Some have been partly replaced by calcite or dolomite. Thus there is evidence for several diagenetic processes in the Durness Carbonates, occurring in the following order:

1. Recrystallisation.
2. Dolomitisation.
3. Silification.
4. Calcitisation and dolomitisation.

These diagenetic changes can be matched in the results of Swett (1965) who has also recognised some modifications and a possible additional stage.

The cherts appear in thin section as granulo-chalcedony, often intermixed with finer-grained areas. Occasional drusy cavities occur, lined with fibro-chalcedony which is sometimes banded to form micro-agate. The cavities are filled with quartz or sparry calcite.

Not all the cherts can be definitely assigned to the Durness Carbonate. Others may be the remnants of the silicified groundmass of igneous rocks or fragments of jasper, being Pre-Cambrian rocks re-worked from the Torridonian (see above).

Igneous rocks:

Granite: Coarse-grained, containing orthoclase, microcline, perthite, oligoclase and quartz, with a little muscovite and biotite.

Granodiorite: Medium to coarse-grained, containing phenocrysts of zoned plagioclase (andesine, with oligoclase rims). Orthoclase and a little quartz are also present, while biotite (altering to chlorite) is abundant and there is a little green hornblende, with sphene, apatite and opaque ores as accessories. The more basic cores of the plagioclases are heavily altered to calcite.

Porphyrite: Contains highly decomposed feldspar phenocrysts with a groundmass of orthoclase and some acid plagioclase, a little quartz and occasional graphic intergrowths of quartz and feldspar. Biotite (often much altered to chlorite) and muscovite are common, and opaque ores occur as accessories. The feldspar phenocrysts appear to have been acid plagioclase (andesine - oligoclase ?) originally, with some orthoclase as well.

Felsite: Fine-grained, containing abundant pink acid plagioclase and orthoclase, with a little quartz in interstices. Biotite altering to chlorite is common, with some muscovite and opaque ores.

Mica-lamprophyre: Contains a fine-grained groundmass with abundant green biotite (altering to chlorite) and also hornblende and feldspar, which may enclose badly altered phenocrysts of plagioclase (labradorite ?) or little crystals of quartz.

These igneous rocks were found only in pebbles in Western Mull, apart from the granite which also occurs in Southeast Mull and Morvern. A selection of slices of Lower Old Red Sandstone igneous rocks of those areas, kindly lent by the Geological Survey, were examined for comparison.

The granites compare favourably with the Ross of Mull and Morvern granites, although the microcline content is somewhat lower. The granodiorites are similar to the 'quartz-diorites' contained in the Ross of Mull granite (Lee and Bailey 1925, p. 47) but the sphene is not so conspicuous as that of the quartz-diorite in the Morvern granite (Lee and Bailey 1925, p. 46). The porphyrites were compared with several specimens from porphyrite sheets in Mull and Morvern, but a match was not obtained, the pebbles containing much more feldspar and less ferromagnesian minerals than the known porphyrites, appearing much pinker. These pink porphyrites may be similar to Old Red Sandstone intrusions of the adjacent mainland, as reviewed by Kynaston et al (1908), Peach et al (1909) and Richey (1938).

The mica-lamprophyres are matched with a specimen collected from the intrusive sheet of 'mica-trap' in the Moine near Eilean Dubh Cruinn (Gribun) which Bailey described among the Lower Old Red Sandstone intrusions (Lee and Bailey 1925, pp. 54-55). In the known rock, however, the feldspars are not developed in phenocrysts.

A Lower Old Red Sandstone igneous source is likely for these pebbles. Photomicrographs are given in Fig. 55 a-e.

Vein quartz: This is present in small quantities in all the conglomerates studied, but is more abundant in the pebble beds of the upper parts of the successions. In thin section it is usually polycrystalline, and constituent crystals may show even or undulose extinction. Many are strongly deformed, with flattened crystals. Its source cannot be defined as it could have been derived from any of the older metamorphic rocks of the West Highlands.

Mylonised rocks: Quartz pebbles are often banded with crush-planes containing fine-grained quartz: these may contain little 'augen' of unsheared quartz. A mylonised sandstone was collected from Scalpay : fragments of the original sandstone are contained in a very finely ground quartzose matrix which has a deep-red stain. While the mylonised quartz grains are widespread and have an undefined metamorphic source, the sandstone pebble was probably derived from the vicinity of a thrust plane such as the Moine Thrust or the Tarskavaig Thrust. (Fig. 55 f).

B. SANDSTONES.

1. MODAL ANALYSIS

The mineralogy of the sandstones was investigated quantitatively in order to:
1. attempt a classification based on mineral content,
2. determine any lateral or vertical variations in composition,

and 3. obtain information about their source.

The selection of samples for modal analysis was designed to provide a wide areal and stratigraphical representation of the Trias sandstones (see Table 1). In addition, specimens of sandstone from the Pseudo-Trias were analysed for comparison with those of the Trias and with a typical pebble of Torridonian sandstone (Gh 20a) which is enclosed in a Pseudo-Trias sandstone matrix (Gh 20b). Sandstones of the clastic dykes were also analysed. Specimens from suspected (Rhaetic) Passage Beds were investigated, and a comparison made between the suspected Carboniferous (formerly designated Trias) of Achranich (Ka 3) and a sample of the proven Carboniferous at Inninmore (In 22).

a. Method.

The thin section method of Chayes (1949) was followed, using a Swift point counter. Hasofer (1963) and Solomon (1963) have shown that there are three principal sources of error involved in modal analysis by this method:

1. operator variation;
2. determination of area by grid counting;
3. determination of volumes from areal analysis.

Although the effect of 1. is likely to be negligible, 2. and 3. may combine to give a variance, which Hasofer calculated as equal to or less than the value

$$\frac{0.44pa^3}{RA}\left[1 + 5.8\left(\frac{R}{a}\right)^3\right]$$

where A = measurement area
a = grid spacing
R = grain radius
and p = the fraction of a particular mineral in the rock.

Solomon suggested that results giving a variance equal to or less than 2 (standard deviation = 1.41) may be accepted as satisfactory.

In this study, thin sections analysed were mostly about 400 mm^2 in area. Two traverses were made per millimetre, the interval between points in each traverse being $\frac{1}{3}$ mm. 2000 points were counted in each analysis, taken over an area of 333 mm^2. With this arrangement, all variances calculated for typical mineral percentages fell within Solomon's limit.

13 components were recorded, viz. quartz, composite quartz grains, untwinned feldspar, microcline, plagioclase, metamorphic rock fragments, orthoquartzite, sandstone, limestone, igneous rock fragments, chert, accessory minerals, and matrix. Crushed vein quartz was assigned to 'composite quartz'; some difficulty arose in dealing with very fine-grained siliceous fragments which could be derived equally well from crushed vein quartz, the siliceous groundmass of igneous rocks, or chert: when uncertain, they were assigned to 'chert'. Indistinct grains were included in the 'matrix' value.

No attempt was made to distinguish between strained and unstrained quartz grains, because such a distinction is of little significance. Hansen and Borg (1962) have demonstrated that deformation lamellae may develop in quartz grains contained in a sandstone on folding, while Blatt and Christie (1963) and Conolly (1965) have confirmed that the presence or absence of undulatory extinction in quartz is of very limited usefulness in determining the provenance of sediments, and the same is true of polycrystallinity in quartz. Greensmith (1963, 1964) also noted that these distinctions do not necessarily give a direct indication of the petrography of the source rocks, although he used them with limited success in his particular study. The distinction between quartz of metamorphic origin (strained) and igneous quartz (unstrained) becomes invalid when 1. the sediment being studied has been subjected to deformation,

or 2. some of the quartz has been derived from older sedimentary formations.

The results of the analysis are given in Table 2.

b. Classification

There is no absolutely standard method of dividing ternary diagrams on which data from modal analysis is plotted. Classification schemes are commonly based on those of Pettijohn (1954) and Folk (1954). Crook (1960) has observed that the schemes of Pettijohn, Folk, and Gilbert (1955) are not validity based genetically; he expanded on the scheme of Packham (1954) which has more genetic significance.

Mineralogical classification: Here the aim is to present a descriptive classification of the sandstones. The 'QFR' diagram in Fig 73 is based on Pettijohn's (1954) classification, with the orthoquartzite field slightly modified, following Folk (1954). Composite quartz grains, orthoquartzite, metaquartzite and chert are all grouped under 'rock fragments'. 'Matrix' includes both chemical and detrital matrix, although in nearly all cases the amount of detrital matrix is negligible (Fig. 76). The Trias sandstones are scattered over the subarkose, protoquartzite and subgreywacke fields, while the limestone conglomerates form a group in the 'R' corner of the subgreywacke field. Passage Beds fall high in the subarkose, protoquartzite and subgreywacke fields, while the Torridonian, Pseudo-Trias and clastic dyke sandstones form a distinct assemblage lying mainly in the arkose field and overlapping slightly into the subarkose sector. Both the Carboniferous sandstones are protoquartzites.

However, this classification does not differentiate between Trias sandstones containing abundant composite quartz and quartzose rock fragments, and those containing unstable rock fragments. To make this distinction, the data is re-plotted in the 'QFR' diagram given in Fig. 74 . Here all the quartzose grains are grouped together under 'Q', leaving only unstable rock fragments and accessory minerals under 'R'. This gives a much truer descriptive picture of the Trias sandstones.

Fig. 75 gives the same diagram on a larger scale, with only Trias sandstones plotted. These may be divided into two main groups:

1. Quartzose sandstones: 75% quartzose fragments; 7% feldspar.
2. Feldspathic sandstones: 7% feldspar; 30% unstable rock fragments + accessories (calculated as percentages of detritals).

The 7% feldspar level is a natural point at which to divide these sediments; Folk's (1954) 'feldspathic' boundary is slightly higher, at 10%, which is also the level given by Krumbein and Sloss (1963, p. 170).

Of 37 Trias sandstones analysed, 12 are quartzose and 22 feldspathic. 3 of the remaining 6 (Ik 3, Ik 7 and Ap 12) are coarser-grained, containing 30-60% of unstable rock fragments; they were collected from the gritty matrix of conglomerates. The other 3 (Gr 44, Lb 3, Al 15) are unusual sediments and will be discussed separately.

Textural classification: Fig 76 shows a 'DCG' diagram based on data given by Pettijohn (1954, p. 304) and Crook (1960, p. 425). The

Trias sandstones all fall within the 'sandstone' field apart from two which have an unusually high detrital matrix content and fall just within the 'greywacke' field. Cornstones (see Chapter VII) fall within the 'limestone' field.

c. <u>Indices calculated from the modal data</u>:

1. Maturity index. Maturity factors in sandstones have been discussed by Pettijohn (1957, pp. 286-288).

No attempt is made here to express the maturity of the Trias sandstones in chemical terms; for mineralogical maturity the ratio quartz: other grains was chosen. It may be argued that chert should be included with quartz, but if so, there would also be a case for including composite quartz grains and other quartzose fragments as well. In any case, chert is not represented to a significant extent.

Maturity index. $M_i = \frac{\text{percent quartz}}{\text{percent other grains}}$

(Walton 1955, p. 348).

2. Total rock fragment index, $R_t = \frac{\text{percent rock fragments}}{\text{percent quartz + percent feldspar}}$

(Allen 1962, p. 669).

3. Limestone rock fragment index, R_l : This is based on the index suggested by Allen (1962, p. 673), but in addition dolomitised limestone and siliceous rock fragments that may be silicified limestone (e.g. silicified "pellet" and oolitic limestone) have been included.

$$R_l = \frac{\text{percent limestone + silicified limestone rock fragments}}{\text{percent quartz + percent feldspar}}$$

Values for these indices are included in Table

Results.

1. Maturity: 9/11 (82%) of the quartzose sandstones have $M_i > 2$; 0% have $M_i < 1$.

5/19 (26%) of the feldspathic sandstones have $M_i > 2$; 7/19 (37%) have $M_i < 1$.

Thus the quartzose sandstones show, as would be expected, a much higher degree of maturity than the feldspathic sandstones.

2. Total rock fragments: 2/11 (18%) of the quartzose sandstones have $R_t > 0.4$.

11/19 (58%) of the feldspathic sandstones have $R_t > 0.4$.

Thus the quartzose sandstones generally contain a smaller quantity of rock fragments than the feldspathic sandstones.

3. Limestone rock fragments: Most of the specimens give very low values, although some coarse-grained sandstone matrices from conglomerates (Ik 3, Ik 7, Ap 12) have $R_l = 0.4$ to 0.6. The index does however pick out the limestone conglomerates of Skye (Br 10, Br 31, Br 61 and Br 36) which have R_l values of 2.8 to 8.4.

There is a direct logarithmic relationship between M_i and R_t, which is shown in Fig. 77 , plotted on a logarithmic scale. Thus there is a decrease in the rock fragment content with increasing maturity; this holds in both the quartzose and feldspathic sandstones.

Maturity is inversely proportioned to the mean size of the sandstone grains i.e. M_i is directly proportioned to M_z (see Chapter Vl). M_i v. M_z is plotted in Fig. 79 . The reverse relationship holds between R_t and M_z. (Fig. 78).

Therefore, decreasing grain-size is accompanied by increasing maturity and decreasing rock fragment content.

2. DESCRIPTION

a. Quartzose sandstones.

These are generally moderately sorted sands, containing a predominance of quartzose minerals. Vein quartz is the most abundant, occurring in subrounded to subangular grains (Pettijohn 1957, pp. 58-59); in all the sections examined at least a few exhibit undulose extinction or strain lamellae. Composite aggregates of similar quartz grains also occur. Quartzose schist is common, with strain lamellae in constituent grains tending to be parallel. Chert is common and orthoquartzite also occurs.

Feldspars are not abundant, but occur in small amounts in all the specimens examined. Untwinned feldspar is consistently the most common : most of it is probably orthoclase which is often kaolinised and sometimes stained red; some of the more heavily altered grains may have been plagioclase originally. Perthite is sometimes present, while fairly fresh microcline is quite common. Plagioclase feldspar (oligoclase) occurs only in infrequent scattered grains which are twinned on the albite law.

Muscovite is invariably present as an accessory mineral, although it may be in very small quantity. Flakes are sometimes bent around and between the larger grains. Other accessory minerals frequently present are chlorite epidote and opaque ores, with occasionally a few scattered grains of garnet.

Apart from the rock fragments mentioned above, others are not common. Limestone is almost always absent, although some of the chert appears to be silicified limestone. In Mull a few fragments of arkose-gneiss and granodiorite occur, but are not present elsewhere, while red sandstone is not represented.

The matrix is calcite, which varies in abundance from 9.8 to 32.8%, averaging 21.5%. In the more closely packed sandstones it is granular, but generally it is crystalline with crystals up to 2.0 mm in diameter in the more loosely packed rocks, being commonly 0.1 to 0.3 mm. Several detrital grains may be enclosed within a single crystal of the matrix. Iron staining is rare, but in An 7 there are thin rims of haematite dust on the smaller detrital grains. The carbonate cement occasionally tends to corrode the detritals slightly, especially the feldspars.

b. Feldspathic sandstones.

These are also moderately sorted sediments, containing a predominance of subrounded to angular quartz grains. Feldspars are more abundant, untwinned varieties being the most common. These include orthoclase which may sometimes exhibit carlsbad twinning, while baveno twins occur more rarely. Perthite and micro-perthite are common, while microcline is often prominent in a very fresh condition, frequently being more abundant than plagioclase. The plagioclases are commonly twinned in the albite law, but combinations with pericline or carlsbad twinning also occur. Most of them are oligoclase and many are very fresh, although sericitisation has affected some. In several of the specimens examined plagioclase is rare. The potash bearing varieties dominate the feldspars throughout this class. The feldspars are generally fresher than those occurring in the quartzose sandstones.

Rock fragments usually resemble the pebbles of adjacent conglomerates and therefore often reflect the local pre-Trias geology. In Mull, fragments of arkose-gneiss are abundant, red sandstone is common, orthoquartzite, limestone, dolomite and chert are frequently present, while fragments of granite, granodiorite, felsite and porphyry also occur. Although northwards most of the igneous rock types are lost and metamorphic rocks change to more quartzose varieties in places, the other varieties are generally represented. On Raasay, scattered fragments of silicified porphyry and spherulitic felsite often occur.

Biotite and muscovite are present as accessories, with some chlorite (mainly after biotite), epidote, garnet and opaque ores.

The matrix is calcite, in all the specimens examined except Ls 3, ranging from 11.4 to 42.0% of the rock, being generally in the range 20-40% and averaging 28.6%. It is granular in only one specimen (Ik 10); in the others it is crystalline, with crystals ranging from 5 up to 5.0 mm, being generally 0.4 to 0.6 mm in diameter. Where the matrix is very coarsely crystalline (e.g. Gh 13, Gh 14, Gh 16) up to 100 grains may be embedded in a single calcite crystal, as seen in the plane of section.

Ls 3 has a matrix consisting of siliceous overgrowths on quartz grains. The grains of quartz and feldspar are well rounded and the sediment appears to be well-sorted. It is clearly distinct from the other sandstones in this class.

c. Other sandstones.

Ik 3 contains an abundance of rock fragments which match the pebbles in the Inchkenneth basal conglomerate, from which it was collected. These include arkose-gneiss, red sandstone, orthoquartzite, limestone, dolomite, chert, granite, granodiorite and porphyry. Quartz comprises 11.5% and feldspar 4.8% of the rock. The feldspars are orthoclase, microcline, perthite and andesine. There is an abundant matrix (47%) which is coarsely crystalline. Many of the fragments are coated with a thin film of deep red haematite.

Ik 7 is similar, but quartzose rock-fragments predominate over the arkose gneiss and red sandstone, and no igneous rocks are present. There is no red staining in the matrix.

Ap 12 is very similar to Ik 3, but does not contain such a variety of rock types. Red sandstone, orthoquartzite, limestone and dolomite are prominent, and chert is also present.

Gr 44 and Lb 3 are unusual in containing high percentages of detrital matrix. This consists of tiny flakes of muscovite and biotite set in a matrix of granular calcite stained red with haematite. In Gr 44 there are scattered rhombs of authigenic dolomite (6-8μ): some of these have developed within mica flakes, forcing them apart along cleavage planes producing a 'shredded' appearance (Fig. 58).

Al 15 is described in Chapter V11.

d. Colours.

The quartzose sandstones are mainly light to very light grey N 7, N 8. The feldspathic sandstones are commonly moderate to dark reddish brown 10 R 4/5, but may also be pale red S R 6/2, light olive grey 5 Y 6/1 or greenish grey 5 GY 6/1.

Red colours in the sandstones are produced mainly by red dust in the matrix and to a lesser extent by pink feldspars. Green tints reflect a high content of green biotite and chlorite.

3. AREAL AND STRATIGRAPHICAL DISTRIBUTION.

Both quartzose and feldspathic sandstones are represented throughout the area mapped. The feldspathic sandstones are more common, occurring in the lower part of the successions in Mull & Skye, throughout the succession in Raasay, Redpoint and Gairloch, and through the major part of the succession at Gruinard Bay. Soft-weathering red sandstones which could not be sectioned but in hand specimen can be seen to be feldspathic, occur in the lower part of the succession in Morvern, Ardnamurchan, Rhum and Applecross, also being prominent in the other areas. The feldspathic sandstones are typically associated with conglomerates, being interbedded with them and forming lenses within them.

Quartzose sandstones are well developed in the upper parts of the successions in Western Mull, Southeast Mull, Morvern and Ardnamurchan. On Rhum they underlie quartzose passage beds, while in the Strath Syncline there is a marked development of quartzose grits and sandstones comprising the upper 5 metres of the Trias succession below Beinn a Chairn and at Heast, and most of the succession along the remainder of the southeast limb. No truly quartzose sandstones were analysed from Raasay, but in Applecross a thin bed occurs near the top of the succession below quartzose passage beds. None was found at Redpoint or Gairloch (where only the lower part of the succession remains), but at Gruinard Bay quartzose sandstones are represented near the top of the succession at Leac Dubh. Similar sandstones occur in the upper part of the succession at Isle of Ewe, but these were not analysed. The quartzose sandstones sometimes contain pebble beds, but are not typically associated with conglomerates.

Specimens Lb 3 and Gr 44 represent rather unusual sandstones which occur as thin impersistent pockets in feldspathic sandstones and conglomerates, near the base of the succession.

Specimens Ik 3, Ik 7 and Ap 12 were collected from the matrices of conglomerates, which accounts for their high content of unstable rock fragments. In the Inchkenneth succession, Ik 3 may be regarded as the coarse-grained equivalent of Ik 5, and Ik 7 the coarse-grained equivalent of Ik 10. These specimens illustrate interesting variations in modal composition associated with change in grain-size and stratigraphical position. These variations are summarised in Fig. 80 which demonstrates the association between grain-size, maturity and rock fragment index. After an increase in maturity accompanied by decreasing grain-size and rock fragment index from the Humpies Conglomerate to the top of the Iollaich Beds, there is a return to immaturity in the conglomerates at the base of the Chapel Beds, followed by a renewed increase in maturity towards the top of the succession.

CHAPTER VI

TEXTURES

VI TEXTURES

A. GRAIN-SIZE ANALYSIS.

INTRODUCTION

Since studies by Udden (1914) and Wentworth (1931) suggested that different sedimentary environments might produce characteristic size distributions, grain-size analyses of modern and fossil sediments have been used by many workers as a guide to their environment of deposition. But in 1957 Pettijohn (p. 39) pointed out that the grain-size distribution did not yet provide a reliable guide to the origin of a sediment and should be used in conjunction with other evidence. However, recent work by Folk and Ward (1957), Mason and Folk (1958), Friedman (1961, 1962 b) and others has made grain-size distribution characteristics much more reliable criteria for distinguishing sedimentary environments.

Analyses of the grain-size distribution of sediments in this study were carried out for two purposes:

1. to provide more evidence for assessing the depositional environment

and 2. to describe more precisely the size distributions of sediments in the various lithological classes.

1. METHODS

Two methods of size analysis were used :

a. mechanical

b. thin section

a. <u>Mechnical analysis:</u> For this method a sedimentary rock must be suitable for complete disaggregation with a minimum of damage to the constituent particles. Poorly consolidated sediments may be suitable, or those containing a cement that can be leached with acid but with no primary carbonate (such as limestone fragments). In this investigation only the soft red sandstones and silts were found to be suitable. They are poorly consolidated with a carbonate cement and virtually no limestone fragments. 5 specimens were analysed from the following localities: Big Sand (Gairloch); from the pebbly base of the "red marl" at Udrigle near Laide; from the "red marl" proper; from the micaceous siltstone at Leac Dubh near Laide; and from a weathered outcrop of orange-red sandstone at Redpoint (Rp2).

Samples were crumbled gently by hand and then treated with dilute hydrochloric acid until disaggregation was complete (checked with a binocular microscope) and then washed and dried. They were sieved in a "Ro-Tap" sieve-shaker as described by Krumbein and Pettijohn (1938, pp. 139-141). The finest British Standard mesh number was 240 (aperture 63μ), and it was found necessary to wet sieve the fraction held by this mesh to ensure that all the finer particles passed through. The fraction smaller than 63 was analysed by a decantation method (Krumbein and Pettijohn 1938, pp. 147-149), using an Atterberg sedimentation cylinder and calculating the grade settled in a given time by Stokes' Law. A summary of the scheme is given with the results in Table

The grain-size distributions were plotted as cumulative curves on logarithmic v. arithmetic paper (Fig. 81), from which readings were obtained which were used to calculate the quartile measures given by Krumbein and Pettijohn (1938). Standard statistical practice is adhered to in the use of percentiles, so that for example the tenth percentile (P_{10}) is the diameter that has 10% of the distribution smaller than itself and 90% larger; for the quartiles, the smaller diameter value is taken as the first quartile, Q_1, i.e. the diameter that has 25% of the distribution smaller than itself, and the larger diameter value as the third quartile, Q_3.

$$\text{Thus} \quad Q_1 \equiv P_{25} < Q_3 \equiv P_{75}$$

The data was also plotted on arithmetical probability paper using the logarithmic phi scale (Krumbein 1938) (Fig. 82), and from these curves statistical parameters were calculated. The Inclusive Graphic Measures of Folk and Ward (1957) were used : these were developed from the moment measures suggested by Inman (1952), being designed to provide a more detailed coverage of the size distributions. They are summarised with the verbal limits set on them in Table 4c , and the results are included in Table 4b .

b. <u>Thin section analysis</u>: Bouma (1962) carried out grain-size analyses of sediments in thin section under a microscope, using an optical micrometer. However, in this study it was found more convenient to use a microprojector, as suggested by Krumbein and Pettijohn (1938) for microscopic mechanical analysis. The microprojector was arranged with a mirror reflecting the projection of the image magnified exactly one hundred times onto a horizontal plane. In each slide the apparent long axes of 250 grains were measured: these were selected by means of a Swift point counter, using a sampling grid designed to cover at least 75% of the section. The maximum diameter of the grain occurring at the intersection of the cross wires was taken in each case, but when this coincided with the cement or an indistinct grain, the grain nearest the centre was measured. It was not found possible to measure grains smaller than 10μ: these were assigned to a "matrix" value in the few specimens in which they occurred. Cement and micas were ignored. Thus following Kelling (1961) and others, 10μ was taken as the grain-matrix boundary, although Spencer (1963) has suggested that 30μ might be more logical.

Most of the sediments proved unsuitable for mechanical analysis and so had to be analysed by this method. Specimens analysed included 12 quartzose sandstones, 19 feldspathic sandstones, 7 miscellaneous Trias sediments, one Carboniferous sandstone from Inninmore and the suggested Carboniferous sandstone from Achranich, a Torridonian sandstone pebble, 9 Pseudo-Trias sandstones and 4 clastic dyke sandstones. Specimens from 3 sandstones of known eolian origin were analysed for comparison.

The measurements were plotted on probability paper using the phi scale which was preferred to an arithmetic scale since it yielded straighter curves. A comparison of results given by the two scales is shown in Fig. Statistical parameters were calculated as Inclusive Graphic Measures.

c. Comparison between the methods: The analysis of a sediment by both sieve and thin section methods does not produce identical results. Many attempts have been made to find correction factors which would bring the results of the two techniques into agreement. The approach has usually been mathematically based, such as the work of Krumbein (1935), Rittenhouse (1941), Greenman (1951 a and b) and Packham (1955). However, Rosenfeld Jacobsen and Ferm (1953) considered all the theoretical factors that might contribute to the descrepancies, and showed that the theoretical approach had proved unsuccessful. Instead, they obtained analytically derived correction factors which demonstrated that no constant relationship between the two techniques could be recognised generally, an empirically derived correction factor being valid only within the study from which it was obtained.

Friedman (1958) also used analytical approach to attempt to establish a correlation between the two methods. From his results he designed a graph paper on which a sieve-size cumulative frequency curve could be constructed from thin section data, or vice-versa, without mathematical conversion. He also (1962a) demonstrated a linear relationship between the mean grain-size for sieving and for thin section analysis. However, as Van der Plas (1965) has pointed out, Friedman's samples were restricted to sediments with characteristics in common (well sorted, unimodal, quartzose) and therefore his conversion graph paper can only be applied validly to similar sediments. It cannot be applied successfully to sediments which have been subjected to mixing, truncation, or other complications, or those with different mineralogical constitutions.

Few of the sediments analysed in this study compare in all respects with Friedman's, so as there is no other satisfactory method of conversion, data from both methods are left unconverted.

But Rosenfeld Jacobsen and Ferm's (1953) results show that

1. thin section techniques tend to give coarser sizes than sieving

and 2. cumulative curves obtained by both techniques are generally parallel to one another.

Therefore comparisons between the characteristics of curves determined from thin section analysis and those from mechanical analysis are valid, although mean sizes are not precisely comparable.

In this study only one rock (Rp2) was suitable for both mechanical and thin section analysis. No investigation was made of the relationship between the two results because evidence from one specimen alone would be of little value, and besides which the analyses were not made on the same specimen of the rock.

2. MECHANICAL ANALYSIS

Cumulative curves for the size distributions of the five samples are given in Fig. 81, plotted on a logarithmic scale on arithmetic paper. The pebbly base of the Laide "red marl" has a bimodal distribution, with gravel comprising nearly 22% and only 2% in the silt grade; it should be more accurately described as a pebbly sandstone, while the "red marl" proper has 85% of its distribution in the medium and fine sand grades. The Gairloch sandstone has 4% gravel and 92% in the sand grades, and the Redpoint sandstone has 87% of sand and 13% of silt. The Leac Dubh siltstone has 33% of sand (only 1% coarse sand) and the remainder is silt.

In Fig. 82 the distributions are plotted on a logarithmic scale on arithmetical probability paper. This accentuates features of the distribution that were not apparent in Fig. 81. The Laide pebbly sandstone is again clearly bimodal, while the Gairloch sandstone is also slightly bimodal. These are comparable with some of the bimodal populations sampled from a river bar by Folk and Ward (1957). The Laide sandstone proper and the Leac Dubh siltstone have approximately log normal distributions, but the Redpoint sands shows a marked deficiency in the 1.5 to 3 Ø (355 to 125 μ) grades.

The size distributions of the Laide and Gairloch sandstones are similar to those found in modern river bed sands by Doeglas (1946), Bull (1963), Nordin and Beverage (1965) and others. They tend to show slightly larger grain-sizes than their possible modern counterparts, a feature observed by Friedman (1962 b) and Schock (1965) in fossil fluviatile sediments. Cumulative curves constructed from data given by Nordin and Beverage (1965) are shown in Fig. 83.

The Leac Dubh siltstone has a size distribution similar to those of modern alluvial silts (Doeglas 1946, 1962; Fisk 1951). It is unlikely to represent loess, in which at least 50% of the distribution must fall between 0.01 and 0.05 mm (Russell 1944, Swineford and Frye 1945, Péwé 1951).

The deficiency in the 1.5 to 3.0 Ø grades of the Redpoint sandstone may be connected with the observation of Udden (1914) that wind-blown sediments seem to show a deficiency in the $\frac{1}{8}$ to $\frac{1}{16}$ mm (3 to 4.5 Ø) grades, although only 77% of the size distribution falls between $\frac{1}{2}$ and $\frac{1}{8}$ mm (Udden, 1898, found over 30% of dune particles within this range), and the quartile sorting (So) is 1.99 which is just outside the normal dune sand range found by Bagnold (1935).

In Fig. 84 the size distributions of these sediments is compared with those of the deposits of six modern flood plains (Wolman and Leopold 1957). They all fall within the range of the Connecticut River flood deposits, but only the Leac Dubh siltstone approaches the fine grain-size of the sediments of the other five flood plains. The sandstones fall too near the apex of the diagram for a comparison with the Connecticut deposits to be significant.

The moment parameters (Table 4b) show that the sediments have the following characteristics:

Laide "red marl" pebbly base:	Coarse-grained sandstone. No other moment parameters could be calculated owing to the lack of a Ø5 value.
Laide "red marl" proper:	Moderately sorted, nearly symmetrical skewed, mesokurtic, medium-grained sandstone.
Gairloch sandstone:	Moderately sorted, nearly symmetrical-skewed, mesokurtic, medium-grained sandstone.
Redpoint sand:	Moderately sorted, positive skewed, leptokurtic, medium-grained sandstone.
Leac Dubh siltstone:	Moderately sorted, negative-skewed, mesokurtic siltstone.

The Laide pebbly sandstone has a much stronger geometric quartile skewness (Sk_g) than the others. It also shows a poorer quartile sorting (So) and a lower arithmetical quartile kurtosis (Kq_a) (Table 4b).

There are not enough samples for an investigation of the relationship between parameters to be significant, but plots of skewness against standard deviation (moment measures) are included in Fig. 94 .

3. THIN SECTION ANALYSIS

a. Trias sediments.

Size distributions are plotted on arithmetical probability paper using the phi scale in Figs.87-89 . Nearly all the Trias sediments have log normal curves. This may be partly explained by the thin section analysis technique, with which it is not possible to sample such a wide range of populations as in mechanical analysis because it is not practicable to include particles larger than 4 mm. Therefore only granules, sand, silt and clay are included, the clays being grouped together as detrital matrix. Thus many of the sands might have given bimodal results comparable with those of Folk and Ward (1957) had it been possible to include pebbles from the same beds.

Spencer (1963) has suggested that all clastic sediments are essentially mixtures of three or less fundamental populations, each with a log normal grain-size distribution. These are:

1. "Gravel", with a median of -3.5 to -2 ∅ units and a standard deviation of 1.0 to 2.0 ∅ units.
2. "Sand", with a median of 1.5 to 4 ∅ units and a standard deviation of 0.4 to 1.0 ∅ units.
3. "Clay", with a median of 7 to 9 ∅ units and a standard deviation of 2.0 to 3.0 ∅ units.

Most of the size distributions of the Trias sediments obtained by the thin section method contain only 'sand' populations, although in some there are characteristics of the 'gravel' population present as well. Only in the siltstones are populations finer than sand grade represented to any great extent, and in only two (Sl 4 and Sl 7) is the clay population present. In Fig. 89 , Sl 7 shows a non-log normal distribution, and although the 'sand' population of Sl 4 is log normal, as would be expected, the presence of 15% detrital (clay) matrix makes its overall distribution non-log normal.

The almost complete lack of two of these three populations has therefore contributed largely towards the log normality of the size distributions. In some, the gravel representation may have been excluded by the method, but in all except the two mentioned above the clay population is absent.

Log normality itself is not of great environmental significance in a sediment. Many sediments from most environments are log normal, which was one reason why Krumbein (1938) first introduced the phi scale. But there seems to be a tendency for finer-grained sediments to be arithmetically normal instead, so that some of the earlier workers (e.g. Doeglas and Smithuyzen 1941, Doeglas 1946, 1947) plotted their results for such sediments on an arithmetic scale which gave much straighter curves than the phi scale.

Doeglas (1946) studied the differentiation of transported detritus which he suggested could produce three types of size frequency distribution, each independent of size, which he termed "R- , S- , and T- distributions" (Fig. 90). Comparison with his diagrams suggests that the Trias sandstones consist of both "R" and "S" distributions together. If these two are combined and the 'tail' of "R" coarser than 4.0 mm removed (not sampled in thin section), the resulting distribution gives a curve which is log normal, producing a straight line when re-plotted on a logarithmic scale. "R" distributions are typically produced by strong continuous currents and "S" distributions by currents of decreasing down-stream capacity, while "R+S" mixtures are associated with running water of varying velocities. "T" distributions are suspensions.

This suggests that the Trias sandstones have formed as sediments deposited by continuous currents with intermittent variations in velocity, from which finer-grained material (in this case particles smaller than 4-5 Ø) has been removed in suspension. This co-incides with the observations of Hjülstrom (1935, 1939) Inman (1949) and Sundborg (1956) who have shown that grain sizes greater than 0.2 mm (c. 5.7 Ø) tend to be transported as bed load, and those smaller than approximately 0.2 mm as suspended load. The same applies to the results of the mechanical analysis.

The most likely environment is river beds, although strong marine currents and wave action could also produce "R+S" distributions (Doeglas 1946).

The moment parameters of the size distributions are given in Table 4d . The main features are as follows (values in Ø units):

Quartzose sandstones.

M_z = range 0.65 to 2.72, average 1.78.

σ_I = range 0.27 to 1.25, average 0.72.

Sk_I = range +0.27 to -0.20.

K_G' = range 0.47 to 0.60.

Feldspathic sandstones.

M_z = range 0.54 to 2.55, average 1.43.

σ_I = range 0.33 to 0.88, average 0.69.

Sk_I = range +0.13 to -0.11.

K'_G = range 0.45 to 0.53.

There is little difference between the properties of the two sandstone classes. The only possible difference is in the mean sizes, the feldspathic sandstones appearing to be a little coarser (i.e. lower M_z) than the quartzose sandstones. However, the two M_z populations were compared statistically, giving the standard error of difference = 0.69 and the difference between sample means = 0.35, so that the latter is not significant.

Relationships between size parameters:

1. Mean Size v. Standard Deviation (Sorting) (Fig. 91). There is a linear relationship, the sorting improving with decreasing grain-size (i.e. σ_I decreases with increasing M_z). Although there are two samples in the silt grade, this relationship is only fully tested in the sand grades. Griffiths (1951) suggested that in water deposited sediments size varies with sorting over the range 0 to 6 ∅. He found the best sorting in the 2 to 5 ∅ range, the sorting becoming poorer in both directions away from the fine sand grade (2 to 3 ∅). The best sorting in the Trias sediments is in the medium to fine sand grades (1 to 3 ∅), but although the regression line descends through the silt grade, the two silts analysed show moderate and poor sorting. Sorting is also poorer in the coarse sand grade, and the repression line calculated for the whole diagram may not be an accurate indication of more detailed trends.

Folk and Ward (1957) found the best sorting in their river bar sediments in the fine-grained sands (moderately to well sorted), with a progressive deterioration through the medium and coarse-grained sands. Their analyses do not include grades much smaller than 3 ∅, but their trend line is drawn rising again in the finer grades. Friedman (1962 b) has also shown that coarse-grained sand sediments ($<$1 ∅) are more poorly sorted than medium to fine and very fine-grained sands from the same environment.

The Trias sandstones are closely comparable with Folk and Ward's results over the same size range, and also tend to confirm the observations of Griffiths (1951) and Friedman (1962 b).

Friedman (1962 b) has made empirical correlations of the sorting measures of Trask (1932), Inman (1952) and Folk and Ward (1957) with the standard deviation. He found Folk and Ward's measures to be satisfactory over the entire range of sorting characteristics, while the others are of only limited value.

2. Mean Size v. Skewness (Fig. 92). The regression line equation $Sk_I = +0.04 + 0$ demonstrates that there is no relationship between these two parameters within the mean size range analysed in the Trias sediments. Most of the size distribution curves in all the grades analysed are nearly symmetrical-skewed or actually symmetrical, with little departure from the normal curve. Folk and Ward found symmetrical curves only when the pure sand mode occurred by itself (mean size 2.5 ∅). The whole range of mean size values from -3 to 3 ∅ gave a sinusoidal trend for the skewness values which were very positive-skewed in the -3 to -1.5 ∅ range, and very

negative-skewed from 0-2 ∅.

3. Mean Size v. Kurtosis (Fig 92). There is only a very slight relationship between these parameters, the regression line having a slight gradient indicating that size distributions become rather more leptokurtic with increasing grain-size. However, most of the samples are mesokurtic. Folk and Ward recorded the same tendency much more strongly in the 1 to 2 ∅ grade, but generally their trend is complex.

This result has no significance in the evaluation of the sedimentary environment because kurtosis is not environment sensitive (Friedman 1961, p. 524). Kurtosis is not investigated further here.

4. Standard Deviation v. Skewness. (Fig. 93). There is a linear trend from positive skewness in well sorted sediments to negative skewness in the poorly sorted ones.

Friedman (1961) has demonstrated that river sands can be distinguished from beach sands on the basis of a comparison between these two parameters. Fig. 94 gives the plots of all the Trias sediments, including those mechanically analysed. These are superimposed on Friedman's diagram (1961 Fig. 4, p. 520), which is based on analyses of 60 beach and 40 river sands and shows that beach sands tend to be better sorted than river sands, thus having lower numerical standard deviation values. The diagram also shows that beach sands tend to be negative-skewed and river sands positive-skewed. [In this diagram the standard deviation is used instead of the inclusive graphic standard deviation employed in this study, but there is a very close correlation between the two values (Friedman 1962 b Fig. 7 p. 747). Friedman's skewness values are close to 10 x Inclusive Graphic Skewness._7

Of 41 Trias sediments plotted, 40 fall in the 'river sand' field, which confirms that the Trias sandstones and silts are of fluviatile origin.

Plots of skewness against other parameters did not provide Friedman with a good separation between the fields of different sedimentary environments.

Not enough sands of possible eolian origin were analysed to enable a significant comparison to be made between them and the fluviatile sands on the basis of size distribution parameter relationships.

Samples of both the quartzose and feldspathic sandstone classes show very similar characteristics in their grain-size distributions and the parameters derived from them. They have been deposited in similar sedimentary environments, according to this evidence, and the differences in their mineralogical content are therefore likely to reflect different source rocks rather than different modes of deposition.

b. Other sediments.

Specimen Ls 3 has been noted as distinct from the other feldspathic sandstones (pp.126-127). The high degree of rounding, siliceous cement as overgrowths on quartz crystals and comparatively high feldspar content (20.8% of the detritals) suggest a possible eolian origin. In Rp 2 the grains are also well rounded and the total feldspar comprises 14.7% of the detritals. The grain-size distribution of these two sandstones was compared with those measured from three fossil sands of known eolian origin.

The sandstones chosen are:

1. Penrith Sandstone(Permian).
2. Mauchline Sandstone (Carboniferous).
3. Cutties Hillock Sandstone, Elgin (Permian).

The cumulative curves are given in Fig.95 and the inter-relations of the parameters of the eolian sands are included in Figs.101-103 The characteristics of the sandstones are:

Penrith Sandstone:	Well sorted, very positive-skewed, leptokurtic coarse-grained sandstone.
Mauchline Sandstone:	Well sorted, positive-skewed, leptokurtic, medium-grained sandstone.
Cutties Hillock Sandstone:	Moderately sorted, negative-skewed, leptokurtic, fine-grained sandstone.
Ls 3 :	Moderately sorted, positive-skewed, mesokurtic, medium-grained sandstone.
Rp 2 :	Moderately sorted, nearly symmetrical-skewed, mesokurtic, medium-grained sandstone.

Because of the small number of known sandstones sampled, this comparison cannot be taken as conclusive, but it does suggest the following features in fossil wind-blown sands:

1. Moderate to good sorting
2. Positive or negative skewness [Bagnold (1941) showed that wind-blown sediments can be quite strongly skewed, and Friedman (1961) demonstrated predominant positive skewness in modern dune sands].
3. Leptokurtosis.

Ls 3 satisfies two of these possible conditions and Rp 2 only one, while because of its skewness the curve of Ls 3 is more similar to those of the known sands than is that of Rp 2.

Passage Beds: These are all fine-grained sandstones and siltstones. Their curves are not closely log normal (Fig. 97) and all but one are positive-skewed. In these respects they are distinct from the Trias sandstones, although they have similar kurtosis values.

Carboniferous: The cumulative size-distribution curves of Ka 3 and In 15 fall close together, although In 15 departs slightly from log normality. They have similar parameter values.

Pseudo-Trias, Torridonian and clastic dykes: Features of the size distributions of these sandstones are summarised in the Appendices.

Plots of the parametral relationships of non-Trias sediments are given in Figs. 101-103.

B. PACKING ANALYSIS

INTRODUCTION

The quantitative study of packing and porosity in sandy sediments has been developed by Taylor (1950), Gaither (1953), and Kahn (1956 a and b), and applied to textural problems by Thompson (1959), Siever (1959), Allen (1962) and others.

Kahn (1956a) introduced two measures of packing:

1. Packing proximity (P_p) : the number of grain to grain contacts, expressed as a percentage.
2. Packing density (P_d) : the space occupied by the grains, expressed as a percentage.

Allen (1962) used the volume of cement and the average number of grain to grain contacts per grain as measures of packing and porosity.

1. METHOD

A modification of Kahn's (1956a) method was used. Instead of using a microscope and optical micrometer as he suggested, it is very much quicker and easier to use a microprojector, arranged as described above for thin section size analysis (pp. 133-134). A fixed stage wired up to a point-counter is again used, and the sampling grit designed to cover at least 75% of the slide in a series of traverses.

In this case the section moved from north to south across the field of view, so that all the grains occurring along the N-S cross-wire were examined. The nature of the contact of the proximal boundary of each grain at its intersection with the cross-wire was noted : in this study it was one of two types : grain to grain, or grain to cement. The number and type of grain contacts and the lengths of grain intercepts on the cross-wire were recorded. Direct measurement of the projected image avoids the tedious adjustments that Kahn described.

Thus $P_p = \frac{q}{n} \times 100$ where n = total number of contacts examined (one contact per grain)

q = total number of grains to grain contacts.

$P_d = \frac{m \sum_{i=1}^{n} g_i}{t} \times 100$ where g_i = intercept size of the ith grain

n = number of grains

t = total length of traverses

m = magnification correction

Simultaneously with these measurements the total number of grain-grain contacts of each grain examined were noted. This gives an average value for all the grains examined, which is referred to as Gc/g.

Representative specimens were selected from the two main classes of Trias sandstones and also from the other miscellaneous sediments studied. Kahn (1956b) demonstrated a direct relationship between packing proximity and packing density, so the latter value, which is rather slower to determine, was only obtained for five specimens. The values obtained are given in Table 5.

2. RESULTS

In Fig. 104 packing proximity is plotted against average grain-grain contacts per grain. This gives a clear separation of the sandstone classes, with the Trias feldspathic sandstone showing poorer packing than the quartzose sandstones. The two Carboniferous sandstones fall close together, while the Pseudo-Trias, Torridonian, and clastic dyke sandstones have high packing values.

The relationship between these two values has not been investigated before and so was examined statistically. A very high positive correlation exists between them (the product moment correlation coefficient 'r' = +0.91). Applying Student's 't' test, the result falls well within the 0.1% level, which is very highly significant.

Fig. 105 shows packing proximity plotted against cement. A similar separation of the sandstones occurs, but although a regression line has been calculated this gives a very low degree of negative correlation (r = -0.28), while applying Student's 't' test the result falls just outside the 5% level and is therefore unlikely to be significant. This linear relationship is also unnatural, because when cement is absent (0%) grains must be in complete mutual contact (i.e. perfectly packed) and therefore the packing proximity value should be 100. A logarithmic relationship is more likely, and a suggested curve is indicated by a broken line.

The five determinations of packing density are plotted against the relevant packing proximities in Fig. 106 There is a very high positive correlation ($r = + 0.97$) and the 't' test shows the result to be highly significant (just within the 0.1% level). This is similar to Kahn's result (1956b, Fig. 9, p. 594) and confirms that either P_p or P_d can be used as a valid measure of packing, with Gc/G as a further alternative.

3. CONCLUSIONS

The quartzose Trias sandstones show distinctly better packing than the feldspathic sandstones. The maximum volume of cement can probably be taken as approximately equal to the porosity of the original deposits, the packing values (P_p, P_d and Gc/g) being related to the degree of subsequent compaction.

In the feldspathic sandstones the very high porosity and low packing values suggest that deposition was very rapidly followed by cementation, the sand being little compacted. Gaither (1953, p. 181) estimated that in a freshly deposited sand the number of (grain-grain) contacts per grain would average 0.85, which is close to the values for half of the feldspathic sandstones. The quartzose sandstones have closer packing, with a consequent reduction in the volume of voids available to cementation. They have been gradually reduced in volume under compactional loading, not being cemented so soon after deposition as were the feldspathic sandstones.

The depositional porosity of well sorted sands with normally shaped particles varies from 35 to 45% (Allen 1962, p. 679). Assuming a depositional porosity of 40% for the Trias sandstones, the feldspathic sandstones (with one exception) have undergone little or no compaction, while the quartzose sandstones have been compacted to 85 to 70% of their original volume since deposition.

C. SHAPE OF PARTICLES

1. PEBBLES

Estimations of pebble roundness were made by comparing field photographs with the visual roundness chart of Dmitriev et al (1962) which is more detailed than that of Krumbein (1941, Plate 1).

Values in the basal conglomerates tend to be low (0.11 to 0.20 for Moine, Torridonian and quartzite; 0.50 for limestone), but in conglomerates higher in the succession there is a higher degree of rounding (up to 0.25 for Moine, 0.40 for quartzite, 0.55 for Torridonian and 0.60 for limestone). In the quartzose pebble beds of the upper parts of the successions meta-quartzite, mica-schist and vein quartz attain roundness of 0.55 to 0.60.

Maximum diameters of pebbles do not vary significantly throughout the area. The largest boulders are usually of orthoquartzite (up to 30-40 cms) and limestone (20-30 cms), while Torridonian sandstone fragments are usually smaller (15-25 cms) although in Wester Ross boulders of red sandstones more than 50 cms in diameter were measured. Pebbles show a marked decrease in size upwards through the successions. Conglomerate beds are typical of the lower parts of most of the sequences described in Chapter III, while in quartzose pebble beds higher in the successions, pebbles attain sizes of only 2 to 4 cms. Pebble sizes are examined in more detail below (pp. 213-215).

2. SAND GRAINS

Sand grains were compared in thin section with the roundness chart of Dmitriev et al (1962). Estimated values for the two main classes of Trias sandstone are:

Quartzose sandstones : range 0.15 to 0.30, average 0.23.
Feldspathic sandstones : range 0.16 to 0.50, average 0.30.

Feldspathic sandstones appear to show more rounding, but the difference is not significant.

Grain roundness is plotted against mean size in Fig. 107 Grains are poorly rounded in the finer grained sandstones, but roundness increases with increasing grain-size. The same relationship was found by Sorby (1880), Wadell (1935), MacCarthy (1935), Russell and Taylor (1937), Pettijohn and Lundahl (1943), and Allen (1962) in sand sized grains from eolian, fluviatile and beach environments. Bluck (1965) found that particles <6.8 cm had decreasing sphericity values with increasing distance from the source, but that the reverse relationship was true for particles >6.8 cm. Sneed and Folk (1958) also found increasing sphericity with decreasing size in pebbles. However, the relationship established for the sandstones is quite usual, and does not appear to be environment sensitive.

Moss (1962) claimed that plots of shape functions against length of sand grains can provide a distinction between wind-lain and water-lain sands. He found that all the fossil sediments he studied fell into one or another of the categories that he identified from modern sediments.

An attempt was made to apply Moss' method to sand grains of sample Rp 2. Following Moss, the length (p), breadth (q) and 'depth' (r) of grains larger than 0.1 mm were measured under a microscope, using an optical micrometer for p and q and a calibrated focussing device for the 'depth' (i.e. the maximum thickness of the grain in its most stable position, determined by focussing on the top of the grain and then on a ground glass plate on which it rests). With practice, 25 grains could be measured in one hour, so to accumulate the number of measurements that Moss used (up to 1850, mostly 500-600 per sample) several days would be required for each specimen. In this case only 260 grains were measured, and the computation of results was found to take almost as long as the measurements.

This result obtained is inconclusive. Fig. 108 shows the plots of p/q (the elongation function) against p, which is perhaps more similar to Moss' curves for water-lain sands than it is to his results for eolian sands. A plot of pqr against p was not attempted.

The obvious disadvantage of this method is that it is very time-consuming. It is suggested that studies of sand grain morphology in the future should not concentrate on the general morphology of the grains but rather on surface textures. A valuable new technique for the examination of sand grain surfaces has been developed recently by Krinsley and Takahashi (1962 a and b), Porter (1962) and Kahle and Turner (1964). Using an electron microscope they have shown that different environments can be recognised from characteristic patterns on grain surfaces. This has already been applied successfully by Krinsley and Funnell (1965) and Waugh (1965), and no doubt soon it will become more widely used by sedimentologists. A study of sand grains from the West Highland Trias with an electron microscope would be interesting.

D. MORPHOLOGY OF LIMESTONE PEBBLES

INTRODUCTION

Measurements were made of a suite of limestone pebbles in order to compare their characteristics with those of pebbles from known sedimentary environments, and also with those used in experimental abrasion studies. Of the three main pebbles types represented in the Trias conglomerates, limestone was chosen in preference to arkosic sandstone or quartzite because there is little data available for comparison with the characteristics of the latter two types.

For use in these studies, pebbles must be well preserved and yet easy to prise undamaged from the matrix of the conglomerate. Many of the conglomerates mapped are fairly well indurated and tend to split across the fabric elements when struck; the most suitable suite of pebbles was found in the basal conglomerate of Gribun and Inchkenneth in Western Mull. Those pebbles that were easiest to collect had usually been subjected to a considerable degree of weathering and were therefore unsuitable, while unweathered pebbles were firmly held in the conglomerate. Only a limited number were found that could be recovered whole and in a good state of preservation. These were collected and measured in the laboratory.

1. METHOD

The most unambiguous method of measuring pebbles has been given by Krumbein (1941, pp. 65-66), who selected measurements as follows:

1. In the plane of maximum projection of the pebble:
   a. the long axis (a),
   and b. the intermediate axis (b).
2. With the plane of maximum projection in a vertical position, the widest part of the pebble in the horizontal plane is measured, perpendicular to the long axis (c) (Fig. 109).

Work on the study of pebble shapes (rounding, sphericity and flattening) falls mainly into two groups:

1. the French school, under the lead of M.A. Cailleux,
and 2. the school of Wentworth (1922), Wadell (1935), and Krumbein (1941).

Methods used are similar, but those of the latter school tend to be more precise and consequently more elaborate and lengthy to perform. The measures used here are:

a. Sphericity : This may be obtained by plotting b/a against c/b as suggested by Krumbein (1941 Fig. 65, p. 68).

b. Shape : The classification of Zingg (1935) is used. It is :

Class No.	b/a	c/b	Shape
I	$> 2/3$	$< 2/3$	Oblate/tabular/discoidal
II	$> 2/3$	$> 2/3$	Equiaxial/equant/spherical
III	$< 2/3$	$< 2/3$	Triaxial/bladed
IV	$< 2/3$	$> 2/3$	Prolate/rod-shaped.

These results can be read directly off the sphericity scatter diagram.

c. Roundness: Wadell (1935) suggested a very precise method for measuring pebble roundness, which he defined as the average radius of curvature of the corners of the maximum projection of the grain image, divided by the radius of the maximum inscribed circle. However, a similar method has been introduced by Bouillet and Cailleux (1947, 1949) and used subsequently by Cailleux (1952) which is much quicker to operate than Wadell's method although it is not quite so precise : this method has been used in this study. "Cailleux's roundness index" (Rc) is obtained by measuring the radius of the arc fitting the corner with sharpest contour (r_1) and comparing it with the length of the long axis of the pebble (L) thus:

$$Rc = \frac{2r_1}{L}$$

Van Andel, Wiggens and Maarleveld (1954) noted that Cailleux's index contains elements of phericity as well as of roundness. To overcome this, Kuenen (1956) suggested a variation involving the use of 'l', the largest diameter at right angles to 'L', instead of 'L' itself. This gives "Kuenen's roundness index":

$$Rk = \frac{2r_1}{l}$$

Kuenen compared the results obtained by his method with those obtained by Cailleux's, and showed that Cailleux's index tends to give exaggerated results. Both indices have been used in this study.

d. Flatness: Cailleux (1945, 1952) proposed the use of a "flatness index".

This involves the use of 'E' the greatest thickness measured perpendicular to the plane containing 'l' and 'L' (i.e. perpendicular to the plane of maximum projection).

Thus "Cailleux flatness index" $Fc = \frac{L + l}{2E}$

These additional measurements may appear to complicate the issue, but in fact they are closely comparable with Krumbein's 'a b and c' - Cailleux (1945, p. 378) stated that

L always corresponds exactly with a,
l in the large majority of cases is close to b,
and E in the large majority of cases is close to c.

For most practical purposes they may be taken as the same.

The measurements described above are illustrated in Fig. 109.

Pebbles were measured using calipers for the linear values. To find the arc fitting the sharpest contour a visual trial and error method was applied, using a piece of celluloid on which arcs of known radii had been inscribed for comparison or 'fit' with the pebble's sharpest contour in the plane of maximum projection. Pebble weights were also recorded.

2. RESULTS

All but two of the pebbles examined fall in Wentworth's (1922) 'cobble' grade. Details of the data are given in Table 6 .

a. Sphericity: The data plotted on Krumbein's (1941) chart for sphericity determination is given in Fig.110.

No. of pebbles	Sphericity
2	8
5	7
9	6
3	5
1	4
0	4 Average: 6 to 7

Thus the pebbles only show a moderate degree of sphericity.

b. Shape: Using the sphericity plots the pebbles are allocated to Zingg shape classes in Fig.

No. of pebbles	Zingg shape class
9	Triaxial
7	Equiaxial
3	Oblate
1	Prolate

Thus 80% of the pebbles are triaxial or equiaxial (bladed or spherical).

Summary of the other parameters (see Table 6)

c. Roundness: Rc = 0.234 to 0.563, average 0.373.
Rk = 0.370 to 0.800, average 0.546.

d. Flatness: Fc = 1.352 to 3.250, average 2.032.

Roundness data are presented on a cumulative curve in Fig.

Relationships between parameters:

Cailleux roundness v. Kuenen roundness (Fig.111) : Directly proportional.
Roundness v. Weight (Fig.112) : No relationship.
Flatness v. Weight (Fig.113) : No relationship.
Flatness v. Roundness (Fig.114) : Indirectly proportional.

Therefore weight has no apparent effect on the final morphology of these pebbles, but increasing roundness is accompanied by decreasing flatness. The two roundness indicates increase together, but the Kuenen index increases more rapidly than the Cailleux index. This shows that in this case it is Kuenen's index that tends to give exaggerated results.

Comparisons with other work:

Relationships between the morphology of pebbles and their depositional environment have not yet been conclusively established, and so that studies described above cannot be expected to provide a foolproof interpretation of the mode of deposition of the conglomerates. However, comparisons with data from several important pioneer papers provides useful information for presentation in support of evidence from detailed stratigraphical mapping and sedimentary structures.

Cailleux (1952, p. 13) presented a table of rounding and flattening data for limestone pebbles from 9 modern sedimentary environments. The average results obtained from the West Mull limestone pebble suite compare favourably with those of pebbles collected from a river bed in the Appenines.

Tricart and Schaeffer (1950) studied the rounding of pebbles from 23 localities, including a wide range of modern sedimentary environments. They summarised their results on histograms, an unsatisfactory and misleading method of presenting data. However, Graulich (1951) used these results to construct cumulative curves, from which he determined graphically two further indices:

1. Roundness distribution index.
2. Roundness asymmetry index.

Both these indices are inversely proportional to the amount of abrasion that a pebble has undergone. When applied to Tricart and Schaeffer's results, these indices, plotted against each other, produce a distinct field on the scatter diagram for each sedimentary environment. The data from the West Mull limestone pebble suite was treated similarly (Fig. 115), which produced a plot falling within Graulich's field for fluviatile formations (Fig. 116).

Kuenen (1956) conducted a series of important experiments to study the effects of abrasion on rock fragments of known weight and shape. Fragments were tumbled in a rotating barrel of water for a known length of time corresponding to a theoretical distance of transportation by water : this only approximates to natural conditions, but is nevertheless the best experiment of its kind devised so far. The results may be taken as a general guide to the behaviour tendencies of rock fragments during transport by a water current.

From data given by Kuenen (Experiment E, p. 360), curves for abrasion of limestone fragments were constructed as shown in Fig. 117. He used the Cailleux rounding index although he claimed that because of parallax it tends to give values that are too high. Progressive rounding of pebbles proceeds rapidly during the first 5 to 10 kms of transport; thereafter the curves flatten out (after 6-7 kms in most cases), achieving very low gradients after 50 kms. Weight appears to have little effect on the nature of the progressive rounding, but in one case a particular initial shape does : the original "double cube" actually achieves a reduction in rounding between 66 and 84 kms.

Comparing these curves with data from the limestone pebble suite from West Mull, it is clear that the pebbles have been transported a fairly short distance, probably no more than 5 to 10 kms. Even if Kuenen's results are not valid enough for direct comparison, it is evident that these limestone pebbles have only a moderate degree of rounding and therefore are unlikely to have travelled far.

The implication of a Durness Carbonate source within 5 to 10 kms of Gribun is tenable if the Moine Thrust is extrapolated southwards from Sleat, beneath the Ardnamurchan and north Mull Tertiary igneous rocks, and southwestwards through the Sound of Iona, as has already been suggested by the Geological Survey (e.g. Phemister 1960, Plate II). Torridonian sandstone (of the stable foreland) has already been recognised in Iona (e.g. Phemister 1960, Plate II), where its altered and crushed condition could be accounted for by the proximity of the Moine Thrust. It is reasonable to suppose that in Trias times the Torridonian, overlain by quartzite and Durness Carbonate, extended from Iona to Skye, west of the suggested position of the Moine Thrust. This arrangement would provide a source of limestone at the proposed distance from Gribun, and could also provide the source of the orthoquartzite and arkosic sandstone that accompany the limestone in the Gribun and Inchkenneth conglomerates.

CHAPTER VII

CORNSTONES

VII CORNSTONES

INTRODUCTION

A rather loose definition of 'cornstone' has been given on p. 6. This is based on Buckland's (1821) 'cornstone' which was "composed of marl or marlstone, filled with concretions of compact limestone, presenting the fracture and colour of mountain limestone and varying in size from that of a pea to blocks of many tons, and sometimes spreading itself into thick and compact beds, to the almost total exclusion of the marl".

Allen (1960) has drawn attention to the common use of the ambiguous term 'cornstone', which has caused confusion by being applied to two dissimilar rocks. He suggested a return to McCullough's (1869, p. 8) distinction between "concretionary cornstone" (calcareous concretions embedded in marls and grading to solid concretionary limestones) and "conglomeratic cornstone" (marl and limestone fragments embedded in more or less sandy and calcareous matrices).

In this study all the 'cornstones' so far referred to are 'concretionary cornstones', but they are developed in sandy beds rather than in marls, which are rare. They have also formed as nodules in conglomerates and at the surface of the basement rocks beneath the Trias. 'Conglomeratic cornstones' are not common. In the descriptions and discussions that follow the term 'cornstone' will be taken to mean 'concretionary cornstone' unless otherwise stated.

1. FIELD OCCURRENCE

Cornstone development is typical of the Trias sediments throughout the area studied, except in Southeast Mull. The carbonate has three modes of occurrence:

1. Veins penetrating downwards from the basal unconformity into the basement rocks (Moine or Torridonian).
2. Nodules in the conglomerate matrices or in sandstone beds.
3. Beds formed at the tops of sandstone units. Pipe-like bodies coalesce upwards into rather nodular and then homogeneous beds.

1. Basal veins

Cornstones are commonly developed at the base of the Trias throughout the West Highlands, but not as an invariable rule. Veins of limestone penetrate the underlying rocks along foliation, joint and bedding planes to depths of as much as 3 m, more commonly only penetrating to 1 m. The most striking development is at Loch Teacuis in Morvern, where the veins have coalesced to such an extent that the underlying Moine gneiss has become almost completely engulfed to a depth of 3 m, with only scattered relicts of quartzo-feldspathic veins remaining to indicate the original structure of the gneiss (Figs. 18,19).

An early stage in the vein development occurs at Gribun (Fig. 9) where thin veins penetrate to a depth of 1 m along joints and bedding planes in the Moine arkose-gneiss. Fig. 18 shows a slightly later stage of replacement at Loch Teacuis. Progressive development involves deeper penetration and widening of veins, culminating in the effect described at the end of the previous paragraph. A similar formation of cornstone has been described by Tomkeieff (1953) at "Hutton's Unconformity" on Arran, where cornstones at the base of the Old Red Sandstone penetrate the underlying Dalradian schists to a depth of 4 feet. As in that instance, the basal Trias cornstones often confuse the actual position of the unconformity, but the rule that has been followed is that the unconformity occurs at the top of <u>in situ</u> basement rocks, regardless of their degree of alteration by cornstone.

2. <u>Nodules</u>

Discrete calcareous concretions up to 50-60 cms in diameter sometimes occur in matrices of conglomerates, usually at an upper surface (Fig. 13). However, nodules are much more common in sandstone beds, where they are smaller, diameters being in the range 2-4 cms. Again they tend to occur in the upper parts of beds, and often coalesce upwards into pipes (Fig. 29a).

3. <u>Beds</u>

The commonest occurrence of the cornstones is in distinct beds. Cornstone pipes usually occur at the base, coalescing upwards into the cornstone bed (Fig. 5). Pipes are from 2-6 cms in diameter and may show remnant bedding of the sandstone in which they developed; they are usually solid, but occasionally pipes with hollow centres occur : the central cavity is filled with sand which is surrounded by a thin rim of sparry calcite within the main mass of cryptocrystalline calcite (Fig. 41).

The cornstone beds may be either rather 'rubbly', with a knobbly nodular appearance, each nodule being coated with a very thin film of sand, or homogeneous. They are sandy towards the base, becoming purer in carbonate upwards. Beds vary in thickness, being generally in the range 20 to 300 cms, measuring from the point of coalition of the pipes. Upper surfaces are usually slightly uneven and erosional (Fig. 24). Sand veins may penetrate to a depth of a few centimetres and sometimes form a polygonal network pattern (Fig. 17). At the top of one cornstone bed at An Leac a shallow channel and basin have been cut, being preserved with a sandstone filling (Al 15) (Fig. 24a).

Cornstone beds with associated pipes and nodules often appear in cycles, alternating with conglomerates and sandstones. The cornstone is developed at the top of crudely graded units of conglomerate and sandstone, and is truncated above by an erosional surface, above which another conglomerate occurs, again grading up into sandstone, sandstone with cornstone, and cornstone. The conglomerate often contains detrital fragments of cornstone near the base : if these are sufficiently abundant, and embedded in a calcareous matrix, they form a conglomeratic cornstone. The cycles are fluviatile, with cornstone superimposed on them. The ideal cycle is :

1. Conglomeratic cornstone

Erosional surface

6b. Bedded concretionary cornstone (homogeneous)

6a. Bedded concretionary cornstone (nodular)

5. Pipes of concretionary cornstone developed in sandstone

4. Discrete nodules of concretionary cornstone developed in sandstone

3. Sandstone

2. Conglomerate

1. Conglomeratic cornstone

Bedded cornstone

The components are rarely all present, the rarest being the conglomeratic cornstone which however is well developed in a bed overlying the basal cornstone on Rhum (Fig. 40) and in some of the cycles at An Leac. The conglomerate may be missing, the sandstone having a thin layer of small scattered cornstone fragments at the base. If the concretionary cornstone is well developed, it may reach right down to the conglomerate, eliminating the sandstone (Fig. 23). When the cornstone is not so well developed only the nodular and pipe cornstones may be present e.g. at Rudha na Leac on Raasay where 3 cycles occur together, but in each the bedded cornstone is only represented by a rubbly horizon (see Frontispiece and Fig. 29). More rarely the bedded cornstone is developed to the almost complete exclusion of pipes and nodules, as at Rudha Baile na h-Airde (Fig. 5a) and Rudha an t-Sassunaich.

Thus a variety of cornstone 'profiles' are represented, ranging from 'mature', in which the bedded component is very well developed (often to the exclusion of pipes and discrete nodules), to 'immature' in which only discrete nodules are developed in sandstone. The 'ideal cycle' and typical modifications showing variations in profile maturity that are superimposed on the fluviatile cycles, are illustrated in Fig. 118. Nowhere was a complete 'ideal cycle' found.

The areal extent of bedded cornstones is difficult to judge accurately owing to lack of three dimensional exposure, but in most cases it can be shown to be small. The largest extent that can reasonably be assigned to a single cornstone bed is that of the main cornstone in the Chapel Beds on Inchkenneth, which extends across that island, and re-appears on Mull at Rudha Baile na h-Airde and again in Allt na Teangaidh at Balmeanach Farm. Its surface area is at least one square mile (2.5 sq kms), and is probably considerably more.

2. PETROGRAPHY

In hand specimen most of the cornstones appear as pale sandy microcrystalline limestones with conchoidal fracture, but variations occur in the beds of concretionary cornstone. Irregular bands and veins of chert are very common in the cornstone beds : they vary from 0.5 to 10 mm in thickness, being normally in the range 1 to 2 mms, lying parallel to the bedding of the original sediment. They often develop as chalcedony exhibiting concentric laminations, sometimes appearing as tiny globular aggregates. The chalcedony has often formed in cavities in the cornstone, the remaining voids being filled with sparry calcite. At Rudha an t-Sassunaich chert comprises 7% of the thickness of the cornstone bed there (this is the average of 10 measurements giving a range of values from 4 to 11%), but generally it is not so abundant. East of Rudha an t-Sassunaich cornstones were found containing abundant ooliths 0.5 to 4.0 mms in diameter. Many of these have been replaced by silica either completely, or as a thin siliceous shell around a carbonate core (Fig. 43). Fig. 44 shows two cut faces of a specimen collected above Inninmore Bay. One has been polished while the other has been etched with dilute acid for comparison. This shows the relationship between microcrystalline carbonate, clear and amorphous chert (both in bands and replacing ooliths) and sparry calcite. Oolitic cornstone is rare however, having been found only at Inninmore and The Wilderness (Ath Dearg).

Colours of the cornstones are mainly pale, being commonly pinkish grey 5R 8/1, very light grey N8, or white N9. Other colours include pale yellowish brown 10 YR 6/2, pale red 10R 6/2, pale yellowish greyish green 10 GY 6/2 and moderate red 5R 5/4. The colour of a nodular or bedded cornstone depends mainly on the colour of the sediment in which it is developed.

The scheme of Folk (1959, 1962) is used for classification. In thin section, concretionary cornstone is seen to be micrite or dismicrite containing scattered detrital grains, usually of quartz but with sometimes a little feldspar. In the nodules, pipes and bedded cornstones these grains often have corroded borders and replacement of grains by carbonate is frequently intense so that many grains appear to be 'floating' in the carbonate (Brown 1956, p. 7), while others are only recognisable as carbonate replacement 'ghosts' (Burgess 1960, Plate II B and p. 149) or can no longer be distinguished at all. Where ooliths occur they may be sufficiently abundant (>25%) to produce oomicrite or, more usually, oosparite. Some aggregates of silicified ooliths appear to be intraclasts, although they do not clearly show the abrasive characteristics described by Folk (1962, p. 63), and so a few rare intrasparites occur, the cement being sparry calcite. The low content of intraclasts (usually nil) in these carbonates indicates very quiet conditions of formation; the few intraclasts present may have been produced by internal brecciation (Burgess 1960, Plate I).

The micrite is composed of calcite, but in specimens from some of the beds it is replaced in parts by scattered rhombs of dolomite, 5 to 20μ in size. Silica occurs either as tiny fibrous chalcedony spherulites developed in cavities and veins in the carbonate, or replacing ooliths. In cavities the chalcedony usually encloses a central void filled with sparry calcite, although in the sparite portions of dismicrite individual spherulites and spherulitic aggregates are enclosed in sparry calcite. Ooliths sometimes demonstrate two stages of silicification : silicified ooliths are surrounded by chalcedony that has used them as centres of crystallisation. Some of the ooliths still retain micrite in the centres, while others have structureless silica nuclei. In the oosparite, many of the silicified ooliths have had their outer shells replaced by sparry calcite which is sometimes, although not invariably, in optical continuity with that of the matrix. Some of the concretionary cornstones are internally brecciated. In these, veins of calcite occur up to 1.5 mm in thickness, sometimes containing patches of spherulitic chalcedony in the centres.

Secondary structures: structures resulting directly from solution processes include: 1. cavernous horizons,
and 2. stylolites.

Cavernous horizons frequently occur, the voids being from a fraction of a millimetre to 1-2 cms in diameter. The larger voids are filled with chert, while the smaller ones (0.5 to 1.0 mm) contain chert, or sparry calcite, or both.

Stylolites are not common. They are small scale features with relief on stylolitic boundaries being only of the order of a fraction of a millimetre (microstylolites). Detrital grains, mainly of quartz but with some feldspar and a few quartzose rock fragments, are concentrated along them, and they are usually marked by a concentration of opaque dust. They cut through micrite, but are not seen in dolomitised or silicified limestone. The most widely accepted theory of the origin of stylolites is that they are the result of pressure solution (e.g. Stockdale 1926), but Prokopovich (1952) has described stylolites that were probably developed through solution processes in relatively soft sediments during sedimentation. The rarity of this structure, combined with the absence of pressure solution effects in the sandstones of the Trias successions suggests that these stylolites are of the latter type, and this is particularly likely because the other solution structure is pre-complete lithification, being filled with authigenic silica.

Cornstone permeating the basement rocks is also micrite or dismicrite. Detrital fragments contained in it are very little corroded, and crystals of sparry calcite up to 20μ in size have grown against the edges of some of the larger particles which remain fresh. No chalcedony was found in any of the cornstones collected from beneath the basal Trias unconformity, and dolomite is also absent.

Fragments of cornstone in the conglomeratic cornstone display the features of carbonatisation and silicification described above, although no oolitic fragments were found. The cement is micrite or dismicrite, with abundant detrital grains of quartz and feldspar which are often slightly corroded.

Textural relationships in the cornstones were investigated by chemical staining. Since the presence of dolomite had been suspected from the thin sections, a stain was required to differentiate between calcite and dolomite, preferably one being positive for dolomite. Holmes (1921, pp. 264-268) described several stains for distinguishing carbonates. All these were recorded as being negative for dolomite, although in fact the result usually obtained from Heeger's Test (usually positive for dolomite and negative for calcite - see below) is opposite to that quoted. Milner (1952 p. 258) also only gives calcite positive, dolomite negative stains. However, Friedman (1959) devised an excellent schematic staining procedure for the identification of carbonate minerals, which has been confirmed, elaborated and adapted by Wolfe and Warne (1960), Warne (1962), Evamy (1963), and Dickson (1965). The most useful of these stains in this investigation are Alizarin Red 'S', potassium ferricyanide, and Titan Yellow.

Alizarin Red 'S' acts in dilute acid solution in the cold, being positive for calcite (stained pink or pale red) and negative for dolomite. It has considerable advantages over the use of logwood hematoxylin (Lemberg's Solution) as described by Johannsen (1918 p. 565), Holmes (1921) and Milner (1952), being more reliable and much quicker and easier to make up.

Potassium ferricyanide acts in dilute acid solution in the cold (Heeger's Solution), normally being positive for dolomite (turquoise-blue stain) and negative for calcite. The stain depends on the presence of iron in the carbonate molecule, and will give a positive result for ferroan calcite and negative for dolomite with no iron. However, dolomite usually contains traces of ankerite, while most of the calcite tested in this study was non-ferroan. The stain worked very well as a positive identification of dolomite.

<u>Titan Yellow</u> acts in dilute alkaline solution and requires boiling. It is positive for dolomite (bright red) and negative for calcite. It cannot be used on thin sections, but was a very useful check on the results obtained with Heeger's Solution on polished surfaces and crushed material.

The first two dyes were applied to thin sections, crushed rock and polished faces, both separately and together. They work well together, and are especially effective if the sample is etched first with dilute acid (great care must be taken here with thin sections). The scheme followed was essentially similar to that outlined recently by Dickson (1965) and so need not be described here. The amount of dye used and the acid concentration are not critical, but they work best near to the values that Dickson has indicated. In this study the potassium ferricyanide was actually applied before the Alizarin Red 'S', but they can equally well be applied as a mixture, as Dickson has suggested.

Thin sections mounted in Lakeside cement were stained uncovered and then the cover slip was mounted as usual with Canada Balsam. Staining procedures confirmed the following diagenetic processes in the cornstones:

1. Crystallisation of micrite and dismicrite in sand, with partial or complete replacement of detrital grains. This is rarely accompanied by the formation of calcareous ooliths around detrital grain nuclei.

2. Dolomitisation : dolomite formed along veins and as scattered rhombs in the calcite, sometimes replacing ooliths.

3. Formation of solution effects : voids and stylolites.

4. Chert formation, mainly as fibrous chalcedony crystallising in bands and globules along the walls of veins and in cavities, but also including drusy chert in cavities and amorphous chert replacing ooliths. Siliceous replacement of micrite occurs to a small extent alongside silica-filled veins and cavities. In some cases there appears to have been selective replacement of groundmass micrite containing dolomite rhombs which remain unaltered, often acting as centres of crystallisation for the chalcedony. However, the silica may have formed in cavities and pore spaces leached out from between the dolomite rhombs by very weakly acid solutions that were able to dissolve calcite but not dolomite. Chert also forms in concentric bands around carbonate or detrital quartz nuclei, so that not all the siliceous ooliths are secondary replacements of carbonate ooliths. Chert also forms around siliceous ooliths.

5. Crystallisation of sparry calcite, sometimes following internal brecciation. Infilling of cavities lined with chalcedony and crystallisation in veins. Replacement of the outer shells of silicified ooliths. Much of the sparry calcite is ferroan (the micrite being non-ferroan); a curious effect was observed with calcite staining which hardly ever took on sparry calcite replacement of oolith shells, even although many of these are in optical continuity with stained calcite crystals in the interstices between ooliths.

Stages 1, 3 and 4 are found in all the concretionary cornstones studied (except those of the basal veins). Stage 2, dolomitisation, was only found in cornstones collected from Ardnamurchan, Morvern and Mull. These processes may have occurred very close together in time.

Oolith formation is uncommon. Stage 5 is common throughout the area. In the cornstones of the basal veins, only crystallisation of micrite and dismicrite occur, the other stages being absent.

These stages are illustrated in Figs. 61-70.

Staining of polished faces of cornstone with Heeger's Solution after etching with dilute hydrochloric acid distinguished dolomite in a network of thin veinlets penetrating micrite. These appear to be based on major vertical veins which are often sandy and reach 3-4 mms in thickness. Horizontal veinlets extend out from these veins, being 0.2 - 2.0 mms thick. The horizontal veinlets sometimes contain sparry calcite which appears to have crystallised after the dolomite. Where veinlets coalesce, small irregular masses of dolomite have developed, growing outwards and sometimes sending out thin radial dolomite veinlets. These results were accurately confirmed by treating the same specimens with Titan Yellow, after removing the first stain with acid. Fig.42 shows an etched face stained with Heeger's Solution. Treatment of an oolitic sample with Titan Yellow demonstrated that many of the oolith cores are dolomite, enclosed in thin shells of amorphous silica (Fig. 43).

Crushed cornstone material (90 - 63μ: passing B.S. mesh 170, held by mesh 240) from all the areas studied was tested for dolomite with Heeger's Solution, checking the results with Titan Yellow. All the specimens tested from Mull, Morvern and Ardnamurchan gave positive results, but those from Rhum, Skye, Scalpay, Raasay, Applecross and Wester Ross were all negative. A geographical distribution of dolomite in the cornstones is therefore indicated.

A crushed specimen from the top of the cornstone bed beneath

Inchkenneth Chapel was subjected to Friedman's (1959) full staining procedure for carbonates, but out of calcite, high magnesian-calcite, dolomite, aragonite, gypsum and anhydrite tested for, only calcite and dolomite were found.

3. PHYSICAL ANALYSIS

A physical examination was made of serialised specimens collected from cornstone profiles at Inchkenneth, Rudha Baile na h-Airde (Gribun), Rudh' a' Mhile (Ardnamurchan), and Rudha na Leac (Raasay). Specimens of cornstone were collected from the base of the scattered nodule zone (if present) up through the pipe cornstone and the bedded cornstone. Prominent chalcedony veins were avoided. Two features were investigated:

1. Specific Gravity.
2. Content of insoluble material (and hence the carbonate content).

a. Specific Gravity

This was determined as described by Johannsen (1918 pp. 32-33) using a Walker steelyard balance. The results are given in Table 7 , and plotted in Figs. 119-121.The Sp.G. of calcite is 2.71 and of dolomite 2.87, while quartz at 2.65 tends to lower the Sp.G. of a carbonate rock if present in any appreciable amount. Thus it is significant that specific gravities are higher in the upper parts of the profiles than in the lower parts, suggesting an upward increase in carbonate content at the expense of the detrital grains. The highest specific gravity obtained in the Inchkenneth profile occurs 360 cms above the base : 2.710. The highest Ardnamurchan value is 2.775 (235 cms above the base) while the highest Raasay value is 2.700 (76.5 cms above the base). The consistently higher values in the Ardnamurchan and Raasay profiles can probably be accounted for by higher iron content there than in the Inchkenneth profile. The sandstones in which the cornstones have developed are red-brown (see Frontispiece) compared with the pale colours of the Inchkenneth profile.

The great majority of Scottish limestones have specific gravities of 2.65 to 2.75, while the average for Scottish dolomites is 2.85 (Robertson et al 1949, p. 27). Apart from calc-silicate bearing limestones, almost the only calcareous rocks with specific gravities greater than 2.75 are the dolomites and ferro-dolomites. There is a scarcity of limestones in the range 2.75 to 2.82. Therefore the Trias cornstones are typical limestones in this respect and do not approach the dolomites, apart from the samples of exceptionally high density from Ardnamurchan.

b. Insoluble content.

A variety of excellent methods for dissolving limestones are described in the literature. In this study, an adapted combination of the methods described by Milner (1952, p. 192) and Burgess (1960, p. 145) was used. The sample was crushed initially with an hydraulic jack and subsequently by hand with a pestel and mortar to pass B.S. sieve mesh 30 ($< 500\mu$). 50 gms crushed material (selected by repeated coning and quartering) was treated with 2N HCl, initially in the cold, and then boiled for 10 minutes to ensure that all the dolomite was dissolved. The residue was washed and dried at 110°C to constant weight. Repeats of the method on the same sample did not produce a significant degree of experimental variance.

36 samples were analysed, including single specimens from other cornstones as well as the serialised collections. The results are given in Table 7 and Figs 119-121. A steady decrease in insoluble material occurs upwards through the cornstone profiles, although in each of the three thickest profiles the highest samples shows a sudden increase in insoluble content. The insoluble material consists mainly of the remains of detrital grains, but authigenic silica is also present, which could partly account for this result : certainly in the field there is seen to be a slight increase in chert abundance upwards through the cornstone beds. A division of the insoluble material into sand and day fractions would be of little significance because of

1. the crushing that has taken place,

and 2. the presence of authigenic insoluble material.

The result would be even more striking in the lower parts of the profiles had it been possible to collect samples representative of whole horizons instead of simply taking specimens from carbonate concretions alone. Two pairs of cornstone and sandstone sampled from the same horizon gave the following insoluble residue values:

1. Pipe cornstone: 22.6%; sandstone : 87.0% (Inchkenneth).
2. Cornstone nodule : 32.2%; sandstone : 87.4% (Raasay).

The purest carbonate was obtained 360 cms above the base of the Inchkenneth profile, containing only 5.1% insoluble residue, compared with 20-25% in the purest part of the Ardnamurchan profile and 15.8% on Raasay. As can be seen from Fig. 118, the Inchkenneth profile is the most 'mature' of these three.

Of the miscellaneous samples, the bedded concretionary cornstone at Rudha an t-Sassunaich (Morvern) gave 6.0% insoluble residue; bedded concretionary cornstone at An Leac (Skye): 8.4%; conglomeratic cornstone from Rhum : 6.2%. Specimen Sl 7 is not in fact a cornstone : it is a specimen of red marl from the south side of Loch Sligachan (Skye) giving 60% insoluble residue.

Insoluble residues were examined under a binocular microscope and found to consist mainly of quartz grains, with some angular chert fragments and a little feldspar and rare mica. Many of the detrital grains have a 'frosted' appearance as a result of corosion by carbonate.

In Fig. 122 percentage insoluble residue is plotted against specific gravity, illustrating the direct relationship existing between them, specific gravity increasing with decreasing insoluble residue.

In conjunction with the physical analysis a rapid investigation of the crushed material was made using stains described above. Fragments 63-90μ in size were seived off and stained with Heeger's Solution, and comparative stains made with Titan Yellow. The results were similar, but the Heeger's Solution produced a clearer distinction between stained and non-stained grains, and so was selected for modal analysis of fragments mounted on a slide (Friedman 1959) using a Swift point counter and taking 1000 grains per slide. This actually tested the amount of ferroan dolomite plus ferroan calcite in the samples, but the close comparison with the Titan Yellow results suggests that the result mainly involves dolomite.

The variations through the profiles are shown in Figs. 119-121. In the Inchkenneth profile, there is a striking correlation between the three cornstone zones and the variation in dolomite plus ferroan calcite content. This is difficult to explain, but may be connected with the distribution of iron in the carbonates. No positive results were obtained from the Raasay profile.

4. CHEMICAL ANALYSIS

Six specimens were selected for analysis : four representative samples from the Inchkenneth profile and one each from the tops of the Ardnamurchan and Raasay profiles. A gravimetric method was used, as described by Kolthoff and Sandell (1952).

Details of the results are given in Table 8 . These confirm the presence of dolomite in five of the samples, and its absence in the Raasay specimen. In the Inchkenneth and Ardnamurchan samples the results when calculated for dolomite percentages are all lower than those obtained for dolomite plus ferroan calcite by modal analysis on stained material.

Dolomite has not been recorded before in the Trias cornstones, but it has been analysed in cornstones from the Upper Old Red Sandstone of Scotland (Robertson <u>et al</u> 1949, p. 39). These are usually low in magnesia (0 - 2.47% $MgCO_3$) but a few exceptional cases of dolomitic cornstone occur, which have even higher $MgCO_3$ than the Trias cornstones:

Upper Old Red Sandstone	$CaCO_3$	$MgCO_3$	Insoluble Residue
(Analysts: H.M. Geol. Survey)			
Toward Taynuill, Argyll (S.L.283)	49.95	38.90	6.30
Kilchattan, Bute (S.L.228)	47.29	30.85	20.83
Gargunnock, west of Stirling (S.L.160)	49.89	36.21	11.76
Trias			
(Analyst: M.J.B. Lowe)			
Inchkenneth (Ikc 13)	58.11	9.06	29.38
Inchkenneth (Ikc 11)	78.68	11.24	7.28
Inchkenneth (Ikc 6)	68.39	13.24	12.10
Inchkenneth (Ikc 2)	54.78	10.80	28.22
Ardnamurchan (Anc 6)	45.23	16.05	34.36
Raasay (RnLc 5)	78.10	Nil	18.85

The range 16 to 46% $MgCO_3$ is rare in all limestones, and only one of the Trias cornstones (Anc 6) just falls within it. The insoluble residue results, based on samples of 0.5 gm, are not so accurate as those obtained from the physical analysis but compare favourably with them.

An X-ray and spectrographic analysis of the insoluble residue from specimen Ikc 12 gave the following results:

The spectrogram showed major amounts of Mg, Al, Si, with some Ti but very little Fe and Na.

The X-ray showed quarts as the main constituent; also potash feldspar, muscovite, and some clay mineral.

This confirms the observations made previously.

5. DIAGENESIS

Three main diagenetic processes are involved, each of which is a current geological problem:

1. Replacement of siliceous detrital grains by carbonate.
2. Dolomitisation.
3. Chert formation.

In these cornstones it is impossible to divorce problems concerning the removal of silica from the allied problem of simultaneous carbonate precipitation, or vice-versa, so processes 1 and 3 will be considered together. Dolomitisation affects only the calcite and appears in turn to be unaffected by silicification, so will be discussed separately.

a. Calcium carbonate and silica

An extensive literature on the "chert problem" has been reviewed by Pettijohn (1957) and the more recent advances discussed by Ireland (1959, ed.) and Siever (1962). The main problems involved are:

1. sources of silica;
2. mechanisms and distances of silica transportation;

and 3. causes and mechanisms of authigenic silica precipitation.

A wide variety of sources have been postulated, including carbonate replacement of detrital quartz, which is the probable source of the chert in the cornstones: chert only occurs when the cornstone is well developed with considerable replacement of detritals, and even then only comprises about 7% of the profile.

Problems of silica movement have been resolved as true solution transport in the form of H_4SiO_4 (monosilicic acid) (Krauskopf, 1959). In normal geological environments the pH range is 2 to 9, within which silica solubility is essentially independent of pH and Eh, although it is markedly influenced by both temperature and pressure. In the Trias cornstones however, diagenesis has occurred at or near the surface (see below) and therefore at normal temperatures and pressures, so neither factor can be satisfactorily invoked to explain diagenetic features.

However, factors controlling the solution and precipitation of carbonates are quite different : these involve pH, activity of CO_2, CO_3^{--} and Ca^{++} (along with pressure and temperature). The interplay between the two systems is not yet clearly understood. Correns (1939, 1950) suggested that high pH values favour silica solution and carbonate precipitation, and vice-versa at low pH, but although this may be true for carbonate the theory concerning silica has been contested by Alexander, Heston and Iler (1954), Iler (1955), Krauskopf (1956), Siever (1959, 1962) and others and can no longer be considered to be valid. Correns' (1950) suggestion was that interstitial waters saturated with $CaCO_3$ and SiO_2 at a particular pH, would tend to precipitate $CaCO_3$ and dissolve more SiO_2 upon migration into an environment of higher pH. According to later work, however, alkalinity above pH 9 would be required, and such conditions are rare in geological environments. Comparing Alexander, Heston and Iler's (1954) amorphous silica solubility curve with Correns' calcium carbonate solubility curve (Figs 124-5) it seems possible that solution of carbonate and precipitation of silica as chalcedony and chert in the voids thus produced could take place at a pH of approximately 6.

Without further work on the conditions of stability and disequilibrium between carbonates and silica, it would be almost sheer speculation to suggest conditions that could permit the replacements observed in the cornstones. However, two points may be noted:

1. Replacement of one mineral by another indicates either a chemical or a physical disequilibrium.
2. Reversibility of replacements (e.g. calcite replacing silicified ooliths) suggests a rather delicate balance of replacement controls, near equilibrium.

b. Dolomitisation

A useful review of the "dolomite question" has been made by Fairbridge (1957). There are still numerous unsatisfied problems regarding dolomite formation, which include problems of Proterozoic and Palaeozoic hydrology, contemporary deep-seas, primary precipitation, magnesium enrichment in organic debris in shallow water, and controls of the equilibrium of aragonite and high-magnesium calcite. However, most of these do not concern this study because, of the several environments of magnesium deposition outlined (Fairbridge 1957, Fig. 3, p. 131), the only likely environment for the Trias cornstones in the continental 'hard pan'.

Magnesium enrichment probably took place from groundwaters percolating through permeable and largely unconsolidated limestone, the routes along which these waters were introduced being marked by dolomite formation (Fig. 42). Thus the dolomite formed as a diagenetic early secondary product, by metasomatic replacement of parts of the $CaCO_3$ framework (Fairbridge 1964, p. 456). There is no evidence to suggest that swampy or ephemeral lacustrine conditions could have been contributing factors, the dolomitisation appearing to have been accomplished by normal groundwater and subaerial processes.

6. ORIGIN

In 1910 H.B. Maufe compared the Trias cornstones in Morvern with calcareous superficial deposits that he had seen in East Africa. He remarked that "they resemble very closely in their form and disposition within the bed the limestone concretions found in the superficial deposits of many tropical lands. They are widely known as 'kankar' in India, where they afford frequently the only source of lime over large areas, and the same may be said of many parts of Central Africa" (Summary of Progress for 1909, p. 35). He described the occurrence of 'kankar' in districts subject to alternating wet and dry seasons, and showed that it is characteristic of terrestrial conditions.

Since then a number of papers have been published describing occurrences of 'kankar' or'caliche' as it is known in the U.S.A. (Sayre 1937, p. 66). Bretz and Horberg (1949, p. 507) have reviewed the most important of these, citing examples from South-Central U.S.A., Mexico, Argentina, South Africa, North Africa, the Middle East and Autralia. More recent papers include those of Rutte (1958) and Gigout (1960). The best descriptions are those given by Bretz and Horberg themselves (1949), and later papers by Judson (1950), Brown (1956), Van Siclen (1957) and Reeves and Suggs (1964), all dealing with caliche of Pliocene, Pleistocene and Recent age in Texas and New Mexico. These tend to confirm the comparisons drawn by Maufe.

Although varying in several points of detail (not only with the Trias cornstones, but also amongst themselves) the caliche profiles of Texas (Llano Estacado) and New Mexico are remarkably similar to the Trias cornstone profiles. In the northeastern Llano Estacado Brown (1956) described caprock and friable caliche in single, double or multiple layers, with total thicknesses up to 30-150 ft, overlain by dark silts which are sometimes calcareous. In New Mexico, however, Bretz and Horberg found profiles that are of an order of thickness more similar to the Trias cornstone profiles. They consist of limestone pebble gravels grading up into calichified pebble conglomerate, nodular caliche (sometimes with calcareous pipes at the base), brecciated caprock and finally dense banded caprock at the top. Thicknesses vary from 10 to 20 ft, of which the caprock comprises 2 to 10 ft (Fig. 123). Both types of profile have been interpreted as fossil calcareous soil deposits (pedocals).

Caliche has been compared with cornstones from the Old Red Sandstone of Britain by Burgess (1960) and Pick (1964). The profiles described by Burgess compare closely in detail with those of Brown (1956) although they are not so thick, while Pick's cornstones (1964, Plate 8 and pp. 211-212) lack the overlying dark calcareous silts of Burgess and Brown and are much thinner. However, both Burgess and Pick recognised that the theory of deposition as calcareous soils accounts for both their formation <u>in situ</u> and their profiles. The same applies to the Trias cornstones.

Theories of caliche formation summarised by Bretz and Horberg (1949, p. 507) include deposition in lakes by organic or physical processes, deposition along streams, deposition by rising artesian waters either at the water table or at the surface, deposition by capillary rise of water form the water table, and deposition in the 'B' zone of the soil profile by descending surface waters or by capillary rise of surface waters following soil zone saturation. They found that only a pedologic hypothesis was significant for the New Mexican caliches, and suggested that they formed as degrading soil profiles "under conditions of alternating saturation and desiccation in a relatively dry climate with periodic rains." The host gravels contain abundant limestone pebbles from which solution occurred as soil waters moved downwards during the rainy period, and precipitation of carbonate took place with capillary rise of saturated alkaline solutions as the soil zone dried out.

Brown (1956) on the other hand suggested that the thick caprock and caliche of the northeastern Llano Estacado formed as an aggrading calcareous eolian deposit, wind and rain gathering the materials to form the soil and associated caliche. The $CaCO_3$ was leached downwards by percolating rainwater and deposited as a subsurface evaporite.

Neither mechanism is fully satisfactory for the Trias cornstones. They could not have been formed by solution and redeposition within the bed because there is not enough limestone detritus in the sandstones to provide the source of lime from within the host bed, and they are unlikely to have formed as eolian deposits because the host sandstones are of fluviatile origin. Assuming that an external source can be found for the lime, a reasonable hypothesis is to invoke downward percolation of alkaline solutions into fluviatile sands and gravels during wet seasons, followed by capillary rise and evaporation of these solutions during dry seasons. Thus the bedded cornstone represents the soil surface at which evaporation occurred, while vertical pipes beneath mark the paths along which the $CaCO_3$ bearing solutions rose. The thickness of the soil profile is then determined by

1. the depth of maximum penetration of soil water,
2. the cumulative effect of alternating saturation and evaporation,

and 3. the amount of lime available.

The Inchkenneth profile represents a mature development, while the Rudha na Leac profiles are immature; bedding planes marked by scattered calcareous nodules represent juvenile stages of development.

Internal brecciation is the result of drying out of the soil zone and also of expansion accompanying cornstone impregnation (see Bretz and Horberg 1949, p. 509) while the nodular bedded cornstone occurring between the pipe zone and the homogeneous bedded 'caprock' is precisely what Brown (1956. p. 12) claimed would be produced by the deposition of $CaCO_3$ from percolating waters as an evaporite beneath a permeable caprock.

Thus we have: Homogeneous bedded cornstone ≡ Caliche caprock
Nodular bedded cornstone + pipe cornstone ≡ Friable caliche

Isolated nodules of cornstone developed in sandstone beneath the pipe zone indicate the horizon at which deposition from alkaline solutions was initiated.

A possible source of lime is the Durness Carbonate formation (which could also provide magnesium for dolomite formation), but the mechanism for its transport poses a problem. Possibly it was introduced as a fine eolian dust (Brown 1956, p. 13) but there is no evidence of this. However, the absence of an obvious transporting medium for the large quantities of lime required is no serious bar to the pedalogical hypothesis because calcareous soils are known to form at the present time in many environments where there is apparently no immediate source of lime (Burgess 1960, p. 152).

The absence of an overlying calcareous silt zone ('Cca horizon') contrasts the Trias cornstone profiles with those of Brown and Burgess, but is comparable with those of Bretz and Horberg, and Pick. Any softer overlying member of the profile would be unlikely to survive the return of a high flow regime in a fluviatile environment, which is usually marked at the tops of the profiles by an erosional surface and an overlying conglomerate. But the marked increase in insoluble detrital content at the tops of the Inchkenneth, Ardnamurchan and Raasay profiles may indicate the basal remnant of a sandier component grading upwards from the 'caprock' and representing a Cca soil horizon.

At one locality (An Leac) when the top of a cornstone bed is exposed, there is a development of shallow cracks and fissures and a sand-filled channel (Fig. 24a). The channel sandstone (Al 15) contains quartz and a variety of rock fragments including a predominance of angular chert, set in a very fine-grained siliceous matrix which is very heavily stained red. Solution pits, cavities and channels are also often found at the top of caliche profiles (Price 1933, 1940, Bryan and Albritton 1943, Bretz and Horberg 1949). The development and preservation of a fossil pedocal implies a pronounced pause in sedimentation, and emergence of such a pedocal is likely to have been accompanied by solution and erosion of the upper surface, producing a karst topography as described above. Polygonal patterns have also been observed in cornstone upper surfaces, usually preserved with infillings of sand (Fig. 17). These are interpreted as desiccation cracks, as described from modern carbonate sediments by Ginsburg (1957, Fig. 14 p. 94).

Calcareous developments along stream beds do not produce profiles, but instead assume a crust-like form (Trowbridge 1926, Price,Elias and Frye 1946, Bretz and Horberg 1949). These are probably the modern equivalents of calcareous developments observed in the Trias conglomerates.

It has been noted above that in the bedded concretionary cornstones there is replacement of detrital grains of the host rock by the invading carbonate, producing 'floating' (i.e. not in mutual contact) and 'ghost' grains. The cornstone mass appears to have grown by expansion in pore spaces and replacement of detrital grains. This is similar to the process illustrated by Swineford and Franks (1959, Fig. 12 p. 118). Chert recorded by Bretz and Horberg, and Brown, in insoluble residues from caliche may be equivalent to the chert in the cornstones. Neither paper however describes oolitic structures, but Swineford,Leonard and Frye (1958) recorded pisolitic structures in the caliche of the Kansas Great Plains.

In the cornstone of the basement veins there is little or no evidence of chemical replacement of grains, fragments surrounded by carbonate often having fresh faces which have actually provided bases for crystallisation in many cases. Therefore the carbonate growth must have a different mechanism from that of the bedded cornstones. Young (1964) has described the disruptive force of caliche crystallising in cracks in sandstone cobbles, which could well explain the spectacular effects beneath the basal Trias unconformity at Loch Teacuis (Fig. 19) and elsewhere. Saturated alkaline solutions were involved, penetrating the exposed pre-Trias basement rocks along joints, bedding and foliation planes during wet seasons, where evaporation in dry periods produced crystallisation with accompanying expansion causing the rock to fracture, producing more pore space for later solutions to penetrate, and so perpetuating the process. The amount of replacement of the basement rock depends on 1. the initial availability of fissures to allow the percolation of alkaline solutions,

2. the availability of a source of lime,
3. the climate,

and 4. the length of time that the rock surface was exposed to the atmosphere before becoming inundated with sediment.

The latter factor can serve as a useful clue to the development of the Trias palaeogeography. For example, it can explain why there are no cornstones developed at the base of the Inchkenneth succession, where sedimentation commenced distinctly earlier than it did at the Gribun unconformity which was at a higher topographical level (Fig. 151) and has a marked cornstone development. Sedimentation may have taken a considerable time to reach the Morvern hinterland (Loch Teacuis) where the thickest basal cornstone is found.

The climatic implications of caliche formation have been discussed by Bryan and Albritton (1943) who suggested that it indicates alternations of arid and humid conditions. This is supported by the occurrence of caliche in arid and semi-arid regions throughout the world (Bretz and Horberg 1949,

p. 510). In the absence of calcareous algae, the presence of diagenetic dolomite is not a useful indicator of climatic or temperature conditions (Fairbridge 1964, p. 457).

CHAPTER VIII

SEDIMENTARY STRUCTURES

VIII SEDIMENTARY STRUCTURES

INTRODUCTION

Sedimentary structures play an important role in the determination of sedimentary environments. Unfortunately the most disappointing aspect of this study has been the lack of structures displayed by the Trias sediments, but the few that do occur greatly assist the recognition of the depositional environment, and confirm suggestions based on textural evidence.

Structures recognised in the sediments, include normal and cross-bedding, imbrication, mud cracks with associated mud flake pseudo-conglomerates, and parting lineation. Lens and flaser bedding occurs in the suggested Rhaetic beds at Applecross.

1. BEDDING

Conglomerates are thin to very thick-bedded, with bedding planes that are often erosional,indicating high flow regime. Sandstones are thin- and very thin-bedded, and occasionally laminated. In both conglomerates and sandstones bedding is generally uneven, with beds showing rapid lateral variations in thickness and interdigitating with each other in lenses. This is apparent in single outcrops, and it is generally impossible to trace specific beds laterally for any distance. Stratigraphical correlations between areas have been based almost entirely on overlying fossiliferous beds, and only generalised stratigraphical variations have been recognised within the Trias (p. 86).

Single units are often crudely graded, from conglomerate at the base through pebbly grits and coarse sandstones to medium-grained sandstone. In the upper parts of the Trias successions cornstones are often developed at the tops of these units. Graded units may be repeated several times (as on Isle of Ewe and at Gruinard Bay) and are interpreted as fluviatile cycles, with upwardly decreasing flow regime in each.

2. CROSS-BEDDING

In the description of field occurrences and stratigraphy of the sediments the classification of McKee and Weir (1953) has been used. This has been elaborated by Allen (1963a) to include more classes and take account of additional important features, and this latest classification will now be used in the more detailed descriptions.

Although it occurs quite commonly, cross-bedding in the Trias sediments is not very clearly developed or often exposed in three dimensions, so that it is difficult to determine details of relationships. However, as far as can be seen the commonest type in the sandstones, grits and fine conglomerates occurs as solitary sets of large-scale erosional or non-erosional planar or non-planar homogeneous cross-strata. The non-erosional sets belong to Allen's 'alpha-cross-stratification' type, and the erosional sets to his 'beta-cross-stratification' (planar) and 'gamma-cross-stratification' (non-planar) types. All three types can be constructed in three different ways, of which the simplest and most natural method is the building in shallow water of solitary banks with straight or curved leading edges above slip-off faces. Such banks are common in modern rivers, particularly those that are braided, although they also occur in estuarine and beach environments. Erosive bases of the 'beta-' and 'gamma-' types indicate either an erosive advance of the solitary bank or an earlier planing-off of the previous deposit in vigorous and changing conditions, while the non-erosive bases of the 'alpha-' type probably reflect less vigorous and more uniform conditions.

Cross-bedded sandstone and grit lenses in the conglomerates are large-scale erosional cylindrical (or possibly scoop-shaped) concordant (or possibly discordant) homogeneous solitary sets of cross-strata. These clearly fall in Group II of Allen's genetic classification (1963a, Table II p. 112) but the lack of three-dimensional exposure makes it difficult to assess the attitude of the erosion surface axis in each case. Generally they appear to be horizontal, referring the structures to the 'zeta-' type which is thought to be produced by channel cutting and filling (McKee 1957), the cut and fill processes being distinct acts separate in time. Again, a fluviatile environment with varying current velocities (erosive and depositional) favours the development of this structure. The structure is usually found developed as sandstone - or pebbly grit-filled wash-outs in conglomerates (Figs. la and b) but at Leac Dubh on Gruinard Bay there is a single instance of a solitary set developed in medium-grained sandstone filling a channel cut into siltstone.

The sandstone at Redpoint from which specimen Rp. 2 was collected has been described above (p. 71) as having a suggestion of 'dune bedding'. This cannot be confidently compared with Allen's 'pi-cross-stratification', or with the structure that Shotton (1937, 1956) attributed to barchan dunes, and therefore cannot be taken as an indication of an eolian origin for that sand, an origin which appears unlikely anyway in view of the textural characteristics of the sandstone.

3. IMBRICATION

Tabular pebbles in the conglomerates often display an overlapping arrangement producing a collective 'shingling' or dip (Fig. 11). This structure was first described from gravels by Jamieson (1860, p. 349) and Becker (1893, p. 54), and has since been studied by others such as Johnston (1922), Fraser (1935), Wadell (1936), Cailleux (1938, 1945) and Krumbein (1940, 1942). A review of the literature is given by Potter and Pettijohn (1963, pp. 35-36).

The structure may be produced in gravels of fluviatile or marine origin. Cailleux (1945) investigated modern beach and river gravels and found that

1. river gravels give pebble inclinations of 15° to 30°

and 2. beach gravels give pebble inclinations of 2° to 12°.

The inclination of pebbles in the Trias conglomerates mainly falls in the former range (see Figs. 128-132) which indicates a fluviatile origin for these sediments, confirming the result obtained from the study of limestone pebble morphology (p. 160).

Direction of dip is predominantly upstream, and will be discussed in more detail in Chapter IX.

4. MUD-CRACKS

Desiccation cracks in mud, filled by sandstone, were found only at Gruinard Bay. The rarity of the structure can be attributed to the rarity of the fine-grained sediment in which it develops. The mud occurs as thin chocolate-brown laminae within a bed of flat bedded medium-grained micaceous sandstone. It has cracked into polygonal fragments 1 to 5 cms in diameter which have curled up slightly at the edges so that the flakes lie with their concave sides upwards. The cracks vary from 1 to 8 mm in width and 0.5 to 2 mm in depth and are filled with sand from the enclosing sandstone bed (Fig. 45a).

These cracks indicate periods of non-deposition when the sediment was exposed to a warm dry atmosphere. When sedimentation resumed some of the mud flakes were prised free and carried a short distance to be re-deposited with sand as a mud-flake pseudo-conglomerate (Fig. 45b).

Polygonal cracks at the tops of cornstone beds are also attributed to desiccation of sediment. Some exceptional cracks penetrate to a depth of 15 to 20 cms.

5. PARTING LINEATION

Parting lineation (Crowell 1955, p. 1361) was found at two localities: Gairloch Big Sand and Leac Dubh (Gruinard Bay). It is a series of parallel off-set ridges and hollows of very low relief and is developed in flat-bedded laminated sandstones at both localities. One sandstone is coarse-grained feldspathic and the other is medium-grained quartzose sandstone.

A review of the literature on the structure is given by Potter and Pettijohn (1963, pp. 137-138), the main earlier works being those of Sorby (1856) who first discovered it, Cloos (1938) and Stokes (1947).

Recently McBride and Yeakel (1963, p. 780) have divided the structure into

1. parting plane lineation : subparallel linear shallow grooves and ridges of low relief on lamination surfaces,

and 2. parting-step lamination : subparallel step-like ridges when the parting surface cuts across several adjacent laminations.

Both types occur in the Trias sandstones (Figs. 46 a&b).

The fabric of a specimen from Leac Dubh (Ab 25) was examined microscopically in six slices : three cut horizontally (parallel to the bedding) and three cut perpendicular to the bedding. The orientation of the axes of grains with a length : breadth ratio of 2:1 or more was measured relative to the vertical cross-wire of the microscope, taking the parting lineation (horizontal sections) or bedding (vertical sections) as parallel to that cross-wire.

The results were analysed statistically by Curray's (1956a) vectorial method for examining circular distributions. Chayes (1954) showed that the main objection to the use of a linear distribution is the lack of a known origin for the frequency curve, and since small changes in origin give different results for the mean and the variance, these cannot be used easily to test for significance, particularly when a wide distribution is involved. The use of a circular distribution overcomes this difficulty. It also solves the problem created by the measurement of the orientation of sedimentary particles in which no distinction is made between the two ends of a particle. The vector distribution and magnitude are calculated using the following formulae:

$$r = \sqrt{(\Sigma n \sin 2\theta)^2 - (\Sigma n \cos 2\theta)^2}$$

$$L = \frac{r}{\Sigma n} \times 100$$

$$\bar{\theta} = \frac{1}{2} \arctan \frac{\Sigma n \sin 2\theta}{\Sigma n \cos 2\theta}$$

where θ = azimuth from 0° to 360° of each observation or group of observations

$\bar{\theta}$ = azimuth of resultant vector

n = observation vector magnitude

r = magnitude of resultant vector

and L = magnitude of resultant vector in terms of percent.

The Rayleigh test for significance is used, although it should be noted that it is not suitable for polymodal distributions where the vector is very weak.

Statistical summary of grain orientations:

1. Sections cut perpendicular to bedding and parallel to lineation.

Section number	Number of grains measured	Angle of imbrication	Long axis vector magnitude (%)	Probability (p)
Ab 25 IV	150	16°	65.9	$<10^{-20}$
Ab 25 2V	150	$13\frac{1}{2}^\circ$	70.8	$<10^{-20}$
Ab 25 3V	150	14°	81.9	$<10^{-20}$

2. Sections cut parallel to bedding.

Section number	Number of grains measured	Deviation of fabric from lineation	Long axis vector magnitude(%)	Probability
Ab 25 IH	250	$6\frac{1}{2}^\circ$	26.5	$< 10^{-5}$
Ab 25 2H	250	$16\frac{1}{2}^\circ$	8.0	$>.10$
Ab 25 3H	250	0°	13.6	.01

$p < .05$ required for significance.

Grains in vertical sections have distributions of very high statistical significance. The angles of imbrication are smaller than those found in up-current imbrication by Schwarzacher (1951) and larger than those of Allen (1964), but fall within the range found by Rusnak (1957). The results of Schwarzacher and Rusnak were obtained from flume-study experiments and Allen's from a study of the fabric of a sandstone showing parting lineation.

In two of the three horizontal sections there is a significant orientation of grains, the vector means being parallel or nearly parallel to the orientation of the macroscopic lineation.

Many workers have noted preferred grain orientation in sands and sandstones (e.g. Dapples and Rominger 1945, Schwarzacher 1951, Griffiths and Rosenfeld 1953, and Rusnak 1957) but only Potter and Mast (1963) and Allen (1964) have related the preferred orientation statistically with macroscopic lineation. Potter and Mast found a deviation of grain orientation from parting lineation of 5°, while Allen's deviation results vary from 5° to 18°. In this study the two significant results give deviations of 0° and $6\frac{1}{2}^{\circ}$.

McBride and Yeakel (1963) interpreted parting lineation in sandstones to be of fluviatile origin, but noted that the structure is believed to occur in other shallow water sandstones and is also commonly developed in deep water turbidite sandstones. Of three internal sedimentary structures in well-washed sands and sandstones discussed by Allen (1963), even laminations with parting lineation was considered by him to be associated with the highest flow intensity.

Allan (1964) demonstrated experimentally that parting ('primary current') lineation can only form as a stable configuration in the upper flow regime (Froude number $\gg 0.75$). He concluded that the structure may have been formed in two distinct geographical environments:

1. a beach subjected to repeated exposure and swash and back-swash action,

and 2. a submerged channel with a 'unidirectional' upper flow regime e.g. river or tidal ebb-flood channel with sandy beds.

From textural considerations the second environment is preferred for the structures in the Trias sandstones, the lineation having been produced in a river channel rather than a tidal ebb-flood channel.

LENS AND FLASER BEDDING

Fine grained silt lenticles alternating with darker mud layers occur in siltstones immediately overlying the Trias at Applecross (see p. 69). The lenticles measure 0.5 to 1.0 cms in thickness and are associated with overlying thinly laminated bedding (Fig. 47a). These compare closely with the 'flaser bedding' of Pettijohn and Potter (1964, Plates 17A, 17B) and bear a striking resemblance to bedding found in tidal muds of the German North Sea Coast and the Dutch Wadden Sea. These have been described by several workers including Häntzchel (1936) and Reineck (1960) : Reineck has described 'lens bedding' (Linsenschichten) and 'flaser bedding' (Flaserschichten) which is similar to the bedding described above. Fig. 47b shows a sample from the German Wattenschlick (Häntzschel 1936) which is almost identical to the lower part of the specimen from Applecross.

Other workers (e.g. Moore and Scruton 1957 and van Straaten 1959) have found similar structures in marine deltas, and it therefore appears that the structure can form in two environments:

1. tidal deposits;
2. shallower parts of deltas (proximal fluviomarine).

In either case marine conditions are involved. This therefore shows that the passage beds overlying the Trias in Applecross should be referred to the Rhaetic rather than to the top of the Trias as was previously thought (see p. 69).

CHAPTER IX

PALAEOCURRENT ANALYSIS

IX PALAEOCURRENT ANALYSIS

INTRODUCTION

One of the first geologists to recognise the relation between asymmetry of many sedimentary structures and current direction was Sorby (1856). Although a few similar observations were made by other geologists during the latter part of the nineteenth century and the early part of this century, it has only been within the last 30 years that serious attention has been given to palaeocurrent data and analysis.

The study of palaeocurrents has now become standard practice in the study of sedimentary formations, and the recent development of the subject has been too rapid to review here. Potter and Pettijohn (1963) have compiled an excellent textbook on the subject : the reader interested in its historical development is referred to the review given in Chapter 2 of their book.

Modern palaeocurrent studies are based on the following properties:

1. Sedimentary structures with directional significance. Individual types of structure can be measured as criteria of current flow, or the results from several significant studies may be combined to give an integrated analysis.

2. Attribute and scalar properties. These must be mapped in order to be of directional significance.

3. Tensor properties. These are dependent on fabric, and have not been used much. It is probably in this field that the subject will develope most in the future.

In this study sedimentary structures, attribute and scalar properties are used.

1. DIRECTIONAL STRUCTURES.

The disappointing lack of sedimentary structures has already been referred to in the previous chapter : this limited the amount of palaeocurrent data that could be obtained. Only two structures could be measured : cross-bedding (rarely weathered out enough to measure) and imbrication of pebbles in conglomerates. Parting lineation was found in only two outcrops and so was not used.

a. Cross-bedding

Numerous experimental studies such as those by McKee (1957) have shown that cross-bedding is formed when sand grains carried by unidirectional currents are built forward into deeper water as superimposed layers inclined at the angle of rest. Cross-bedding may therefore be taken as a guide to current direction, and its measurement and mapping are now commonplace.

Measurements of the direction of dip of cross-bedding planes were made with a compass and clinometer, and plotted on a rose diagram after correction for the dip of the bedding by rotation on a lower hemisphere sterographic projection using a Schmidt equal area net. The results were analysed statistically by Curray's (1956a) vectorial method as described in the previous chapter. The formulae given on p. 200 are again used, except that in this case

$$r = \sqrt{(\Sigma n \sin\theta)^2 + (\Sigma n \cos\theta)^2}$$

and $$\tan\bar{\theta} = \frac{\Sigma n \sin\theta}{\Sigma n \cos\theta}$$

The Rayleigh test for significance is also used again.

A sufficient number of well exposed cross-bedding planes suitable for measurement were found only at Inchkenneth (Humpies Conglomerate, and near the top of the Chapel Beds), Rudha an t-Sassunaich (Morvern), Mingary (Ardnamurchan), and Udrigle (Gruinard Bay). The plots are given in Figs. 134-138, and a statistical summary of the results is as follows:

Locality	No. of measurements	Mean Vector	Vectorial Mean %	Probability
Inchkenneth (Humpies Congl.)	25	106°	95.6	$< 10^{-5}$
Inchkenneth (Humpies Congl.)	25	199°	93.2	$< 10^{-5}$
Gribun (Humpies Congl.)	25	$100\frac{1}{3}^{\circ}$	99.7	$< 10^{-10}$
Rudha an t-Sassunaich	25	122°	88.0	$< 10^{-5}$
Mingary	25	$144\frac{2}{3}^{\circ}$	98.4	$< 10^{-10}$
Udrigle	63	$298\frac{2}{3}^{\circ}$	85.9	$< 10^{-20}$

These are all very significant groups of results, the highest possibility that any of them could have arisen by chance being 1 in 100,000.

The Gribun measurements were made on a single set of cross-strata (Fig. 12) while those from the Humpies Conglomerate on Inchkenneth were taken from several cross-bedded grit and sandstone lenses which gives a less concentrated result.

Measurements were also made of cross-bedding at Rudha na Leac on Raasay and at Camas Mor, but neither produced a significant grouping of vectors.

Comparisons were made between the results by comparing the variance ratio with the standard error of different (S.E.D.). The variance ratio between two vector populations is $\bar{\theta}_1 - \bar{\theta}_2$ where $\bar{\theta}$ = mean vector azimuth.

$$\text{S.E.D.} = \sqrt{\frac{(L_1)^2}{n_1} + \frac{(L_2)^2}{n_2}}$$ where L = standard deviation and n = number in the population.

If the variance is less than the S.E.D. there is no significant difference between the two sets of results.

Inchkenneth : Humpies Conglomerate v. Chapel Beds	: different.
Gribun v. Inchkenneth (Chapel Beds)	: different.
Gribun v. Inchkenneth (Humpies Conglomerate)	: not different.
Gribun v. Rudha an t-Sassunaich	: not different.
Gribun v. Mingary	: different.
Rudha an t-Sassunaich v. Mingary	: not different.

Udrigle : different from all the others.

Thus currents depositing the basal conglomerates in Western Mull and the sandstones in Morvern and Ardnamurchan flowed southeastwards from a westerly or northwesterly source. The Ardnamurchan currents contained significantly more of the south component in these directions than those of Western Mull. At Udrigle, currents flowed in a northwesterly direction.

b. Imbrication.

Studies of gravel fabric, as summarised by Potter and Pettijohn (1963, p. 35) have shown that in modern rivers the overwhelming majority of disc-like and ellipsoidal particles have their planes of maximum projection dipping up-current. Down-current imbrication is very rare : Krumbein (1940, 1942) recorded localised reversed imbrication in the "shadow zone" of a large boulder which had caused reversed currents and eddies to be generated, but such an arrangement is unusual, although a few other anomalous occurrences have been reported (Kalterherberg 1956, Rushkin 1958). Thus the direction of imbrication of disc-shaped pebbles in conglomerates provides a reasonable guide to the direction of flow of the depositing current.

Potter and Pettijohn (1963 p. 36) have also reviewed the literature concerning orientation of the long axis of pebbles in streams. These may lie either parallel or perpendicular to the stream flow direction. Both size and shape may act as controls, while Cailleux (1940) has suggested environmental control, with long axes of beach pebbles always arranged parallel to the shore, regardless of size and shape, and stream pebbles having their long axes perpendicular to the current. Fig. 48 shows small disc-shaped pebbles in a Trias sandstone (Gh 5) orientated with their long axes perpendicular to the current direction as indicated by parting lineation. However, it is difficult to determine the position of the long axis when a pebble is incompletely exposed in a conglomerate, particularly discoidal pebbles which have little difference between the long and intermediate axes. In this study it was decided not to use this directional property, particularly as the other pebble orientation property is so effective.

In the field the strike and dip of the AB plane of Kalterherberg (1956) was measured. This is equivalent to the plane containing a and b (Krumbein 1941) or L and l (Cailleux 1945) and is therefore the plane of maximum projection. In most cases of pebbles contained in conglomerates only the apparent maximum projection plane (A'B') can be measured, but generally this is identical to the real one (although the apparent longest axes is very often quite different from the real one). Care was taken to record the principal surface of accumulation (S_p), which is usually the bedding plane : as Potter and Pettijohn (1963 p. 35) have pointed out, misleading results can arise if this precaution is not taken. Fig. 4 shows pebbles on a foreset bedding plane giving an apparent down-current imbrication with respect to the normal bedding, whereas with respect to the foreset bed , which is S_p, the imbrication is still up-current.

Poles to the measured planes were plotted on a lower hemisphere equal area stereographic (Schmidt) net and rotated to correct for the dip of S_p. The resulting distribution was contoured using a 1% counter centred at the intersection of a grid of 1 cm squares (Phillips 1954). Although this method is conventional, it produces much detail that is of no statistical significance (Kamb 1959). An alternative method has been proposed by Johansson (1963), but as it produces distortion in certain parts of the field it was not used in this study. If little account is taken of the finer detail, the original method is satisfactory.

Imbrication was measured at Inchkenneth, Gribun, Rudha an t-Sassunaich, Rudha na Leac and Udrigle. A small amount of reversed imbrication was recognised at Gribun and Inchkenneth (Fig. 11a) which is reflected in the measured results. However, a prominent maximum concentration was obtained at each of the five localities indicating the current flow direction. The plots are given in Figs. 128-132 and are summarised as follows:

Locality	No. of pebbles measured	Direction of current flow
Inchkenneth (Humpies Congl.)	100	S.E.
Gribun (Humpies Congl.)	100	S.E.
Rudha an t-Sassunaich	100	S.E.
Rudha na Leac	100	N.
Udrigle	100	S.W.

The Mull and Morvern results compare closely with the directions obtained from cross-bedding at the same localities. The Udrigle result only shares a westerly component with the cross-bedding evidence, but the latter was measured approximately 60 m higher in the succession, which suggests that the source swung from southeast to northeast. The Raasay result is interesting, indicating a source to the south in the Central Skye area, while the tendency at Rudha na Leac is for conglomerates to give way northwards to sandstones (p. 66 and Fig. 152).

2. ATTRIBUTE AND SCALAR PROPERTIES

Mapping of the presence or absence of pebbles types in the Trias conglomerates has not on its own produced precise evidence of palaeocurrents. Fragments of Durness Carbonate, Cambrian orthoquartzite and Torridonian sandstone occur throughout the area mapped, except in Ardnamurchan and Morvern. There their absence does not necessarily indicate currents with their source in a direction different from that in which these formations lay (i.e. west and northwest) : palaeocurrents interpreted at these localities from directional structures flowed from the northwest, and the absence of these three pebble types therefore shows that the depositing streams could not have flowed far, their sources being southeast of the projected position of the Moine Thrust. In Central Skye the clear-cut distribution of the limestone conglomerate can only be used as a directional property when considered in conjunction with the mapping of scalar properties (see below). There is marked rarity of quartzose Moine schists in the lower parts of the successions, particularly in Western Mull where directional structures show palaeocurrents flowing from the west and north-west i.e. a direction almost opposite to that in which quartzose Moine rocks are now known to occur. The increase in these pebbles in the upper parts of the succession is associated with the northeasterly source direction obtained from cross-bedding at the top of the Inchkenneth Chapel Beds and the southeasterly source from cross-bedding high in the succession at Gruinard Bay. The presence of fossiliferous Durness Carbonate pebbles in Raasay, with a possible source in Ben Suardal, Strath (the most fossiliferous Durness Carbonate locality known at the present time) fits well with the evidence from imbrication and lithology that the currents in Raasay flowed from the south.

Scalar studies of pebbles produced more precise results. Schlee (1957) and Pelletier (1958) succeeded in mapping current directions based on down-current decline in maximum pebble size in conglomerates. Pelletier found that the largest diameters of the 10 largest pebbles at a specific locality were generally within a few millimetres of each other in size : he recorded the average of the 10 largest quartz pebbles at each locality and plotted the results on a map, the technique being similar to that first described by Eckis (1928).

In this study the method was applied to an analysis of the Trias outcrops around the flanks of the Strath Syncline in Central Skye. Measurement localities were determined by the availability of exposures so that grid sampling could not be followed closely, although a reasonably detailed coverage of the outcrops was obtained. At each locality apparent maximum diameters of the largest pebbles were measured until the 10 largest were recorded : this usually involved the measurement of 20 to 30 obviously large pebbles, from which the 10 largest were selected and their average taken. Three pebble types were used : Torridonian sandstone, Cambrian orthoquartzite and Durness Carbonate, each being treated separately. The 10 largest diameters of each type usually fell within a few centimetres of each other, which is a fairly close grouping considering that many of the averages fall between 20 and 35 cms. Plots of the results were not corrected for crustal shortening in the syncline because dips are so low (c. 15°) that the correction factor would be negligible.

The results are shown in Figs 140-2 with isopleths drawn in. Each of the three sets of data shows that the current flowed from southwest to northeast. The Torridonian sandstone patterns show some apparent anomalies, but these arise because the basement rocks are Torridonian almost throughout, and fragments of the basement have been incorporated in the base of the Trias successions almost everywhere, although red sandstone may be completely absent higher up. The very distinct distribution of the limestone conglomerate as mapped in the field is superimposed on the 'limestone' pebble isopleth map. The western limit of the quartzose sandstones and grits is also shown for comparison : it corresponds closely with the eastern limit of the limestone conglomerate, giving only a slight overlap.

This result is in accord with the observation made in the field that the Trias is banked against a low hill south of Beinn an Dubhaich causing it to thin southwestwards in that part of the syncline until it is overlapped by the Lias (Fig. 143). The very large size and angularity of the boulders around Beinn a Mheadhoin suggests that the clastic material there has travelled little or no distance from its source.

From their morphology and lithology the Trias sediments in Strath appear to form an alluvial fan focussed on the Bein Bhuidhe area, spreading out northwestwards, thickening fairly rapidly off the slopes of the buried hill, and then thinning gradually again northwestwards. This is rather similar to the alluvial fans mapped by Bluck (1964, 1965) who found both mudflow and water lain deposits in recent and fossil fans. The major part of the Strath fan has been water lain, but the fine-grained calcareous muddy matrix occurring near the base of parts of the limestone conglomerate suggests a probable modification by mudflow deposition. Blissenbach (1952) demonstrated an exponential rate of change in maximum particle size with an equal rate of change of slope; the interval between isopleths may therefore indicate the relative steepness of the surface upon which the sediments were deposited.

Similar measurements were made in each of the other main areas studied, to test whether there is any overall regional pattern of current deposition. The results are given in Fig. 143a and show no significant trend, from which it is concluded that sedimentation took place under localised current conditions. This is supported by outcrop distribution, lack of correlation of successions, and the results of the palaeocurrent analysis from directional structures.

CHAPTER X

DISCUSSION AND CONCLUSIONS

X DISCUSSION AND CONCLUSIONS

In this chapter an attempt is made to assess the depositional environment of the Trias sediments from the evidence presented above. The palaeogeography, including the nature and position of the source areas, is also considered. The regional setting of the West Highland Trias is briefly considered in a comparison with evidence from Trias sediments of the Moray Firth area, Arran, and northeast Ireland.

1. DEPOSITIONAL ENVIRONMENT

Textural and structural evidence indicates that nearly all the clastic sediments are of fluviatile origin, and may be compared with recent river deposits that have similar characteristics. The one exception is a sandstone collected from Loch Spelve in Southeast Mull, which may be eolian.

Leopold and Wolman (1957) have proposed that rivers may be classified according to their trace, into:
1. straight rivers;
2. braided rivers;
3. meandering rivers.

These are related to various factors, such as regime, load, gradient and velocity, which also control the amount and kind of alluvium deposited. Thus they may be recognised by the types of alluvium associated with them. Shantser (1951) recognised three facies of alluvium:

1. Flood-plain: essentially fine-grained sands, silts and clays deposited out of suspension at times of flooding.

2. Channel deposits: mainly coarse sands and gravels deposited by fast flowing traction currents in the river themselves.

3. Oxbow: silts and clays laid down in temporary lakes formed by cutting-off of old river channels.

Flood-plain and oxbow facies strongly predominate over channel deposits in meandering rivers (Fisk 1947, Turnbull Krinitzsky and Johnson 1950), but coarse-grained channel facies are typical of braided rivers (Kartashov 1961, Doeglas 1962).

The oxbow facies is unlike almost anything in the Trias sediments, and so may be discounted as a possible modern equivalent. It has been shown above (Chapter VI) that the Trias sandstones are characterised by the lack of material carried in suspension, while comparison with recent flood-plain deposits shows that most of the sediments cannot belong to this facies. However, siltstones occasionally found near the top of the succession belong to the flood-plain facies, and can therefore be considered to have been deposited by meandering rivers.

Sandstones and conglomerates comprising the main part of the Trias succession conform with the characteristics of the channel facies. This therefore indicates that they have been deposited by braided rivers in a moderate to high flow regime, rather than by meandering or straight rivers. The latter tend to be very fast flowing, depositing very little alluvium which is only temporary when present.

Comparison with the characteristics of modern fluviatile sediments as described by Twenhofel (1932, p. 800 et seq) and others suggests in the Trias that the coarse conglomerates and breccias with their associated grits and sandstones have formed as piedmont deposits, while sandstones higher in the succession may have accumulated as valley-flat deposits or in an environment transitional between piedmont and valley-flat.

a. <u>Piedmont deposits</u>

In the Strath Syncline an alluvial fan or 'fanglomerate' (Lawson 1913) has been traced (pp. 213-214). This is characterised by several of the criteria that Twenhofel (1932) listed for piedmont deposits, and is similar to alluvial fans described by Blissenbach (1952, 1954), Bull (1963) and Bluck (1964, 1965). Although coarse basal deposits elsewhere could not be mapped on a three-dimensional scale, they nevertheless exhibit many features that these writers have described. The principal ones present are:

1. Large range of particle sizes giving very poor sorting.
2. A few predominant rock types occur, all of local derivation.
3. Poor stratification.
4. Lenticular nature of stratification.
5. Sand-filled cross-bedded stream channels (channel cut-and-fill).
6. Imbrication of gravels.
7. Angular, subangular and subrounded fragments.
8. Particles become finer with increasing distance from the source area.

The Humpies Conglomerate (and breccia) at Inchkenneth and Gribun is a fine example, although it contains a wide variety of rock types in the pebbles : these, however, have been shown to have been derived from an area within an arc of 5 to 10 kms radius to the west, while the abundant angular Moine fragments are even more local.

Blissenbach (1954) noted that mudflows are common features of alluvial fans, although they are not present in all, and their frequency depends on climatic variations (more common with less rainfall).

Bull (1963) classified alluvial fan deposits in California into

1. mudflows,

2. water-laid sediments,

and 3. intermediate types.

The presence of mudflow sediments in Strath has been suggested above (p. 214), which is worth considering in more detail here. There are very few published size analyses of mudflow deposits, but Bull (1963) gave cumulative curves for 6 mudflows : these have gentle low angle slopes which extend from the gravel to the clay fraction. Unfortunately the probable mudflow deposits encountered in this study could not be analysed for size distribution because good induration and high carbonate detrital content precluded mechanical methods, while the range of grain sizes was too great for the thin section method. However, inspection in hand specimen shows that a very wide range of grain sizes is present (gravel to clay), and it is reasonable to assume that this would produce curves similar to those given by Bull. In polished section the mudflow limestone conglomerate is similar to the deposit illustrated by Bull (1963, Plate 1A). A photomicrograph of part of the rock is shown in Fig. 60c . The mudflow hypothesis is the most likely explanation for the wide range of size grades.

Bluck (1965) also found an association of mudflows and water-laid sediments in alluvial fans. He concluded that they have the following characteristics:

Stream flood (mudflow) deposits	Stream deposits
Lobate in shape	Fan shaped
Contain 'rafts' of older fan material	No 'rafts' of older material
Poorly sorted	Better sorted
Mud in matrix	No mud in matrix

The Strath mudflow occurs at the base of the Trias and therefore cannot contain 'rafts' of older fan material. Its shape is uncertain, but its distribution is well-defined, being found only on the northeast slopes of Beinn a Mheadhoinn and along the north side of Beinn a' Chairn. It is poorly sorted and contains a muddy matrix.

Bull (1963) reviewed the formation and mechanism of mudflows, showing that they move in surges down stream channels. They may be viscous (no graded bedding and no preferred orientation of flat gravel fragments) or fluid (graded bedding, gravel fragments lie parallel to the bedding). The Strath mudflow was probably fairly viscous.

All the other coarse-grained Trias sediments, both in Skye and elsewhere, have clean-washed matrices and clearly are stream deposits. They are poorly or moderately sorted and contain no re-worked 'rafts' of older fan material.

The Trias piedmont deposits are not generally thick by comparison with their modern counterparts, although thick deposits which are not purely piedmont occur in the north of the area (Isle of Ewe and Gruinard Bay). It is difficult to determine the original surface dips, but they appear to have been generally low ($< 10^{\circ}$). Trowbridge (1911) suggested that stratification planes of alluvial fans have inclinations of up to 16° to 18°, but in fans studied by Blissenbach (1952) apical dips have values of 20°, 7°, 6° and $3\frac{1}{2}^{\circ}$, which fall off very rapidly away from the apex. Talus slopes, occurring at the fan-head, have higher dips, but none were recognised in the Trias deposits.

Particles in alluvial fans are not invariably angular : Blissenbach (1954) found pebbles of up to roundness 0.7 (Krumbein 1941) in a fan of 4 miles radius. Particles in the Trias fanglomerates are predominantly angular, but moderately rounded carbonate pebbles occur in the Humpies Conglomerate at Inchkenneth and Gribun.

The coarse sand and gravel of the fanglomerates were deposited in the main stream channels, but over these deposits flowed networks of braided streams which deposited sand in sheets and small channels. There is some evidence of strong erosive currents (e.g. at the base of the Iollaich Beds on Inchkenneth) representing the action of streams with straight traces.

b. Intermediate and valley-flat deposits

Parts of the Trias successions are composed of indistinct fluviatile cycles consisting of crudely graded units with conglomerate at the base grading up into grits and sandstones. These cannot be confidently compared with either true alluvial fan or valley-flat deposits, and are likely to represent deposits intermediate between the two, where alluvial fans grade insensibly into the valley-flat environment, or where the lower outer margins of two adjacent fans coalesced. They have a more regular stratification than true piedmont deposits, yet are still much coarser than typical valley-flat sediments. The upper portions of the Trias successions are of this nature and may reflect 1. the smoothing out of the Trias landscape as depressions in the topography became filled with debris and 2. a more distant sediment source area. Cornstones are typically associated with these deposits, being developed at the tops of cycles.

True valley-flat deposits are rare, but a good example occurs at Laide, at the southeastern end of the section along Gruinard Bay, where there are micaceous shaly siltstones that are sufficiently fine-grained to be considered as flood-plain sediments. They are associated with fine-grained laminated sandstones and desiccated muds, and contain scattered irregular cornstones developed at the top. The finest-grained sediments may represent oxbow facies. At one locality (Leac Dubh) the siltstones are cut by a shallow channel 7 m wide which is filled with cross-bedded medium-grained sandstone and probably represents the path of a stream migrating over its flood-plain. A similar siltstone, without channels, occurs at the top of the Trias at Heast, Strath (1.5 m), and the fine-grained sediments at Loch Sligachan and the top of the Applecross succession are also probably valley-flat deposits.

Thus as a general rule we have piedmont deposits followed by intermediate and occasionally valley-flat deposits. Sedimentation was probably initiated by seasonal wet periods, followed by slackening of currents and then the drying up of rivers during dry seasons when cornstones may have developed. It is not clear how quickly a caliche soil profile can be produced, but it seems likely that a mature profile requires considerably more than a single season to develope, with many episodes of wetting and evaporation. The presence of a pedocal probably indicates not only the absence of fluviatile deposition during a single season, but also that the river channel migrated elsewhere for a period of perhaps many years. This could occur within a network of braided streams with a constantly changing pattern and channels that carried water spasmodically, with enormous variations in discharge.

Feldspathic sandstones are typically associated with the piedmont deposits, while the quartzose sandstones occur as intermediate or valley-flat deposits. This illustrates the observation of Pettijohn (1957) and Hayes (1962) that the relative percentage of feldspar decreases rapidly in high gradient streams.

Most of the Trias successions are rather thin (complete successions in the centre and south of the area range from a few metres to over 70 m) but the thick successions at Isle of Ewe and Gruinard Bay are rather enigmatic. The rapid alternations of sandstone and conglomerate that comprise the major parts of both successions are reminiscent of the sediments mapped by Bryhni (1964 a and b) on a very much larger scale in the Devonian of Norway, which he interpreted as the product of a migrating basin which was initiated as a trough bordered by hinge-faults. This produces a large stratigraphical thickness of sediment, which however may not occur complete in a vertical section (Fig. 143c). In support of this hypothesis it is noted that the Trias at Gruinard Bay occurs within a graben formed by two major N.E. striking normal faults (with another of similar strike in between). The Trias at Isle of Ewe, interpreted by the Geological Survey as a continuation of a strip of Trias (unexposed) extending across the neck of land between Gruinard Bay and Loch Ewe, is not faulted against the Torridonian. Therefore the faulting dies out southwestwards, having a hinge-like resultant displacement. It has been mentioned above (Chapter IV) that many of the faults in Wester Ross have had several phases of movement : if this fault system dates back at least to Trias times it could have played an important role in the accumulation of the relatively large thickness of sediment there. Similarly, the Loch Maree fault may have influenced the deposition of the Trias sediments at Camas Mor, which may also have been very thick.

In a geophysical investigation of Trotternish (N. Skye), Tuson (1959) discovered an area of low Bouguer anomalies at Loch Snizort. He considered that the most likely interpretation, subject to certain reservations, is that beneath the Trotternish Tertiary lavas there is a wedge of Trias sediments 2,400 ft thick, terminated by a near vertical fault along the eastern margin of the wedge. Alternatively, the anomalies could have been caused by an enormous thickening of Jurassic, Cretaceous or Tertiary sediments, as these could equally well have produced the observed results, but the presence of thick Trias sediments was preferred by Tuson on geological grounds. Nevertheless, this interpretation is not unique, and either Permian, Carboniferous or Old Red Sandstone sediments could be responsible for the low (Dr. M.H.P. Bott, pers.comm.). Fault control of sedimentation could explain the occurrence of such a relatively large thickness of the Trias in north Skye, when in the rest of Skye it is thin (c. 50 ft maximum).

However, this remains a tentative hypothesis, and the evidence from the palaeocurrent data at Gruinard Bay is inconclusive.

2. SOURCE ROCKS AND PALAEOCURRENTS

It has been established in Chapter V that the materials in the Trias sediments were derived mainly from Moine, Torridonian and Cambro-Ordovician source rocks, with Old Red Sandstone igneous rocks providing a subsidiary source in Western Mull and Morvern and the Lewisian to a very small extent in the centre of the area (possibly re-worked from the Torridonian, together with 'exotic' igneous pebbles). A few of the pebbles have been derived from rocks involved in tectonic movements, probably adjacent to one of the major thrusts.

Palaeocurrent evidence is sparse; the main features are summarised in Fig. 143b. In Western Mull currents flowing from the northwest initially deposited very local detritus derived from the Moine, followed by a mixture of Moine, Old Red Sandstone igneous rocks, Torridonian and Cambro-Ordovician rocks. This indicates an Old Red Sandstone igneous complex intruding the Moine west of Inchkenneth (of which the Ross of Mull granite is the remnant), with an upland area of Torridonian overlain by Cambrian quartzite and Durness Carbonate beyond the Moine Thrust, but not more than about 10 kms distant. This upland area was probably the focus of the Humpies fanglomerate which covered the lower-lying Moine surface first, and then spread out onto the slopes of a low hill of Moine rising to the southwest. The changes in pebble content in the fanglomerate at Inchkenneth reflect slight changes in the source : at the base of the Iollaich Beds there is a reversion to Moine fragments only. In the upper part of the Chapel Beds, which are of intermediate type, a current source to the northeast is indicated, accompanied by a predominence of quartzose Moine fragments which are rare lower in the succession.

In Morvern and Ardnamurchan currents flowed from the northeast, and must have been of very local derivation because no rocks of the stable foreland beyond the Moine Thrust are present. In Skye a thin alluvial fan with a mudflow was built out northeastwards from an upland source in the southwest of Strath, and the pebbles are dominantly of local rock-types: Torridonian, Cambrian quartzite and Durness Carbonate. However, the sandstones and grits in the upper part of the succession contain abundant fragments of Moine, and may have had a more southerly or southeasterly source as the local source rocks become denunded and buried. Thus the alluvial fan gives way northeastwards to intermediate deposits, while thin valley-flat deposits occur at the top in places (e.g. Heast).

The Raasay sediments have been derived from the south (either the Ben Suardal area of Strath, or the Scalpay area). In the Laide graben currents have had an easterly derivation : in the middle of the succession imbrication indicates a current flowing from the northeast, along the length of the graben, while cross-bedding 60 m further up in the succession shows a current derived from the southeast, at right angles to the graben. This change could have been influenced by a changing topography, determined by movement along the boundary faults. At Laide there is a development of a very coarse conglomerate of Torridonian sandstone, Cambrian quartzite and Durness Carbonate near the base which represents a fanglomerate facies, but this soon gives way to intermediate facies, with valley-flat (floodplain) sediments at the very top possibly indicating a late-stage peneplanation of the topography. The isolated horizon of coarse conglomerate high in the succession, near Udrigle House, may reflect a rejuvenation of the source area by fault movement. In the upper part of the succession quartzose Moine rocks predominate, having a rather more distant easterly or southeasterly source which corresponds to the facies change.

Lack of correlation between areas, variations in palaeocurrents and pebble contents, and the outcrop distribution indicate that the Trias accumulated in a series of at least partially isolated basins. The underlying topography is uneven both on a local and a regional scale and apart from thick deposits in the north, variations in thickness are controlled mainly by variations in the topography. Towards the end of Trias times some of these basins may have coalesced, with smoothing out of the topography.

Fig. 143bshows the palaeocurrents superimposed on the palaeogeography. Areas of Trias deposition are minimum : several of them may have been joined. Many of the palaeogeological boundaries are obviously very hypothetical, but they are drawn to fit evidence from the pebble type distributions and present day relationships. The Moine Thrust outcrop is shown in its present position, although this was probably somewhat further west in Trias times. The Lewisian exposure was certainly much less than at the present time; very little Lewisian material was found in the Trias and therefore only relatively small outcrops representative of the larger Lewisian areas known today are shown. The Cambrian quartzite in the north may have extended further west across the Lewisian than shown : large fragments occur in the conglomerates at Camas Mor.

The Southeast Mull outcrops are difficult to interpret. No positive determination of palaeocurrents was possible, although single solitary sets of cross-bedding at Craignure and Loch Don suggest a northerly derivation, and the southward decrease in particle size in the Loch Don anticline appears to support this. However, it is inconceivable that the abundant cobbles of orthoquartzite at Loch Spelve could have been derived from that direction : a likely source is the Garvellachs, Scarba and Jura where there is a large extent of quartzite which may be Cambrian. Two possible current directions are therefore shown on the map.

3. PALAEOCLIMATE

The predominance of water-laid sediments indicates that the area enjoyed an appreciable rainfall during Trias times. From observations of recent alluvial fans, Blissenbach (1954, p. 188) concluded that no mudflow deposits are expected if the mean annual precipitation exceeds 20 or 25 inches. In the West Highland Trias, a probable mudflow was found at only one locality, and so the rainfall may have been near to this value. The evidence that the rainfall is seasonal is as follows:

1. A mudflow is caused by a sudden release of abundant water.
2. The structure of coarse deposits indicates deposition from periodic torrents rather than continuous sedimentation.
3. Materials of the alluvial fans represent the parent rocks in composition and therefore indicate a predominance of mechanical over chemical weathering.
4. Desiccation cracks occur in fine sediments, indicating arid periods.
5. Pedocal formation requires alternating moist and dry conditions.

A climate that satisfies all the observed features of the sediments is a semi-arid one with a wet season. Temperatures must have been sufficiently high to allow the formation of pedocals, which are only known today in arid and semi-arid regions in low latitudes (tropical, sub-tropical or Mediterranean).

Colours in the Trias sediments are very variable and do not provide an accurate guide to the palaeoclimate. Although pale hues are common, there is a slight majority of red beds. These owe their colour not so much to pink feldspars reworked from the Torridonian (the feldspathic sandstones include grey and white varieties) but rather to red pigment in the thin film of dust surrounding grains and enclosed in a clean calcite cement. Red colours are therefore mainly first cycle rather than inherited second cycle. Van Houten (1964) showed that there is no simple explanation for this, but that first cycle deposits are derived from a source material weathered deeply enough to supply free ferric oxide as the potential pigment, either in chemical solution or in colloidal suspension. To the extent that source areas must provide adequate ferric oxide and deposits must accumulate in an oxidising environment, red beds had a common origin in red or brown upland soils of warm-temperate or tropical climates, but within this broad climatic range red beds as a group have no direct climatic significance (Van Houten 1964, p. 657). The hot semi-arid climate proposed above for the West Highland Trias falls within this range. The nature of the red pigment was not investigated, but Dunham (1952) has shown that the red colouration in many New Red Sandstone sediments is due to turgite (hydrohaematite : Fe_2O_3 with adsorbed water). The basement rocks beneath the Trias are stained red at two localities : Larachbeg (Moine) and Tarskavaig (Torridonian). An investigation of clay minerals, the red pigment and the heavy minerals in the Trias sediments would be required to establish the climate more accurately on the basis of sedimentary composition.

Palaeomagnetic evidence.

Clegg et al (1954) have shown from a study of the remnant magnetisation of the Trias of Britain that the pole was about 40° E of the present meridian, and the latitude of Britain was about 30° to 35°, while Creer, Irving and Runcorn (1958, Fig. 2 f) and Briden and Irving (1964, Fig. 8) showed Britain between 15° and 20° N in Trias times. Runcorn (1961, 1964) showed that easterly palaeowind measurements obtained by Shotton (1937, 1956) from the Bunter sandstone become northeasterly trade winds when corrected for palaeomagnetic declination, although the limited extent of the measurements (English Midlands and Dumfriesshire) renders the argument that they are planetary winds less convincing than the similar case in the western United States. Northeasterlies today are typical of the tradewind zone with latitudes of up to 30°, and lower latitudes than at present are inferred for the Trias of Britain. The climatic conditions proposed for the West Highlands are in accord with these observations.

4. REGIONAL COMPARISONS

A general comparison is made below between the Trias in the West Highlands of Scotland and the Trias sediments in other parts of Scotland and in Northern Ireland. For descriptions of the Trias in other parts of Britain and the rest of the world the reader is referred to the comprehensive review by Sherlock (1947).

a. The Moray Firth area.

Trias sediments occur at Golspie, at the base of the Mesozoic succession of East Sutherland, where they have been described by H.H. Read et al (1925, pp 67-68). A brief visit was made to area, where the Trias is not well exposed. The best section is seen on the shore beneath Dunrobin Castle where calcareous sandstones are overlain by cornstones. Above these, a conglomerate occurs which contains much detrital cornstone. It has been tentatively referred by the Geological Survey to the Rhaetic, and it certainly bears a striking resemblance to the Passage Beds conglomerate at An Leac on Skye, although it does not contain plant fragments. Cornstone collected from Golspie Burn contains abundant chert bands, and in thin section shows many of the textures described from the cornstones at Inninmore and Western Mull, including silicified ooliths. It also contains well-rounded, well-sorted, medium-sized sand grains set in a sparry calcite matrix, which may be of eolian origin.

At Lossiemouth and Elgin in Moray, the Trias has attracted particular attention to the reptilian fauna that it bears. The geology has been described by Murchison (1859), Judd (1873), and Watson (1909), and the reptiles by Huene (1908), Taylor (1920), Westoll (1951) and Walker (1961). A short visit was also made to this area. The Trias sandstones, which are predominantly eolian, are well-exposed at Lossiemouth and in Spynie Wood quarry. At Stotfield the 'Cherty Rock' occurs, which was compared by Judd (1873) with the chert at Golspie. The chert is at least 3 to 5 m thick and is traversed by quartz veins containing galena; it overlies a cornstone which is brecciated and oolitic in parts, being veined by chert in the upper 1 m. This mass of chert cannot have been formed simply from silica freed by diagenetic processes in the cornstone, and it is not comparable with anything observed in the West Highlands.

No evidence was found for a river connecting the Moray Firth and West Highland areas, along the Great Glen Fault or anywhere else (as tentatively suggested by Wills 1951, Plate XIII c).

b. Arran.

The Trias of Arran has been described by Gregory (1915) and Tyrrell (1928, pp 96-103), and briefly summarised by Richey (1961, p. 24). Its total thickness has not been accurately established, but it is well over 1000 ft (300 m). It consists of sandstones, shales and 'marls', with some cornstones associated with the 'marls'. The succession is thicker and finer-grained than most of the West Highland Trias.

c. Northeast Ireland.

The distribution of the Trias in this area has been summarised by Charlesworth (1963, Chapter XII). It reaches nearly 3,000 ft (900 m) in thickness, and the succession includes sandstones exhibiting dune-bedding, ripple-marks, sun-cracked clay partings, rain-pits and clay galls, and red and green 'marls' in which rock-salt and gypsum are developed. There is a basal conglomerate and breccia which may be up to several hundred feet thick, but generally the sediments are finer grained and the succession much thicker than the Trias of the West Highlands of Scotland, and no cornstone is recorded by Charlesworth.

d. Stornoway Beds

Around Broad Bay at Stornoway (Isle of Lewis) there is exposed a great thickness of chocolate-brown conglomerates with a few sandy horizons and lenses. Assuming no repetition by faulting, these are at least 3,000 m thick. The material that they contain is all of local origin : sheared and unsheared Lewisian gneiss. They are the only unmetamorphosed sediments of the Outer Hebrides, and can be referred to one of the three continental formations known in Britain.

Stevenson (1928) and Jehu and Craig (1934) considered the conglomerate to be Torridonian, but Peach and Horne (1930) thought that this was doubtful, while Stevens (1914) referred it to the Trias. However, on the basis of three days fieldwork in the area, the writer is more inclined to agree with Kürsten (1957) that the beds should be assigned to the Devonian. They are much softer than any of the Torridonian deposits observed on the mainland : so much so that much of the building stone in Stornoway has been shipped across the Minch from a quarry in the Torridonian on Isle Martin, near Ullapool. The thickness is much greater than the thickest Trias successions mapped in the West Highlands and the beds contain no recognisable cornstone horizons. Kürsten (1957) suggested that the presence of sheared Lewisian gneiss and pseudotachylite in the conglomerates show them to be post-thrusting : he postulated an affinity between the thrusting in the Outer Hebrides and the Moine Thrust, which would date the conglomerate as post-Cambrian.

Therefore it is considered that the most likely age for these rocks is Devonian and they are not included in a consideration of the West Highland Trias sedimentation. One possible method of finally ascertaining their age is the application of palaeomagnetic techniques, the Torridonian, Devonian and

Trias each giving distinct directions of natural remnant magnetism in Britain. This would depend on finding a fine-grained sandstone sufficiently indurated for coring and the cutting of discs for measurement.

e. Conclusions

In Trias times the West Highland area appears to have been an upland region of variable topography. To the south lay plains where generally finer grained sediments were deposited under fluviatile, lacustrine and possibly some eolian conditions. To the east, dune sands accumulated in the Moray Firth area, where there is a lack of evidence of fluviatile action.

5. SUMMARY

The Trias sediments of the West Highlands accumulated as fluviatile deposits laid down on an uneven surface which consisted mainly of Moine, Torridonian and Cambro-Ordovician rocks. The climate was semi-arid with alternating wet and dry seasons and high temperatures. Sedimentation was initiated as alluvial fans which covered the lower lying basins, spreading out and coalescing into intermediate deposits. On higher land or land not reached by the rivers calcareous soils developed which were eventually overlain by sediment as the area became progressively buried. Sedimentation was mainly from braided rivers which acted spasmodically with frequently changing network patterns. When sediment was exposed for a considerable time calcareous soils developed, especially in sandstones, and were buried by fluviatile gravels and sands on the return of river action.

Most of the sedimentation occurred in rather localised basins with locally derived currents which in the southern part of the area flowed from the west and northwest (and possibly also from the south), and in the centre flowed from the south and southwest. Later, some of these basins may have coalesced, and as the topography became smoother and the source rocks more distant, valley-flat deposits accumulated. Generally the sedimentary successions are rather thin, but in the north contemporaneous fault movements may have influenced the development of thick successions.

Throughout the Trias there is no positive evidence of influence by a prominent upland area in the position of the present Scottish landmass. Early on, sedimentation has been dominated by a discontinuous chain of hills consisting of Torridonian sandstone overlain by a succession of Cambro-Ordovician rocks extending from Loch Broom south-southwestwards to Iona (see Fig. 143b). With progressive denudation, however, the influence of these masses diminished, and in the upper parts of the succession currents with easterly sources began to play an important rôle, bringing in quartzose Moine detritus. This may have marked the start of the exhertion of a positive influence by a Scottish upland area, but by the end of Trias times, when the Rhaetic marine transgression occurred, the Hebridean area was still not fully peneplaned, with monadnocks protruding above the Trias sediments. Thus the Rhaetic transgression took place around scattered islands, with rather sandy sediments deposited in shallow water. The Rhaetic marked a climatic change, with increased rainfall of probably more regular distribution allowing the growth of plants. According to Hallam (1959) in Lower Lias times the islands were still evident, and there was still no apparent 'Scottish landmass'.

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APPENDIX I

PSEUDO-TRIAS

APPENDIX I PSEUDO-TRIAS

In this Appendix the main mineralogical and textural features of the Pseudo-Trias sandstones are briefly summarised and a comparison is made between the Pseudo-Trias sediments and those of the true Trias of the West Highlands.

1. Mineralogy

The sandstones are mainly arkoses with a few subarkoses. They contain abundant quartz (58.3 to 74.5%) and untwinned feldspar (11.2 to 25.6%), while other feldspars include microcline and a little acid plagioclase. Opaque heavy minerals, epidote and muscovite are common accessory minerals, and there is usually a sparse siliceous matrix (2.5 to 8.5%). There is very little composite quartz, and there are few rock fragments (R_t = 0 to 0.10) which are all sandstone. The maturity index is rather low (M_i = 1.57 to 3.97). Grains are coated with ferric oxide dust and the feldspars, particularly the untwinned varieties, are stained red. In thin section the 'reduction spots' observed in the field are revealed as areas lacking the red dust or stain.

2. Textures

Of 9 sandstones analysed, 5 are medium-grained and 4 fine-grained. 8 of these are moderately sorted and 1 well sorted, while 5 are nearly symmetrical skewed, 3 are positive-skewed and 1 is very negative-skewed. All are mesokurtic except one which is platykurtic.

The low matrix contents are reflected in high packing values. In the 5 specimens analysed, P_p is 79.6 to 85.2%, and Gc/g is 4.84 to 5.03%.

Grain shapes were not investigated.

3. Colours

These are moderate to dusky red 5R 4/5, dark reddish brown 10R 3/4, greyish red 10R 4/2 or dusky blackish-red 5R 3/5. These are similar to pebbles of Torridonian sandstone collected from the Pseudo-Trias which are dark reddish-brown 10R 3/4 or medium red 5R 4/6, while the clastic dykes cutting the Pseudo-Trias at Badluarach and Achiltibuie are all dark reddish brown 10R 3/4.

4. Comparison with the Trias

Pseudo-Trias	Trias
Conglomerates:	Conglomerates:
Contain a little Lewisian gneiss	Contain a little Lewisian gneiss
Torridonian sandstone	Torridonian sandstone
a little quartzite	quartzite
no limestone	limestone
vein quartz	vein quartz
no igneous rocks	igneous rocks
Sandstones:	Sandstones:
Arkosic, a few subarkoses	Subarkoses, protoquartzites and subgreywackes
Matrix sparse, siliceous	Matrix abundant, calcareous
High packing values	Moderate or low packing values
Coarse (not analysed), medium and fine-grained	Coarse, medium and fine-grained
Mainly moderately sorted	Mainly moderately sorted
Red and red-brown colours only	Often red, but many are grey, white, or green
Contain prominent ore bands	Few heavy minerals, never in concentrations
Hard	Soft

<u>Pseudo-Trias</u> (Cont.)	<u>Trias</u> (Cont.)
General:	General:
No cornstones	Typically contains cornstones
Cut in places by clastic dykes	Nowhere cut by clastic dykes
Overlies and underlies Torridonian strata	Only overlies Torridonian strata

The last point has been illustrated in Chapter III, and the several contrasts that have been subsequently demonstrated between the Trias and Pseudo-Trias confirm the field evidence that the rocks previously mapped as Trias at Rubha Reidh, Loch a Ceann Carnaich, Badluarach and Achiltibuie bear little resemblance to the Trias sediments of the West Highlands and are in fact Torridonian.

Observing that the conglomerates contain mainly re-worked Torridonian material, the Geological Survey may have thought that the sandstones were re-worked Torridonian sand material, thus taking them as second-cycle arkoses. In fact, they are first cycle Torridonian sediments. If they were second cycle, they would be very unusual sandstones indeed, having a composition that is closely similar to that of the sandstones from which they were supposedly derived.

Certain resemblances between the Trias and the Torridonian (e.g. grain-size, sorting) may be accounted for by the fact that the Torridonian arkoses have also formed under fluviatile conditions (see e.g. Selley 1965). Plots of all the Torridonian 'Pseudo-Trias' (and of the Torridonian sandstone pebble) skewness against sorting, although not given in the figures, fall within Friedman's (1961) 'river' field.

APPENDIX II

CLASTIC DYKES.

APPENDIX II CLASTIC DYKES.

1. FIELD RELATIONSHIPS

The Pseudo-Trias and underlying Older Torridonian at Badluarach and Achiltibuie are cut by clastic dykes containing hard red medium to fine-grained sandstone which is homogeneous and apparently structureless.

The dykes have straight parallel margins and are not deflected by boulders in the conglomerates which they cut straight through (Fig. 36). They often split into separate 'stringers' which may rejoin along their strike, and they may thin out either upwards or downwards. They also rarely form thin sills (Fig. 38).

The dykes tend to be associated with jointing in the country rock, appearing to run parallel with a major joint trend. At Badluarach a swarm of 31 clastic dykes intruding the Pseudo-Trias was mapped (Fig. 144). These have a marked parallelism, and their orientations were plotted on a lower hemisphere equal area projection (Schmidt Net) as shown in Fig. 146. Measurements were also made of jointing in the country rock, and these were plotted similarly (Fig. 147). Comparison of the two results shows a close similarity between them, and it is reasonable to conclude that the clastic dykes are associated with a major component of the joint system.

Dykes in the Badluarach swarm range in thickness from negligible to 45 cms, with an average of 12 cms.

At Achiltibuie a single sandstone dyke occurs intruding the Pseudo-Trias south of Achlochan. It is 9 cms wide, strikes 15° to 18° E and has a variable dip of about 80°E.

At both localities clastic dykes are also seen intruding Lewisian gneiss beneath the sediments. On Carn an Droma, a Lewisian hill 300 yards south of Carn Dearg na h-Uamha (the most southerly outcrop of the Pseudo - Trias at Badluarach) 6 sandstone dykes are seen cutting the gneiss. They are identical to those of the main swarm and have the same strike. In a face of Lewisian gneiss 350 yards northeast of Achiltibuie Hotel, two sandstone dykes, 4 and 34 cms thick, penetrate the gneiss to an exposed depth of at least 10 m. They strike E.N.E., the thicker one splitting into two 'stringers' halfway up the face, rejoining further up. The thinner dyke has been recorded by the Geological Survey (Peach et al 1907, p. 182).

2. FABRIC

In hand specimen the fabric elements of the dykes show no preferred orientation apart from occasional slivers from the dyke walls which are orientated parallel to the walls (Fig. 148).

A microscopic investigation was made of orientated thin sections prepared from two dykes of the Badluarach swarm. Taking the dyke walls as perpendicular, the sections were cut in three mutually perpendicular planes, viz :

a. Vertical, at right angles to the dyke wall.
b. Horizontal.
c. Vertical, parallel to the dyke wall.

(See Fig. 149).

A preliminary macroscopic investigation of these sections revealed no obvious preferred orientation of fabric elements such as mica flakes. However, microscopic measurement of grain orientation in five sections, by the method described above (pp199-200) produced the results shown in Fig. 150.

Statistical analysis gives the following results:

Specimen	Deviation*	Vector Magnitude	Probability
Bh 36a	2^{o}	49.4%	$< 10^{-10}$
Bh 36b	5^{o}	34.2%	$< 10^{-5}$
Bh 36c	10^{o}	22.6%	$< .01$
Bh 30a(i)	$37\frac{1}{2}^{o}$	68.9%	$< 10^{-20}$
Bh 30a(ii)	9^{o}	65.0%	$< 10^{-15}$
Bh 30b	10^{o}	18.2%	$< .04$

*In 'a' and 'b' sections, deviation is given from the dyke wall position, while in the 'c' section, it is given from the vertical.

The sand grains show a preferred orientation which appears to be influenced by the dyke walls. This is most marked in the vertical 'a' sections when the greatest vector magnitudes and therefore the smallest probabilities are obtained. Orientation in the vertical 'c' section, taken parallel to the dyke wall, gives a vector magnitude which is barely significant. 'b' sections also give less significant results.

In Bh 30a grains show a remarkable 'imbricate' arrangement along one margin, which is gradually lost across the dyke. The grains may have been originally orientated parallel to the dyke wall, as in Bh 36a, and then disturbed by a slight secondary movement of the sediment while it was still semi-consolidated.

3. TEXTURES AND MINERALOGY

Sandstones from the dykes were examined under the microscope as described above (Chapters V and VI) and the results are incorporated in Tables 2a, 2b, 4d, 5 and Figs.

Three of the four specimens analysed for size distribution (Bh 32, Bh 36 and Ach 6) are medium or fine-grained sandstones, moderately or poorly sorted, nearly symmetrical-skewed and platykurtic. The fourth (Bh 30) was collected 0.5 m beneath the shearing at the unconformity at Carn Dearg na h-Uamha (see Fig. 37) and possibly may have been affected by the shearing which occurred before the dyke sediment was fully indurated (see below). There is a marked concentration of grains in the coarse sandstone fraction, producing a skewness that is greater than that of any other sandstone measured in this study.

The sandstones are all fairly well packed, with matrix values ranging from 3.9% to 13.4%. Again, specimen Ab 30a is unusual in having by far the least matrix. Specimen Ach 6 has P_p = 72.4 and Gc/g = 4.28 which are rather lower values than those obtained from the Pseudo-Trias sandstones, suggesting that the sandstones of the dykes are rather less compact than those of the country rock.

All the sandstones are arkoses or subarkoses. The feldspars include a predominance of untwinned fragments which are rather decomposed and often iron stained, with a little microcline and acid plagioclase in addition. The range of total feldspar values is 14.7% to 26.9%, while quartz is abundant (53.0% to 67.0%). Some quartz grains contain euhedral epidote inclusions. A few fragments of chert and sandstone also occur, with garnet, muscovite, chlorite, epidote and opaque heavies as accessories. The matrix is siliceous with coatings of ferric oxide on the grains. In hand specimens minute quartz crystals (<1 mm) may be seen occasionally, developed in tiny 'drusy' cavities between grains. M_i is low: 1.78 to 3.41.

Some of the clastic intrusions show a 'chilled margin' effect at the edges which appear finer-grained and more brightly coloured than the rest of the sandstone. In thin section this is seen to be produced by a concentration of iron dust in the matrix at the margins.

In most respects the sandstones compare very closely with those sampled from the Older Torridonian and Pseudo-Trias, contrasting with the Trias sandstones (see Figs.73,100,104).

4. MODE OF FORMATION

The literature on clastic dykes has been briefly reviewed by Potter and Pettijohn (1963, pp. 162-165) and more comprehensively by Schrock (1948, pp. 212-220). They have a very varied manner of occurrence, but may be generally divided into two groups:

1. Regular tabular bodies with sharp margins.
2. Irregular, sinuous, sometimes pod-shaped masses.

The mechanism of their emplacement is not yet perfectly understood, but it has probably involved the injection of quicksand from either above or below. Type 1) dykes were probably formed by late-stage injection, possibly along joint planes, while those of type 2), which are less common, were injected at a much earlier stage in the history of the country rock, thus being subject to compaction and deformation of the host beds.

The Wester Ross clastic dykes belong to type 1). Examples of this type have been described by Diller (1890) and Vitanage (1954) who both found preferred orientation of the fabric elements parallel to the dyke walls and recognisable in hand specimen, and by Scharbert (1963). The Wester Ross dykes show internal microscopic preferred orientation with a strong tendency for alignment of grains parallel to the dyke walls rather than in transverse arrangement. This strongly suggests injection of the dyke material accompanied by wall influence on the fabric.

Scharbert (1963) described a type 1) dyke in granite, but did not investigate its fabric. He considered it to have been formed by the filling of a joint by wind-blown sand, followed by secondary movement of the joint. He records the sorting So = 1.43 ("very good"), the parameter being obtained from an optical method of grain-size analysis. However, from his data (Fig. 3 p. 186) sorting was worked out on the phi scale, giving $\sigma_I = 0.75$ which is only 'moderately sorted' (Folk and Ward 1957) and is of a different order from the wind-blown sands investigated in this study ($\sigma_I = 0.48$ to 0.54), being nearer to the values obtained for the Wester Ross clastic dykes (0.84 to 1.12).

Since the dykes penetrate the basal Lewisian gneiss, the sediment must have been injected from above, water-saturated sand filling deep joints (up to at least 25 m, and probably very much more) in the country rock. Some of the field evidence suggests a small amount of injection from below (e.g. stringers fingering upwards) : this may have been caused by the partial closing of joints after being filled, while the sediment was still not fully consolidated. Sediment would then be forced sideways and upwards, intruding planes of weakness in the country rock and producing sills and stringers. The orientation of grains in section Bh 30a supports this hypothesis : the fabric which is now 'imbricate' with respect to one dyke wall may have been originally parallel to it, being disturbed by remobilisation before the sediments became fully indurated. Certainly the shearing at the unconformity beneath Carn na h-Uamha occurred after the emplacement of the two clastic dykes but before they were fully indurated : although the dykes are off-set 35 to 40 cms to the west above the shearing, they are not truncated, but follow the shear plane in irregular sinuous form (Fig. 37). Clearly the sediment was still mobile when the shearing occurred. This may also have influenced the nature of the fabric in the dykes, as in Bh 30a. A similar process has been described by Scharbert (1963) in a clastic dyke intruding granite, but unfortunately he did not investigate the fabric.

The injection process may have been triggered off by earthquake shocks, perhaps those that produced the jointing. Unconsolidated water-laden sand became momentarily liquefied and was injected into the newly-formed joints, which were subsequently involved in further movement.

5. REGIONAL SETTING

Although only one of the dykes described above has been recorded by the Geological Survey, the North-West Highland Memoir refers to a number of other occurrences of similar bodies scattered over a wide area in Wester Ross (Peach et al 1907, pp. 182, 193, 306, 325, 333-334). Fig. 145 shows the main localities of these, along with those mapped in this study.

The dykes mapped by the Survey are essentially similar to those at Badluarach and Achiltibuie, having straight sides, containing homogeneous hard red sandstone, and striking N.N.E. They range in size from two enormous ones over 5.5 m wide near Red Point, to 1 cm in width, and intrude both the Torridonian and Lewisian. It is likely that these are part of the same swarm as those at Badluarach and Achiltibuie.

Dykes recorded in Assynt near Lochinver, also have the same strike, but contain fragments of basal Torridonian breccia. No evidence is given by clastic dykes intruding the Suilven Torridonian outlier, and they are probably only infillings by the basal Torridonian sediments of joints in the Lewisian, as at Clachtoll Bay where the Lewisian gneiss is veined by red sandstone beneath the basal Torridonian breccia which is not itself intruded by clastic dykes.

6. SIGNIFICANCE

The chief significance of the clastic dykes in this thesis is their relationship to the Pseudo-Trias at Badluarach and Achiltibuie. They have intruded these beds from above, after the beds were well indurated, and are therefore distinctly younger than the Pseudo-Trias. The sandstones in the dykes are closely similar in nearly all respects to sandstones of both the Older Torridonian and the Pseudo-Trias, but differ from the Trias sandstones. Nowhere is the Trias seen to be intruded by these dykes, but in fact the Trias outcrops do lie slightly west of the main trend of the swarm.

Intrusion by younger sandstones with Torridonian characteristics does not prove the Pseudo-Trias to be of Torridonian age, although it strongly suggests it. It does however indicate that sometime after the deposition of the Pseudo-Trias (and indeed after deposition of Applecross sediments at Red Point) a further period of non-deposition occurred during which the sediments became firmly indurated. Later, similar arkosic sandstones were deposited and then injected into the older sediments, probably in conjunction with joint formation.

Now that it has been shown that the Pseudo-Trias belongs to the Torridonian, it is reasonable to assume on lithological grounds that the sandstone of the clastic dykes is also Torridonian. Its age is uncertain, but the Geological Survey (Peach et al 1907, p. 334) recorded clastic dykes at Red Point intruding Torridonian sandstones 3,000 ft above the base of the Applecross Group. The sandstone of those dykes must therefore be at least as young as late Applecross. It is very likely that these sandstones represent an even later stage of the Torridonian and may be the surviving representatives of an upper Torridonian horizon no longer existing *in situ*. This is a very tentative suggestion, but it would be interesting to discover if the dykes are seen anywhere intruding sediments of the Aultbea Group.

Summary of grain-size parameters in sandstones from the clastic dykes.

Specimen	M_z	I	Sk_I	K_G	K_G'
Bh 32	1.93	1.12	+0.08	0.91	0.48
Bh 36	1.39	0.98	-0.09	0.93	0.48
Ach 6	2.07	0.84	-0.10	1.11	0.52
Bh 30	1.32	1.03	+0.43	0.84	0.46

APPENDIX III

TABLES

TABLE 1

SPECIMENS REFERRED TO

TABLE 1

SPECIMENS REFERRED TO

(Studies of modal composition, grain-size distribution and packing properties)

Specimen	Formation	Locality	Map Reference	Study
Ld 4	Trias	Achnacroich path, S.E. Mull	NM 725350	M
Ld 6	Trias	Loch Don anticline	NM 734317	M SA
Ld 7	Trias	Loch Don anticline	NM 734317	M SA P
Ls 3	Trias	Seanvaile, Loch Spelve	NM 683285	M SA
Ik 3	Trias	Humpies, Inchkenneth	NM 435347	M SA
Ik 5	Trias	Humpies, Inchkenneth	NM 434352	M SA P
Ik 7	Trias	Bagh an Iollaich, Inchkenneth	NM 436353	M SA
Ik 10	Trias	N.E. end of Inchkenneth	NM 443355	M SA P
Ikc 3	Trias	Inchkenneth Chapel	NM 437354	M
Ikc 11	Trias	Inchkenneth Chapel	NM 437354	M
Gr 20	Trias	Ath Dearg, Wilderness	NM 438317	M SA P
Gr 38	Trias	Gribun	NM 444333	M SA P
Gr 39	Trias	Gribun	NM 445334	M SA P
Gr 44	Trias	Gribun	NM 446338	M SA
Uc 2	Trias	Uamh nan Calman, Wilderness	NM 405294	M SA
In 15	Trias	Inninmore Bay, Morvern	NM 716422	M SA P
In 22	Carboniferous	Inninmore Bay, Morvern	NM 716423	M SA P
Ka 3	Carboniferous	Achranich quarry, Morvern	NM 702473	M SA P
La 8	Trias	Kinlochaline, Morvern	NM 694476	M SA
Lb 3	Trias	Larachbeg, Morvern	NM 695484	M SA
An 7	Trias	Rudh a Mhile, Ardnamurchan	NM 506628	M SA
Rh 7	Trias	Monadh Dubh, Rhum	NG 341030	M SA
Rh 8	Passage Beds	Monadh Dubh, Rhum	NG 341030	M SA P
Rh 9	Passage Beds	Monadh Dubh, Rhum	NG 333027	M SA
Rh 10	Passage Beds	Monadh Dubh, Rhum	NG 342027	M SA
Al 6	Passage Beds	An Leac, W. Skye	NG 439169	SA
Al 7	Passage Beds	An Leac, W. Skye	NG 439169	SA
Al 15	Trias	An Leac, W. Skye	NG 439169	M
Sl 4	Trias	Sconser, Central Skye	NG 529318	M SA
Sl 7	Trias	Loch Sligachan, Central Skye	NG 524318	SA

Specimen	Formation	Locality	Map Reference	Study		
Br 5	Trias	N.E. of Heast, Strath, Central Skye	NG 663194	M	SA	P
Br 10	Trias	Beinn a Mheadhoinn, Strath	NG 622178	M		
Br 17	Trias	Heast, Strath	NG 645173	M	SA	
Br 27	Trias	Allt na Pairte, Strath	NG 625174	M	SA	P
Br 31	Trias	Allt na Pairte, Strath	NG 624175	M		
Br 34	Trias	Beinn a Mheadhoinn, Strath	NG 621177	M	SA	
Br 60	Trias	Allt a Mhuillin, Strath	NG 646227	M	SA	
Br 61	Trias	Allt a Mhuillin, Strath	NG 646227	M		
Br 36	Trias	Beinn a Mheadhoinn, Strath	NG 623176	M		
Ey 3	Trias	N. of Eyre lighthouse, Raasay	NG 582345	M	SA	
Ey 7	Trias	E. of Suisnish Hill, Raasay	NG 572345	M	SA	
Ey 8	Trias	E. of Suisnish Hill, Raasay	NG 573345	M		P
Ey 9	Trias	Eyre, Raasay	NG 577342	M	SA	
RnL 2	Trias	Rudha na Leac, Raasay	NG 600382	M	SA	P
RnL 6	Trias	Rudha na Leac, Raasay	NG 600383	M	SA	P
RnL 8	Trias	Rudha na Leac, Raasay	NG 599383	M	SA	
RnL 10	Trias	Rudha na Leac, Raasay	NG 599383	M	SA	
Ap 10	Trias	Milton, Applecross	NG 706439	M	SA	P
Ap 12	Trias	N. of Camusteel, Applecross	NG 707428	M		
Ap 25	Trias	S.W. of Applecross House	NG 732445	M	SA	
Ap 30	Passage Beds	South of Applecross House	NG 726447	M	SA	
Rp 2	Trias	Redpoint clachan, Red Point	NG 727696	M	SA	P
Ab 5	Trias	Laide fishing station, Gruinard Bay	NG 900929	M	SA	
Ab 25	Trias	Leac Dubh, Gruinard Bay	NG 913915	M	SA	P
Gh 5	Trias	Big Sand, Gairloch	NG 760789	M	SA	
Gh 13	Trias	Camas Mor, N. of Gairloch	NG 759918	M	SA	
Gh 14	Trias	Camas Mor, N. of Gairloch	NG 759918	M	SA	P
Gh 8	'Pseudo-Trias' (Torridonian)	Rubha Reidh	NG 740916	M	SA	P
Gh 20a	Torridonian	Loch a Ceann Carnaich	NG 776890	M	SA	P
Gh 20b	'Pseudo-Trias'	Loch a Ceann Carnaich	NG 776890	M	SA	
Bh 2	'Pseudo-Trias'	Carn Dearg Ailean, Badluarach	NG 994953	M	SA	

Specimen	Formation	Locality	Map Reference	Study		
Bh 24	'Pseudo-Trias'	Uamh an Oir, Badluarach	NG 976958	M	SA	P
Bh 29	'Pseudo-Trias'	W. of Leac an Ime, Badluarach	NG 985957	M	SA	P
Ach 3	'Pseudo-Trias'	Achlochan, Coigach	NC 025068		SA	
Ach 4	'Pseudo-Trias'	Achlochan, Coigach	NC 025068	M	SA	P
Ach 5	'Pseudo-Trias'	Achlochan, Coigach	NC 025068	M	SA	
Bh 30	Clastic dyke	Leac an Ime, Badluarach	NG 988957	M	SA	
Bh 32	Clastic dyke	Carn Dearg na h-Uamha, Badluarach	NG 975945	M		
Bh 36	Clastic dyke	Carn Dearg na h-Uamha, Badluarach	NG 975945	M	SA	P
Ach 6	Clastic dyke	Achlochan, Coigach	NC 025068	M	SA	P

M : Mode SA: Size Analysis P: Packing

Specimens mechanically size analysed:

Specimen	Map Reference
Red Point sandstone	NG 727696
Gairloch, Big Sand sandstone	NG 762793
Laide 'red marl' pebbly base	NG 897943
Laide 'red marl'	NG 897943
Leac Dubh siltstone	NG 913915

All map references given on the National Grid.

TABLE 2a

MODAL ANALYSES

Specimen	Qtz.	Comp. Qtz.	U/t. F'spar	Micr.	Plag
Trias.					
Ld 4	35.8	2.7	11.6	0.1	6.2
Ld 6	51.2	9.0	1.1	-	2.3
Ld 7	56.2	9.3	4.0	0.2	0.3
Ls 3	72.2	0.1	18.2	0.2	0.7
Ik 3	11.5	2.6	2.4	0.5	0.4
Ik 5	47.2	1.5	3.7	0.4	0.7
Ik 7	15.9	3.5	3.6	0.9	0.3
Ik 10	67.4	6.2	3.6	1.1	0.5
Gr 20	67.6	1.4	2.1	0.5	0.4
Gr 38	32.0	7.2	6.5	1.3	0.5
Gr 39	75.1	0.2	8.0	0.4	0.2
Gr 44	22.2	-	0.3	0.1	0.1
Uc 2	51.2	15.6	6.1	-	-
In 15	67.2	1.6	2.0	1.5	0.2
La 8	19.0	1.8	1.7	0.1	1.8
Lb 3	27.9	1.7	6.5	0.3	0.4
An 7	56.1	2.3	2.2	0.8	0.4
Rh 7	59.1	1.2	3.1	0.6	0.8
Al 15	34.8	0.6	-	-	0.2
Sl 4	31.3	1.8	6.6	0.3	1.1
Br 5	40.7	6.6	0.2	-	-
Br 10	13.6	1.3	-	-	-
Br 17	31.5	8.3	1.1	0.1	0.2
Br 27	79.9	1.9	0.5	0.2	-
Br 31	8.5	1.5	0.2	-	-
Br 34	42.1	0.6	12.8	2.5	0.6
Br 36	7.4	1.2	-	-	-

2a

LISIS.

	ROCK FRAGMENTS						
Met.	O/Qtzite	Sstn.	Lstn.	Ign.	Chert	Access	Matrix
3.4	-	-	-	18.7	-	1.3	11.4
-	-	-	-	-	-	1.2	32.8
3.7	-	-	2.0	-	-	0.3	24.0
-	0.6	-	-	-	-	-	8.0
10.9	4.1	5.8	5.6	6.0	1.3	1.0	47.9
1.3	0.2	0.5	1.2	0.1	0.2	1.0	42.0
15.4	2.2	0.5	7.4	[illegible]	4.5	0.3	41.9
8.7	0.3	0.4	0.2	0.9	0.6	0.3	9.8
1.4	0.2	-	-	0.2	0.2	0.8	25.2
3.3	0.9	1.5	4.7	2.3	1.7	0.2	38.0
0.4	-	-	-	0.2	0.3	0.9	14.3
0.3	-	-	0.1	0.1	-	6.3	70.5
3.2	-	-	-	-	-	-	33.9
15.1	1.3	-	-	-	-	0.2	10.9
18.5	-	-	2.7	0.2	0.1	5.8	48.3
-	-	-	-	-	0.2	5.3	57.7
3.0	10.1	-	-	-	-	1.4	23.7
2.4	-	0.1	7.5	-	-	0.4	24.7
5.4	1.6	0.6	0.5	-	13.8	-	42.5
10.2	2.8	2.2	11.4	-	1.5	0.7	30.1
16.8	14.4	-	-	-	-	-	11.3
2.2	-	0.2	30.4	-	7.6	0.1	44.6
9.8	10.3	-	0.3	0.8	-	0.2	37.4
1.2	3.4	-	-	-	-	0.1	12.8
0.2	0.6	-	54.6	-	18.2	0.1	16.1
0.5	2.2	13.7	4.2	1.8	-	0.2	18.8
0.2	-	-	41.2	-	6.2	-	43.8

MOD[illegible]ALYSIS.

Specimen	Qtz.	Comp. Qtz.	U/t. F'spar	Micr.	Plag	Met.	O/Qtzite	Sstn.	Lstn.
						ROCK FRAGMENTS			
Trias.									
Ld 4	35.8	2.7	11.6	0.1	6.2	3.4	-	-	-
Ld 6	51.2	9.0	1.1	-	2.5	-	-	-	-
Ld 7	56.2	9.3	4.0	0.2	0.3	5.7	-	-	2.0
Ls 3	72.2	0.1	18.2	0.2	0.7	-	0.6	-	-
Ik 3	11.5	2.6	2.4	0.5	0.4	0.9	4.1	5.8	5.6
Ik 5	47.2	1.5	3.7	0.4	0.7	1.3	0.2	0.5	1.2
Ik 7	15.9	3.5	3.6	0.9	0.3	5.4	2.2	0.5	7.4
Ik 10	67.4	6.2	3.6	1.1	0.5	8.7	0.3	0.4	0.2
Gr 20	67.6	1.4	2.1	0.5	0.4	1.4	0.2	-	-
Gr 38	32.0	7.2	6.5	1.3	0.5	3.3	0.9	1.5	4.7
Gr 39	75.1	0.2	8.0	0.4	0.2	0.4	-	-	-
Gr 44	22.2	-	0.3	0.1	0.1	0.3	-	-	0.1
Uc 2	51.2	15.6	6.1	-	-	3.2	-	-	-
In 15	67.2	1.6	2.0	1.5	0.2	5.1	1.3	-	-
La 8	19.0	1.8	1.7	0.1	1.8	8.5	-	-	2.7
Lb 3	27.9	1.7	6.5	0.3	0.4	-	-	-	-
An 7	56.1	2.3	2.2	0.8	0.4	3.0	10.1	-	-
Rh 7	59.1	1.2	3.1	0.6	0.8	2.4	-	0.1	7.5
Al 15	34.8	0.6	-	-	0.2	5.4	1.6	0.6	0.5
Sl 4	31.3	1.8	6.6	0.3	1.1	0.2	2.8	2.2	11.4
Br 5	40.7	6.6	0.2	-	-	6.8	14.4	-	-
Br 10	13.6	1.3	-	-	-	2.2	-	0.2	30.4
Br 17	31.5	8.3	1.1	0.1	0.2	9.8	10.3	-	0.3
Br 27	79.9	1.9	0.5	0.2	-	1.2	3.4	-	-
Br 31	8.5	1.5	0.2	-	-	0.2	0.6	-	54.6
Br 34	42.1	0.6	12.8	2.5	0.6	0.5	2.2	13.7	4.2
Br 36	7.4	1.2	-	-	-	0.2	-	-	41.2

Specimen	Qtz.	Comp. Qtz.	U/t. F'spar	Micr.	Plag.	ROCK FRAGMENTS Met.	O/Qtzite	Sstn.	Lstn.	Ign.	Chert.	Access	Matrix.
Br 60	19.3	7.6	8.2	0.1	0.9	29.6	1.0	3.7	-	-	1.2	0.5	27.9
Br 61	7.5	0.8	0.1	-	0.1	0.7	2.5	-	46.6	0.7	9.4	-	31.6
Ey 3	32.1	1.1	7.5	3.1	0.4	22.6	2.4	2.8	-	1.5	0.3	-	26.2
Ey 7	36.6	0.9	3.6	1.3	0.7	14.4	3.8	2.3	-	0.3	0.6	0.5	35.0
Ey 8	35.1	1.3	6.7	0.1	2.1	17.2	2.8	0.7	0.4	-	0.3	0.2	33.1
Ey 9	37.1	1.5	7.7	3.5	0.4	20.8	3.1	1.2	-	1.8	0.4	-	22.5
RnL 2	24.4	2.4	6.6	0.8	0.7	20.3	0.4	2.1	1.9	0.2	0.3	0.3	39.6
RnL 6	31.4	2.8	4.6	0.7	1.1	22.9	1.6	1.2	0.3	0.7	0.4	0.2	32.1
RnL 8	28.8	12.8	5.6	0.2	1.0	32.8	2.4	0.2	-	-	0.3	0.1	15.8
RnL 10	23.7	6.4	7.1	0.1	1.5	18.5	2.0	0.2	2.3	-	0.3	0.3	37.6
Ap 10	35.5	2.6	6.6	2.4	0.1	2.8	16.6	1.8	-	0.2	-	-	31.4
Ap 12	30.4	2.2	3.2	0.3	-	1.1	10.8	16.5	10.4	0.7	0.6	-	23.8
Ap 25	67.3	1.4	2.1	0.6	0.6	0.3	0.7	-	0.3	-	-	1.7	25.0
Rp 2	52.9	0.3	7.9	1.6	0.2	0.9	0.6	1.2	-	0.2	0.1	0.1	34.0
Ab 25	73.9	3.2	0.6	-	0.2	0.5	-	-	-	-	0.1	0.8	20.7
Ab 5	35.8	0.9	6.2	2.6	0.6	5.7	3.8	3.9	-	-	-	-	40.5
Gh 5	62.0	1.4	7.1	1.0	0.6	1.4	-	-	-	1.3	0.1	-	25.1
Gh 13	50.2	0.7	4.2	2.5	0.5	13.8	2.4	0.3	-	1.1	0.4	0.2	23.7
Gh 14	39.7	0.7	4.1	2.0	0.7	8.4	3.1	2.3	-	1.2	0.5	-	37.3
Ikc 3	14.6	0.5	0.4	0.5	0.2	-	0.1	-	-	0.2	-	-	83.5
Ikc 11	5.6	-	0.1	-	-	-	0.3	-	-	-	-	0.1	93.9
<u>Passage Beds</u>.													
Rh 8	52.6	-	0.7	-	-	0.6	-	-	-	-	-	0.7	45.4
Rh 9	57.7	0.4	4.2	0.7	1.0	1.9	-	0.1	-	-	0.3	-	33.8
Rh 10	77.6	-	-	-	-	-	-	-	-	-	-	0.8	21.6
Ap 30	52.2	0.2	3.5	0.8	1.5	-	-	-	-	-	-	0.3	41.5

Specimen	Qtz.	Comp. Qtz.	U/t. F'spar	Micr.	Plag.
<u>Carboniferous.</u>					
In 22	87.4	2.8	0.9	0.4	-
Ka 3	79.1	1.7	3.0	1.1	0.3
<u>Torridonian.</u>					
Gh 20a.	64.0	0.8	12.2	1.3	3.3
<u>Pseudo-Trias.</u>					
Gh 8	74.5	-	11.2	-	0.4
Gh 20b.	58.3	0.6	25.6	1.2	5.9
Bh 2	60.9	2.6	19.9	1.5	1.9
Bh 24	66.6	1.7	16.9	0.4	1.3
Ach 4	65.0	0.8	23.2	1.2	1.4
Ach 5	68.6	0.9	14.3	-	1.1
Bh 29	67.3	0.3	21.7	0.8	1.8
<u>Clastic dykes.</u>					
Bh 30	61.5	0.7	23.5	1.1	2.3
Bh 35	58.0	1.2	12.2	2.7	3.2
Bh 36	67.0	0.5	13.9	-	0.8
Ach 6	62.2	0.8	16.2	3.6	3.4

	ROCK FRAGMENTS						
Met.	O/Qtzite	Sstn.	Lstn.	Ign.	Chert.	Access	Matr
0.5	0.2	-	-	-	-	0.9	6
3.7	1.1	-	-	-	0.6	3.7	5
10.4	-	-	-	-	-	3.1	4
0.7	-	-	-	-	0.1	6.4	6
2.7	-	-	-	-	-	1.1	4
3.2	-	0.6	-	-	1.6	0.4	7
-	-	-	-	-	-	3.6	9
3.5	-	0.4	-	-	0.1	0.7	3
4.6	-	2.6	-	0.2	0.4	0.2	7
4.8	-	-	-	-	0.1	0.7	2
4.1	-	-	-	-	0.1	2.8	3
7.7	-	0.2	-	-	0.6	1.7	12.
1.4	-	1.0	-	-	0.3	1.7	13.
3.4	-	0.1	-	-	-	3.0	7.

TABLE 2b.

MODAL INDICES

TABLE 2b

Values calculated as percentages of the whole rock excluding matrix.

Specimen	Qtz. A	F'spar B	R.F. + Access C	Total - Qtz. D	Lstn. + Silic.lstn. E	R.F. F	R_t $\frac{F}{A+B}$	R_1 $\frac{E}{A+B}$	M_1 $\frac{A}{D}$	Qtz. + Qtzose R.F.	Non-qtzose R.F. + Access
Trias.											
Ld 4	44.9	22.4	32.7	55.1	0	31.1	0.46	0	0.82	51.9	25.7
Ld 6	79.0	5.2	15.7	20.9	0	13.9	0.17	0	3.78	92.6	2.1
Ld 7	73.9	5.9	20.1	26.0	2.6	19.7	0.25	0.03	2.84	86.1	7.9
Ls 3	78.5	20.8	0.8	21.6	0	0.8	0.01	0	3.63	79.3	0
Ik 3	22.1	6.3	71.6	77.9	12.1	69.7	2.45	0.43	0.28	37.5	56.2
Ik 5	81.4	8.3	10.3	18.6	2.4	8.6	0.10	0.03	4.38	84.7	7.0
Ik 7	27.4	8.2	64.4	72.6	20.5	63.9	1.80	0.58	0.38	45.0	46.8
Ik 10	74.7	5.8	19.5	25.3	0.9	19.2	0.24	0	2.95	82.6	11.6
Gr 20	90.4	4.0	5.6	9.6	0.3	4.5	0.05	0	9.42	92.8	3.2
Gr 38	51.5	13.4	35.2	48.6	10.3	34.8	0.54	0.16	1.06	67.3	19.4
Gr 39	87.6	10.0	2.3	12.3	0.3	1.3	0.01	0	7.12	88.2	1.7
Gr 44	75.3	1.7	23.1	24.8	0	1.7	0.02	0	3.04	75.3	23.1
Uc 2	77.5	9.2	13.3	22.5	0	13.3	0.15	0	3.44	90.8	0
In 15	75.4	4.2	20.4	24.6	0	20.2	0.25	0	3.07	95.6	0.2
La 8	36.7	7.0	56.3	63.3	5.2	45.1	1.03	0.12	0.58	40.0	53.0
Lb 3	66.0	17.0	17.0	34.0	0	4.5	0.05	0	1.94	70.5	12.5
An 7	73.5	4.5	22.0	26.5	0	20.2	0.26	0	2.77	76.5	19.0
Rh 7	78.5	6.0	15.4	21.4	1.0	14.9	0.18	0.01	3.67	83.3	10.6
Al 15	60.5	0.3	39.1	39.4	24.9	39.1	0.64	0.41	1.54	68.0	31.6
Sl 4	44.8	11.4	43.8	55.2	18.5	42.8	0.76	0.33	0.81	46.5	42.1
Br 5	45.9	0.2	53.9	54.1	0	53.9	1.17	0	0.85	99.8	0
Br 10	24.5	0	75.5	75.5	68.6	75.3	3.07	2.80	0.33	35.6	64.4
Br 17	50.3	2.2	47.4	49.6	0.5	47.1	0.90	0.01	1.01	95.7	2.0
Br 27	91.6	0.8	7.6	8.4	0	7.5	0.08	0	10.91	96.2	3.0

Specimen	Qtz. A	F'spar B	R.F. + Access C	Total - Qts. D	Lstn. + Silic.lstn. E	R.F. F	R_t $\frac{F}{A+B}$	R_1 $\frac{E}{A+B}$	M_1 $\frac{A}{D}$	Qtz. + Qtzose R.F.	Non-qtzose R.F. + Access
Br 31	10.1	0.2	89.6	89.8	86.8	89.5	8.69	8.43	0.11	34.5	65.2
Br 34	51.8	19.6	28.6	48.2	5.2	28.3	0.40	0.07	1.08	55.9	24.5
Br 36	13.2	0	86.8	86.8	84.3	86.8	6.58	6.39	0.15	26.7	73.3
Br 60	26.8	12.8	60.5	73.3	1.7	59.8	1.51	0.04	0.37	81.4	5.9
Br 61	11.0	0.3	88.7	89.0	81.9	88.7	7.85	7.25	0.12	30.6	59.1
Ey 3	43.5	14.9	41.6	56.5	0	41.6	0.71	0	0.77	79.3	5.8
Ey 7	56.3	8.6	35.1	43.7	0	34.3	0.53	0	1.29	86.6	4.8
Ey 8	52.5	13.3	34.2	47.5	1.0	33.9	0.52	0.02	0.11	84.8	1.9
Ey 9	47.9	15.0	37.2	52.2	0	37.2	0.59	0	0.92	81.2	3.9
RnL 2	40.4	13.4	46.2	59.6	3.16	45.7	0.85	0.07	0.68	79.1	7.5
RnL 6	46.2	9.4	44.3	53.7	1.0	44.0	0.79	0.02	0.86	87.0	3.5
RnL 8	34.2	8.1	57.7	65.8	0	57.6	1.36	0	0.52	91.6	0.3
RnL 10	38.0	13.9	48.1	62.0	4.2	47.6	0.92	0.08	0.61	81.6	4.3
Ap 10	51.7	13.3	35.0	48.3	0	48.3	0.74	0	1.07	83.5	3.2
Ap 12	39.9	4.6	55.4	60.0	14.4	55.4	1.25	0.32	0.67	59.2	36.1
Ap 25	89.7	4.4	5.9	10.3	0.4	3.6	0.04	0	8.71	92.9	2.7
Rp 2	80.2	14.7	5.2	19.9	0	5.0	0.05	0	4.03	83.1	2.3
Ab 25	93.2	1.0	5.8	6.8	0	4.8	0.05	0	13.71	98.0	1.0
Ab 5	60.2	15.8	24.1	39.9	0	24.1	0.32	0	1.51	77.7	6.6
Gh 5	82.8	11.6	5.6	17.2	0	5.6	0.59	0	4.81	86.7	1.7
Gh 13	65.8	9.4	24.8	34.2	0	24.5	0.33	0	1.92	88.5	2.1
Gh 14	63.3	10.8	25.8	36.6	0	25.8	0.35	0	1.73	83.6	5.5
Ikc 3	88.5	6.7	4.8	11.5	0	4.8	0.05	0	7.70	92.1	1.2
Ikc 11	91.8	1.6	6.6	8.2	0	4.9	0.05	0	11.20	96.7	1.7
Passage Beds.											
Rh 8	96.3	1.3	2.4	3.7	0	0.7	0.01	0	26.03	97.4	1.3
Rh 9	87.2	8.9	3.9	12.8	0	3.9	0.04	0	6.81	91.1	0
Rh 10	99.0	0	1.0	1.0	0	0	0	0	99.00	99.0	1.0

Specimen	Qtz. A	F'spar B	R.F. + Access C	Total - Qtz. D	[illegible]n. + [illegible]ic.lstn. E	R.F. F	R_t $\frac{F}{A+B}$	R_1 $\frac{E}{A+B}$	M_1 $\frac{A}{D}$	Qtz. + Qtzose R.F.	Non-qtzose R.F. + Access
Passage Beds. (cont.)											
Ap 30	89.2	9.9	0.8	10.7	0	0.4	0.01	0	8.34	89.5	0.5
Carboniferous.											
In 22	93.9	1.4	4.7	6.1	0	3.1	0.03	0	15.36	97.7	0.9
Ka 3	83.9	4.7	11.5	16.2	0	7.5	0.09	0	5.18	91.4	4.0
Torridonian.											
Gh 20a	67.3	17.7	15.0	32.7	0	11.8	0.14	0	2.06	79.1	3.2
Pseudo-Trias.											
Gh 8	79.8	12.4	7.7	20.1	0	0.9	0	0	3.97	79.9	7.6
Gh 20b	61.1	34.3	4.6	38.9	0	3.5	0.04	0	1.57	84.6	1.1
Bh 2	65.8	25.2	9.1	34.3	0	8.6	0.10	0	1.92		
Bh 24	73.6	20.6	5.9	26.5	0	1.9	0.02	0	2.78	71.0	3.9
Ach 4	67.5	26.8	5.7	32.5	0	5.0	0.05	0	2.08	75.5 72.1	4.0 1.1
Ach 5	73.8	16.6	9.6	26.2	0	9.4	0.10	0	2.82	80.2	3.2
Bh 29	69.0	24.9	6.1	31.0	0	5.3	0.06	0	2.23	74.3	0.8
Clastic dykes.											
Bh 30	64.0	28.0	8.0	36.0	0	5.3	0.06	0	1.78	69.1	2.9
Bh 35	66.3	20.7	13.0	33.7	0	11.1	0.13	0	1.97	77.2	2.1
Bh 36	77.4	17.0	5.7	22.7	0	3.7	0.04	0	3.41	79.9	3.2
Ach 6	67.1	25.0	7.9	32.9	0	4.6	0.05	0	2.04	71.3	3.7

TABLE 3

PEBBLE DISTRIBUTIONS

TABLE 3

Distribution of pebbles occurring in the Trias conglomerates

	Lewisian	Torridonian		Cambro-Ordovician			Moine		Igneous	
	acid gneiss	sandstone	o/qtzite	limestone and dolomite	chert	arkose-gneiss	m/qtzite	mica-schist	Pre-Camb (ex. Torr)	O.R.S.
W. Mull		x	x	x	x	x	x	x		x
S.E. Mull		(x)	x	(x)	(x)	x	x	x		(x)
Morvern						x	x	x		(x)
Ardnamurchan						x				
Rhum		x	x	x	x		(x)			
Skye (An Leac		x	x	x	x		(x)	(x)		
Skye (Strath		x	x	x	x	x	x	x		
Skye (Tarskavaig		x	x	x	x		(x)	x		
Skye (Sligachan	(x)	x	x	x	x		(x)	x		
Scalpay	(x)	x	x	x	x		(x)	x		
Raasay	(x)	x	x	x	x		(x)	x	(x)	
Applecross	(x)	x	x	x	x			x	(x)	
Redpoint	(x)	x	x	x	x				(x)	
Gairloch		x	x	(x)	x			x		
Camus Mòr		x	x	(x)	x					
Isle of Ewe		x	x	x	x		x	x		
Laide		x	x	x	x		x	x		

x Commonly present.

(x) Sparsely present.

Vein quartz occurs throughout.

TABLE 4a.

MECHANICAL SIZE ANALYSES

TABLE 4a

MECHANICAL SIZE ANALYSES.

1. Redpoint (Rp 2) Weight of sample : 123 gms.

a. "Ro-Tap" sieving, 15 mins.

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
18	850	1.1	0.90	0.90
22	710	2.2	1.80	2.70
30	500	10.0	8.20	10.90
44	355	28.6	23.44	34.34
60	250	32.8	26.89	61.23
120	125	31.7	25.98	87.21
170	90	9.4	7.70	94.91
240	63	4.2	3.44	98.35
Passing 240	< 63	2.0 → Decantation		
Total		122.0		

% loss by sieving : 0.8

b. Decantation.

Weight of sample : 2.0 gms.

Grade (μ)	Wt. settled (gms.)	%	% original net sample.	Cumulative % (cont.)
63-31	1.92	96.00	1.57	99.92
31-16	0.07	3.5	0.06	99.98
16-8	0.005	0.25	Negligible	100.00

2. Gairloch, Big Sand. Weight of sample : 198 gms.

a. "Ro Tap" sieving, 15 mins.

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
8	2000	3.3	1.68	1.68
12	1040	2.3	1.17	2.85
18	850	9.3	4.73	7.58
22	710	11.2	5.69	13.27
30	500	30.3	15.40	28.67
44	355	54.2	27.55	56.22
60	250	44.2	22.47	78.69
120	125	33.8	17.18	95.87
170	90	5.2	2.66	98.53
240	63	1.71	0.87	99.40
Passing 240	< 63	1.19 → Decantation		
		Total 196.7	% loss by sieving : 0.7	

b. Decantation.

Weight of sample : 1.19 gms.

Grade (μ)	Wt. settled (gms.)	%	% original net sample	Cumulative % (cont.)
63-31	0.73	61.34	0.37	99.77
31-16	0.46	38.66	0.23	100.00
16	-	-	-	-

3. Laide "red marl" (pebbly base) Weight of sample: 201 gms.

a. "Ro-Tap" sieving, 15 mins.

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
-	10000	17.7	8.85	8.85
-	5000	2.3	1.15	10.00
8	2000	15.5 (<5mm)	7.75	17.75

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
12	1040	5.5	2.75	20.50
18	850	15.2	7.60	28.10
22	710	10.4	5.20	33.30
30	500	27.0	13.50	46.80
44	355	46.7	23.33	70.13
60	250	32.0	15.99	86.12
120	125	22.9	11.44	97.56
170	90	2.6	1.30	98.86
240	63	1.2	0.60	99.46
Passing 240	< 63	1.8 → Decantation		

Total 200.1 gms. % loss by sieving : 0.4

b. Decantation

Weight of sample : 1.1 gms.

Grade (μ)	Wt. settled (gms.)	%	% original net sample.	Cumulative % (cont.)
63-31	0.83	75.45	0.41	99.87
31-16	0.25	22.73	0.12	99.99
16-8	0.02	1.82	0.01	100.00
8	-	-	-	-

4. Laide "red marl" (proper). Weight of sample : 153 gms.

a. "Ro-Tap" sieving 15 mins.

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
18	850	0.5	0.33	0.33
22	710	1.5	0.99	1.32
30	500	9.7	6.39	7.71
44	355	41.4	27.25	34.96

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
60	250	52.6	34.63	69.59
120	125	36.4	23.96	93.55
170	90	7.4	4.87	98.42
240	63	1.2	0.79	99.21
Passing 240	63	1.2	Decantation	

Total 151.9 gms. % loss by sieving: 0.8

b. Decantation

Weight of sample : 1.2 gms.

Grade (μ)	Wt. settled (gms.)	%	% original net sample.	Cumulative % (cont.)
63-31	1.05	87.50	0.69	99.90
31-16	0.12	10.00	0.08	99.98
16-8	0.02	1.67	0.01	99.99
8	-	-	-	-

5. Leac Dubh calcareous siltstone. Weight of sample = 45.0 gms.

a. "Ro-Tap" sieving, 15 mins.

B.S. Mesh No.	Aperture (μ)	Wt. retained (gms.)	%	Cumulative %
30	500	0.1	0.2	0.2
44	355	1.7	3.8	4.0
60	250	3.1	7.0	11.0
120	125	10.5	23.5	34.5
170	90	8.3	18.6	53.1
240	63	8.1	18.2	71.3
Passing 240	< 63	12.8 → Decantation		

Total 44.6 gms. % loss by sieving : 0.9

b. Decantation.

Weight of sample = 12.8 gms.

Grade (μ)	Wt. settled (gms.)	%	% original net sample.	Cumulative % (cont.)
63-31	12.05	94.1	27.0	98.3
31-16	0.45	3.5	1.0	99.3
16-8	0.25	2.0	0.6	99.9
8	0.05	0.4	0.1	100.0

Decantation:

Settling times calculated from Stokes' Law. (Krumbein and Pettijohn 1938, p. 148).

Time	Length of water column	Size grade
5 mins. 45 secs.	30 cm	1/32 mm (31)
7 " 40 "	10 cm	1/32 - 1/64 mm. (31-16)
31 "	10 cm	1/64 - 1/128 mm (16-8)

TABLE 4b

PARAMETERS OF GRAIN-SIZE DISTRIBUTIONS
(Mechanical Analysis)

TABLE 4b

PARAMETERS OF GRAIN-SIZE DISTRIBUTIONS (Mechanical Analysis).

μ units.	P_{90}	P_{84}	$P_{75}(Q_3)$	$P_{50}(Md)$	$P_{25}(Q_1)$	P_{16}	P_{10}	M	So	$Log_{10}So$	Sk_g	Kq_a
1. Laid "red marl" (pebbly base)	5100	2650	930	475	322	260	215	1128	1.70	0.230	1.36	0.073
2. Laide "red marl" (proper)	475	420	390	325	222	180	135	299	1.33	0.124	0.82	0.247
3. Gairloch, Big Sand	780	665	535	375	265	205	185	415	1.42	0.152	1.01	0.227
4. Redpoint	510	450	400	293	180	140	112	294	1.49	0.173	0.84	0.276
5. Leac Dubh calcareous siltstone	260	200	155	92	60	50	45	114	1.61	0.207	1.05	0.442

ϕ units.	$\phi5$	$\phi16$	$\phi25$	$\phi50$	$\phi75$	$\phi84$	$\phi95$	M_z	σ_I	Sk_I	K_G	K'_G
1. Laide "red marl" (pebbly base)	-	1.35	0.13	1.00	1.65	1.95	2.55	0.53	-	-	-	-
2. Laide "red marl" (proper)	0.85	1.20	1.30	1.63	2.18	2.50	3.18	1.78	0.68	+0.33	1.09	0.52
3. Gairloch, Big Sand	0.10	0.60	0.90	1.35	1.90	2.15	2.90	1.37	0.81	+0.07	1.15	0.53
4. Redpoint	0.70	1.18	1.29	1.78	2.39	2.78	3.81	1.91	0.87	+0.28	1.16	0.54
5. Leac Dubh calcareous siltstone	1.60	2.30	2.67	3.42	4.07	4.32	4.76	3.35	0.98	-0.13	1.07	0.52

TABLE 4c

CALCULATION OF MOMENT PARAMETERS

TABLE 4c

Moment Parameters

(Folk and Ward 1957, pp. 12-15)

Name	Sign	Formula	Verbal limits
Mean Size	M_z	$\frac{\phi 15 + \phi 50 + \phi 84}{3}$	<0 : grit and gravel 0 to 1.0 : coarse-grained sand 1.0 to 2.0 : medium-grained sand 2.0 to 3.0 : fine-grained sand 3.0 to 6.0 : silt >6.0 : clay (This thesis, based on Wentworth 1922)
Inclusive Graphic Standard Deviation (Sorting)	σ_I	$\frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$	<0.35 : very well sorted 0.35 to 0.50 : well sorted 0.50 to 1 : moderately sorted 1.00 to 2.00 : poorly sorted 2.00 to 4.00 : very poorly sorted >4.00 : extremely poorly sorted
Inclusive Graphic Skewness	Sk_I	$\frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$	-1.00 to -.30 : very negative-skewed - .30 to -.10 : negative-skewed - .10 to +.10 : nearly symmetrical-skewed + .10 to +.30 : positive-skewed + .30 to +1.00 : very positive-skewed
Graphic Kurtosis	K_G K_G'	$\frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$ $\frac{K_G}{K_G+1}$	(K_G') <0.40 : very platykurtic 0.40 to 0.47 : platykurtic 0.47 to 0.53 : mesokurtic 0.53 to 0.60 : leptokurtic 0.60 to 0.75 : very leptokurtic >0.75 : extremely leptokurtic

TABLE 4d

PARAMETERS OF GRAIN-SIZE DISTRIBUTIONS
(Thin Section Analysis)

T[illegible]d.

PARAMETERS OF THE [illegible] DISTRIBUTIONS.

	$\phi 5$	$\phi 16$	$\phi 25$	$\phi 50$	$\phi 75$	$\phi 84$	$\phi 95$	M_z	σ_I	Sk_I	K_G	K'_G
1. Trias : quartzose sandstones.												
Ld 6	1.78	2.15	2.30	2.65	3.03	3.32	3.77	2.72	0.60	+0.14	1.05	0.51
Ap 25	1.85	2.14	2.27	2.55	2.93	3.15	3.55	2.61	0.27	+0.20	0.88	0.47
An 7	-0.12	1.00	1.60	2.45	2.87	3.44	4.10	2.30	1.25	-0.20	1.36	0.58
Ab 25	1.35	1.72	1.88	2.25	2.68	2.90	3.25	2.29	0.58	+0.08	0.97	0.49
Rh 7	0.26	1.23	1.56	2.14	2.46	3.05	3.53	2.14	0.95	+0.07	1.49	0.60
Ld 7	1.11	1.36	1.47	1.88	2.38	2.72	3.36	1.99	0.68	+0.28	1.01	0.50
Ik 10	0.39	0.92	1.17	1.70	2.16	2.38	2.78	1.67	0.73	-0.08	0.99	0.50
Br 5	0.31	0.65	0.96	1.45	1.97	2.21	2.68	1.44	0.75	+0.01	0.96	0.49
Br 27	0.18	0.65	0.89	1.39	1.87	2.10	2.68	1.38	0.74	+0.01	1.05	0.51
Br 17	-0.03	0.55	0.71	1.08	1.49	1.70	2.12	1.11	0.61	+0.02	1.13	0.53
Gr 20	0.15	0.57	0.75	1.11	1.45	1.66	2.18	1.11	0.58	+0.03	1.19	0.54
In 15	-.53	-.16	0.02	.50	1.22	1.60	2.46	0.65	0.89	+0.27	1.02	0.51
2. Trias : feldspathic sandstones.												
Ik 5	1.37	1.90	2.10	2.52	3.02	3.24	3.80	2.55	0.70	+0.06	1.09	0.52
Gh 5	1.03	1.38	1.56	1.97	2.36	2.55	3.08	1.97	0.60	+0.04	1.05	0.51
RnL 6	0.99	1.36	1.53	1.95	2.35	2.54	2.94	1.95	0.59	+0.01	0.97	0.49
Ey 7	0.16	0.97	1.26	1.92	2.55	2.92	3.45	1.94	0.99	-0.02	0.85	0.46
Rp 2	1.07	1.38	1.53	1.85	2.23	2.43	2.78	1.89	0.52	+0.10	1.00	0.50
Gr 39	1.05	1.29	1.42	1.78	2.22	2.40	2.77	1.82	0.54	+0.13	0.88	0.47
Br 34	0.25	0.92	1.20	1.77	2.34	2.61	3.19	1.77	0.88	-0.11	1.06	0.51
RnL 2	0.89	1.18	1.33	1.67	2.03	2.23	2.70	1.69	0.54	+0.10	0.82	0.45
Gr 38	-.05	0.69	1.01	1.50	2.00	2.22	2.70	1.47	0.80	-0.10	1.14	0.53
RnL 8	0.56	0.79	1.06	1.44	1.87	2.08	2.59	1.44	0.33	+0.06	1.03	0.51
RnL 10	0.34	0.72	0.90	1.41	1.87	2.07	2.45	1.40	0.66	-0.02	0.89	0.47
Ls 3	0.40	0.73	0.87	1.27	1.71	1.92	2.48	1.31	0.61	+0.13	1.02	0.50
Gh 14	-0.20	0.27	0.47	1.05	1.53	1.75	2.32	1.02	0.75	0.00	0.97	0.49
Ey 9	-0.46	0.18	0.43	0.95	1.53	1.77	2.26	0.97	0.81	+0.04	1.01	0.50
Ap 10	-0.18	0.27	0.47	0.91	1.37	1.58	2.02	0.93	0.66	+0.02	1.00	0.50

	Ø5	Ø16	Ø25	Ø50	Ø75[illegible]
Gh 13	-0.46	0.21	0.40	0.87	1.5[illegible]
By 3	-0.55	-0.05	0.21	0.85	1.4[illegible]
Ab 5	-0.36	-0.07	0.17	0.86	1.3[illegible]
Br 60	-0.66	-0.18	0.05	0.4[illegible]	1.0[illegible]
3. Other Trias sediments.					
Sl 7	3.15	3.52	3.91	4.88	5.4[illegible]
Gr 44	1.68	2.30	2.80	3.66	4.5[illegible]
Lb 3	1.50	1.96	2.16	2.60	3.1[illegible]
Sl 4	-0.02	0.70	1.12	1.63	2.2[illegible]
La 8	-0.31	0.43	0.74	1.42	1.7[illegible]
Ik 7	-.86	-.14	0.17	0.74	1.3[illegible]
Ik 3	-1.24	-.66	-.36	0.47	1.4[illegible]
4. Passage Beds.					
Rh 10	3.24	3.85	4.23	5.12	5.8[illegible]
Rh 8	2.80	3.08	3.23	3.60	4.10
Ap 30	2.30	2.58	2.74	3.08	3.42
Rh 9	1.55	1.91	2.08	2.42	3.0[illegible]
Al 6	1.52	1.85	2.00	2.52	3.02
Al 7	2.48	2.59	2.72	2.97	3.27
5. Carboniferous sandstones.					
In 22	.36	.85	1.03	1.33	1.67
Ka 3	0.13	0.71	1.03	1.56	2.03
6.a Torridonian sandstone.					
Gh 20a	0.90	1.17	1.33	1.69	2.10

$\phi 84$	$\phi 95$	M_z	σ_I	Sk_I	K_G	K'_G
1.63	2.16	0.90	0.75	+0.03	1.11	0.53
1.66	2.10	0.82	0.83	-0.05	0.88	0.47
1.59	2.02	0.79	0.78	-0.07	0.81	0.45
1.32	1.91	0.54	0.76	+0.11	1.11	0.53
5.65	5.99	4.68	0.96	-0.25	0.75	0.43
4.80	5.60	3.59	1.22	-0.05	0.93	0.48
3.30	4.02	2.62	0.72	+0.09	1.08	0.52
2.46	-	1.60	-	-	-	-
2.55	3.45	1.47	1.10	+0.08	1.51	0.60
1.57	2.12	0.72	0.88	-0.05	1.08	0.52
1.80	2.55	0.54	1.19	+0.09	0.73	0.42
-	-	-	-	-	-	-
4.31	5.01	3.66	0.64	+0.22	1.04	0.51
3.61	4.12	3.09	0.53	+0.09	1.10	0.52
3.37	3.98	2.57	0.73	+0.29	1.08	0.52
3.32	3.85	2.56	0.72	+0.12	0.94	0.48
3.41	3.65	2.99	0.38	+0.12	0.87	0.47
1.84	2.27	1.34	0.54	+0.01	1.22	0.55
2.25	2.75	1.51	0.78	-0.10	1.07	0.52
2.34	2.79	1.73	0.58	+0.14	1.01	0.50

$\phi 25$	$\phi 50$	$\phi 75$	$\phi 84$	$\phi 95$	M_z	σ_I	Sk_I	K_G	K'_G
0.62	1.14	1.57	1.81	2.46	1.12	0.72	+0.02	1.05	0.51
0.97	1.37	1.79	1.99	2.40	1.36	0.63	-0.01	1.03	0.51
0.83	1.25	1.85	2.20	2.82	1.37	0.79	+0.20	1.07	0.52
0.75	1.28	2.14	2.52	3.23	1.45	0.46	+0.29	0.89	0.47
0.74	1.54	2.37	2.75	3.57	1.93	0.71	+0.05	1.08	0.52
1.61	2.08	2.55	2.72	3.08	2.07	0.64	-0.02	0.89	0.47
1.57	2.04	2.50	2.77	3.32	2.07	0.68	+0.01	1.00	0.50
1.67	2.05	2.59	2.98	3.35	2.18	0.68	+0.27	0.90	0.47
1.61	2.55	3.07	3.24	3.60	2.33	0.97	-0.31	0.85	0.46
0.56	1.00	2.14	2.57	3.30	1.32	1.03	+0.43	0.84	0.46
0.68	1.45	2.08	2.35	2.91	1.39	0.98	-0.09	0.93	0.48
1.46	1.92	2.38	2.62	3.23	1.93	1.11	+0.09	0.91	0.48
1.56	2.12	2.58	2.86	3.37	2.07	0.84	-0.10	1.11	0.53
0.64	0.86	1.20	1.44	2.07	0.95	0.48	+0.38	1.22	0.55
1.57	1.82	2.10	2.28	2.71	1.85	0.43	+0.15	1.16	0.54
1.68	2.04	2.35	2.49	2.75	2.01	0.54	-0.18	1.19	0.54

TABLE 5

PACKING PROPERTIES

TABLE 5

PACKING PROPERTIES

Specimen	Total grain-grain contact intercepts q	Packing Proximity P_p	Total grain-grain contacts G_c	Average grain-grain contacts per grain G_c/g	P_d	Matrix (% of rock)
Trias						
Ld 7	98	39.2	763	2.78	-	24.0
Gr 20	98	39.2	768	3.07	-	25.2
Gr 38	30	12.0	291	1.16	-	38.0
Gr 39	122	48.8	786	3.14	-	14.3
Ik 5	18	7.2	176	0.70	-	42.0
Ik 10	166	66.4	1068	4.27	80.5	9.8
In 15	92	36.8	743	2.97	-	10.9
Br 5	138	55.2	877	3.51	-	11.3
Br 27	126	50.4	835	3.34	68.7	12.8
Ey 7	73	29.2	533	2.13	-	35.0
Ey 8	66	26.4	475	1.90	-	33.1
RnL 2	67	26.8	504	2.02	-	39.6
RnL 6	76	30.4	508	2.03	70.9	32.1
Ap 10	5	2.0	102	0.41	-	31.4
Rp 2	17	6.8	230	0.92	57.4	34.0
Ab 25	97	38.8	695	2.78	-	20.7
Gh 14	32	12.8	291	1.16	-	37.3
Passage Beds						
Rh 8	55	22.0	383	1.53	-	45.4
Carboniferous						
In 22	150	60.0	1127	4.51	-	6.9
Ka 3	142	56.8	1043	4.17	-	6.9

Specimen	Total grain-grain contact intercepts q	Packing Proximity P_p	Total grain-grain contacts G_c	Average grain-grain contacts per grain G_c/g	P_d	Matrix (% of rock)
Torridonian						
Gh 20a.	216	86.4	1290	5.16	-	4.9
Pseudo-Trias						
Gh 8	199	79.6	1210	4.84	85.4	6.7
Bh 24	201	80.4	1191	4.76	-	9.5
Bh 29	219	87.6	1353	5.41	-	2.5
Ach 4	213	85.2	1258	5.03	-	3.7
Clastic dyke						
Ach 6	181	72.4	1071	4.28	-	7.3

In all cases, number of grains examined (g) = 250.

$$P_p = \frac{q}{250} \times 100$$

TABLE 6

LIMESTONE COBBLE MORPHOLOGY

TABLE 6

Measurements of limestone cobbles from the basal Trias conglomerate, Western Mull.

Locality	Limestone Cobble No.	a (L)	b (l)	c (E)	r_1	Cailleux Roundness $R_C = \frac{2r_1}{L}$	Kuenen Roundness $R_K = \frac{2r_1}{l}$	Cailleux Flattening $F_C = \frac{L + l}{2E}$	$^b/_a$	$^c/_b$	Weight in gms.
Inchkenneth (Humpies basal conglomerate).	1	7.7	5.4	2.8	[illegible]	0.260	0.370	2.339	0.701	0.519	218
" "	2	8.6	4.4	2.0	[illegible]	0.349	0.682	3.250	0.512	0.455	145
" "	3	6.5	5.4	1.4	[illegible]	0.538	0.648	1.352	0.831	0.815	239
Gribun (basal conglomerate on shore).	4	12.9	10.7	5.2	[illegible]	0.388	0.467	2.314	0.829	0.486	1031
" "	5	10.6	7.9	6.3	[illegible]	0.330	0.443	1.486	0.745	0.797	930
" "	6	12.4	7.3	3.7	[illegible]	0.242	0.411	2.662	0.589	0.507	570
" "	7	7.0	5.6	4.1	[illegible]	0.429	0.536	1.537	0.800	0.732	253
" "	8	6.4	4.0	2.6	[illegible]	0.234	0.375	2.000	0.625	0.650	112
" "	9	12.7	10.2	7.0	[illegible]	0.433	0.539	1.636	0.803	0.686	892
" "	10	9.8	6.5	3.1	[illegible]	0.204	0.308	2.629	0.663	0.477	313
" "	11 (pebble)	4.2	2.5	1.5	[illegible]	0.357	0.600	2.233	0.595	0.600	22
" "	12 (pebble)	4.3	3.0	1.9	[illegible]	0.465	0.667	1.921	0.698	0.633	37
" "	13	6.4	4.6	3.9	[illegible]	0.469	0.652	1.410	0.719	0.484	165
" "	14	6.8	4.3	3.5	[illegible]	0.368	0.581	1.614	0.632	0.814	160
" "	15	7.1	5.0	3.5	[illegible]	0.563	0.800	1.729	0.704	0.700	240
" "	16	10.1	6.3	3.6	[illegible]	0.396	0.635	2.278	0.624	0.571	483
" "	17	13.9	7.8	4.8	[illegible]	0.360	0.641	2.260	0.561	0.615	1021
" "	18 (pebble)	5.8	3.5	1.8	[illegible]	0.259	0.429	2.583	0.603	0.514	66
" "	19	12.8	7.9	5.2	[illegible]	0.391	0.633	2.029	0.617	0.658	1097
" "	20	8.4	7.0	5.6	[illegible]	0.417	0.500	1.375	0.833	0.800	628

a, b, c and r_1 are given in centimetres.

Average R_C = 0.373.
" R_K = 0.546.

Average F_C = 2.032.

Long axis range : 4.2 to 13.9 cms.

Wentworth cobble grade : 6.4 to 25.6 cms.

TABLE 7

CORNSTONES : PHYSICAL ANALYSIS

CORNST

	Ikc 1	Ikc 2	Ikc 3	Ikc 4
Height above base of profile (cms)	0	40	80	120
Specific Gravity	2.646	2.652	2.664	2.678
Insoluble residue (%)	24.3	31.1	22.6	12.7
Dolomite + ferroan calcite (%) (point count)	33.1	26.5	15.4	11.2

	Bhc 1	Bhc 2	Bhc 3	Anc 1
Height above base of profile (cms)	0	40	80	20
Specific Gravity	-	-	-	2.647
Insoluble residue (%)	44.3	13.9	10.2	96.1
Dolomite + ferroan calcite (%)	-	-	-	1.6

	In 14	Rh bc	Rh c	Alc
Insoluble residue (%)	6.0	6.2	20.0	8.4

[illegible]E 7

[illegible]ALYSIS

Ikc 5	Ikc 6	Ikc 7	Ikc 8	Ikc 9	Ikc 10	Ikc 11	Ikc 12	Ikc 13
160	200	240	280	320	360	400	440	480
[illegible].149	2.657	2.696	2.702	2.710	2.701	2.705	2.697	2.679
1[illegible].4	13.1	5.5	5.9	6.6	5.1	7.5	7.1	25.6
[illegible].5	46.8	32.0	8.8	2.7	2.0	25.3	53.4	66.4

Anc 2	Anc 3	Anc 4	Anc 5	Anc 6	RnLc 1	RnLc 2	RnLc 3	RnLc 4	RnLc 5
[illegible]0	140	200	235	290	0	0	36	77	92
2.6[illegible]5	2.675	2.761	2.775	2.745	2.695	2.614	2.687	2.700	2.640
78.1	76.4	23.1	21.4	33.6	23.9	78.7	32.2	15.8	65.0
23.5	24.5	18.8	19.5	44.2	0	0	0	0	0

[illegible] 4	Ey 11	Sl 7
12.9	11.8	60.2

TABLE 8

CORNSTONES : CHEMICAL ANALYSIS

TABLE 8

CHEMICAL ANALYSES OF CORNSTONES

	Ikc 13	Ikc 11	Ikc 6	Ikc 2	Anc 6	RnLc 5
Weight of sample	.5013	.5001	.5024	.5007	.5003	.5013
Insoluble Residue	.1473	.0364	.0608	.1413	.1719	.0945
Carbonate dissolved	0.3540	.4637	.4412	.3594	.3284	.4068
R_2O_3	.0072	.0058	.0131	.0110	.0146	.0051
CaO	.1631	.2205	.1926	.1538	.1269	.2194
* $CaCO_3$	.2913	.3935	.3436	.2743	.2263	.3915
$Mg_2P_2O_7$	.0600	.0742	.0878	.0715	.1060	.0002
MgO	.0217	.0269	.0318	.0259	.0384	.00007
* $MgCO_3$	.0454	.0562	.0665	.0541	.0803	.000146
H_2O - (<110°c)	.0008	.0006	.0007	.0011	.0008	.0008
Total	.4987	.4925	.4847	.4818	.4939	.4920
Total %	98.14	98.48	96.48	96.23	98.72	98.14
Calcite	.2374	.3268	.2646	.2101	.1310	.3913
Calcite %	47.36%	65.35%	52.67%	41.97%	26.18%	78.06%
Dolomite	.0993	.1229	.1455	.1163	.1756	.0003
Dolomite %	19.81%	24.58%	28.96%	23.63%	35.10%	0.06%
Calcite: Dolomite Ratio	2.39	2.66	1.82	1.78	0.75	
Percentages						
$CaCO_3$	58.11	78.68	68.39	54.78	45.23	78.10
$MgCO_3$	9.06	11.24	13.24	10.80	16.05	00.00
Insoluble Residue	29.38	7.28	12.10	28.22	34.36	18.85
R_2O_3	1.44	1.16	2.61	2.20	2.92	1.02
H_2O-	.15	.12	.14	.22	.16	.16
	98.14	98.48	96.48	96.22	98.72	98.13

* Assuming all CaO and MgO present as carbonate.

* Assuming all CaO and MgO present as carbonate Weight given in gms.

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SOME STUDIES ON THE STRATIGRAPHY AND SEDIMENTATION OF THE TRIAS OF THE WESTERN HIGHLANDS AND HEBRIDES, SCOTLAND.

by

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VOLUME II : ILLUSTRATIONS

Fig. 1a. Grit horizons and a small wash-out (beside hammer) in the Humpies Conglomerate, Inchkenneth.

Fig. 1b. Cross-bedded grit lens, Humpies Conglomerate, Inchkenneth.

Fig. 2. Uneven bedding and poor sorting in the Humpies Conglomerate, Inchkenneth.

Fig. 1a.

Fig. 1b.

Fig. 2.

Fig. 3. Uneven base of the Iollaich Beds above the eroded top of the Humpies Conglomerate. Bagh an Iollaich, Inchkenneth.

Fig. 4. Cross-bedding in conglomerate, Iollaich Beds. Note attitude of tabular pebbles on the foreset beds giving apparent reversed imbrication with respect to the true bedding. Bagh an Iollaich, Inchkenneth.

Fig. 5. Cornstone profile showing 'pipe' cornstone overlain by rubbly and homogeneous bedded cornstone. Inchkenneth Chapel.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 5a. Homogeneous bedded cornstone with slight development of 'pipes' in sand at the base. Rudha Baile na h-Airde, Gribun.

Fig. 6. Successive in upper part of the Chapel Beds, Inchkenneth. Rubbly cornstone is developed in sandstone in the central part, above which is a sandstone containing well developed cornstone 'pipes' and nodules, overlain by conglomerate.

Fig. 7. View of part of Inchkenneth, looking southwest to The Humpies. 'The Wilderness' of Western Mull is on the left, middle distance, and in the far distance are the Ross of Mull and Iona.

Fig. 5a.

Fig. 6.

Fig. 7.

Fig. 8. Trias-Moine unconformity. Gribun shore beneath Balmeanach Farm.

Fig. 9. Thin veins of cornstone developed in the Moine beneath the unconformity. Gribun shore near Balmeanach Farm.

Fig. 10. Geology and landscape of the coast between Balmeanach and Mackinnon's Cave. (From Bailey and Anderson, 1920).

Fig. 8.

Fig. 9.

Fig. 10.

Fig. 11. Imbrication of Moine pebbles in conglomerate. Gribun shore.

Fig. 11a. Two pebble beds with different imbrication directions. The upper bed (beneath hammer) shows some reversed imbrication. Gribun shore.

Fig. 12. Single set of cross-strata in conglomerate, southwest end of Inchkenneth seen beyond. Gribun shore.

Fig. 11.

Fig. 11a.

Fig. 12.

Fig. 13. Cornstone concretion (left of hammer shaft) developed in conglomerate and overlain by pebbly grit. Gribun shore.

Fig. 14. Part of the Trias succession in Ath Dearg. Pipes and nodules of cornstone developed at the top of a soft sandstone bed, overlain by hard pebbly sandstone and grit.

Fig. 15. Cross-bedded grit lens in quartz pebble conglomerate. Craignure, S.E. Mull.

Fig. 13.

Fig. 14.

Fig. 15.

Fig. 16. Cross-bedding in conglomerate, Loch Don. Oblique surface upper right indicate the true bedding.

Fig. 17. Polygonal crack pattern on upper surface of cornstone. Gualann Dubh, N.E. Mull.

Fig. 18. Veining of Moine by Trias cornstone : early stage. Loch Teacuis, Morvern.

Fig. 16.

Fig. 17.

Fig. 18.

Fig. 19. Permeation of Moine by Trias cornstone : later stage. Loch Teacuis, Morvern.

Fig. 20. Complete replacement of cross-bedded sandstone by cornstone. Mingary pier, Ardnamurchan.

Fig. 21. Basal cornstone and Torridonian. Sea cliff at A' Mharagach, Rhum.

Fig. 19.

Fig. 20.

Fig. 21.

Fig. 22. Permeation of Torridonian by basal cornstone; original convolute bedding in Torridonian still apparent. Stream 250 m S.S.E. of A' Mharagach.

Fig. 23. Uneven eroded top of homogeneous bedded cornstone, overlain by conglomerate and 'pipe' cornstone. An Leac.

Fig. 24. Erosional base of conglomerate overlying homogeneous bedded cornstone. Fragments of cornstone are seen just detached from the upper surface.

Fig. 22.

Fig. 23.

Fig. 24.

Fig. 24a. Sand infilling a crack at the top of a cornstone bed. The overlying conglomerate is upper right. Dark streaks in the foreground are chert bands. An Leac.

Fig. 25. Base of limestone conglomerate, cut by thin basic sill. Beinn a Mheadhoinn, Strath.

Fig. 26. Limestone conglomerate. Beinn a' Mheadhoinn, Strath.

Fig. 24a.

Fig. 25.

Fig. 26.

Fig. 27. Sandy basal beds of Trias with cornstone nodules, overlain by conglomerate. Scalpay.

Fig. 28. Joint plane in conglomerate. Eilean Leac na Gainimh, Scalpay. Dark pebbly are Torridonian, light pebbles with crosses are Durness Carbonate, and light pebbles without crosses are quartzite.

Fig. 29. Three immature cornstone profiles; the white fragment on the right is a detrital block of Durness Carbonate. Rudha na Leac, Raasay. (see Frontispiece).

Fig. 27.

Fig. 28.

Fig. 29.

Fig. 29a. Development of cornstone 'pipes' beneath the upper bedding plane of a sandstone bed overlain by conglomerate. Eyre, Raasay.

Fig. 30. Part of the Trias succession in the cliffs at Camas Mor, N. of Gairloch. The cliffs are 12 m high.

Fig. 31. 'Pseudo-Trias' conglomerate overlying the unconformity at Rubha Reidh. The loose boulder is 1 m high.

Fig. 29a.

Fig. 30.

Fig. 31.

Fig. 31a. Interbedded 'Pseudo-Trias' sandstone and conglomerate; the white streaks are secondary quartz veins. Roadside, Rubha Reidh.

Fig. 32. 'Pseudo-Trias' conglomerate overlying the unconformity. Rucksac top right for scale. Coastal cliffs 0.6 kms E.N.E. of Rubha Reidh lighthouse.

Fig. 33. 'Pseudo-Trias conglomerate overlying the unconformity. The larger boulder in the conglomerate (upper right) is 4.6 m in diameter. Uamh an Oir, Badluarach.

Fig. 31a.

Fig. 32.

Fig. 33.

Fig. 34. Secondary calcite vein. Craignure, S.E. Mull.

Fig. 35. Secondary calcite vein. Gairloch, Big Sand.

Fig. 34.

Fig. 35.

Fig. 36. Clastic dykes. Leac an Ime, Badluarach.

Fig. 37. Clastic dyke off-set at the unconformity marking the base of the 'Pseudo-Trias'. Carn Dearg na h-Uamha, Badluarach.

Fig. 38. Clastic dyke and sill in 'Pseudo-Trias' sandstone. Leac an Ime, Badluarach. X 1.

Fig. 36.

Fig. 37.

Fig. 38.

Fig. 39. Invasion of a quartzo-feldspathic vein in the Moine by cornstone, showing fresh faces not attacked by carbonate. Polished surface. X 1. Loch Teacuis, Morvern.

Fig. 40. Conglomeratic cornstone with secondary calcite veins. southwest end of the Trias outcrop. Rhum. x 1½

Fig. 39.

Fig. 40.

Fig. 41. Sketch of section through a cornstone pipe. Rhum. ×1

a : Granular calcite.

b : Sparry calcite.

c : Coarse-grained sandstone (grey).

d : Medium-grained sandstone (red).

Fig. 42. Etched face of cornstone stained with potassium ferricyanide showing dolomitic areas. X 1 Inchkenneth Chapel.

Fig. 43. Etched surface of oolitic cornstone stained with Titan Yellow. Ooliths have shells of amorphous silica and dolomitic centres. Inninmore Bay. ×1

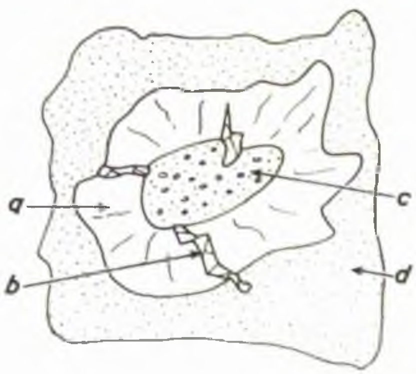


Fig. 41.

Fig. 42.

Fig. 43.

Fig. 44. Polished face of cornstone showing micrite, sparry calcite, ooliths and chert. X 1 Innimore Bay.

Fig. 44a. Opposite face, etched with dilute acid. X 1

Fig. 44.

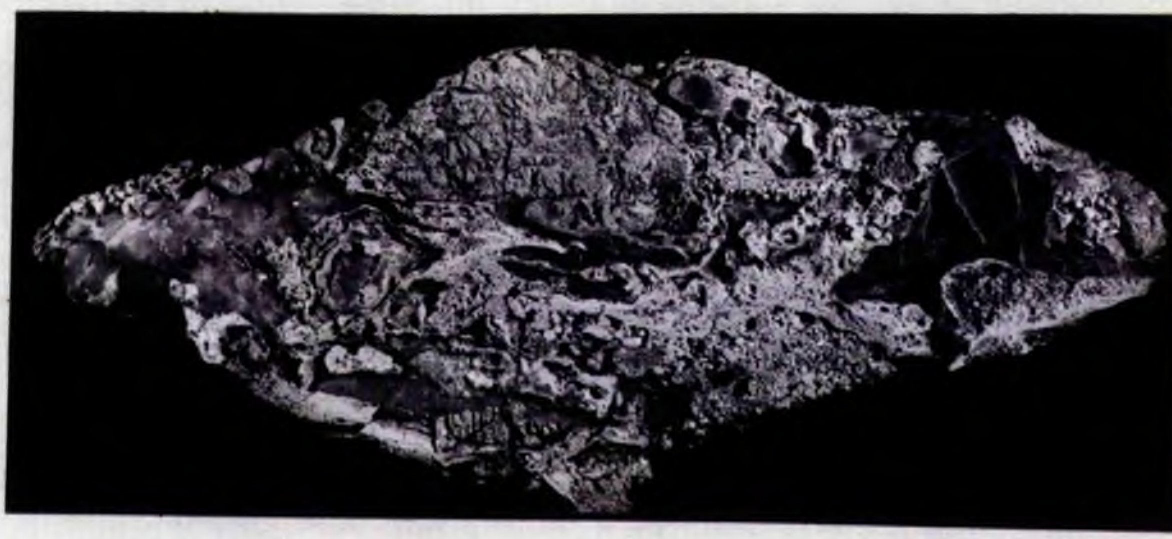


Fig. 44a.

Fig. 45a. Mud-cracks (lower surface). X $\frac{1}{3}$. Laide, Gruinard Bay.

Fig. 45b. Mud-flake pseudo-conglomerate (upper surface). X $\frac{1}{3}$. Laide, Gruinard Bay.

Fig. 45a.

Fig. 45b.

Fig. 46a. Parting ('parting step') lineation (upper surface). X $\frac{3}{4}$. Leac Dubh, Gruinard Bay.

Fig. 46b. Parting ('parting plane') lineation (upper surface). X $\frac{2}{3}$. Leac Dubh, Gruinard Bay.

Fig. 46a.

Fig. 46b.

Fig. 47a. Lens and flaser bedding overlain by laminated bedding. X $\frac{1}{3}$. Passage Beds, Applecross.

Fig. 47b. Lens and flaser bedding from the German Watten^schlick (Häntzchel, 1936).

Fig. 47a.

Fig. 47b.

Fig. 48. Small disc-shaped pebbles orientated with their long axes normal to the current direction (indicated by the arrow) in a sandstone showing parting lineation (Gh 5). X 1½. Gairloch, Big Sand.

Fig. 49. 'Sponge' form in Durness Carbonate pebble X 3. Glen Boreraig, Strath. (Also found at Eilean Leac na Gainimh, Scalpay).

Fig. 49a. 'Sponges' in Durness Carbonate _in situ_, east of Beinn an Dubhaich, Strath.

Fig. 48.

Fig. 49.

Fig. 49a.

Fig. 50. *Lesueurilla* Koken, in Durness Carbonate pebble. X 1½. Glen Boreraig, Strath.

Fig. 51. *Ectomaria* Koken, in Durness Carbonate pebble. X 3. Glen Boreraig, Strath.

Fig. 52. Dorsal valve of *Diparelasma* ? , in Durness Carbonate pebble. X 3. Rudha na Leac, Raasay.

Fig. 50.

Fig. 51.

Fig. 52.

Fig. 53. a. Felsite pebble from the Trias conglomerate, S. Raasay. X 45.

b. Felsite pebble from a Torridonian pebble bed, N. Raasay. X 45.

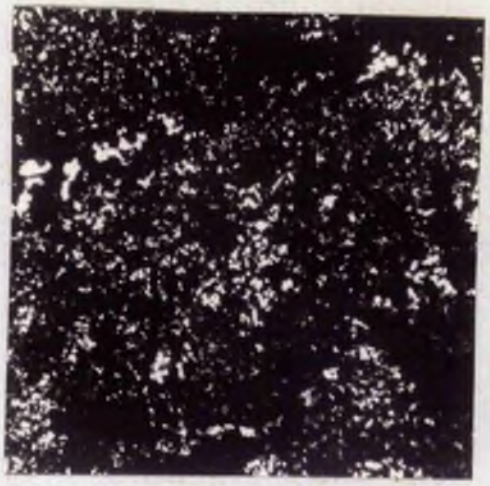
c. Arkosic sandstone pebble (Torridonian). X 15.

d. 'Arkose gneiss' pebble (Moine). X 15.

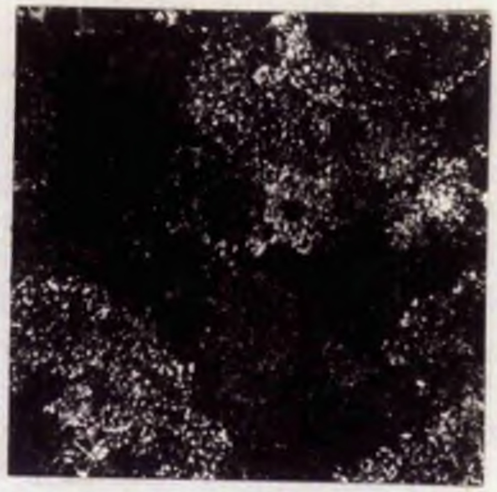
e. Metaquartzite pebble (Moine). X 15.

f. Orthoquartzite pebble (Cambrian). X 15.

All are under crossed nicols.



a.

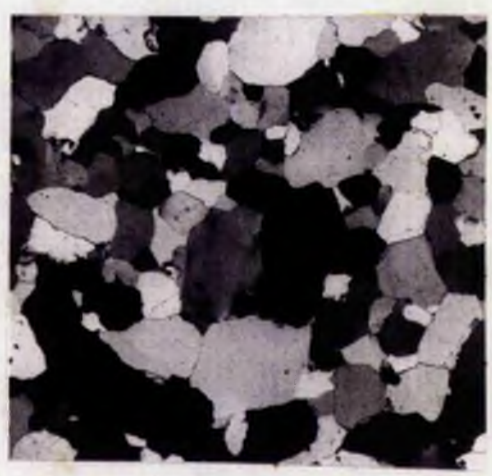


b.

c.

d.

e.



f.

Fig. 54. Durness Carbonate pebbles.

a. Stylolite between micrite and intramicrite. X 15.

b. 'Algal' banding. X 15.

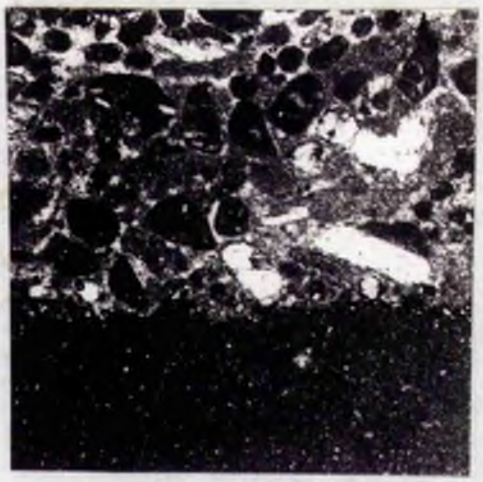
c. Intrasparite. X 15.

d. Oosparite, shewing recrystallised sparry calcite centres in the ooliths. X 15.

e. Dolomite. X 45.

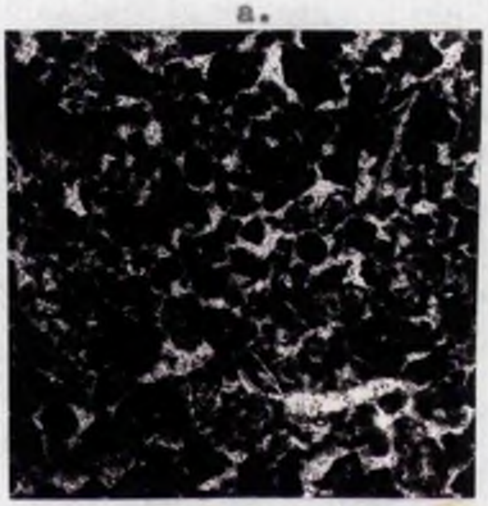
f. Dolomite rhombs replacing chert. X 45.

All are in plane polarised light.

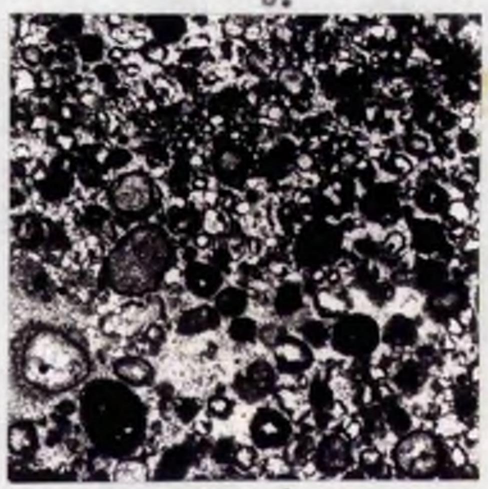


a.

b.

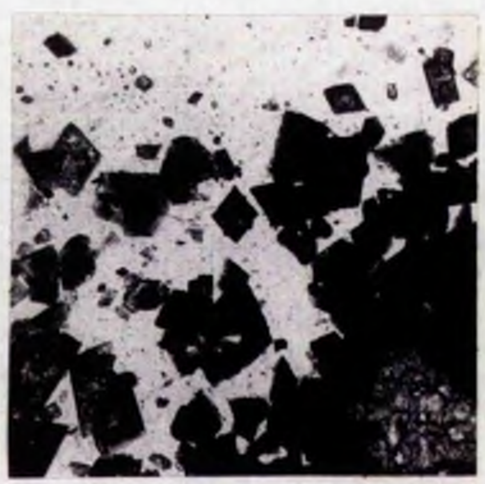


c.



d.

e.



f.

Fig. 55. Igneous pebbles (Old Red Sandstone) : a-e

a. Granite. Crossed nicols. X 15.

b. Granophyre. Crossed nicols. X 15.

c. Porphyrite. Plane polarised light. X 15.

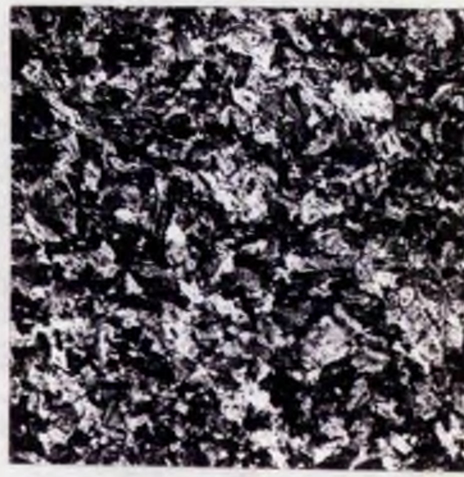
d. Felsite. Crossed nicols. X 15.

e. Mica-lamprophyre. Plane polarised light. X 15.

f. Mylonised sandstone. Crossed nicols. X 15.

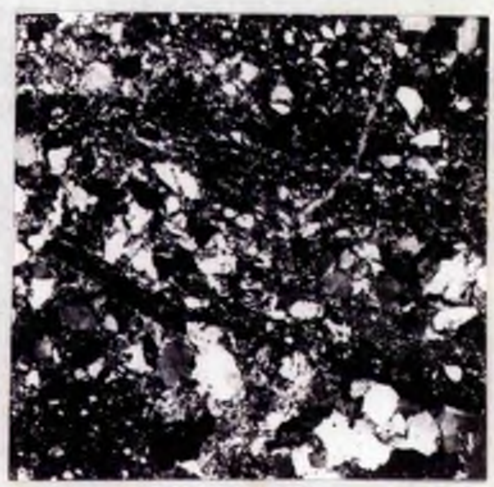
a.

b.



c.

d.



e.

f.

Fig. 56. a. Quartzose sandstone. Crossed nicols. X 15.

b. Feldspathic sandstone. Crossed nicols. X 15.

c. Possible eolian sandstone (Ls 3). Shows shearing in the top right-hand corner. Crossed nicols. X 15.

d. Sandstone with a well-developed crystalline calcite cement. Crossed nicols. X 15.

e. Micaceous sandstone. Plane polarised light. X 15.

f. Silty marl. Plane polarised light. X 15.

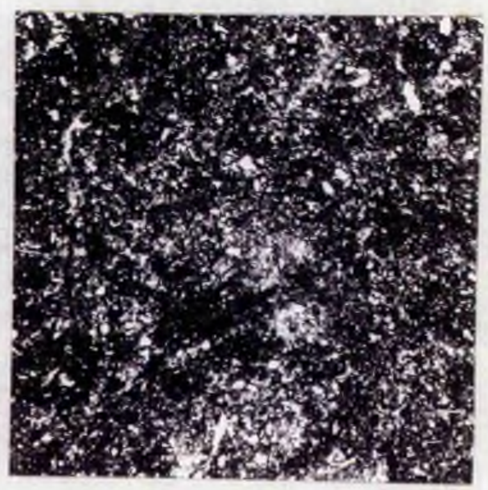
a.

b.

c.

d.

e.



f.

Fig. 57 a. Sandstone containing quartzose Moine rock fragments, composite quartz, quartz and feldspar in a matrix of crystalline calcite. Crossed nicols. X 15.

b. Sandstone containing a large fragment of crushed quartz. Grains have opaque rims. Crossed nicols. X 15.

Fig. 58. Dolomite rhombs developed within the cleavage planes of a biotite flake. Plane polarised light. X 105.

Fig. 59. Trias grit altered by Tertiary pneumatolysis in S.E. Mull. Crossed nicols. X 15.

Fig. 57a.

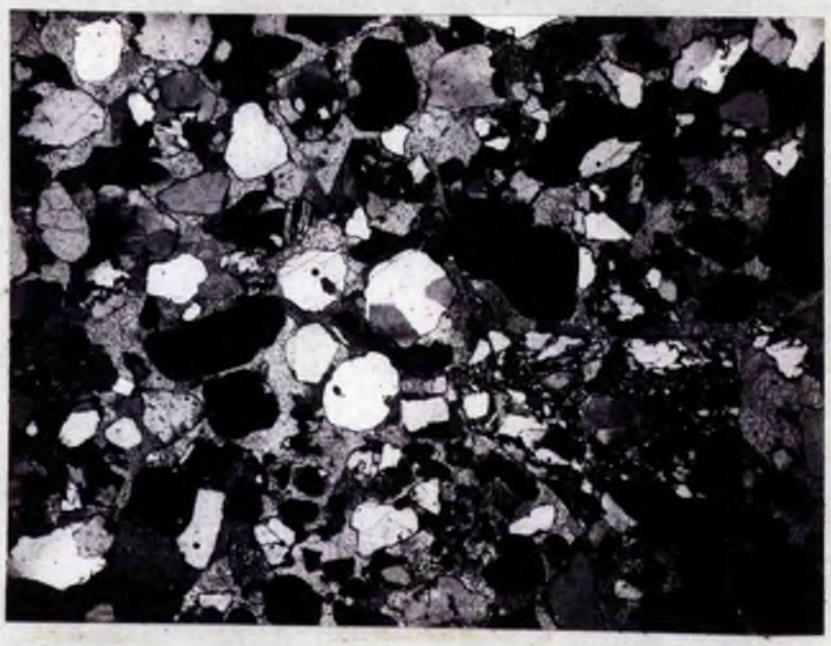


Fig. 57b.

Fig. 58.

Fig. 59.

Fig. 60 a. Limestone conglomerate, containing fragments of chert, silicified intramicrite and micrite. Crossed nicols. X 15.

b. Limestone conglomerate (mudflow?). Crossed nicols. X 15.

c. Two specimens of probable mudflow limestone conglomerate, showing abundant detrital matrix. Plane polarised light. X 15.

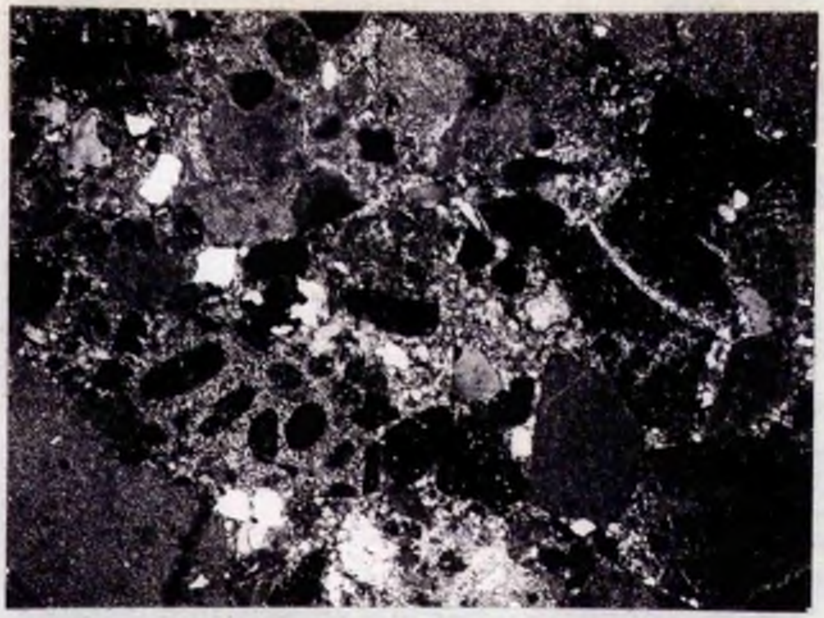


Fig. 60a.

Fig. 60b.

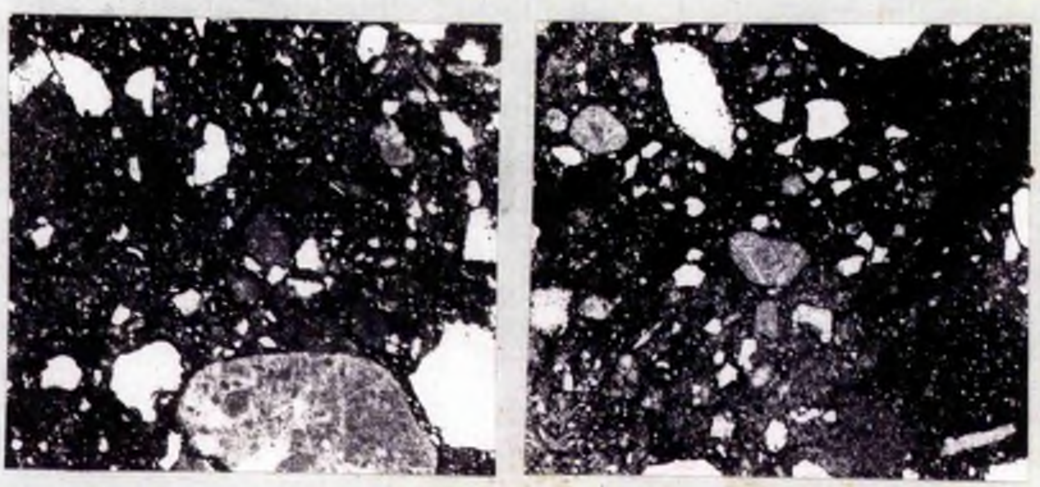


Fig. 60c.

Fig. 61. a. Cornstone : dismicrite containing 'floating' corroded detrital quartz grains. Plane polarised light. X 45.

b. Cornstone : microcrystalline calcite with a few tiny detrital grains. Plane polarised light. X 45.

Fig. 62. Conglomeratic cornstone. Plane polarised light. X 15.

Fig. 61 a.

Fig. 61 b.

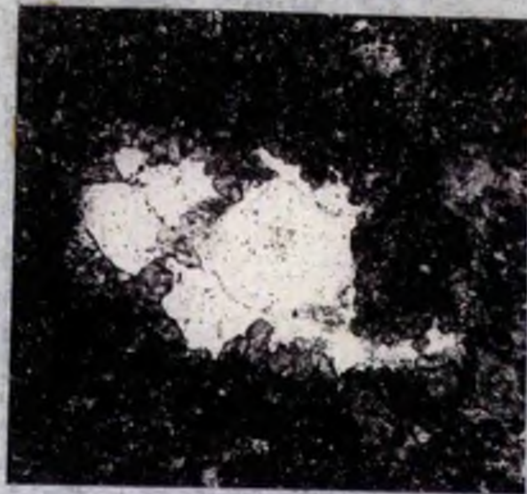
Fig. 62.

Fig. 63 a. Carbonate attacking feldspar grain in cornstone. Plane polarised light. X 105.

b. Carbonate attacking feldspar grain in caliche. Crossed nicols. X350. (Swineford and Franks, 1959).

c. Detail of carbonate attack on a quartz grain in cornstone. Crossed nicols. X 360.

Fig. 64. Dolomitised cornstone, with a little sparry calcite in the interstices between the dolomite rhombs. Plane polarised light. X 45.



a.

b.

c.

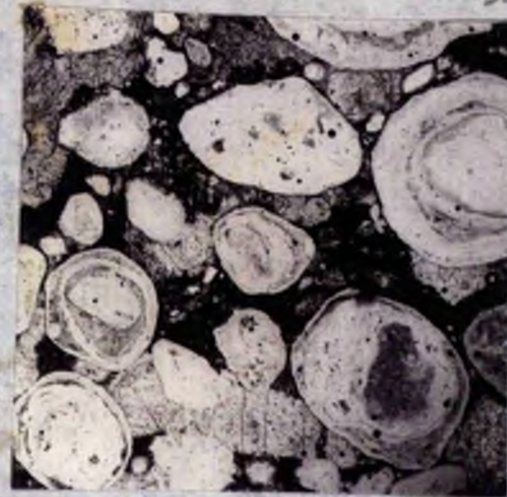
Fig. 64.

Fig. 65. a. Carbonate oolith centred on a quartz grain. Plane polarised light. X 45.

b. Silicified ooliths in sparry calcite cement (stained with Alizarin Red 'S' solution). Plane polarised light. X 15.

Fig. 66. a–c. Chalcedonic silica developed along the walls of cavities in cornstone micrite, with a later infilling of sparry calcite. Crossed nicols. X 15.

a.



b.

Fig. 66 a.

b.

c.

Fig. 67. Selective replacement of carbonate by chalcedony in cornstone: calcite is replaced, but dolomite is unaffected.

a. Plane polarised light

b. Crossed nicols.

X 105.

Fig. 68. a. Sparry calcite replacing silicified oolith. Stained with Alizarin Red "S" solution. Crossed nicols. X 105.

b. As in a., showing the remnant outer shell of one oolith. Crossed nicols. X 105.

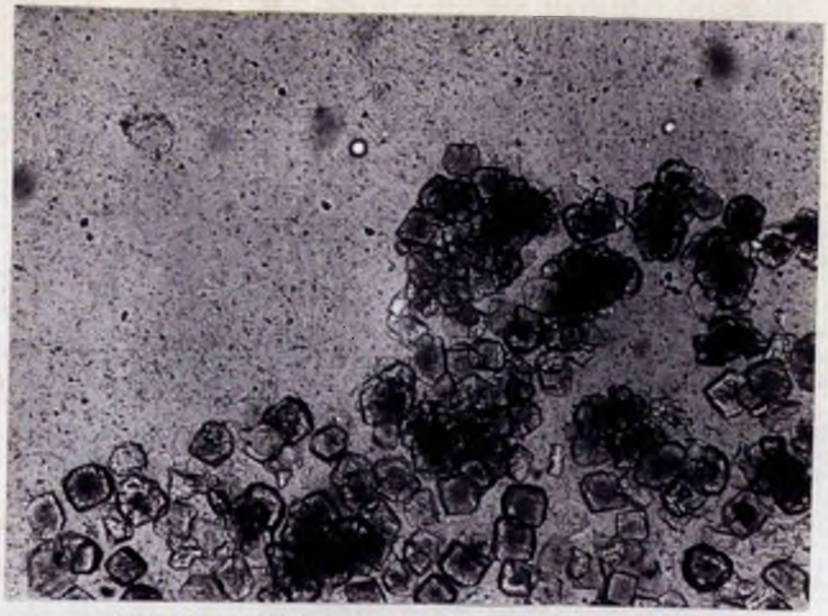


Fig. 67.a

Fig. 67.b

a.

b.

Fig. 69. Stylolite in cornstone. Plane polarised light. X 15.

Fig. 70. Attack by basal Trias cornstone on feldspathic Moine with thin quartz veins. Both quartz and feldspar show fresh faces. Crossed nicols. X 15.

Fig. 71. Barytes, showing plumose and bladed habit (W. Mull). Crossed nicols. X 15.

Fig. 69.

Fig. 70.

Fig. 71.

Fig. 72. a. Torridonian sandstone pebble (coarse-grained) enclosed in Pseudo-Trias sandstone (fine-grained). Plane polarised light X 15.

b. Pseudo-Trias sandstone with heavy mineral concentrations in bands. Plane polarised light. X 15.

c. Pseudo-Trias sandstone. Plane polarised light. X 15.

d. Quartzite pebble from the Pseudo-Trias conglomerate at Loch a Cearn Carnaich. Crossed nicols. X 15.

e. Contact between clastic dyke sandstone (on the left) and Torridonian sandstone 'country rock'. Crossed nicols. X 15.

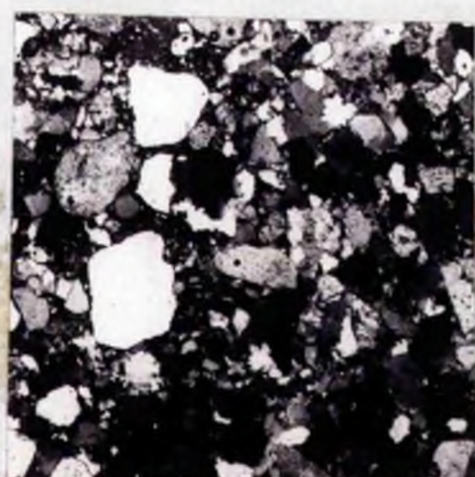
f. As in e, with plane polarised light.

a.

b.

c.

d.



e.

f.

Fig. 73. 'QFR' diagram: all the sediments analysed.

○ Passage Beds

• Trias

+ Carboniferous

× Pseudo-Trias, Torridonian and clastic dykes.

Fig. 74. 'QFR' diagram: samples as above.

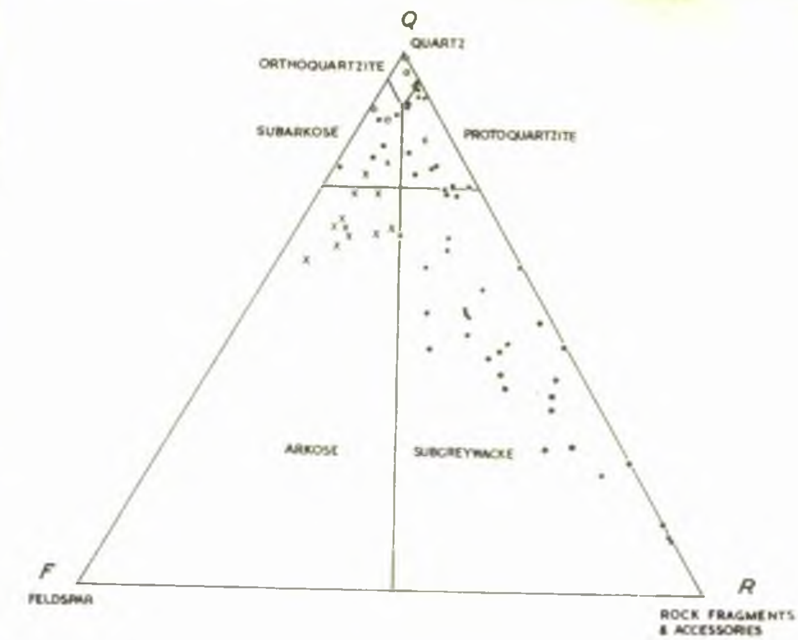

Q
QUARTZ
ORTHOQUARTZITE
SUBARKOSE
PROTOQUARTZITE
ARKOSE
SUBGREYWACKE
F
FELDSPAR
R
ROCK FRAGMENTS
& ACCESSORIES

Fig. 73.

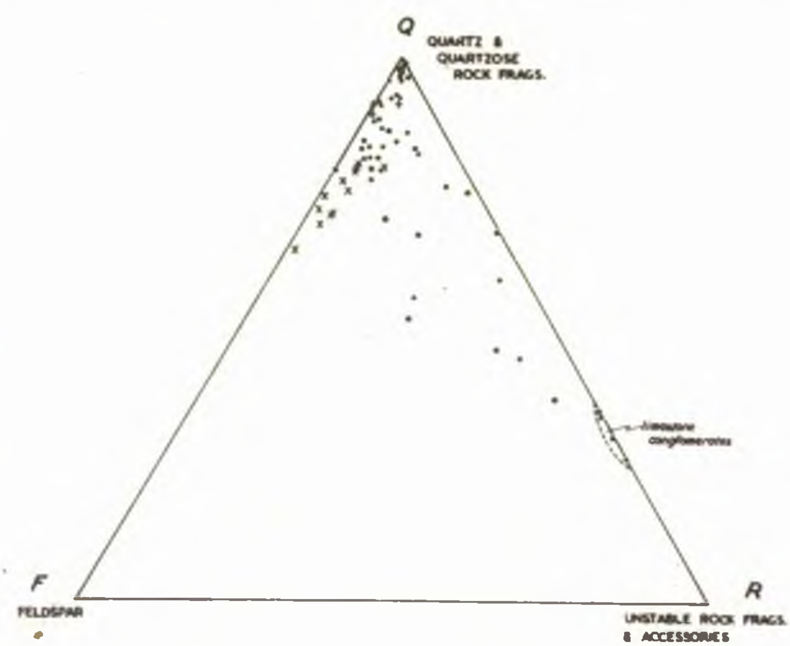

Q
QUARTZ &
QUARTZOSE
ROCK FRAGS.
F
FELDSPAR
R
UNSTABLE ROCK FRAGS.
& ACCESSORIES

Fig. 74.

Fig. 75. 'QFR' diagram: Trias sandstones.

o Quartzose sandstones

+ Feldspathic sandstones

• Other sandstones.

Fig. 76. 'DCG' diagram: Trias sediments.

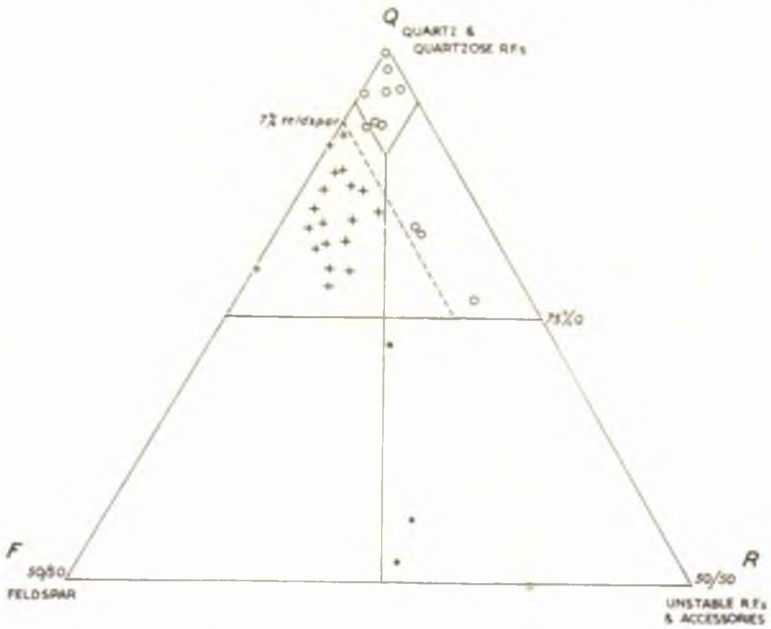

Q QUARTZ & QUARTZOSE RFs
7% feldspar
75% Q
F 50/50 FELDSPAR
R 50/50 UNSTABLE RFs & ACCESSORIES

Fig. 75.

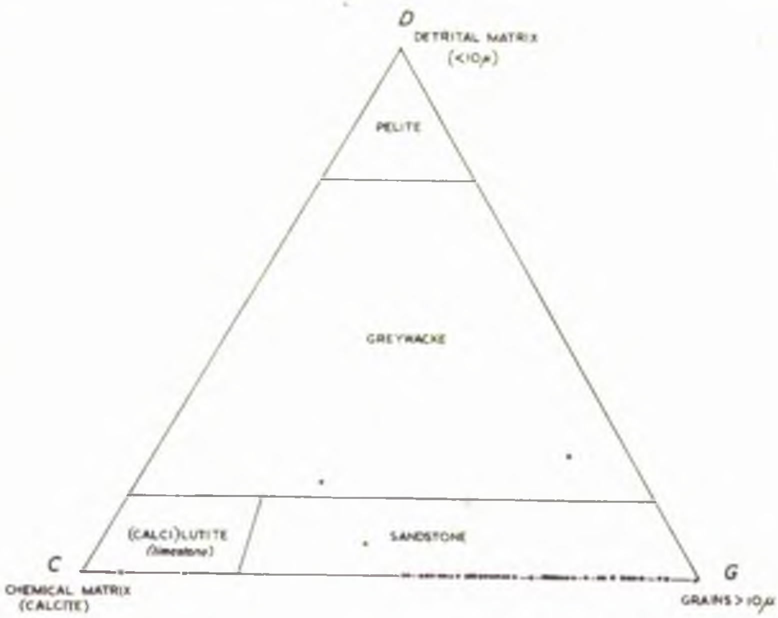

D DETRITAL MATRIX (<10μ)
PELITE
GREYWACKE
(CALCI)LUTITE (limestone)
SANDSTONE
C CHEMICAL MATRIX (CALCITE)
G GRAINS > 10μ

Fig. 76.

Fig. 77. Maturity index (M_i) plotted against total rock fragment index (R_t).

o Quartzose sandstones

+ Feldspathic sandstones

• Other Trias sandstones

Fig. 78. Total rock fragment index (R_t) plotted against mean size (M_z).

o Quartzose sandstones

+ Feldspathic sandstones

• Other Trias sandstones

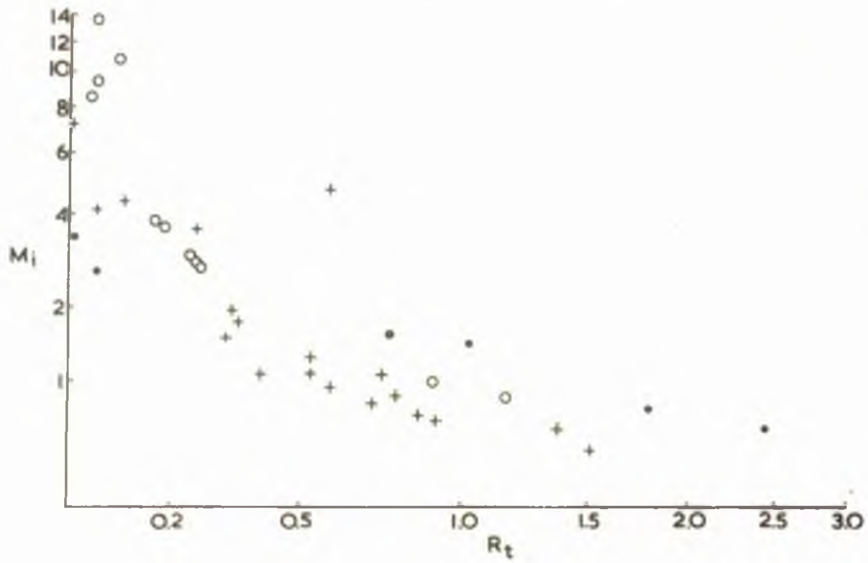

M_i
14
12
10
8
6
4
2
1
0.2
0.5
1.0
1.5
2.0
2.5
3.0
R_t

Fig. 77.

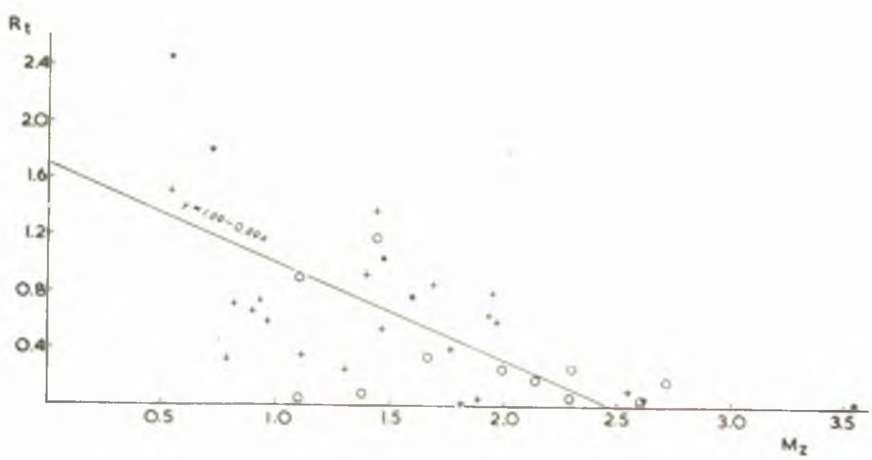

R_t
2.4
2.0
1.6
1.2
0.8
0.4
0.5
1.0
1.5
2.0
2.5
3.0
3.5
M_z

Fig. 78.

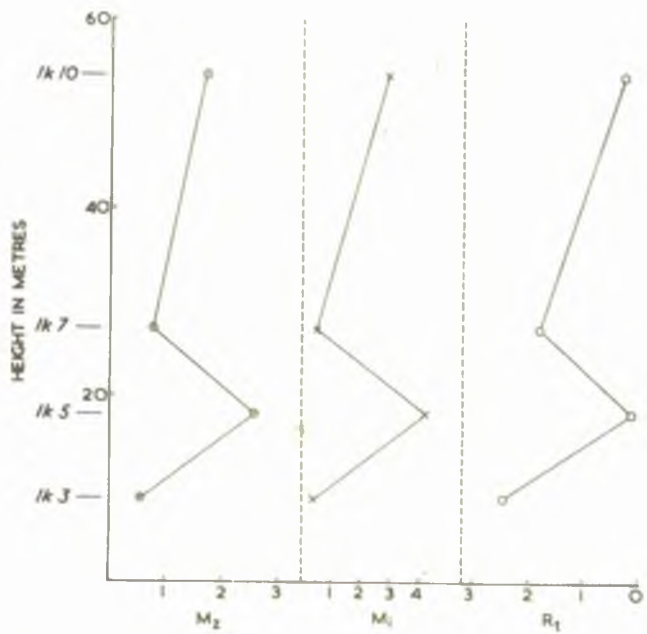
Fig. 79. Maturity index (M_i) plotted against mean size (M_z)

o Quartzose sandstones

+ Feldspathic sandstones

• Other Trias sandstones

Fig. 80. Variation in mean size (M_z), maturity index (M_i) and total rock fragment index (R_t) through the succession at Inchkenneth.



HEIGHT IN METRES
60
40
20
Ik 10
Ik 7
Ik 5
Ik 3
1 2 3
M2
1 2 3 4
M1
3 2 1 0
R1

Fig. 80.

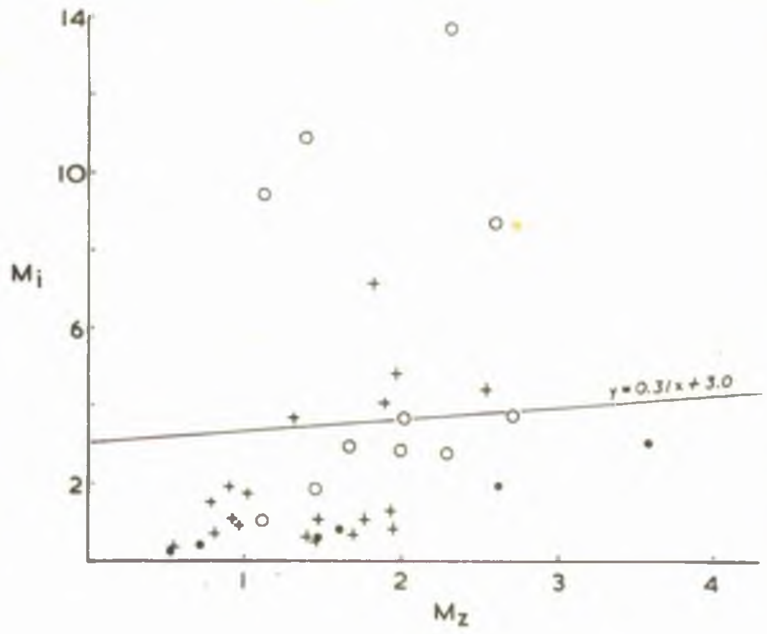


Fig. 79.

Fig. 81. Grain-size distributions from mechanical size analysis

A Laide 'red marl' pebbly base

B Laide 'red marl' proper

C Gairloch, Big Sand

D Redpoint

E Leac Dubh siltstone

Fig. 82. Grain-size distributions from mechanical size analysis, plotted on arithmetical probability paper.

Samples as above

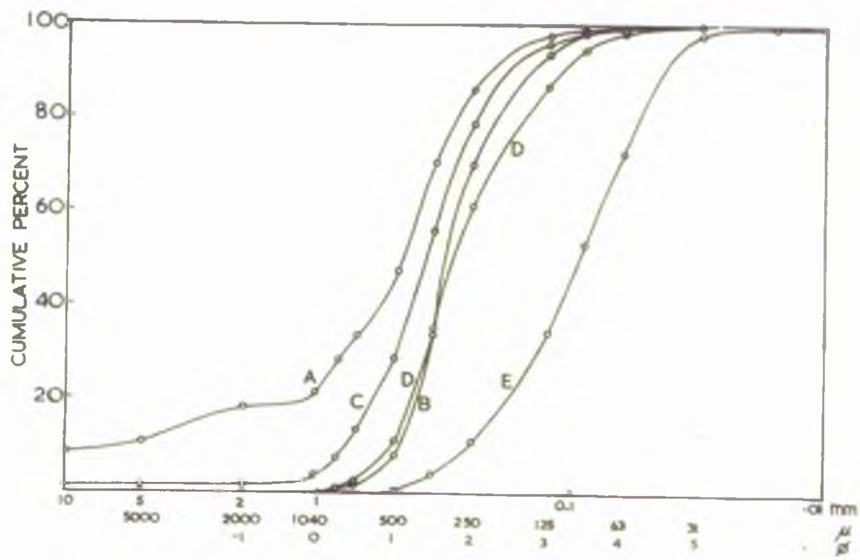

CUMULATIVE PERCENT
100
80
60
40
20
A
C
D
B
E
D
10
5
5000
2
2000
-1
1
1040
0
500
1
250
2
125
3
0.1
63
4
31
5
·01 mm
μ
ø

Fig. 81.

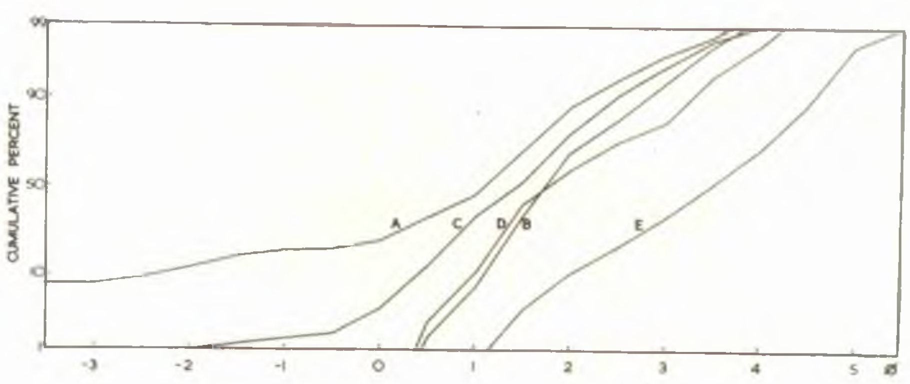

CUMULATIVE PERCENT
A
C
D
B
E
-3
-2
-1
0
1
2
3
4
5
ø

Fig. 82.

Fig. 83. Grain-size distributions of modern river bed sediments, Rio Grande, New Mexico.

a–d: Samples collected at weekly intervals in one locality during increasing river velocity.

e: Sample collected 65 miles further downstream.

f: Sample collected 90 miles further downstream.

Plotted from data given by Nordin and Beverage (1965, Figs. 3 and 22).

Fig. 84. Comparison of the Trias sediments with deposits of modern flood plains.

+ Trias sediments

Shaded area: Connecticut river flood deposits, September 1938.

o Other modern river flood deposits.

(After Wolman and Leopold, 1957).

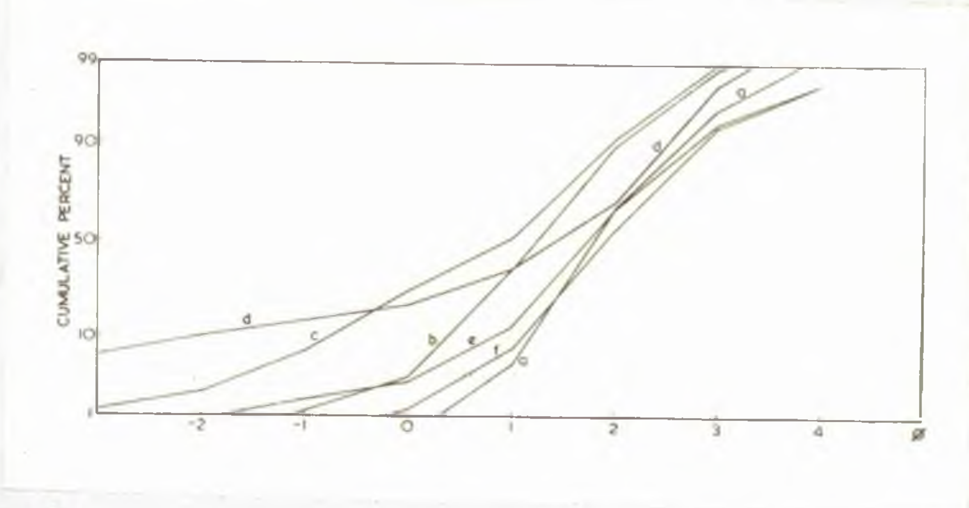

99
90
50
10
1
CUMULATIVE PERCENT
-2
-1
0
1
2
3
4
ø
a
b
c
d
e
f
g

Fig. 83.

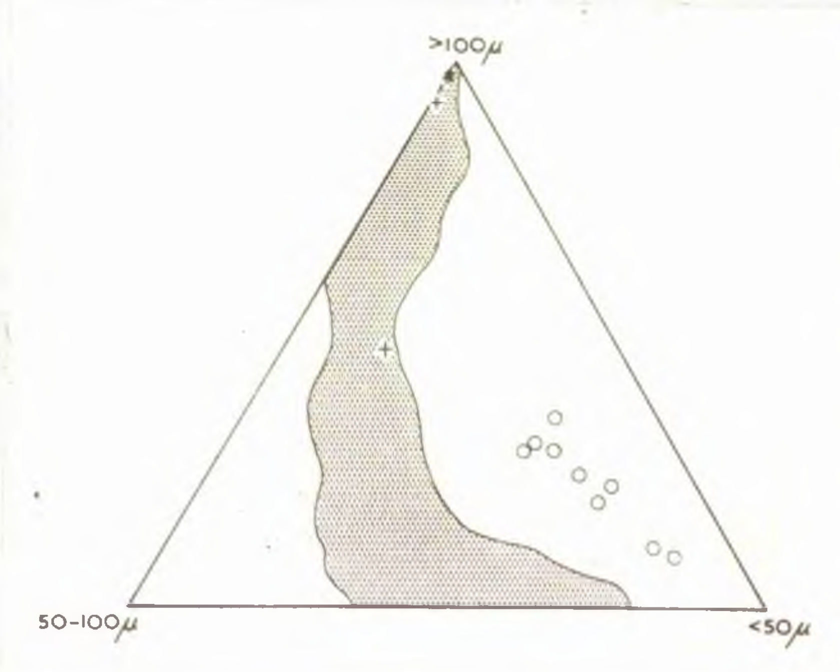

>100μ
50-100μ
<50μ

Fig. 84.

Fig. 85. Cumulative size distributions of three typical Trias sandstones, plotted on arithmetical probability paper, against an arithmetic scale.

Fig. 86. Cumulative size distributions of the same three sandstones plotted on arithmetical probability paper, against a logarithmic scale (phi scale).

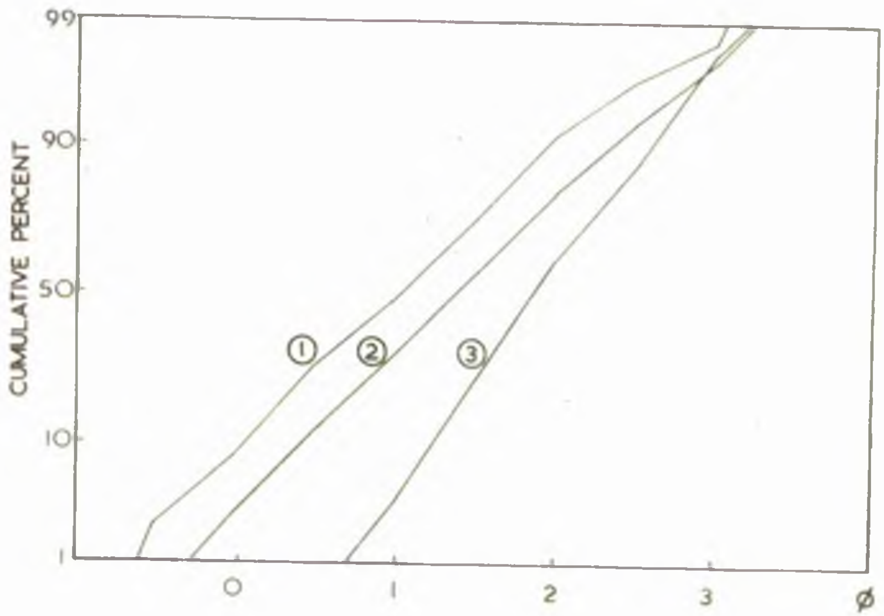


Fig. 86.

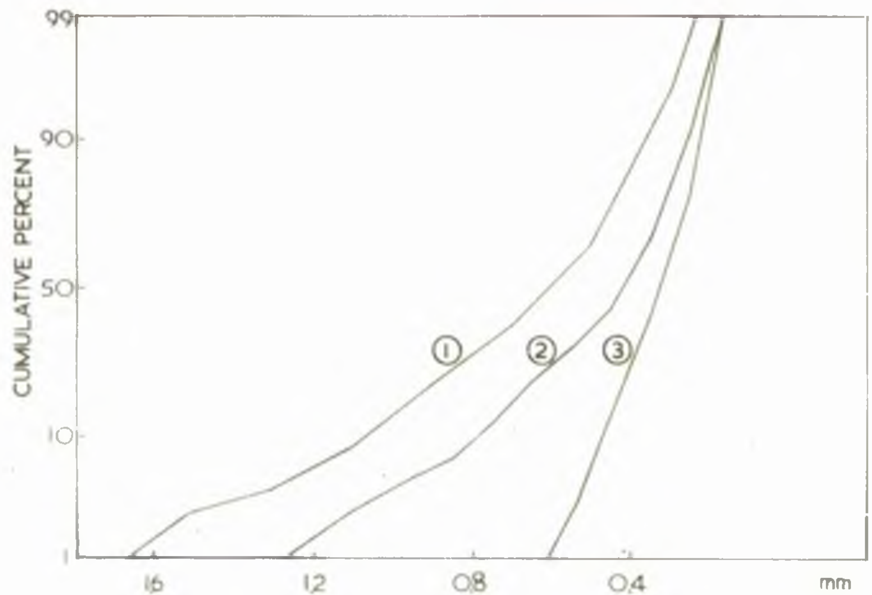


Fig. 85.

Fig. 87. Cumulative curves of Trias quartzose sandstones. 11 samples.

Fig. 88. Cumulative curves of Trias feldspathic sandstones. 20 samples.

Fig. 89. Cumulative curves of other Trias sandstones.
a: Ik 3; b: Ik 7; c: Gr 44; d: Lb 3;
e: La 9; f: Sl 4; g: Sl 7.

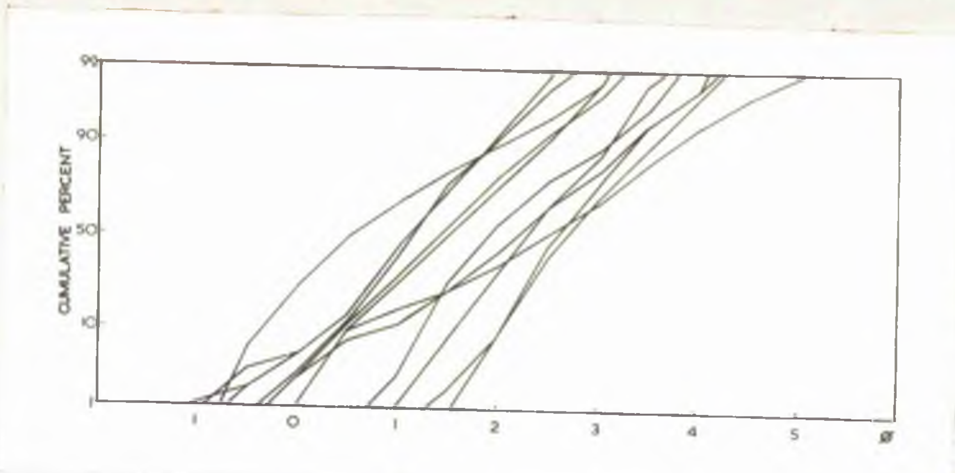


Fig. 87.

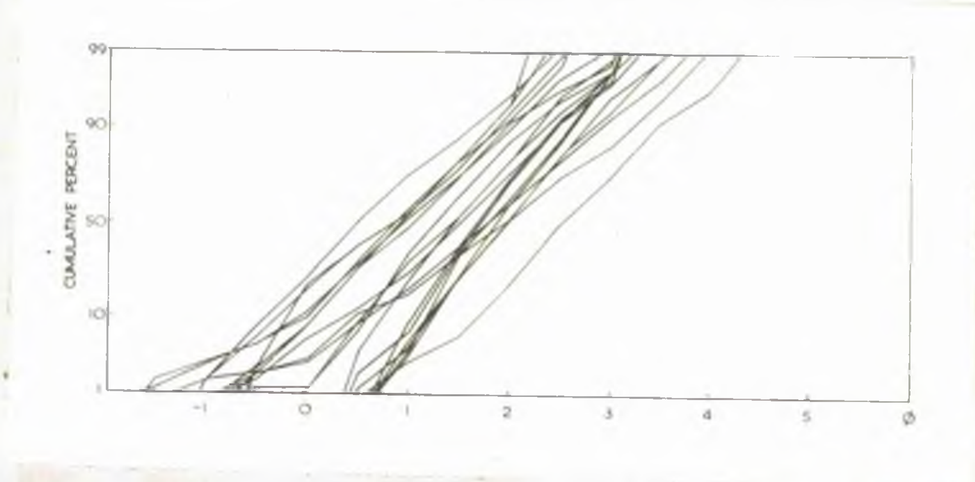


Fig. 88.

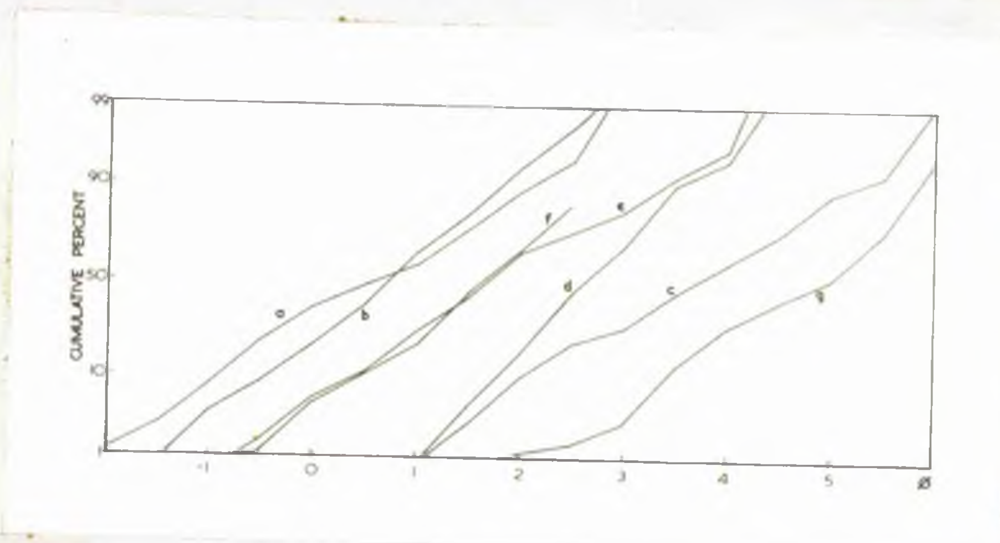


Fig. 89.

Fig. 90. 'R-, S-, and T' distributions: Doeglas' (1946) theory of sedimentary differentiation.

Fig. 91. Mean size (M_z) plotted against standard deviation (σ_I)

o Quartzose sandstones

\+ Feldspathic sandstones

• Other Trias sandstones

ps : poorly sorted

ms : moderately sorted

ws : well sorted

vws : very well sorted

csd : coarse-grained sandstone

msd : medium-grained sandstone

fsd : fine-grained sandstone

Fig. 92. Mean size (M_z) plotted against skewness (Sk_I). Samples as above.

psk : positive-skewed

nssk : nearly symmetrical-skewed

nsk : negative-skewed

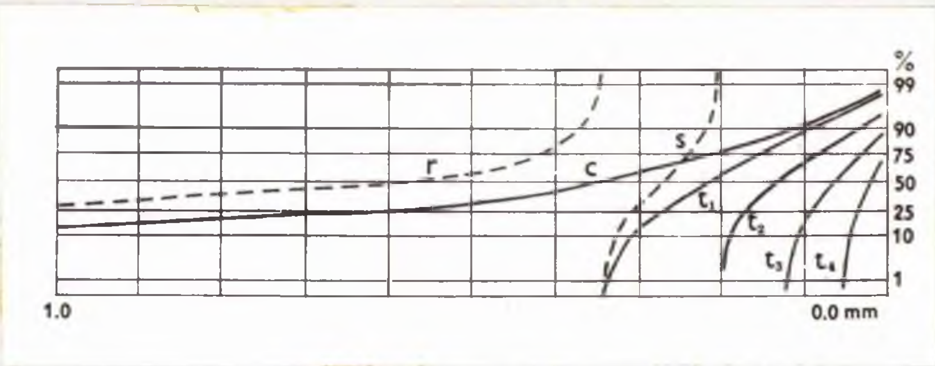


Fig. 90.

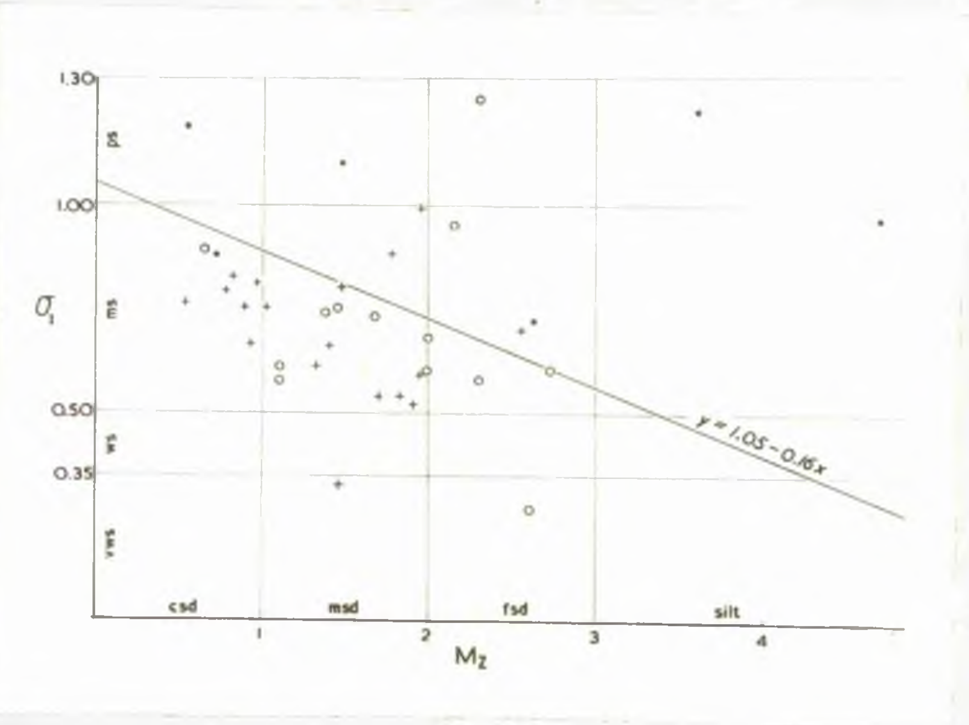


Fig. 91.

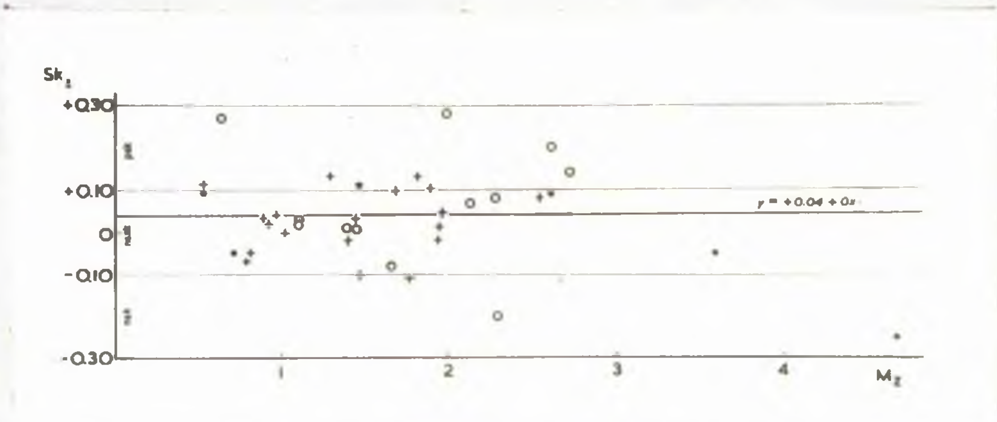


Fig. 92.

Fig. 92a. Mean size (M_z) plotted against kurtosis (K'_G). Samples as above.

lk : leptokurtic

mk : mesokurtic

pk : platykurtic

Fig. 93. Skewness (Sk_I) plotted against standard deviation (σ_I). Samples as above.

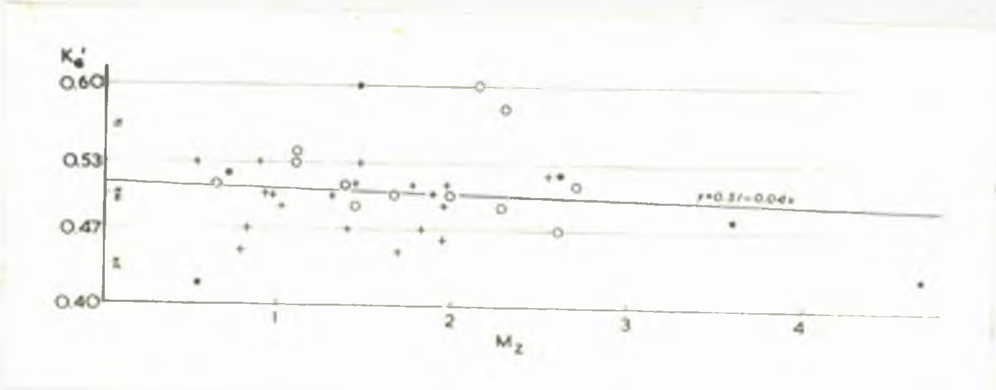


Fig. 92a.

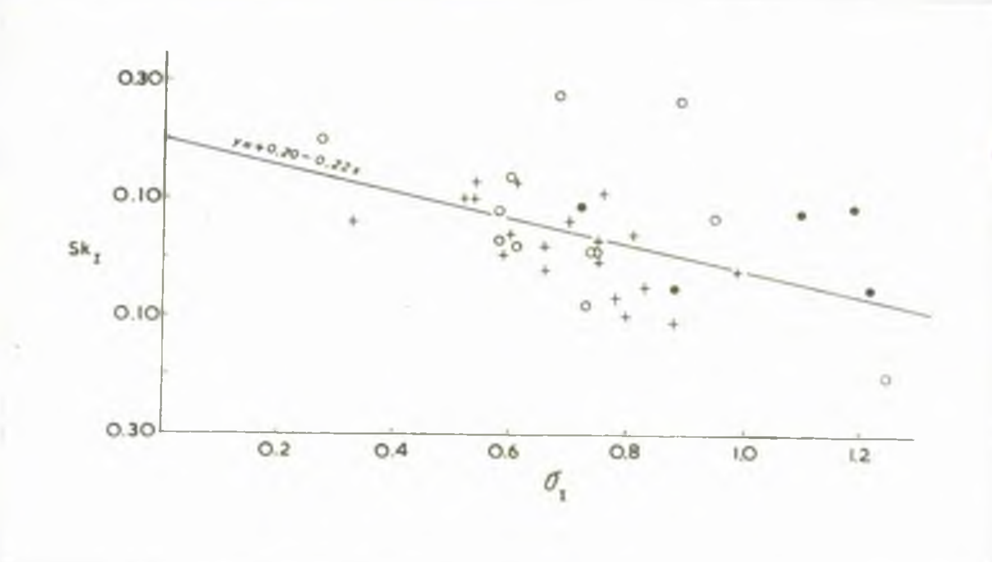


Fig. 93.

Fig. 94. Skewness plotted against standard deviation for all the Trias sediments analysed (thin-section and mechanical methods), superimposed on Friedman's (1961) diagram.

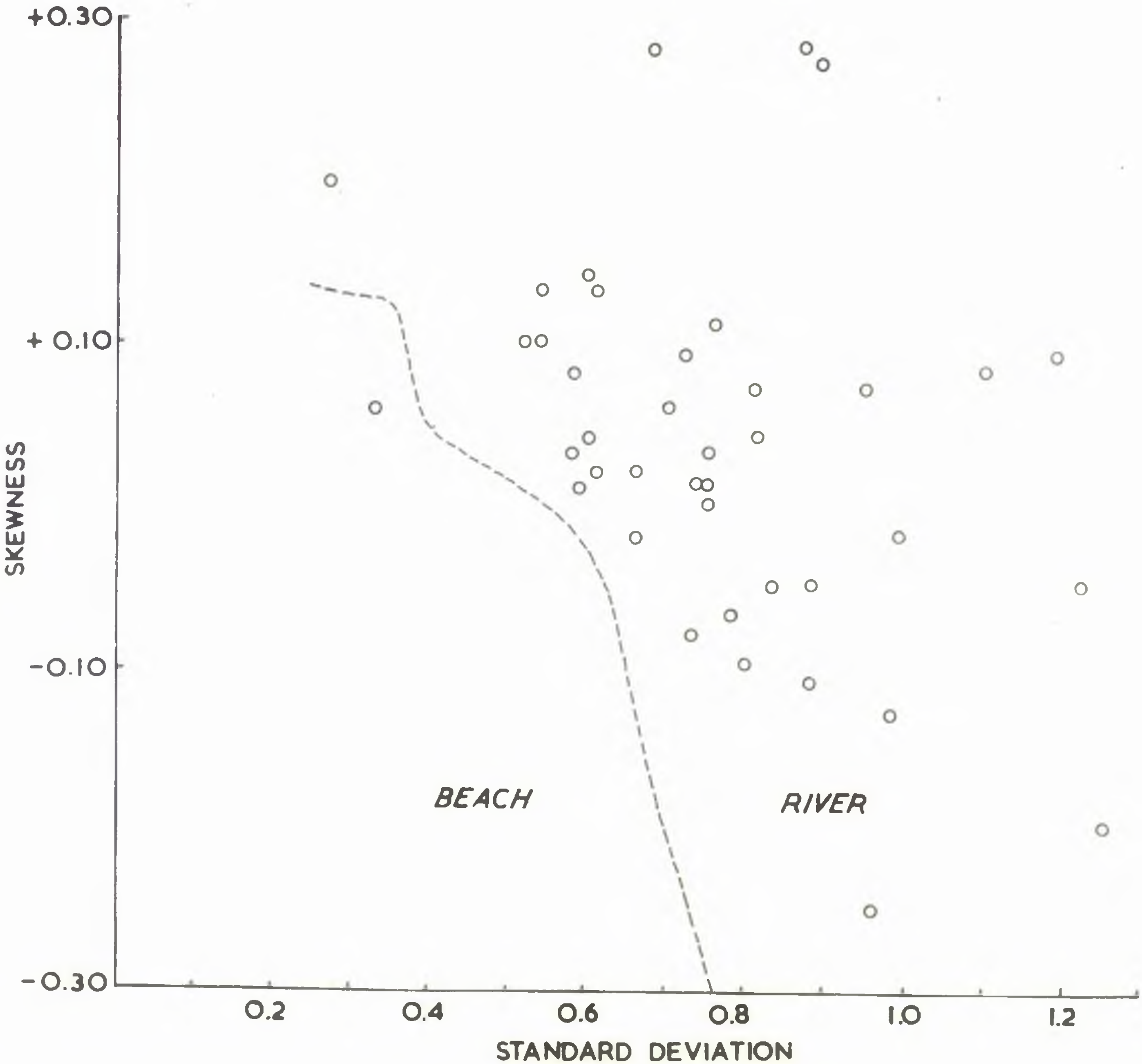

+0.30
+0.10
-0.10
-0.30
SKEWNESS
0.2
0.4
0.6
0.8
1.0
1.2
STANDARD DEVIATION
BEACH
RIVER

Fig. 95. Cumulative curves of known eolian sandstones.

ps : Penrith sandstone

ms : Mauchline sandstone

ch : Cutties Hillock sandstone

Fig. 96. Cumulative curves of possible eolian sandstones from the Trias.

Fig. 97. Cumulative curves of Passage Beds.

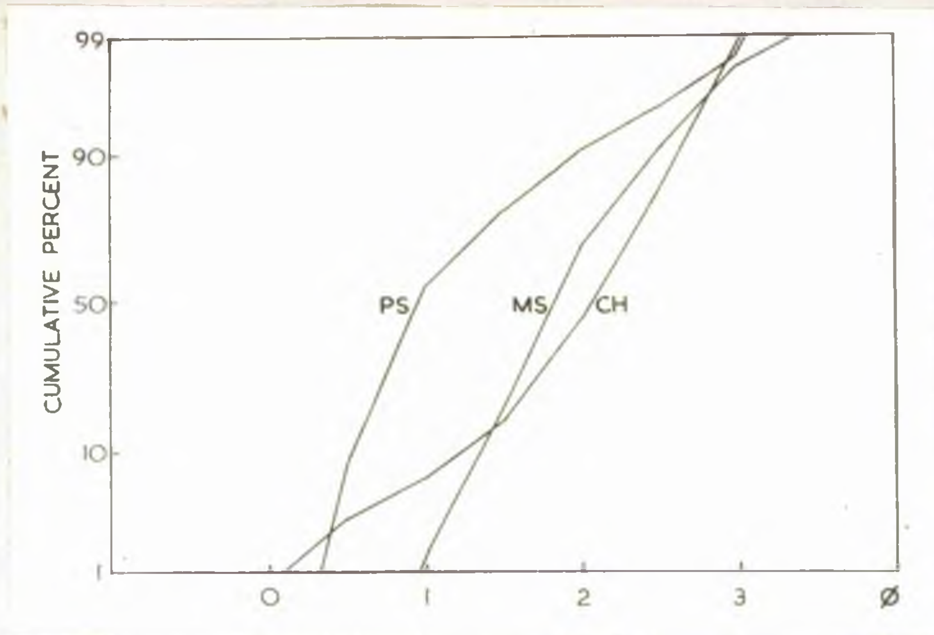


Fig. 95.

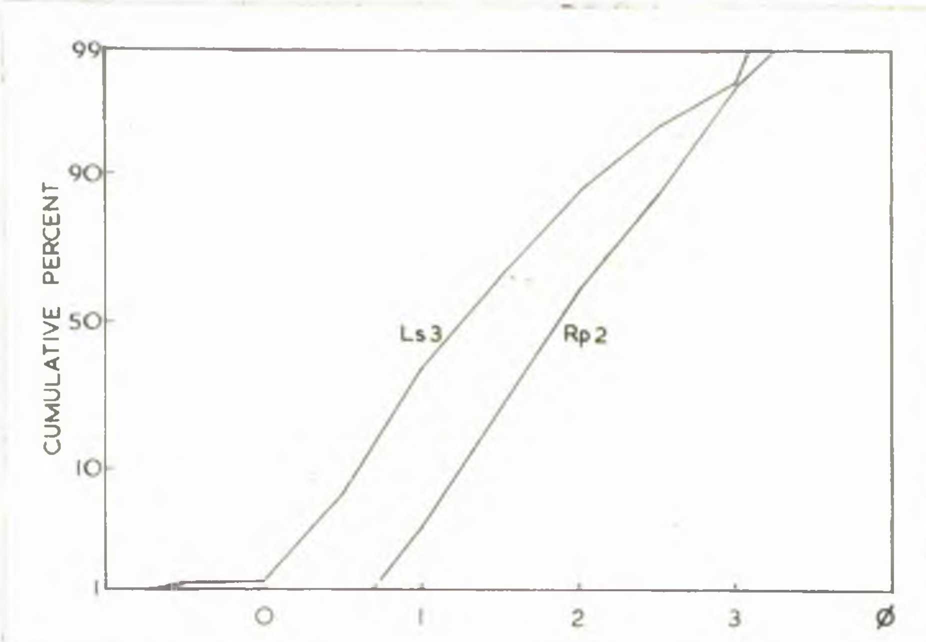


Fig. 96.

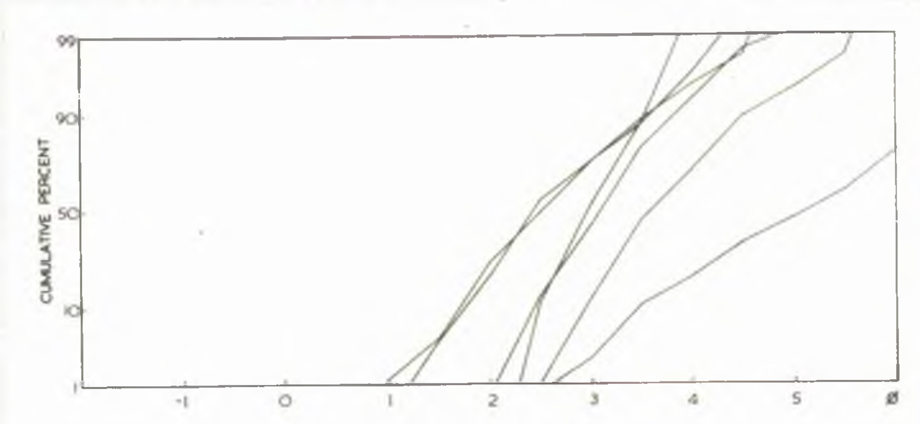


Fig. 97.

Fig. 98. Cumulative curves of Carboniferous sediments. (Ka 3, previously mapped as Trias, compared with In 22).

Fig. 99. Cumulative curves of Pseudo-Trias and Torridonian.

— Pseudo-Trias

----- Torridonian.

Fig. 100. Cumulative curves of clastic dykes.

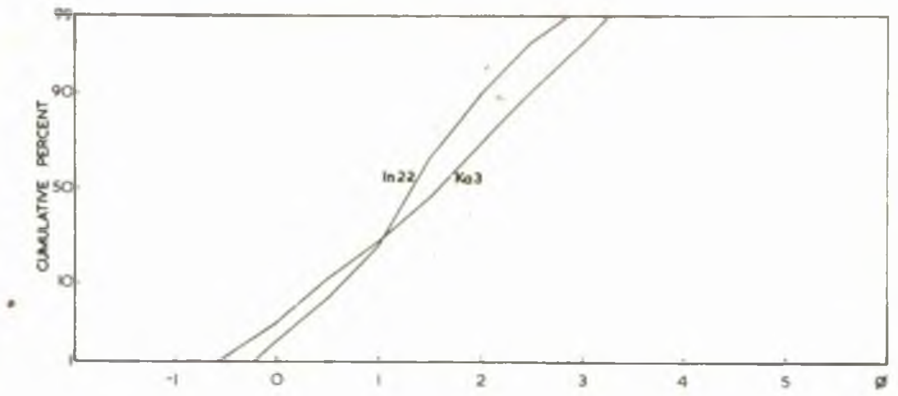


Fig. 98.

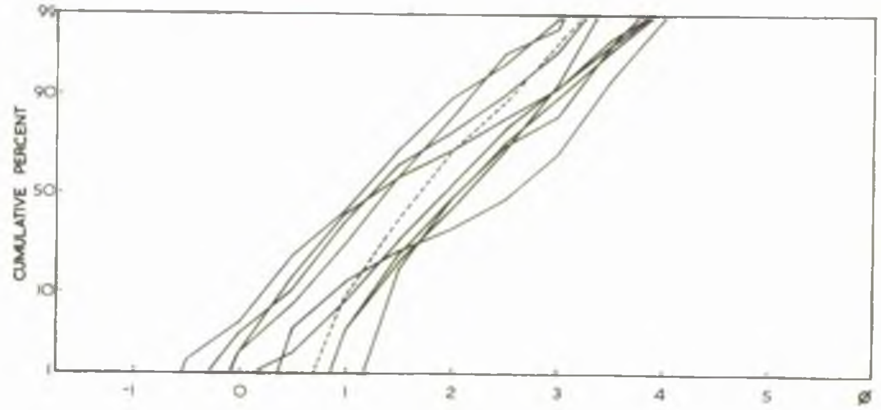


Fig. 99.

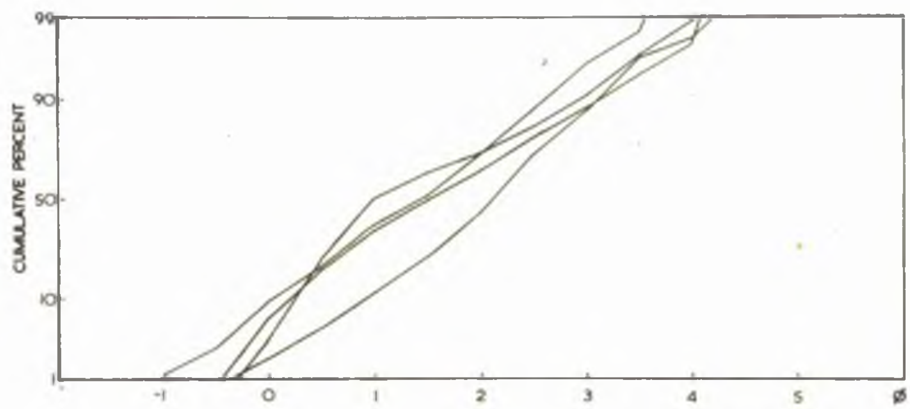


Fig. 100.

Fig. 101. Mean size (M_z) plotted against standard deviation (σ_I) : miscellaneous sediments.

◑ Known eolian sandstones

⊗ Passage Beds

⊙ Carboniferous

⊠ Clastic dykes

× Pseudo-Trias

◈ Torridonian

Fig. 102. Mean size (M_z) plotted against skewness (Sk_I) : miscellaneous sediments. Samples as above.

Fig. 103. Mean size (M_z) plotted against kurtosis (K'_G) : miscellaneous sediments. Samples as above.

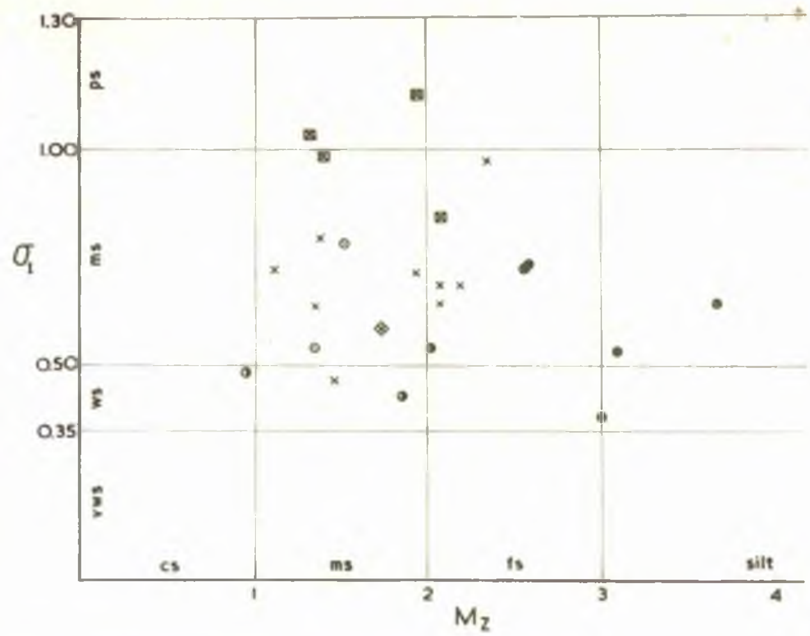


Fig. 101.

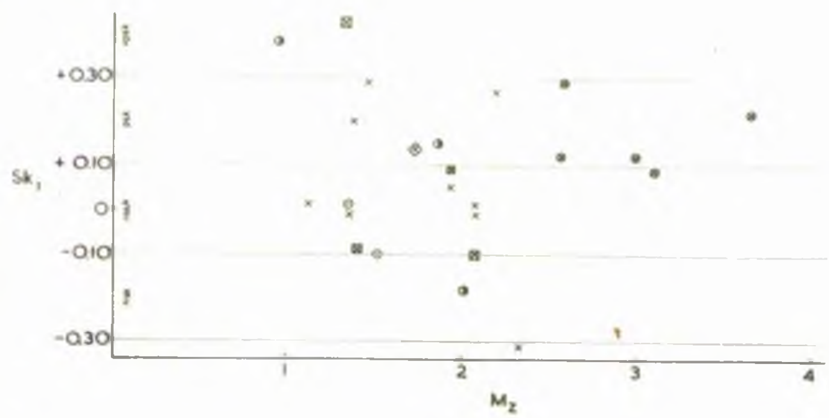


Fig. 102.

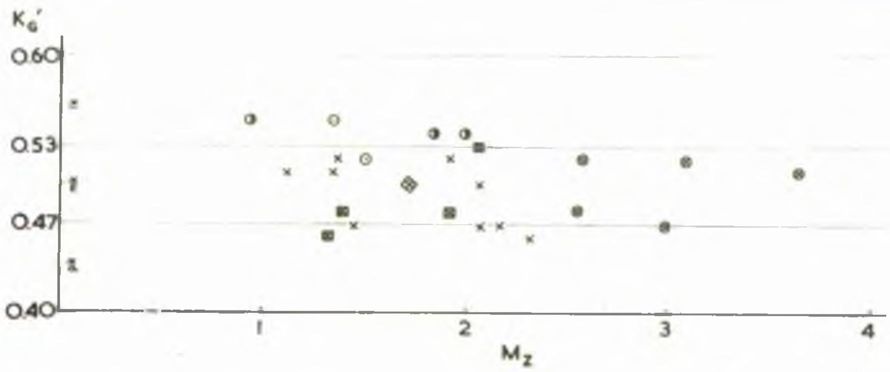


Fig. 103.

Fig. 104. Packing proximity (P_p) plotted against average grain-grain contacts per grain (Gc/g)

⊗ Passage Beds

○ Trias quartzose sandstones

+ Trias feldspathic sandstones

⊙ Carboniferous

⊠ Clastic dyke

× Pseudo-Trias

◈ Torridonian

Fig. 105. Packing proximity (P_p) plotted against matrix. Samples as above.

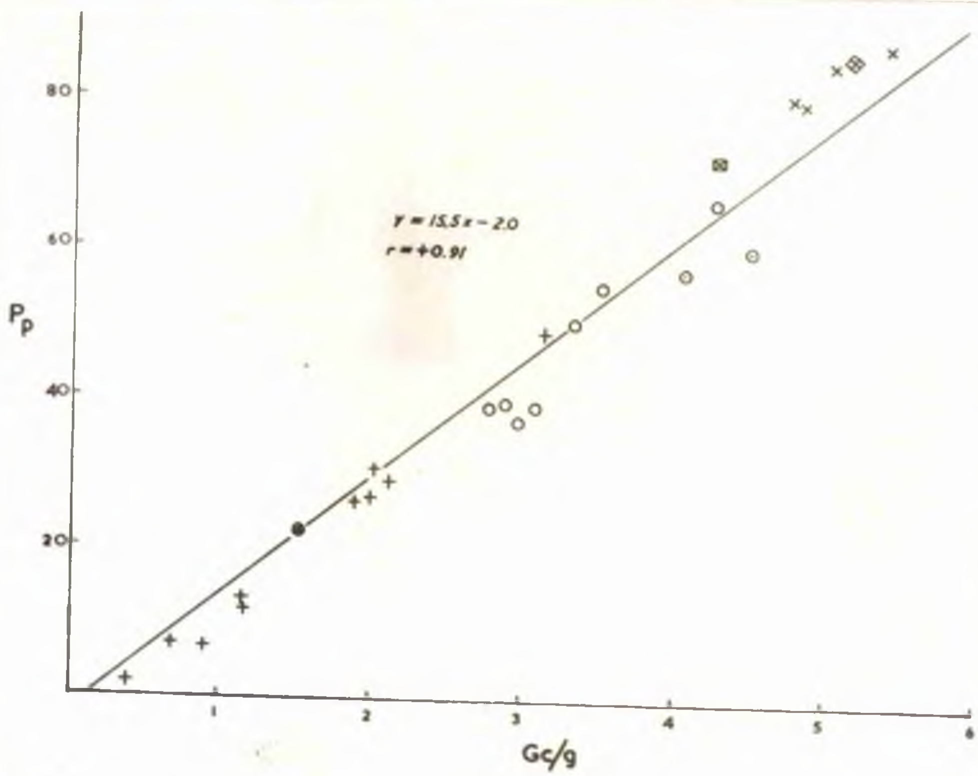


Fig. 104.

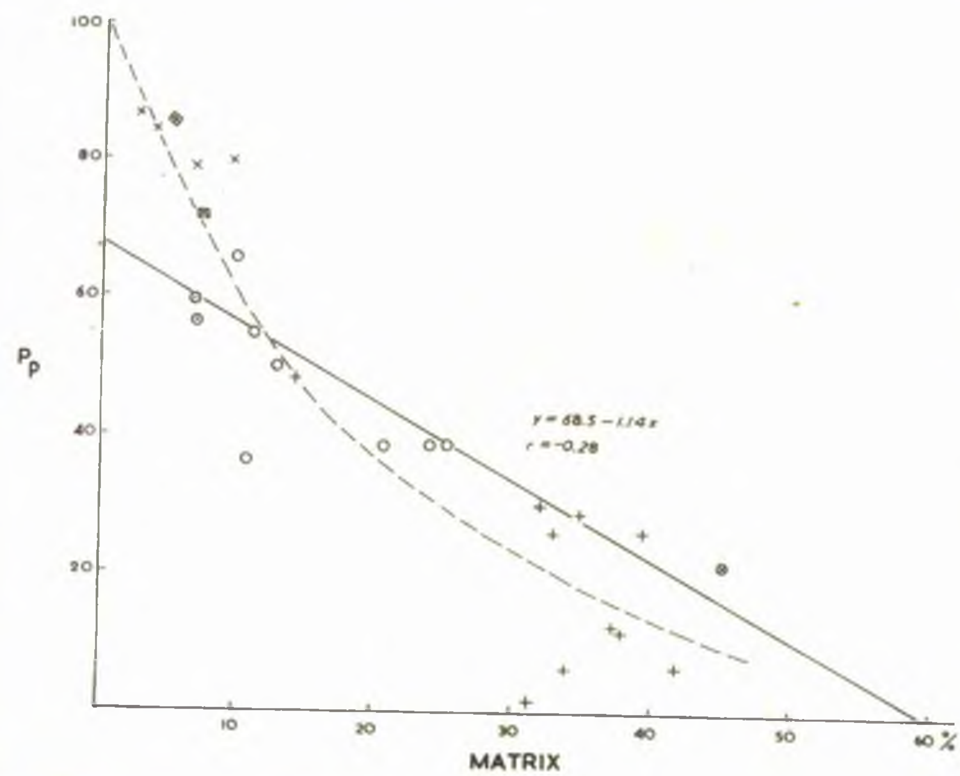


Fig. 105.

Fig. 106. Packing proximity (P_p) plotted against packing density (P_d). Selected Trias sandstones.

Fig. 107. Roundness of grains plotted against mean size.

o Trias quartzose sandstones

+ Trias feldspathic sandstones

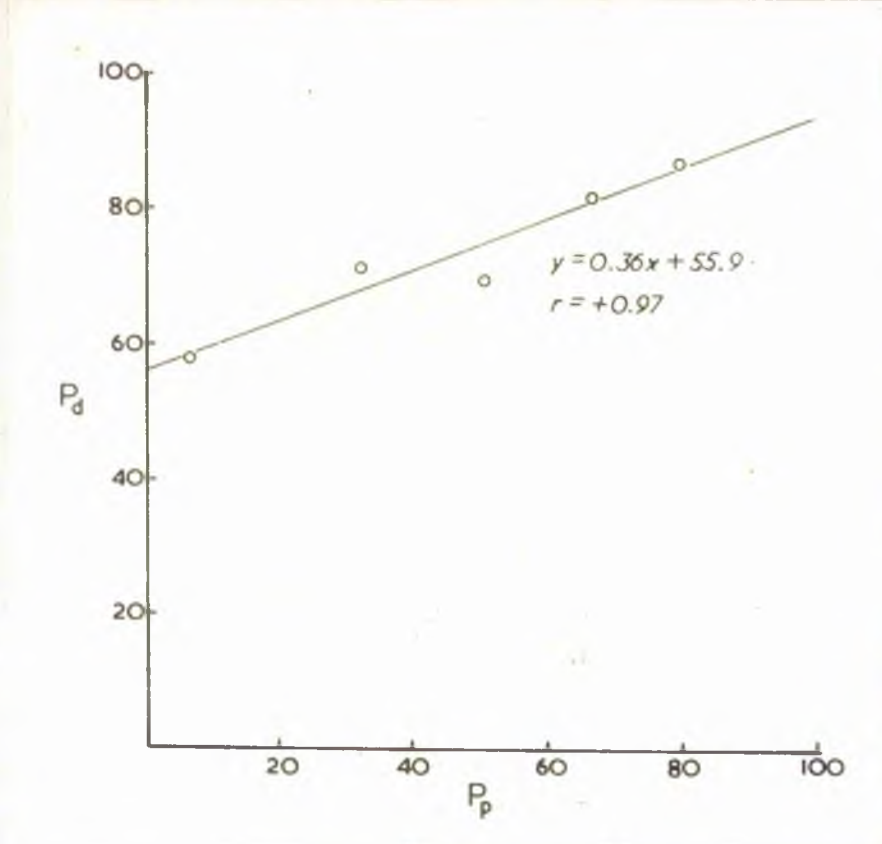


Fig. 106.

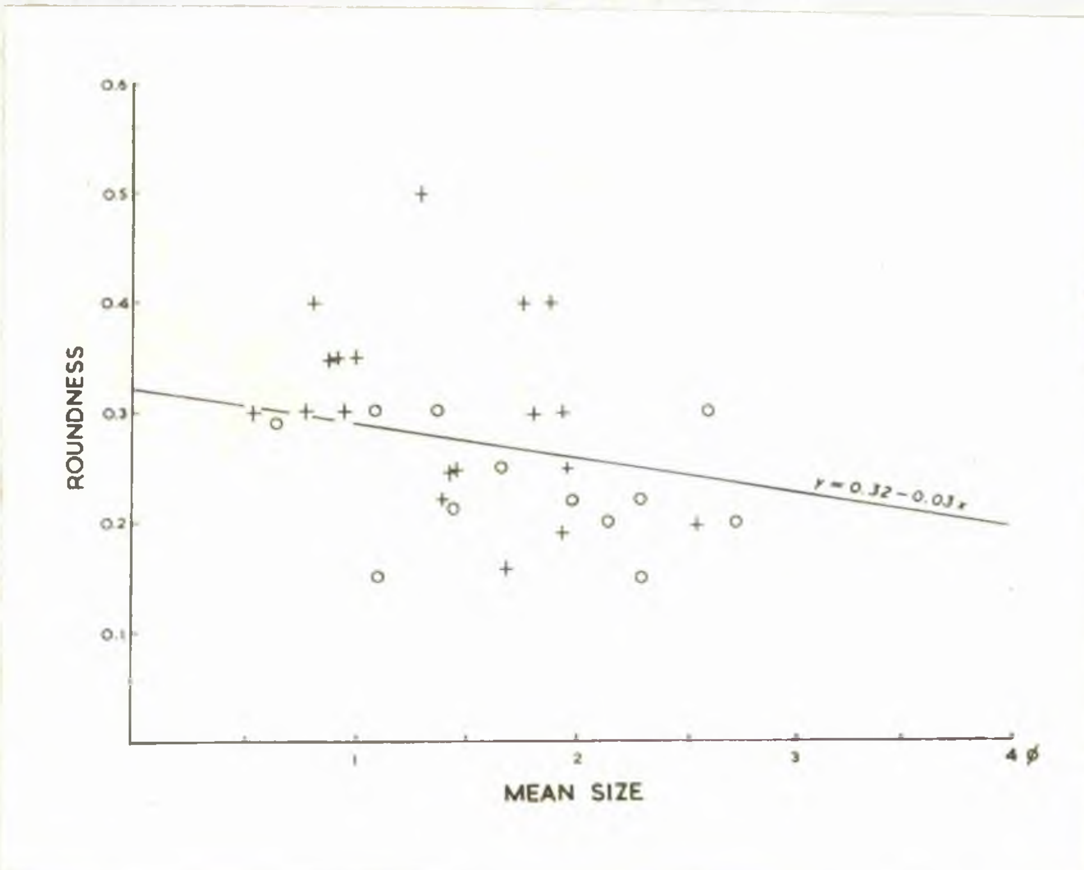


Fig. 107.

Fig. 108. Elongation function (p/q) plotted against long dimension (p) for sand grains in sample Rp 2.

Average p/q value for groups of 20 grains of consecutive p value.

Fig. 109. Diagram illustrating pebble measurement.

(1) In the plane of maximum projection.

(2) In the plane normal to (1).

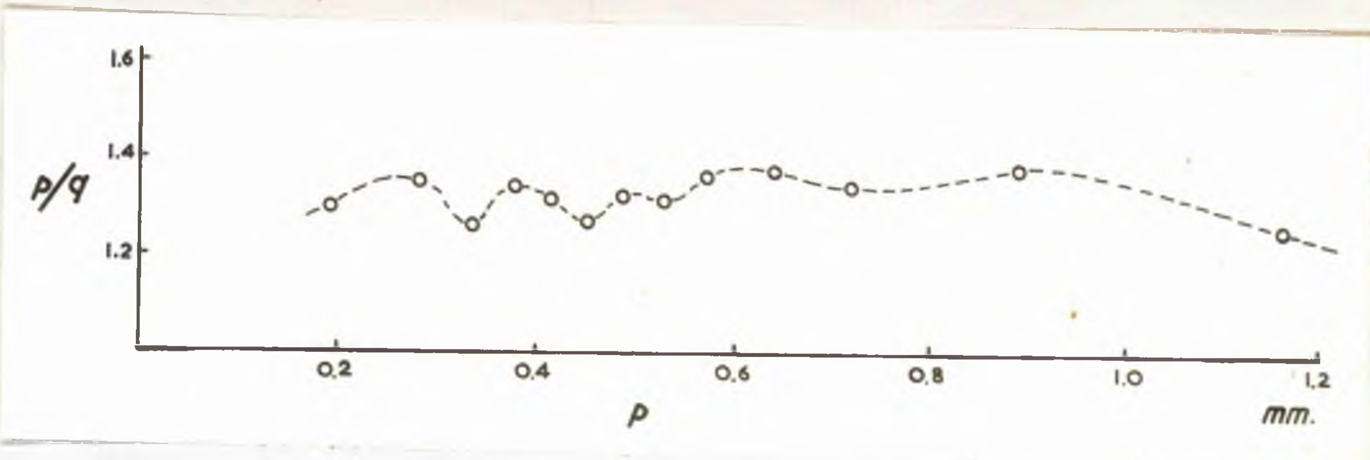


Fig. 108.

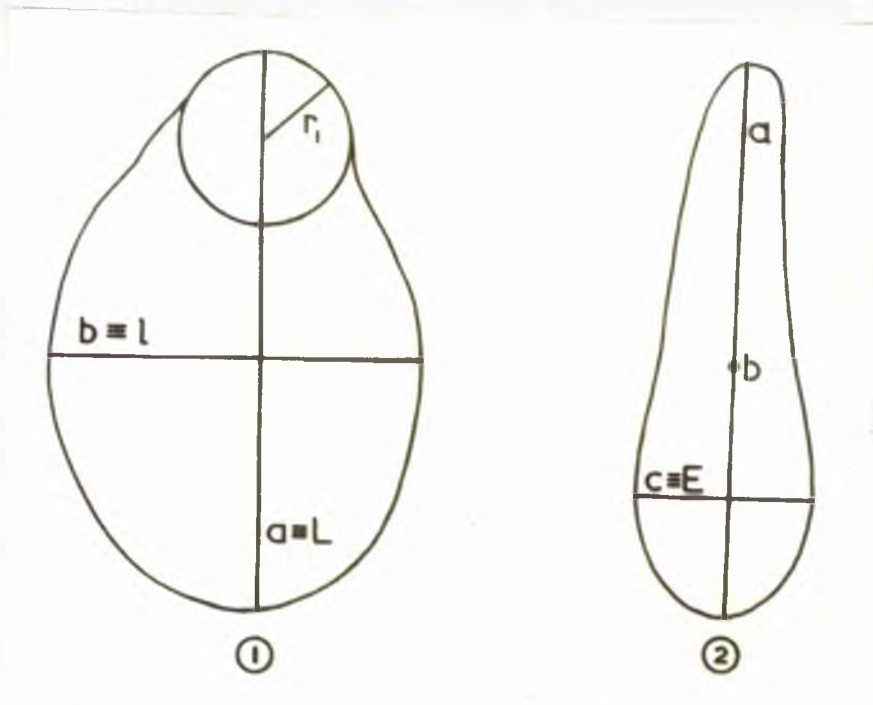


Fig. 109.

Fig. 110. Shape of limestone pebble suite from W. Mull.

Fig. 111. Cailleux's roundness index (R_c) plotted against Kuenen's roundness index (R_k). Limestone pebbles, W. Mull.

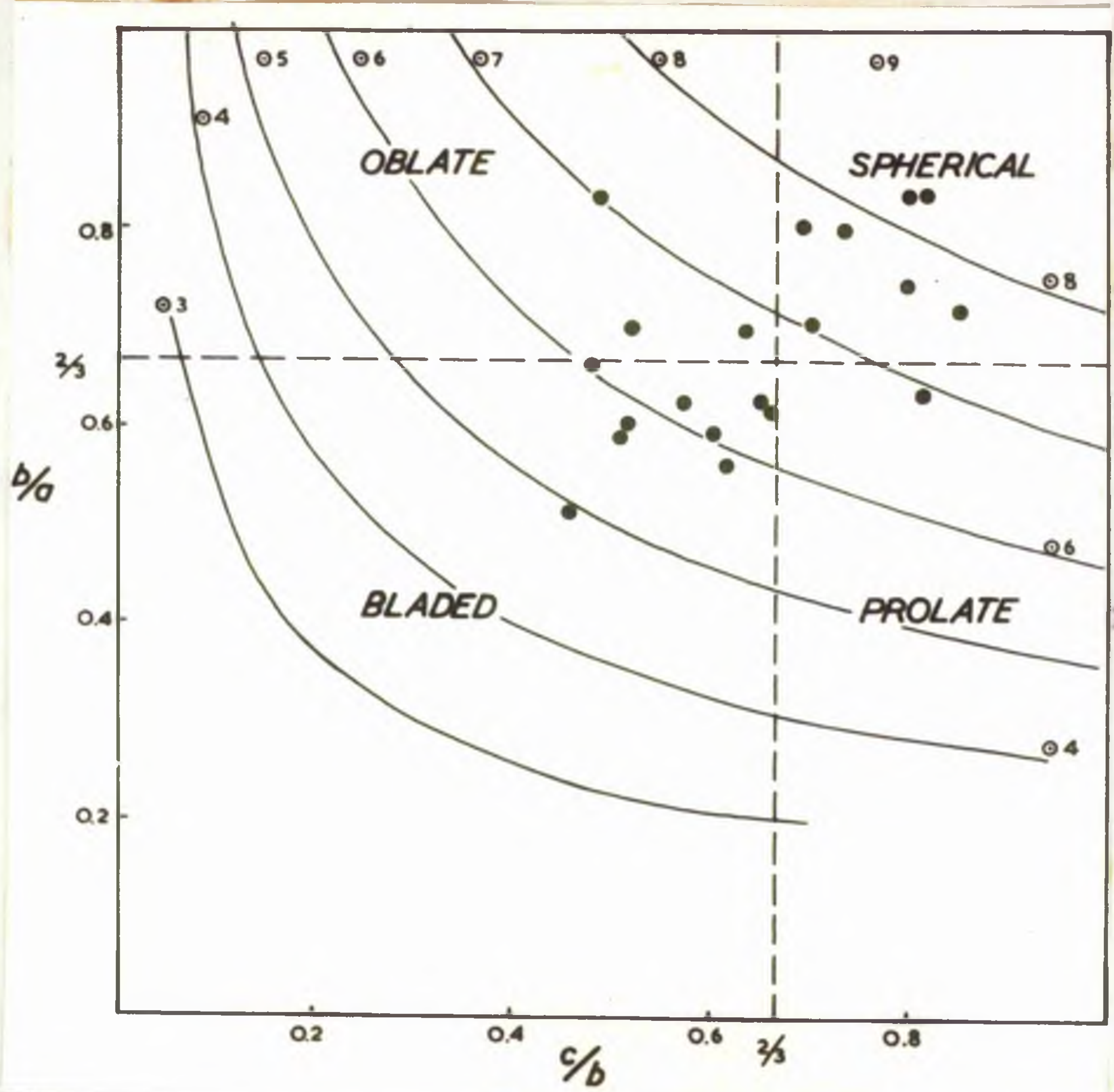


Fig. 110.

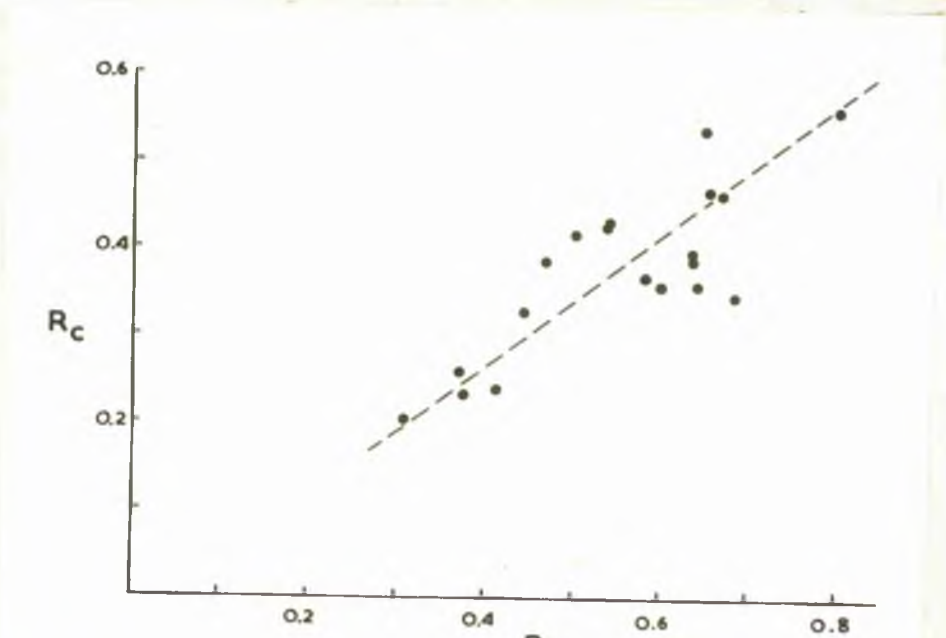


Fig. 111.

Fig. 112. Roundness (R_c) plotted against weight. Limestone pebbles, W. Mull.

Fig. 113. Flatness (F_c) plotted against weight. Limestone pebbles, W. Mull.

Fig. 114. Roundness (R_c) plotted against flatness (F_c). Limestone pebbles, W. Mull.

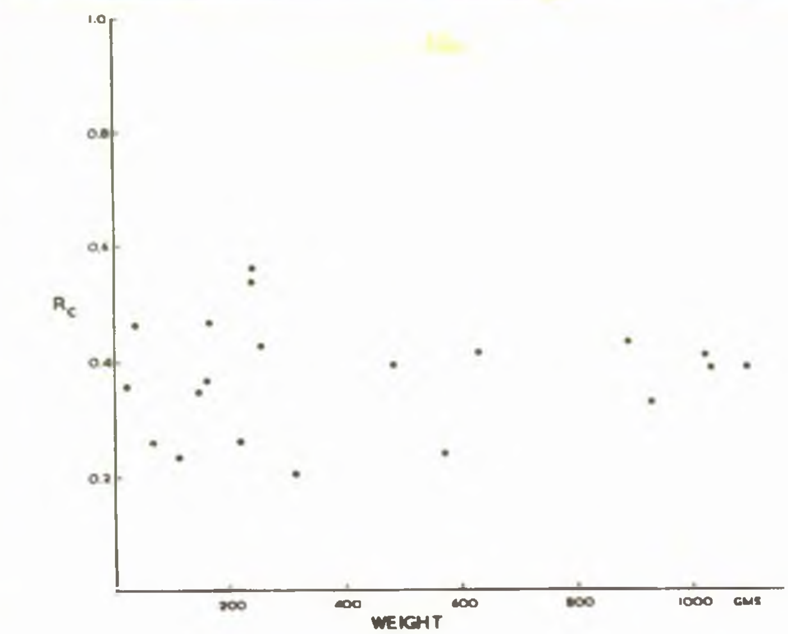


Fig. 112.

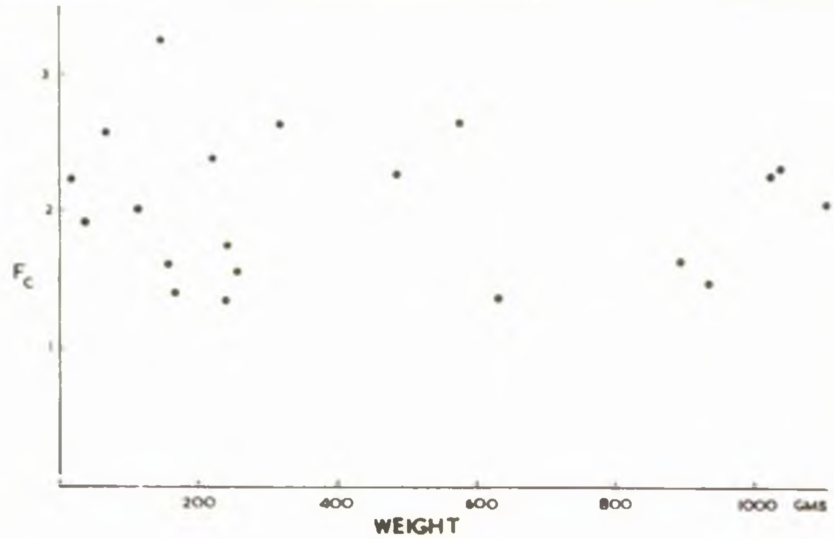


Fig. 113.

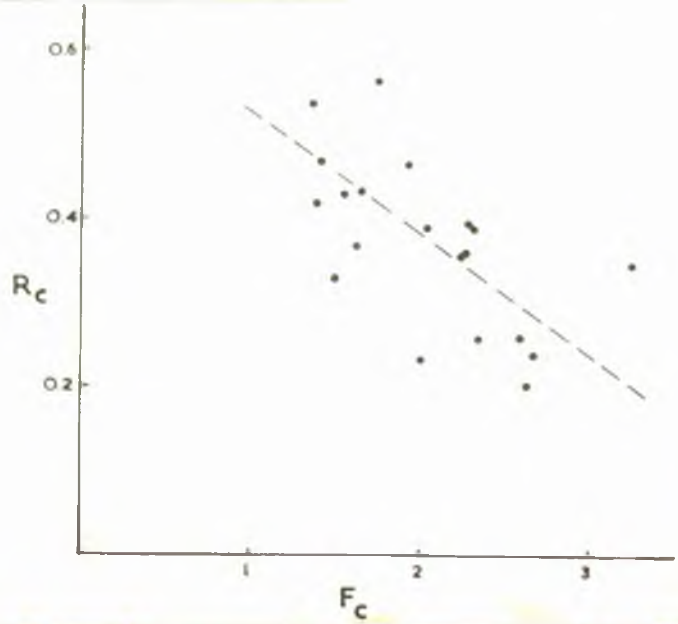


Fig. 114.

Fig. 115. Cumulative curve of roundness (R_c) treated by Graulich's (1951) method.

Fig. 116. Resultant plot (from Fig. 115) on Graulich's (1951) diagram.

Roundness distribution index, RD_I = AB

Roundness asymmetry index, RA_I = (AC−CB)/100

Field II : Fluviatile deposits.

I, III, IV : Others.

Fig. 117. Roundness (R_c) plotted against distance travelled.

● Limestone, 21 g.

○ " 150 g.

△ " 159 g. (cube)

+ " 173 g.

◑ " 281 g. (double cube)

◓ " 216 g.

Data from Kuenen (1956, Experiment E p. 360).

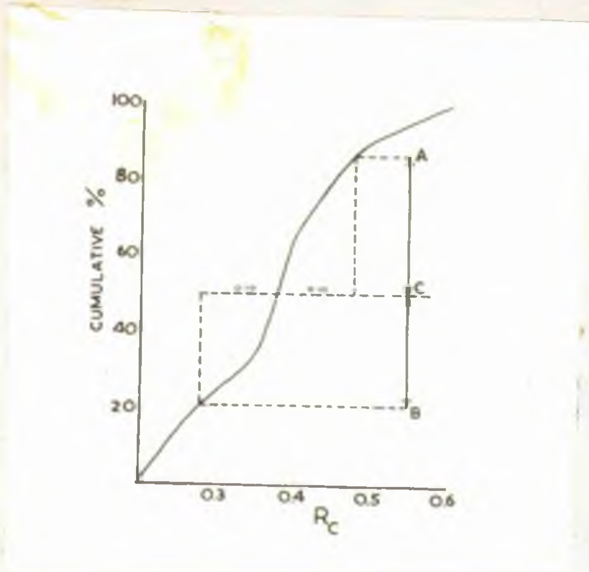


Fig. 115.

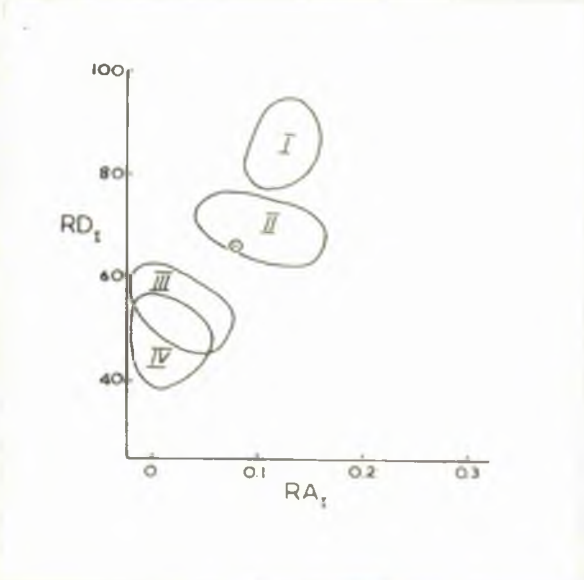


Fig. 116.

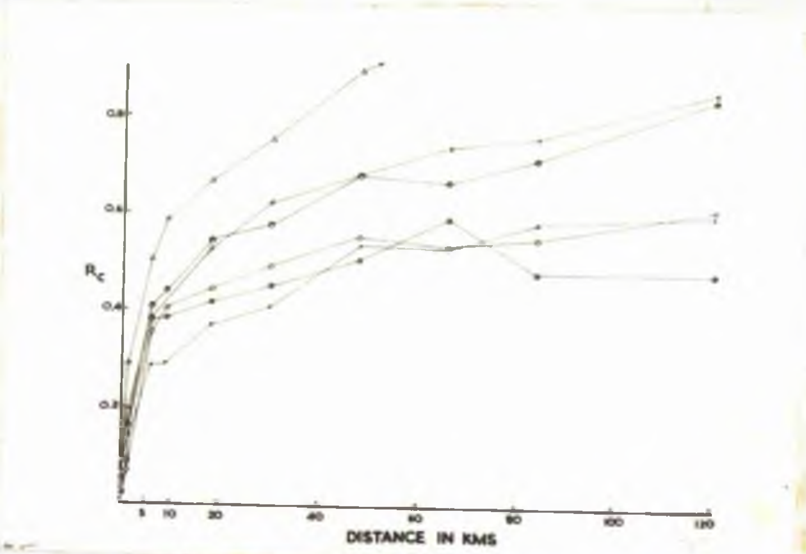
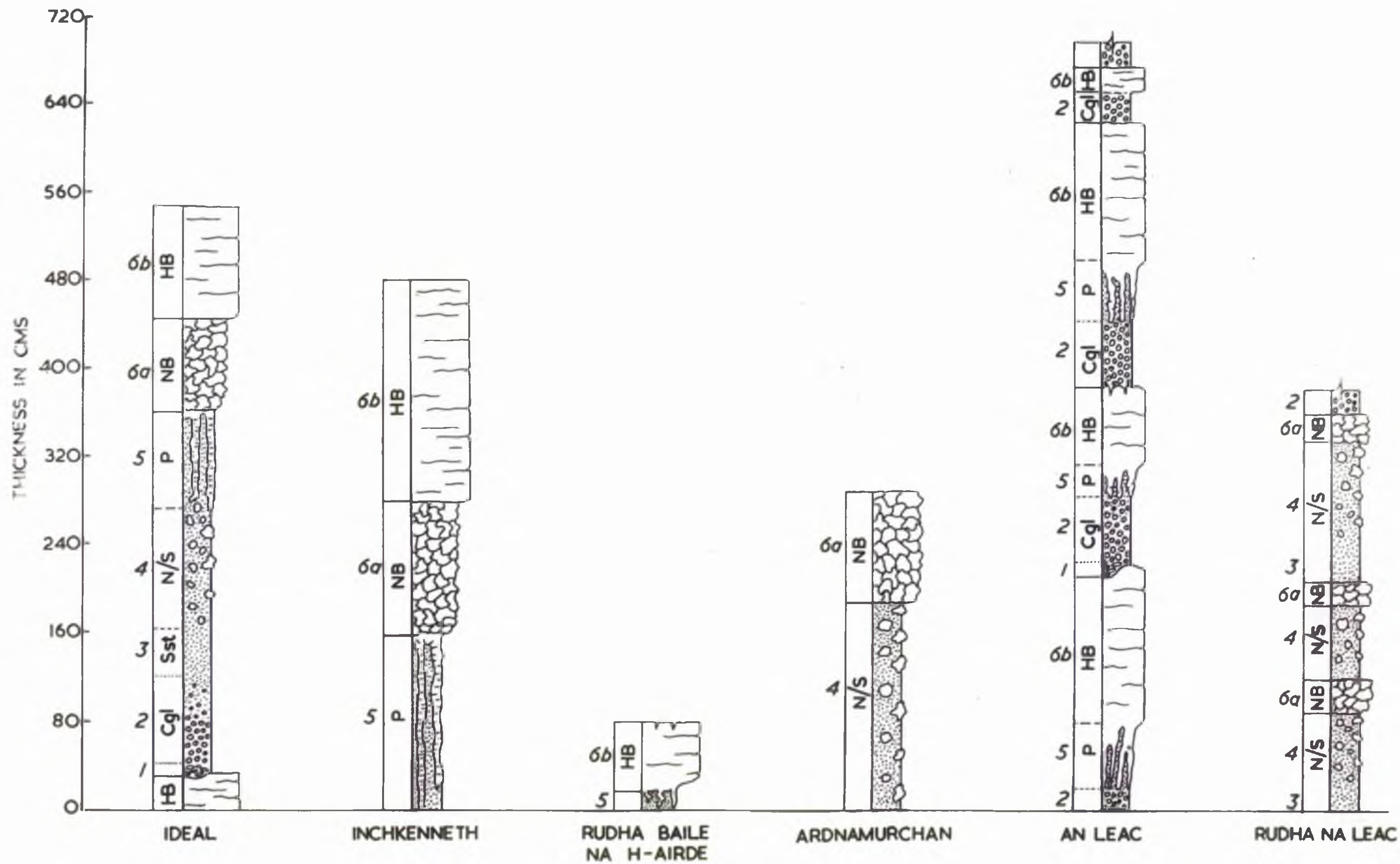


Fig. 117.

Fig. 118. The 'ideal' cornstone profile (arbitrary thickness) and some typical developments.

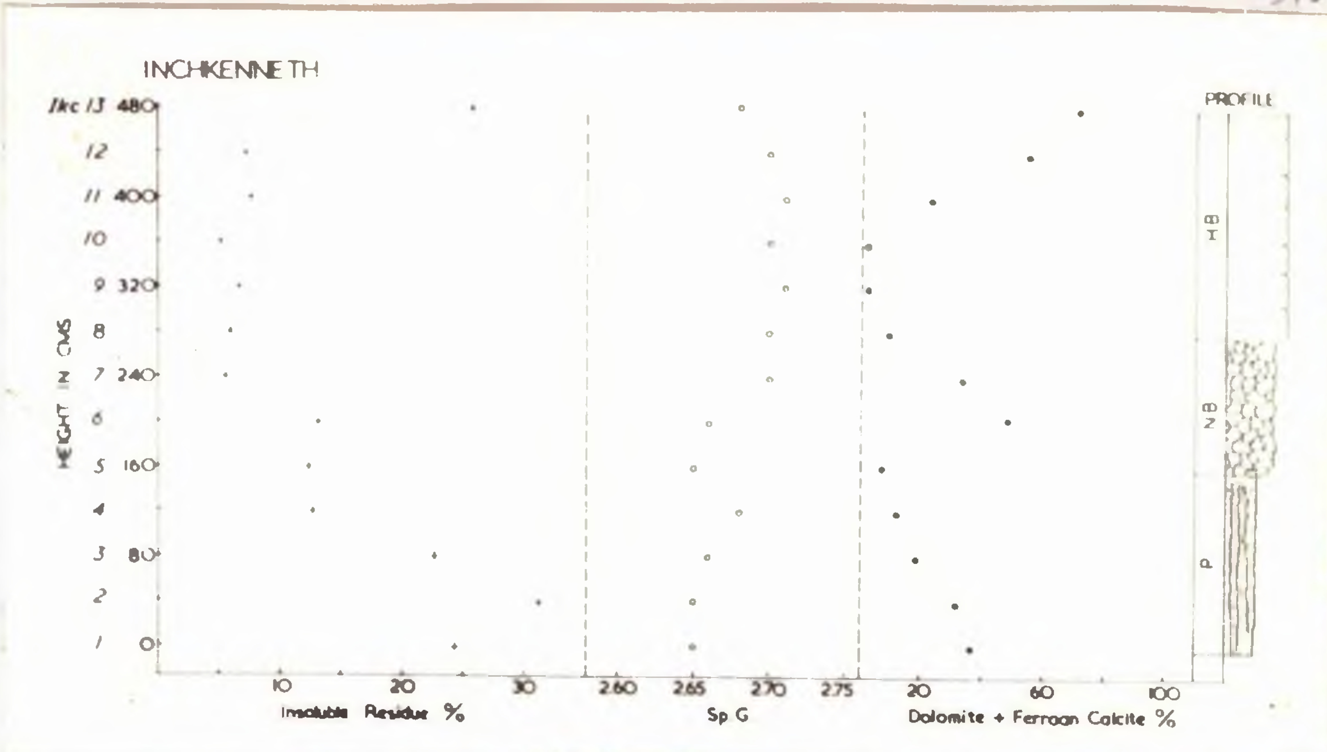


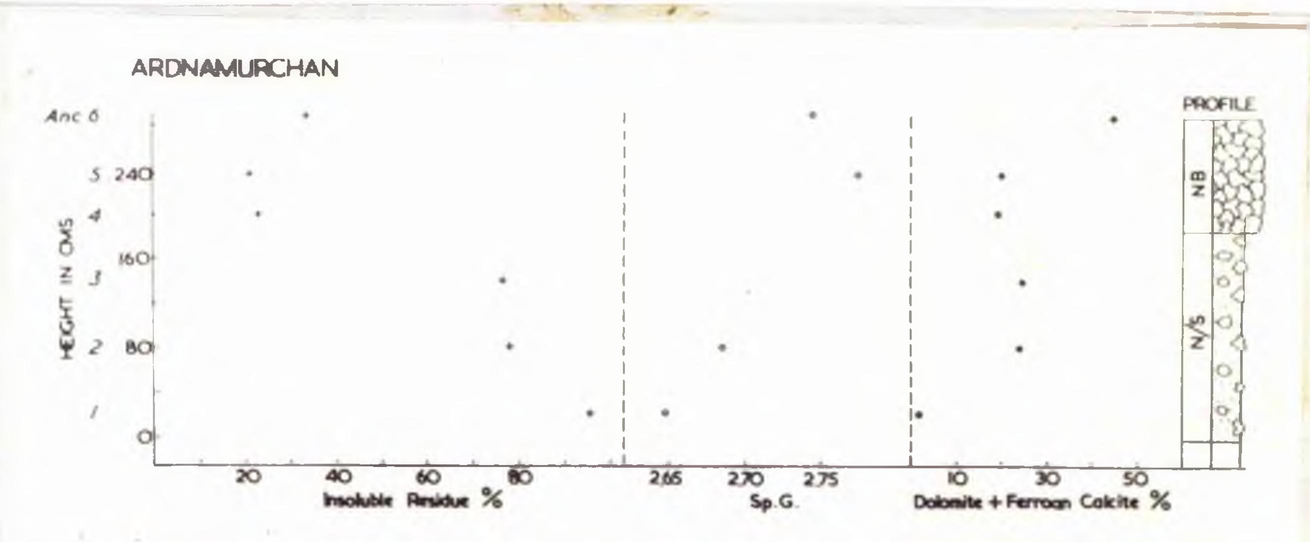
THICKNESS IN CMS
720
640
560
480
400
320
240
160
80
0
IDEAL
INCHKENNETH
RUDHA BAILE NA H-AIRDE
ARDNAMURCHAN
AN LEAC
RUDHA NA LEAC
HB
NB
P
N/S
Sst
Cgl
6b
6a
5
4
3
2
1

Fig. 119. Variations in percent insoluble residue, specific gravity and percent dolomite plus ferroan calcite, cornstone profile. Inchkenneth Chapel.

Fig. 120. Variations in a cornstone profile, Rubh a Mhile, Ardnamurchan.

Fig. 121. Variations in a cornstone profile, Rudha na Leac, Raasay.


INCHKENNETH
PROFILE
HEIGHT IN CMS
Ikc 13 480
12
11 400
10
9 320
8
7 240
6
5 160
4
3 80
2
1 0
10 20 30
Insoluble Residue %
2.60 2.65 2.70 2.75
Sp. G
20 60 100
Dolomite + Ferroan Calcite %
HB
NB
P


ARDNAMURCHAN
PROFILE
HEIGHT IN CMS
Anc 6
5 240
4
160
3
2 80
1
0
20 40 60 80
Insoluble Residue %
2.65 2.70 2.75
Sp.G.
10 30 50
Dolomite + Ferroan Calcite %
NB
N/S

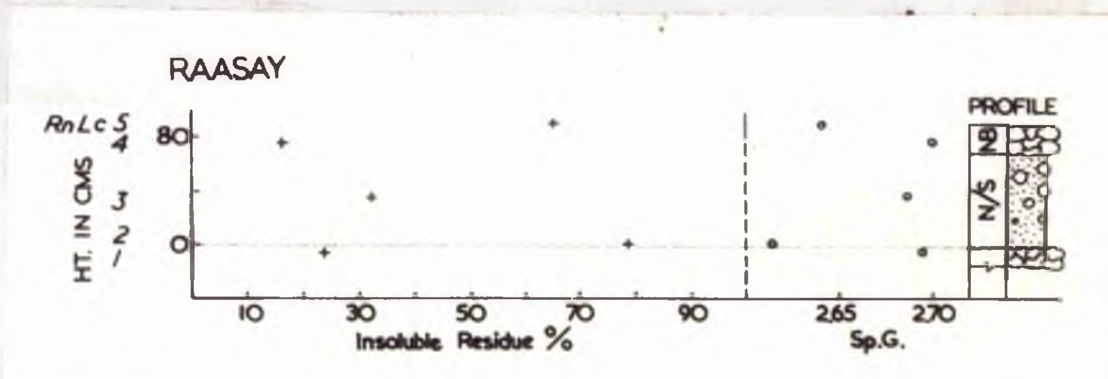

RAASAY
PROFILE
HT. IN CMS
RnLc 5
4
3
2
1
80
0
10 30 50 70 90
Insoluble Residue %
2.65 2.70
Sp.G.
NB
N/S

Fig. 122. Percent soluble material (carbonate) plotted against specific gravity: Inchkenneth, Ardnamurchan (Rubh a' Mhile) and Raasay (Rudha na Leac) cornstones.

Equations for regression lines are :-

Inchkenneth : $y = 412x - 1021$

Raasay : $y = 577x - 148$

Ardnamurchan : $y = 529x - 1390$

Fig. 123. Profiles developed in caliche (Bretz and Horberg, 1949).

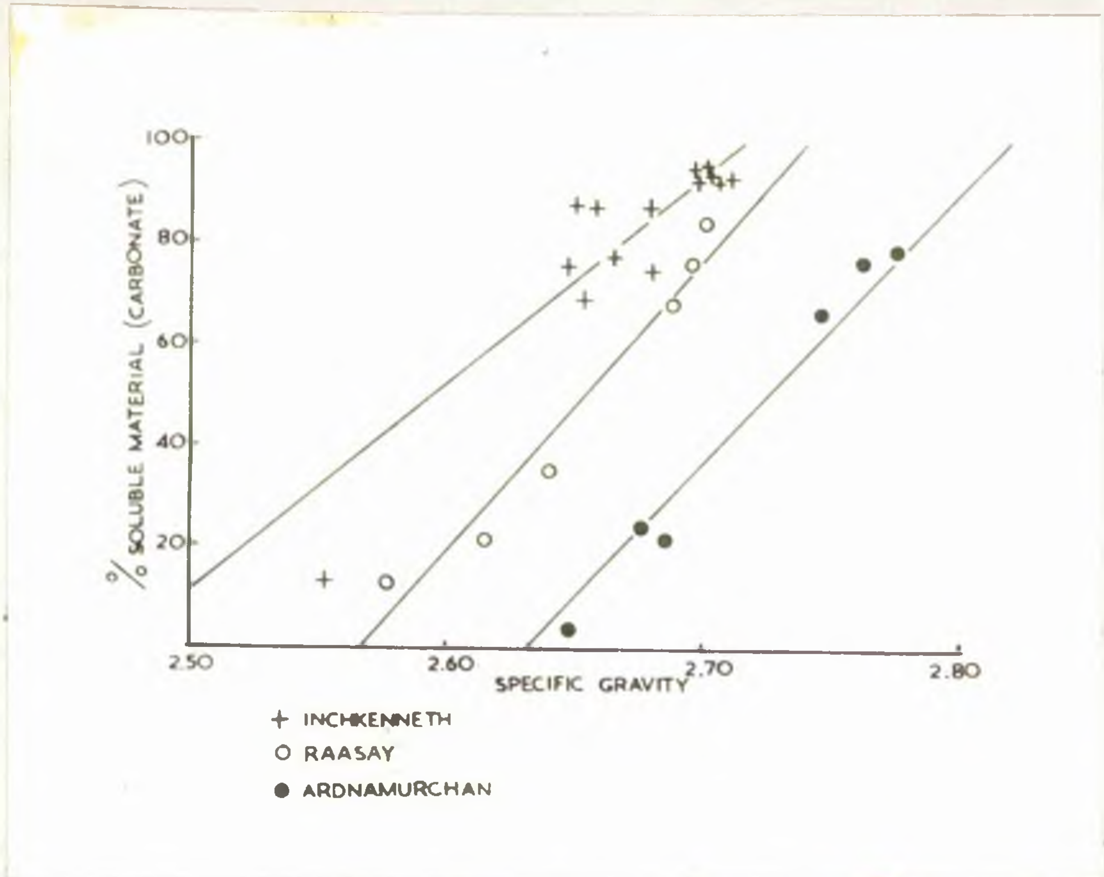


Fig. 122.

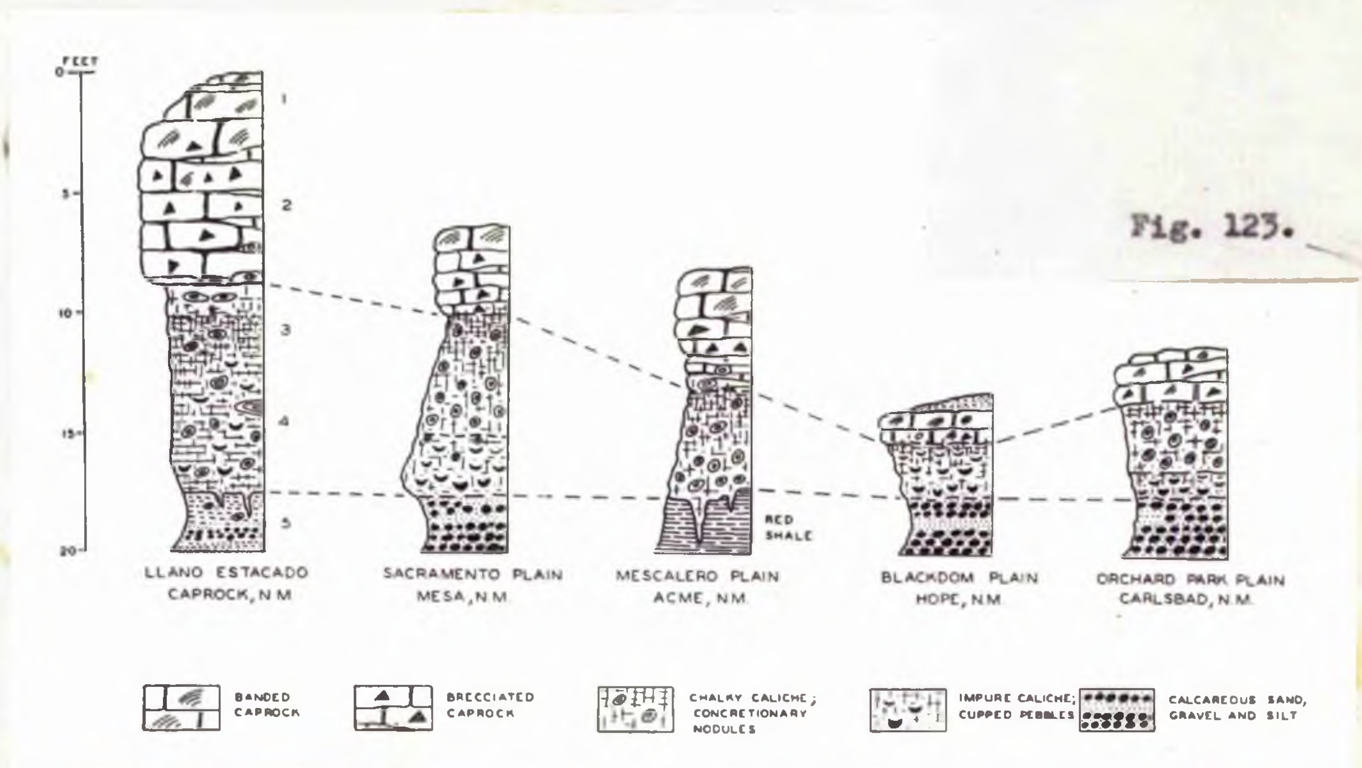
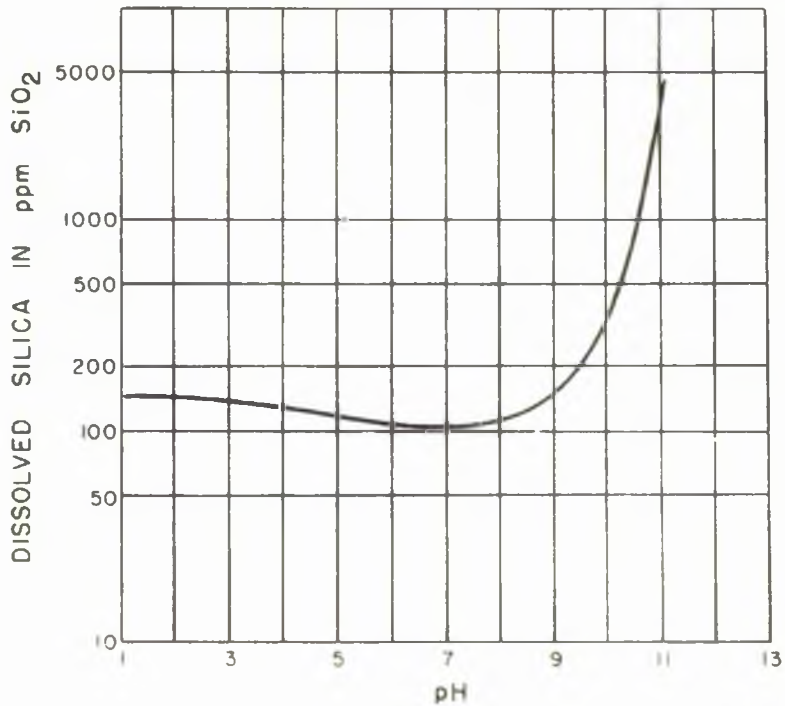


Fig. 123.

Fig. 124. Solubility of amorhpous silica and calcium carbonate in waters of varying pH (from Correns, 1950).

Fig. 125. Solubility of amorphous silica in waters of varying pH (from Alexander, Heston and Iler, 1954).



DISSOLVED SILICA IN ppm SiO_2
5000
1000
500
200
100
50
10
1
3
5
7
9
11
13
pH

Fig. 125.

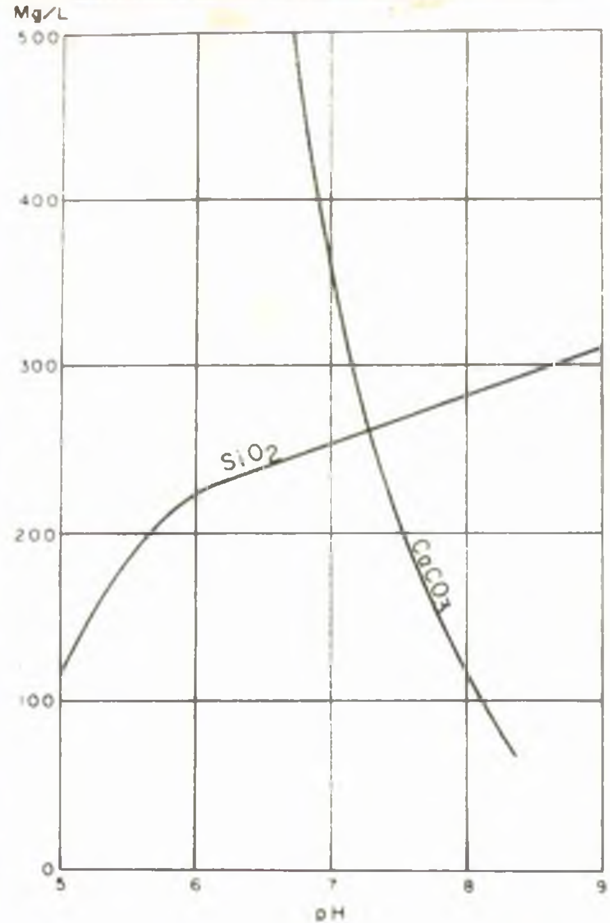
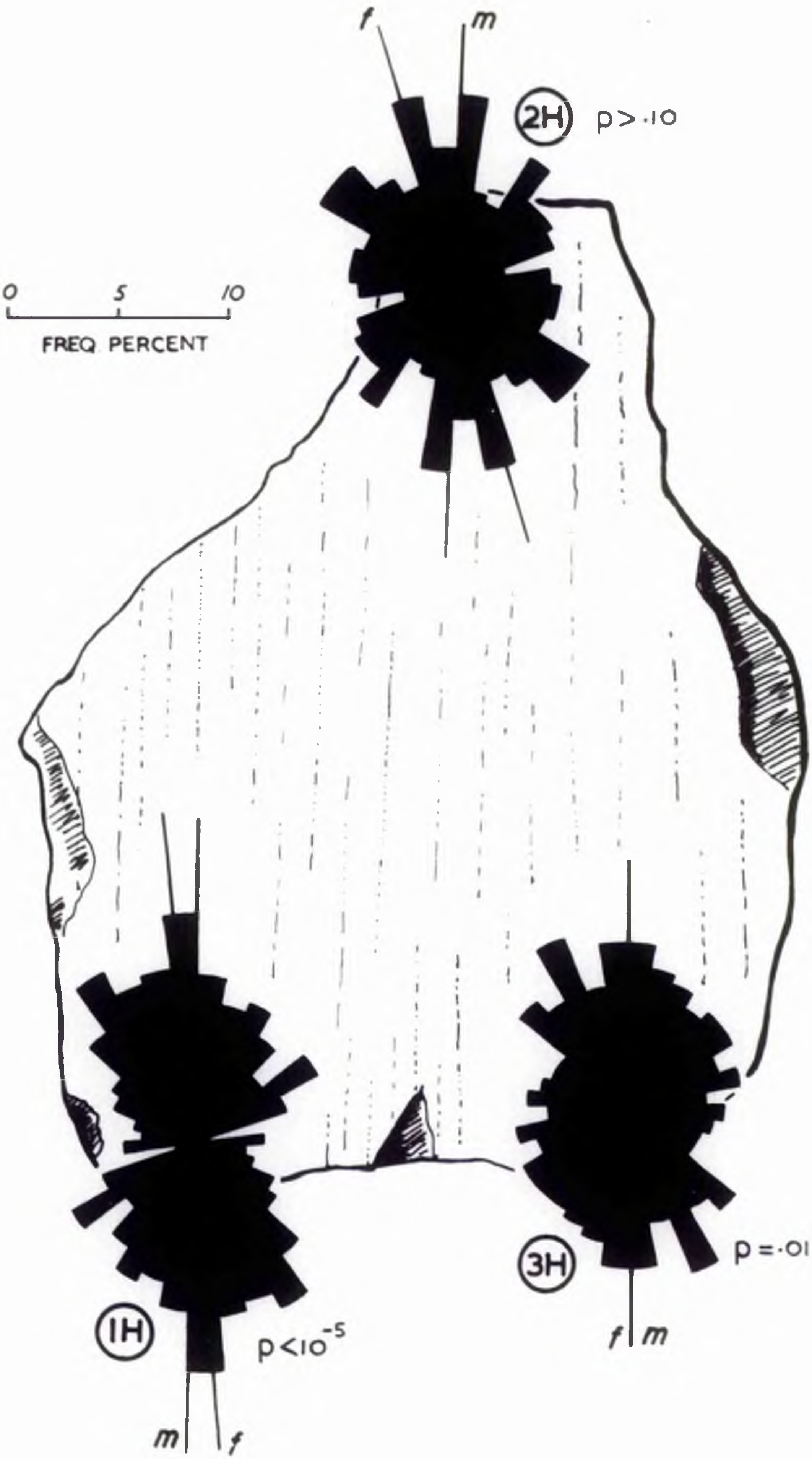


Fig. 124.

Fig. 126. Fabric of sandstone with parting lineation : orientation of sand grains with respect to the lineation.

m : direction of macroscopic lineation

f : mean vector of grain orientations (250)



f
m
2H
p>.10
0
5
10
FREQ PERCENT
1H
p<10^-5
m
f
3H
p=.01
f
m

Fig. 127. Fabric of sandstone with parting lineation : orientation of sand grains with respect to the bedding.

b : bedding

i : imbrication (vectorial mean of the orientation of 250 grains).

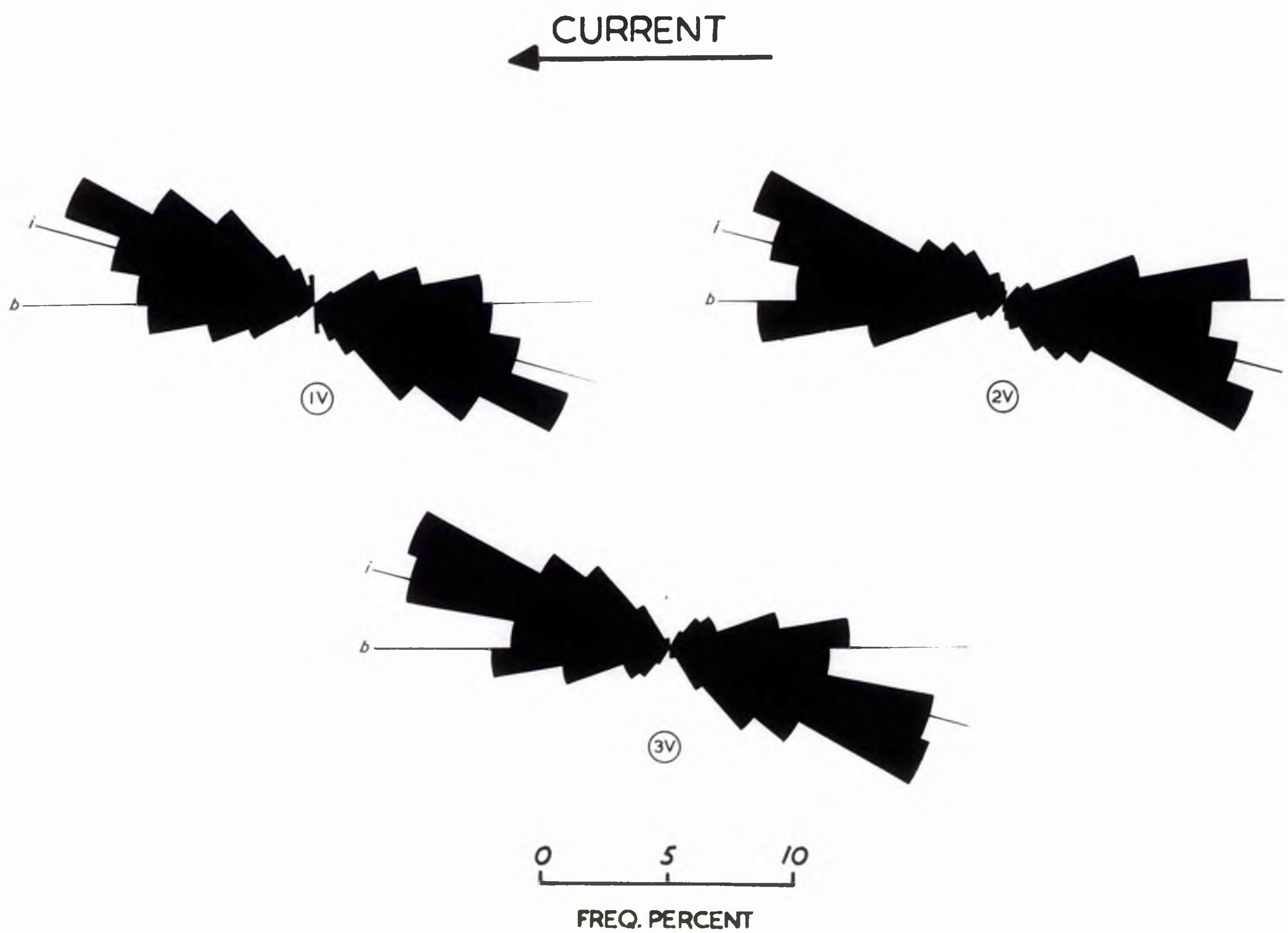

CURRENT
i
b
1V
2V
3V
0
5
10
FREQ. PERCENT

Fig. 128. Stereographic equal area projection of imbrication : contour diagram of poles to AB planes of pebbles. Inchkenneth, Humpies Conglomerate.

Contours at 1%, 3%, 5% and 7%.

Arrow indicates direction of current flow.

Fig. 129. Contour diagram of poles to AB planes of pebbles. Humpies Conglomerate, Gribun.

Contours at 1%, 3%, 5% and 7%.

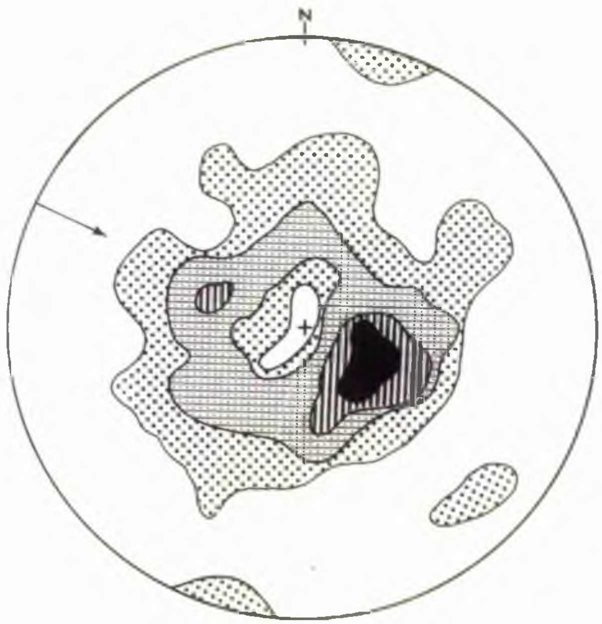


Fig. 128.

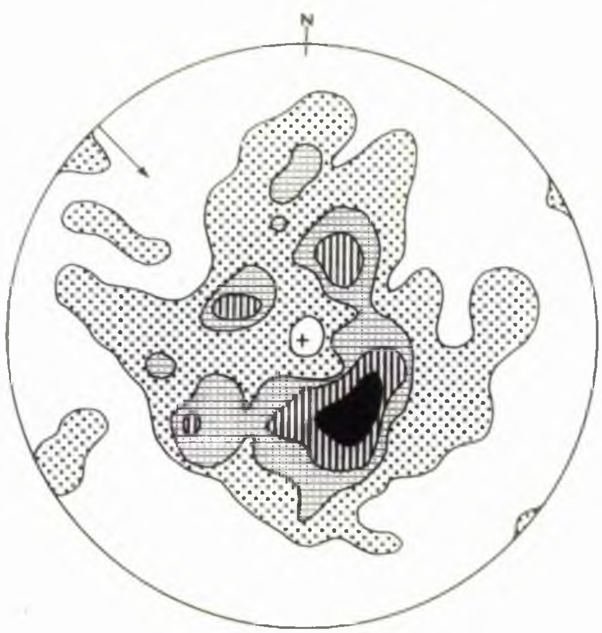


Fig. 129.

Fig. 130. Contour diagram of poles to AB planes of pebbles. Rudha an t-Sassunaich, Morvern.

Contours at 1%, 3%, 5%, 7% and 11%.

Fig. 131. Contour diagram of poles to AB planes of pebbles. Rudha na Leac, Raasay.

Contours at 1%, 2%, 7%, 13% and 15%.

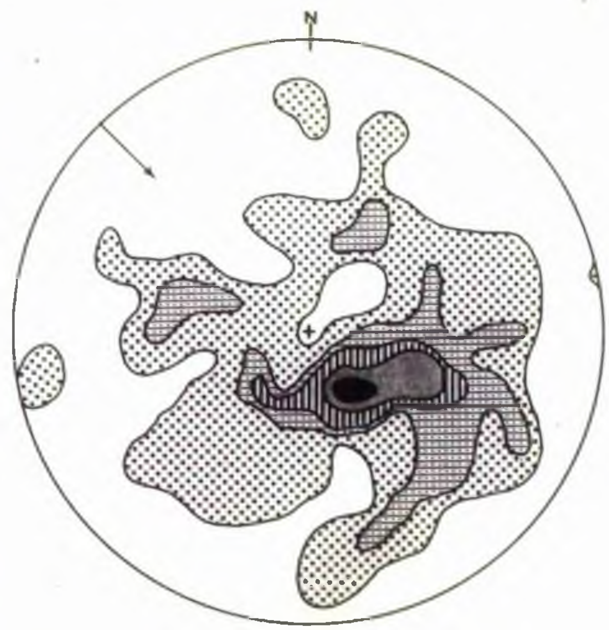


Fig. 130.

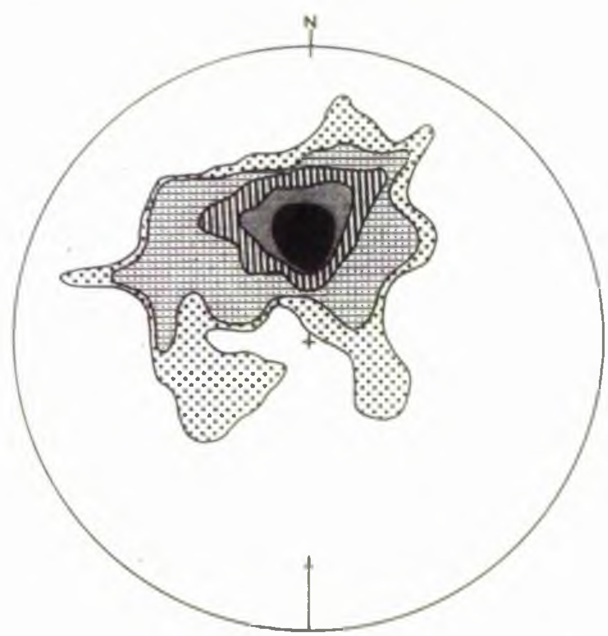


Fig. 131.

Fig. 132. Contour diagram of poles to AB planes of pebbles. Udrigle, Gruinard Bay.

Contours at 1%, 6%, 11%, 15%.

Fig. 133. Rose diagram of dip direction of foreset beds. Inchkenneth, Humpies Conglomerate.

$p < 10^{-5}$

vm : mean vector

Arrow indicates the direction of current flow.

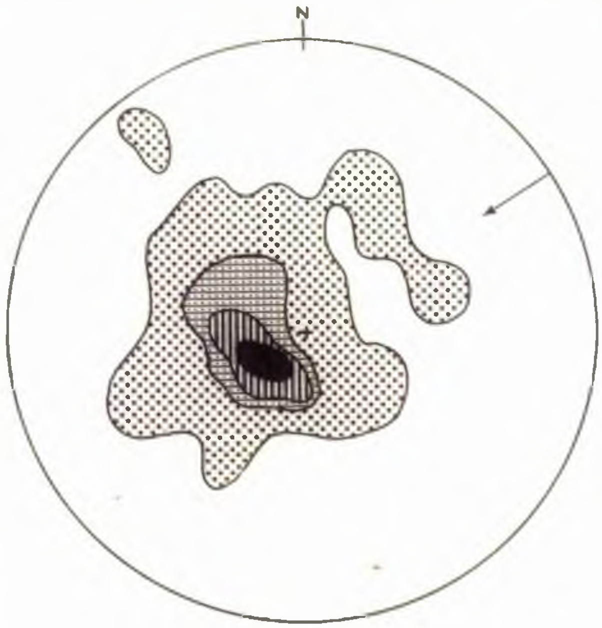


Fig. 132.

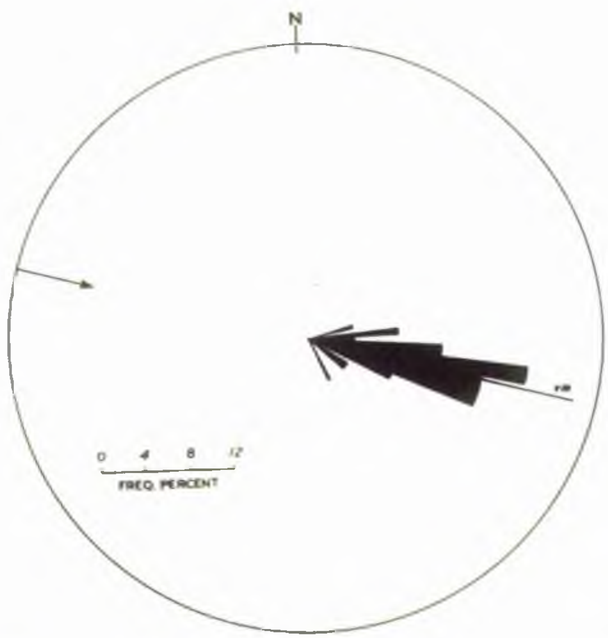


Fig. 133.

Fig. 134. Rose diagram of dip direction of foreset beds. Inchkenneth, Chapel Beds.

$p < 10^{-5}$

Fig. 135. Rose diagram of dip direction of foreset beds. Gribun.

$p < 10^{-10}$

Fig. 134.

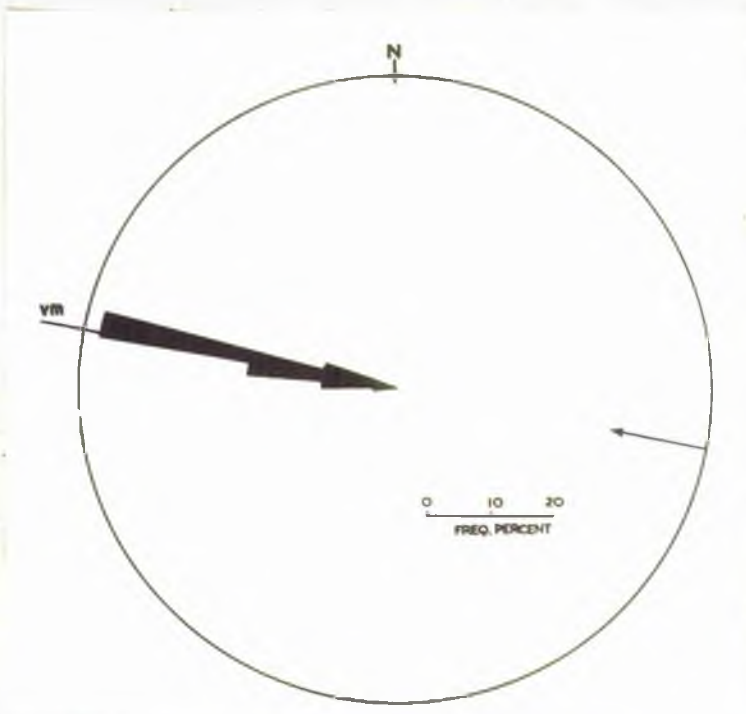


Fig. 135.

Fig. 136. Rose diagram of dip direction of foreset beds. Rudha an t-Sassunaich, Morvern.

$p < 10^{-5}$

Fig. 137. Rose diagram of dip direction of forset beds. Mingary, Ardnamurchan.

$p < 10^{-10}$

Fig. 136.

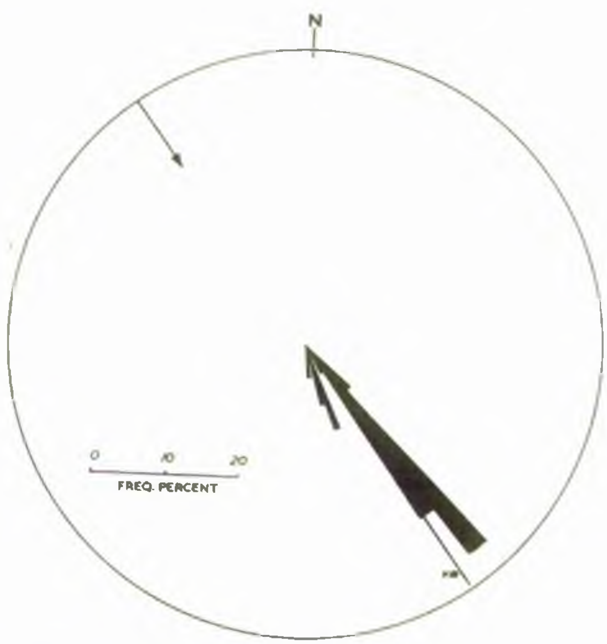


Fig. 137.

Fig. 138. Rose diagram of dip direction of foreset beds. Udrigle, Gruinard Bay.

$p < 10^{-20}$

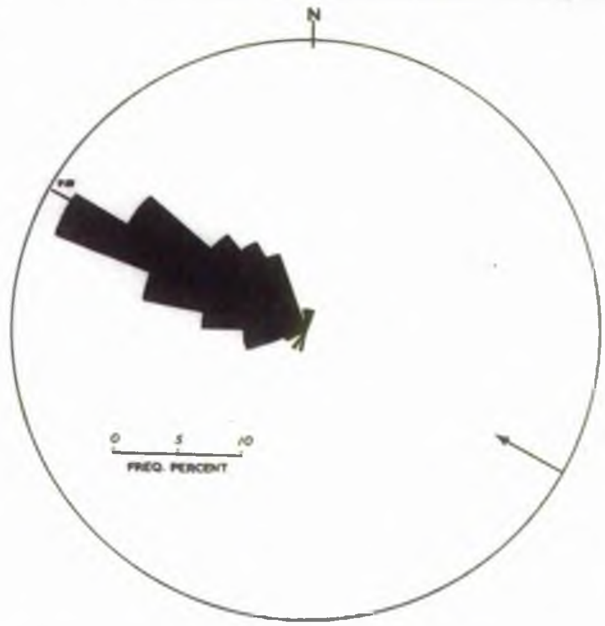


Fig. 138.

Fig. 139. Pebble measurement localities, Strath (Skye).

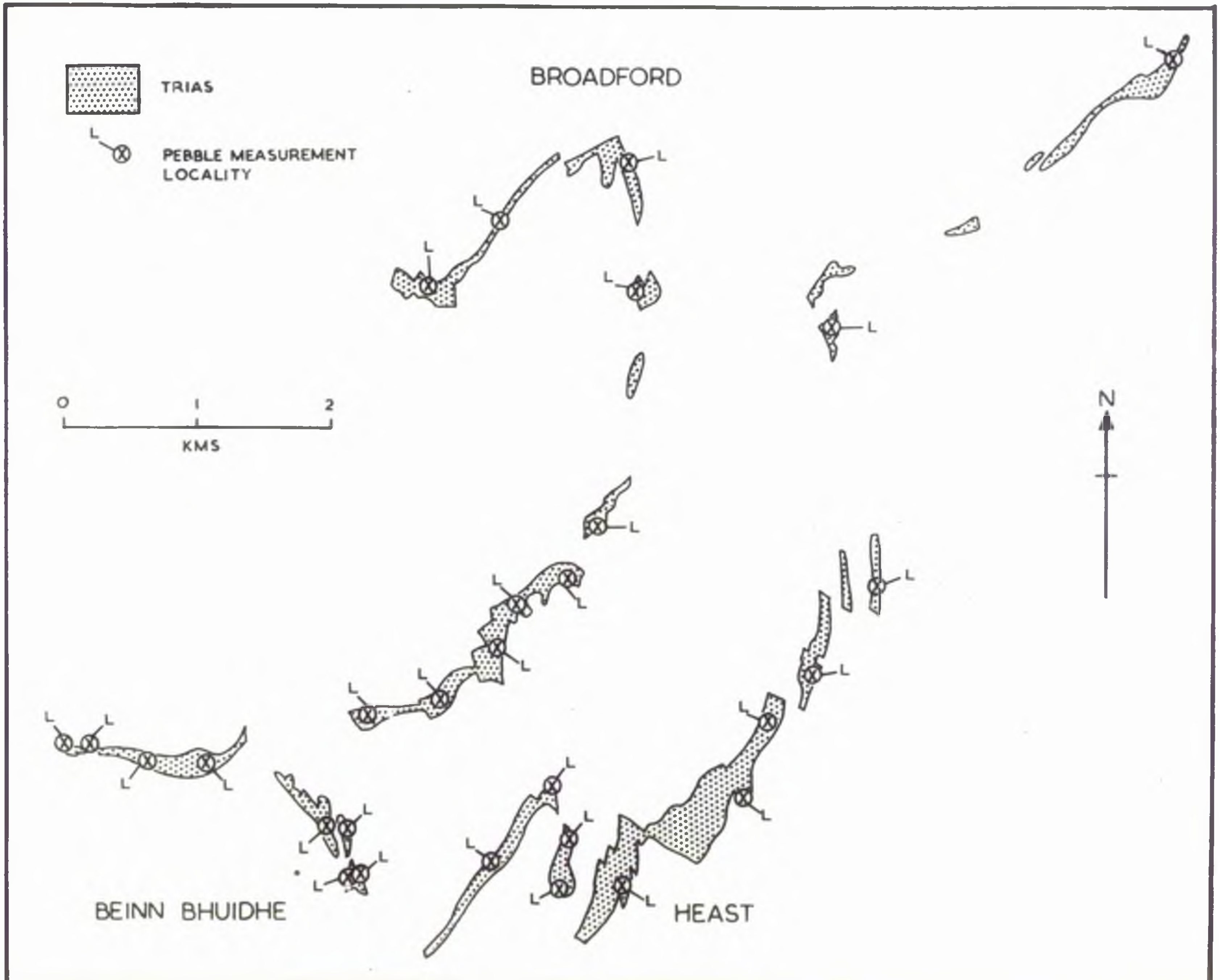

TRIAS
PEBBLE MEASUREMENT LOCALITY
L
BROADFORD
0
1
2
KMS
N
BEINN BHUIDHE
HEAST

Fig. 140. Quartzite pebble isopleths, Strath.

Isopleths given in cms.

Fig. 141. Durness Carbonate pebble isopleths, including distribution of limestone conglomerate and quartzose sandstones and grits. Strath.

1

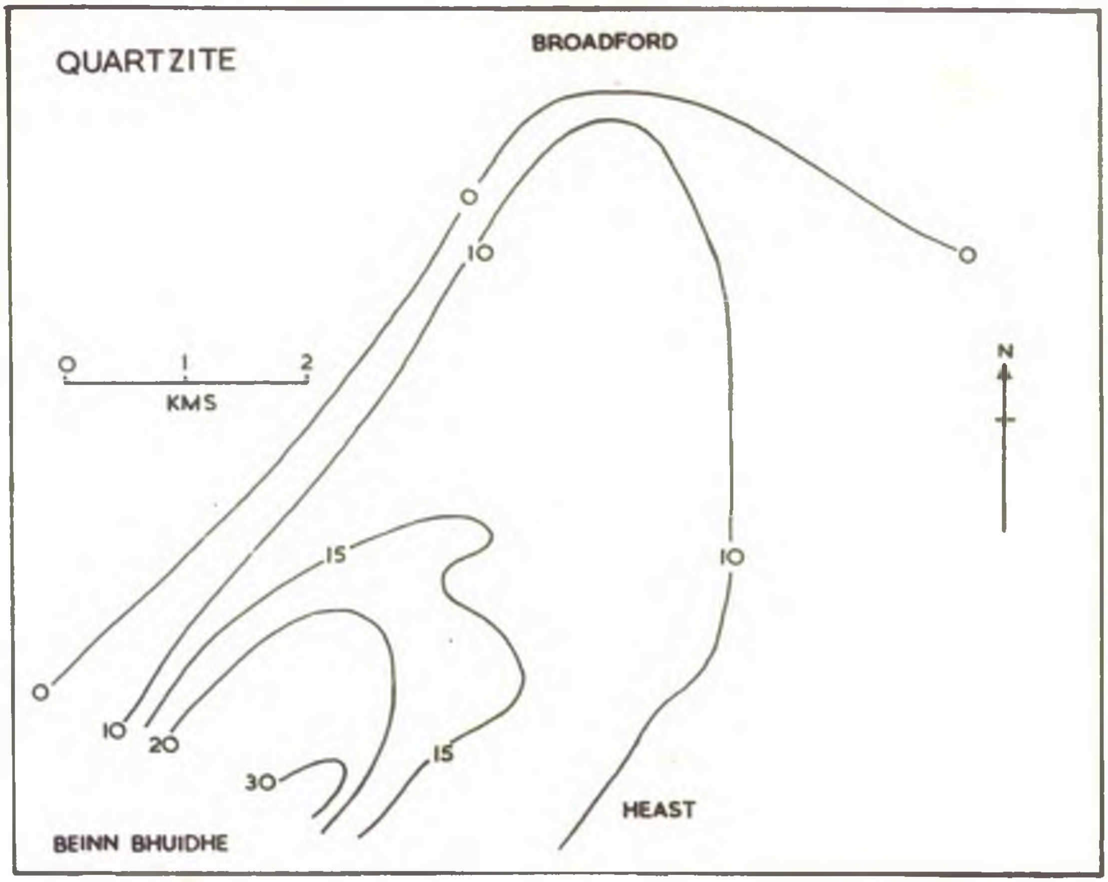


Fig. 140.

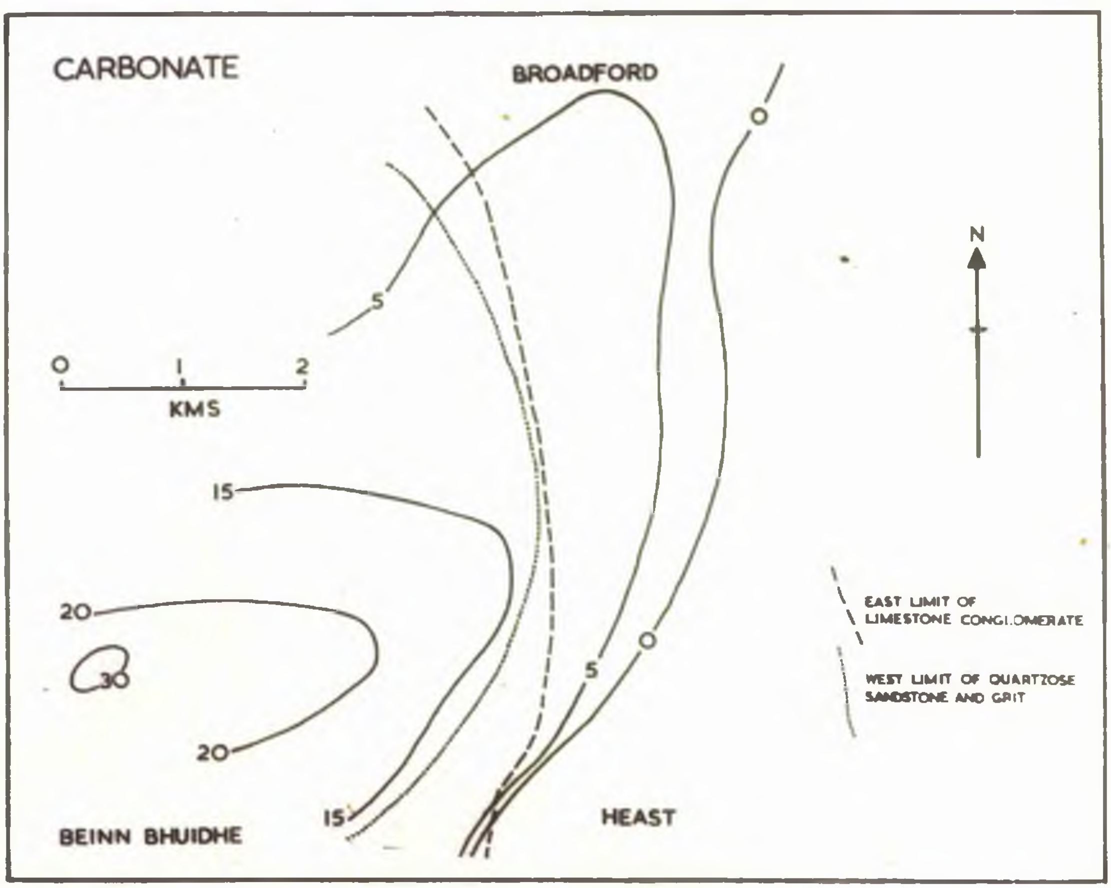


Fig. 141.

Fig. 142. Torridonian sandstone pebble isopleths, Strath.

Fig. 143. Diagrammatic section across the Strath area.

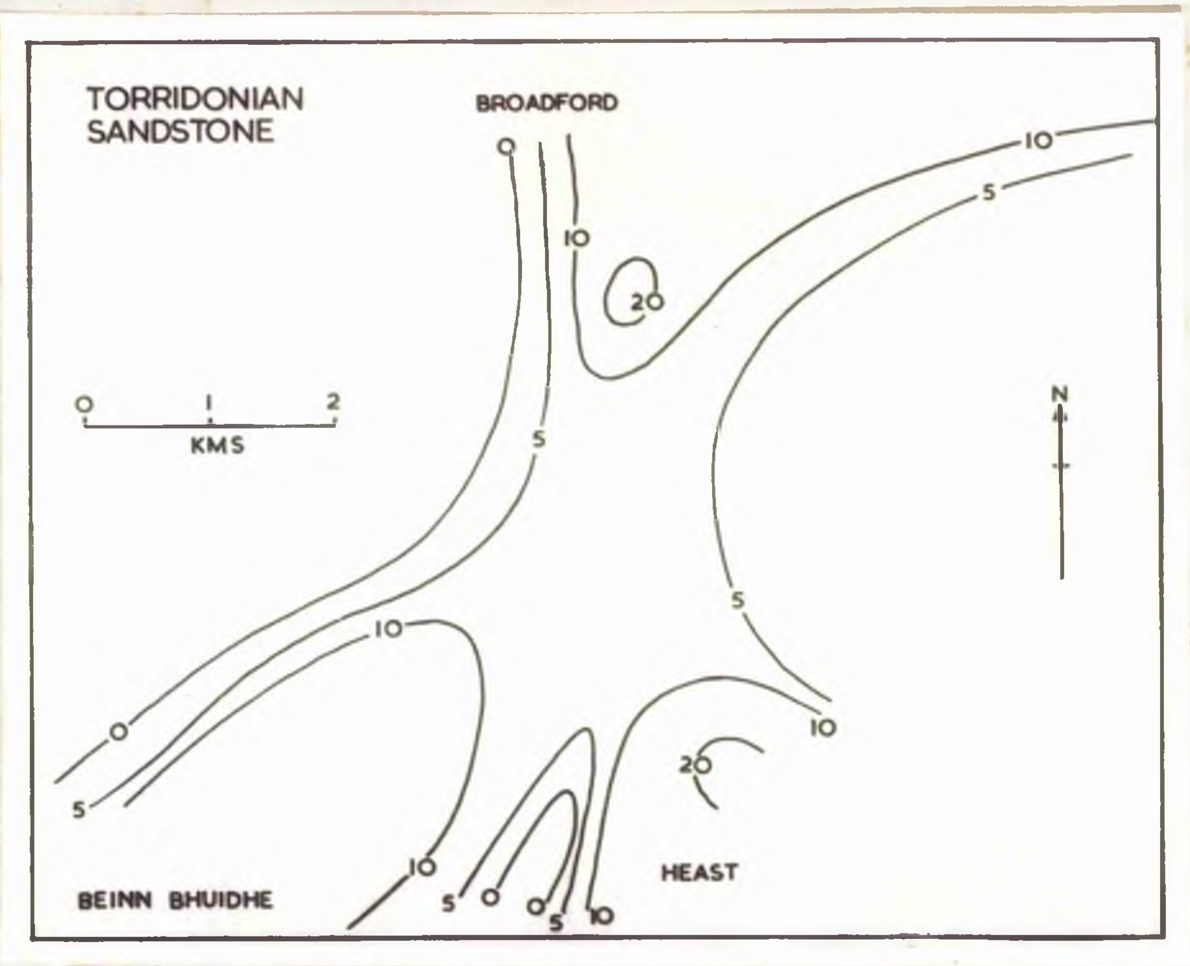


Fig. 142.

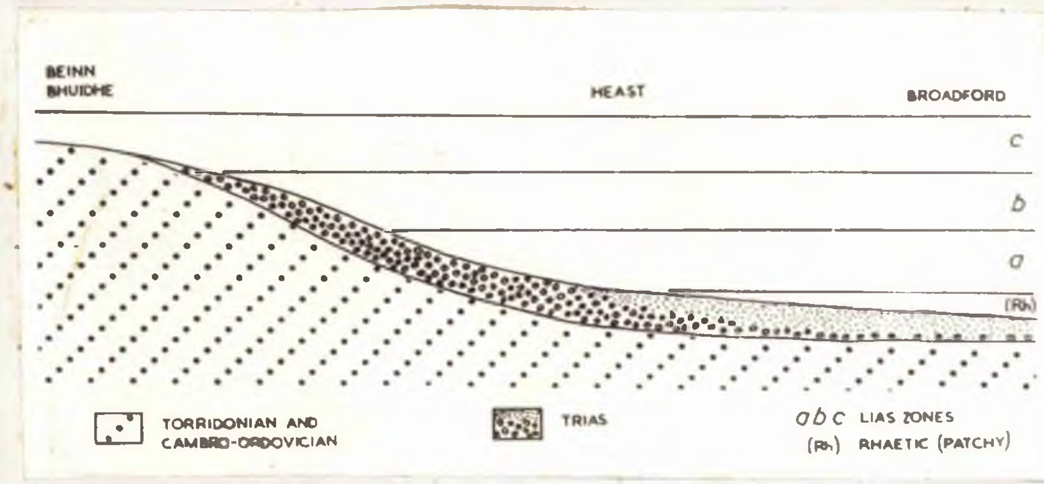


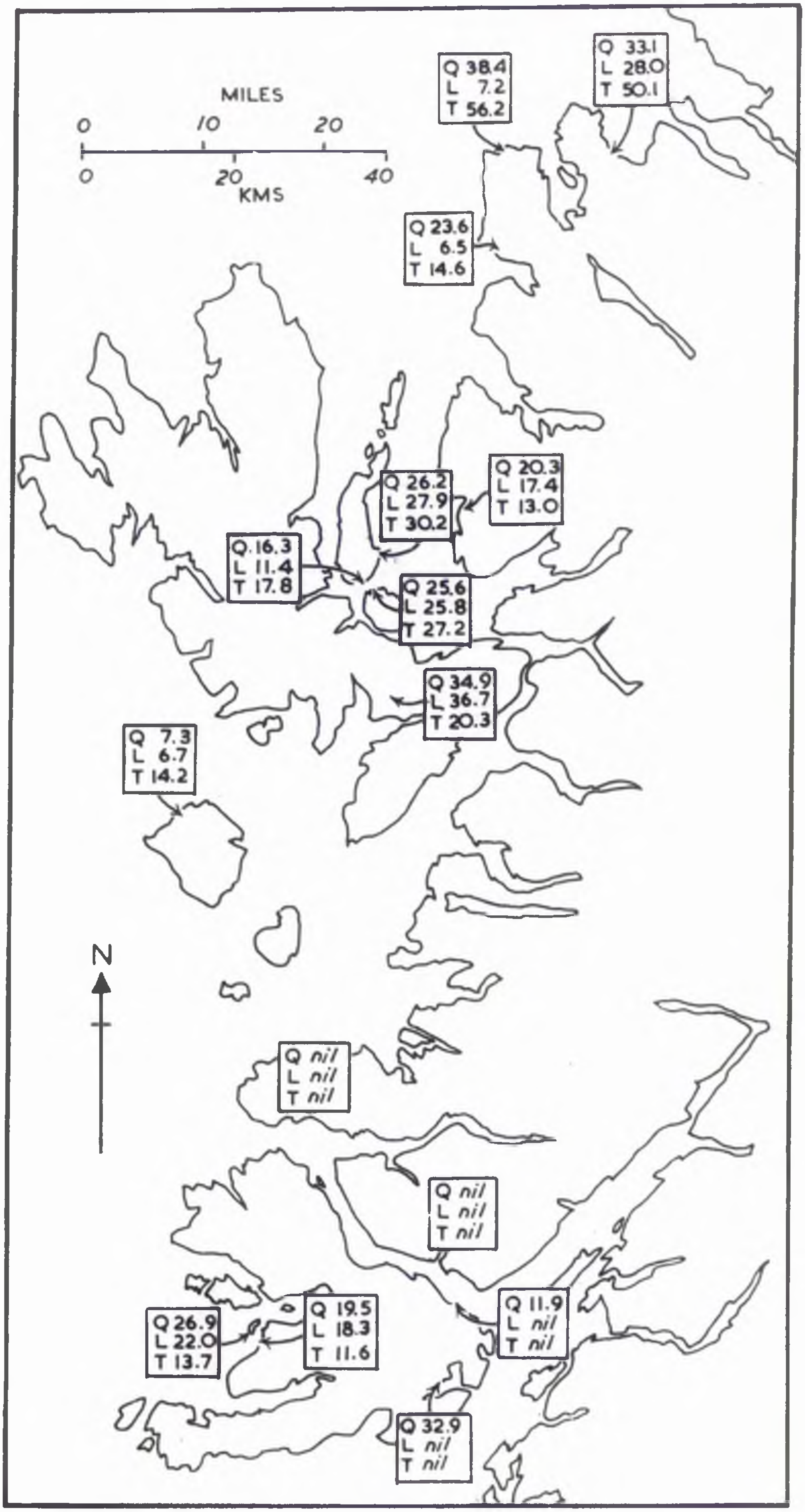
Fig. 143.

Fig. 143a. Regional distribution of maximum pebble sizes.

Q = Quartzite

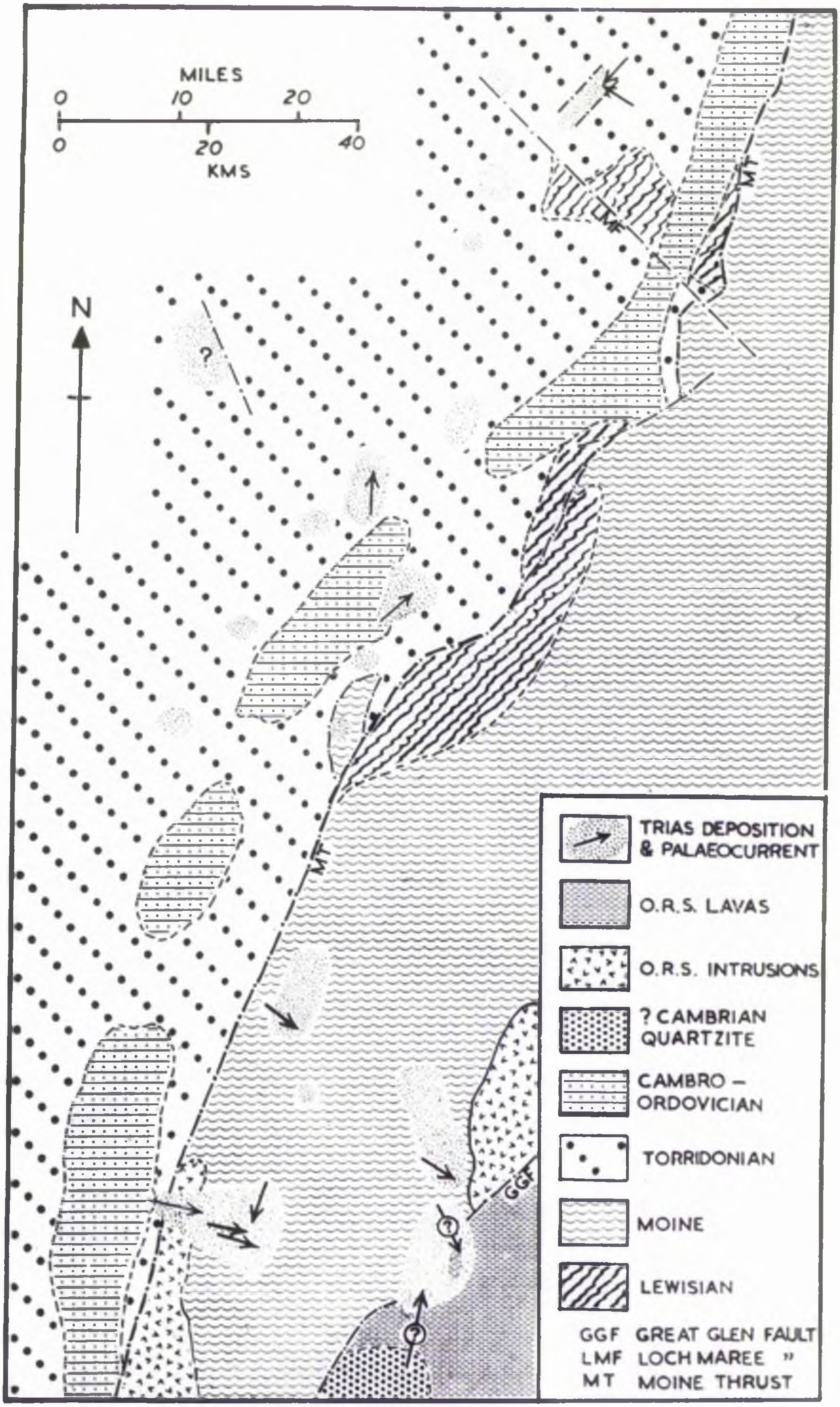
L = Durness 'limestone'

T = Torridonian sandstone



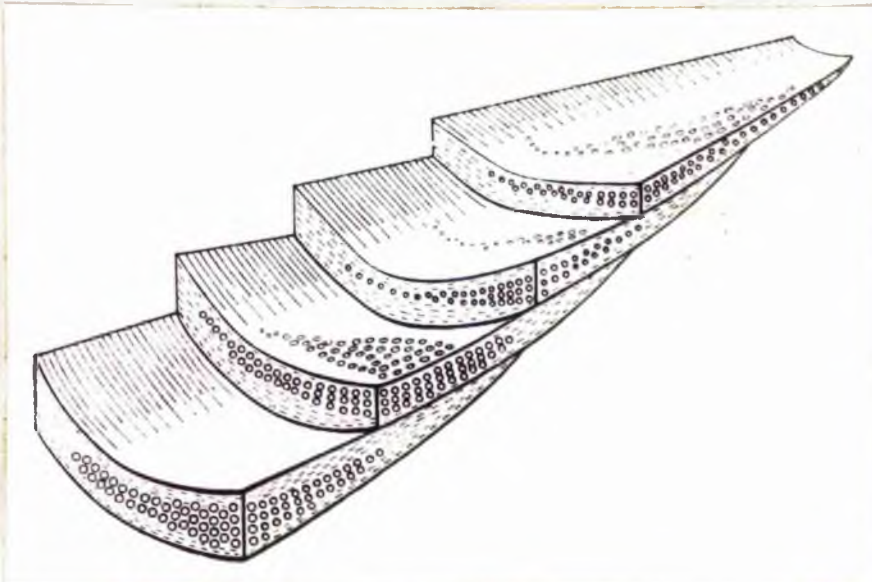
MILES
0
10
20
0
20
40
KMS
Q 38.4
L 7.2
T 56.2
Q 33.1
L 28.0
T 50.1
Q 23.6
L 6.5
T 14.6
Q 26.2
L 27.9
T 30.2
Q 20.3
L 17.4
T 13.0
Q.16.3
L 11.4
T 17.8
Q 25.6
L 25.8
T 27.2
Q 34.9
L 36.7
T 20.3
Q 7.3
L 6.7
T 14.2
N
Q nil
L nil
T nil
Q nil
L nil
T nil
Q 26.9
L 22.0
T 13.7
Q 19.5
L 18.3
T 11.6
Q 11.9
L nil
T nil
Q 32.9
L nil
T nil

Fig. 143b. Palaeogeology and palaeocurrents of the West Highland area in Trias times.



MILES
0
10
20
0
20
40
KMS
N
?
LMF
MT
MT
GGF
TRIAS DEPOSITION & PALAEOCURRENT
O.R.S. LAVAS
O.R.S. INTRUSIONS
? CAMBRIAN QUARTZITE
CAMBRO – ORDOVICIAN
TORRIDONIAN
MOINE
LEWISIAN
GGF GREAT GLEN FAULT
LMF LOCH MAREE "
MT MOINE THRUST

Fig. 143c. Diagram illustrating the accumulation of large thicknesses of conglomerate alternating with sandstone (Bryhni, 1964).



143c.

Fig. 144. Map of the Badluarach clastic dykes.

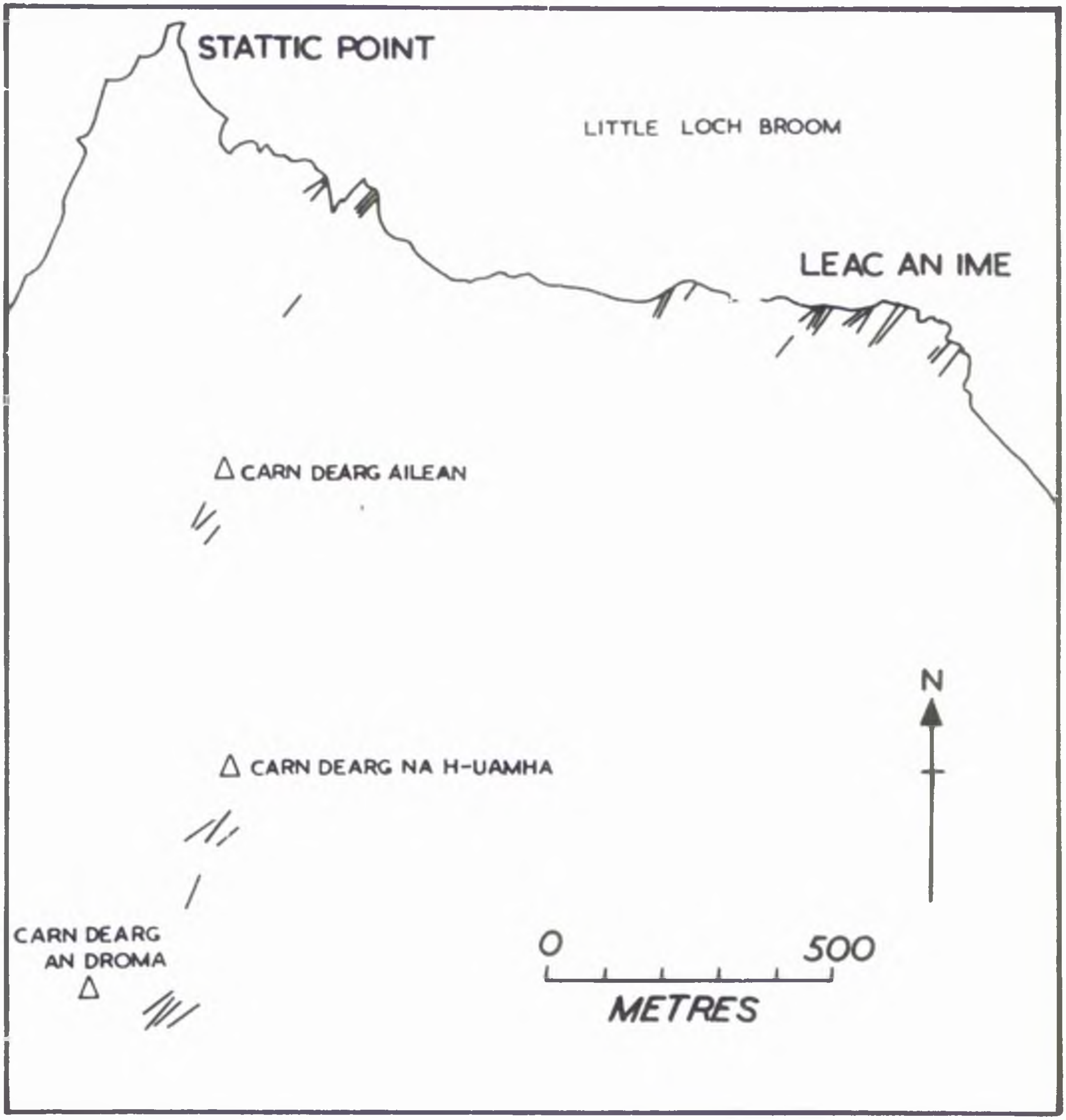

STATTIC POINT
LITTLE LOCH BROOM
LEAC AN IME
CARN DEARG AILEAN
N
CARN DEARG NA H-UAMHA
CARN DEARG
AN DROMA
0
500
METRES

Fig. 145. Map of clastic dykes in Wester Ross. Dykes in the Gairloch area are after Peach _et al_.(1907).

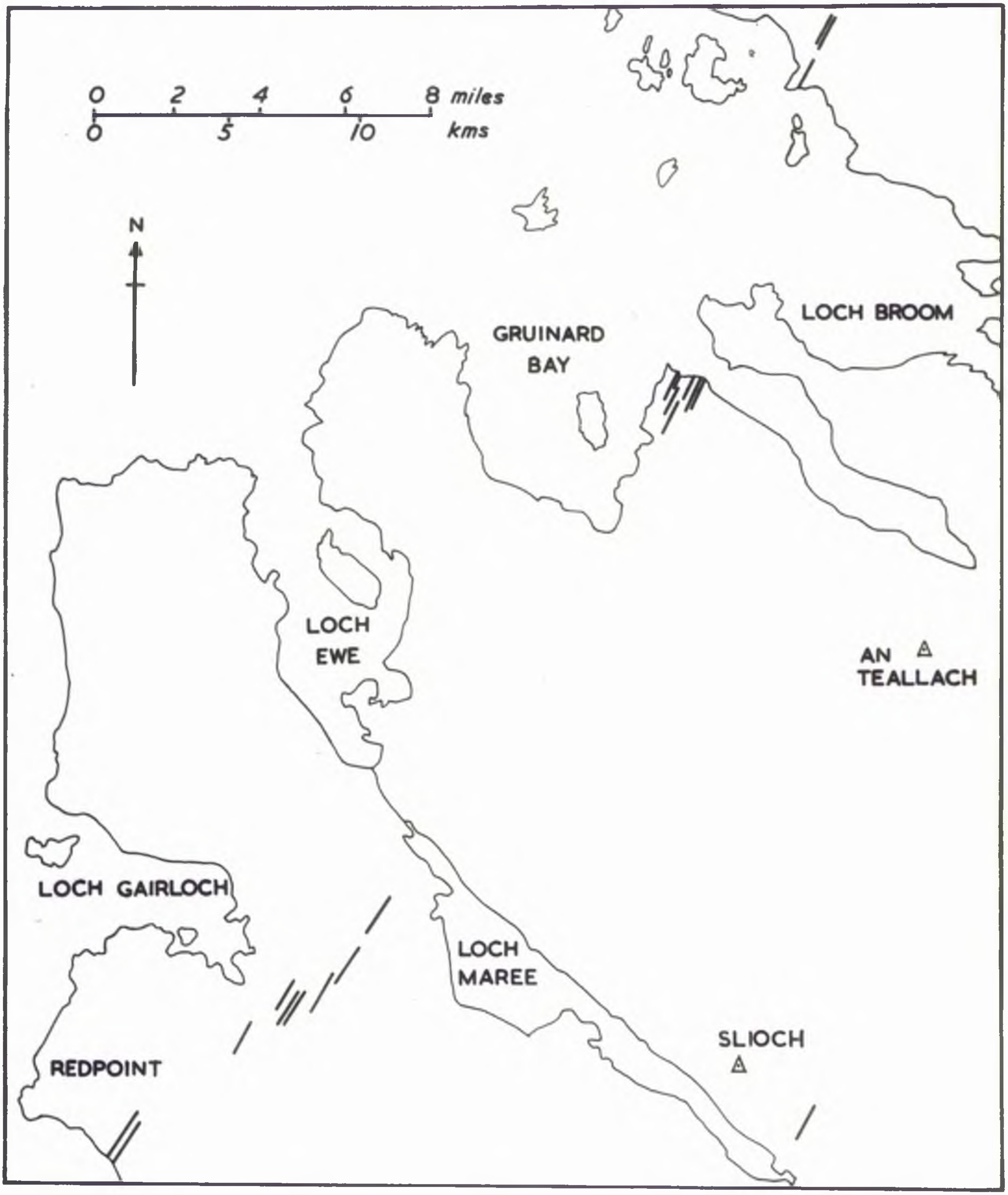

0 2 4 6 8 miles
0 5 10 kms
N
GRUINARD BAY
LOCH BROOM
LOCH EWE
AN TEALLACH
LOCH GAIRLOCH
LOCH MAREE
SLIOCH
REDPOINT

Fig. 146. Contoured stereographic equal area projection of poles to clastic dykes, Badluarach.

Contours at 1%, 4%, 6%, 10% and 15%

Fig. 147. Contoured stereographic equal area projection of poles to joint planes, Badluarach.

Contours at 1%, 6%, 10%, 15% and 20%.

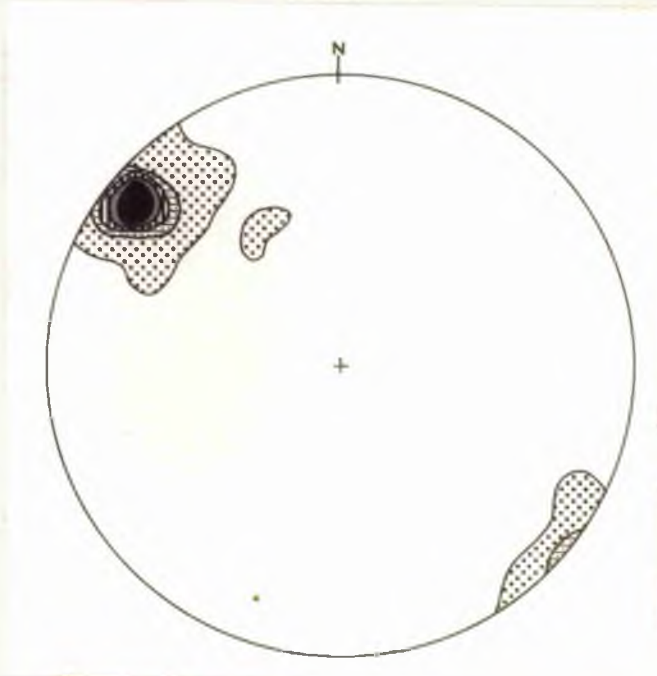


Fig. 146.

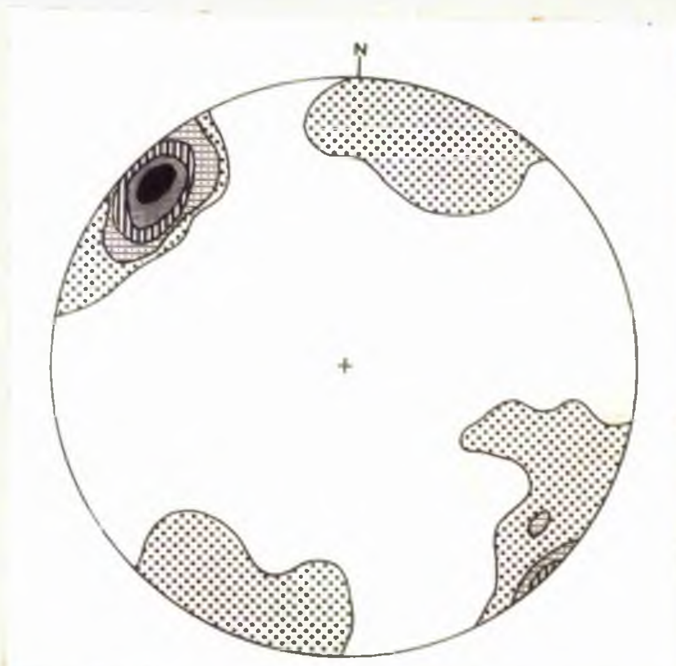


Fig. 147.

Fig. 148. Field sketch of fragments of country rock contained in a clastic dyke. Leac an Ime, Badluarach.

Fig. 149. Position of sections made from clastic dykes for fabric analysis.

Fig. 150. Orientation of long axes of sand grains.

f = mean vector

dw = dyke wall

v = vertical

The largest number per 10° interval is indicated.

i) Bh 36a = L = 49.4%

$p < 10^{-10}$

ii) Bh 36b = L = 34.2%

$p < 10^{-5}$

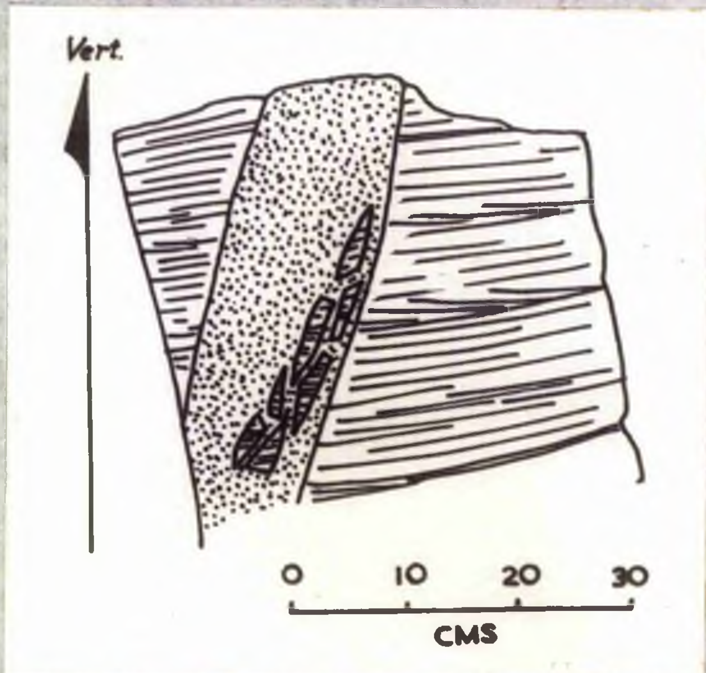


Fig. 148.

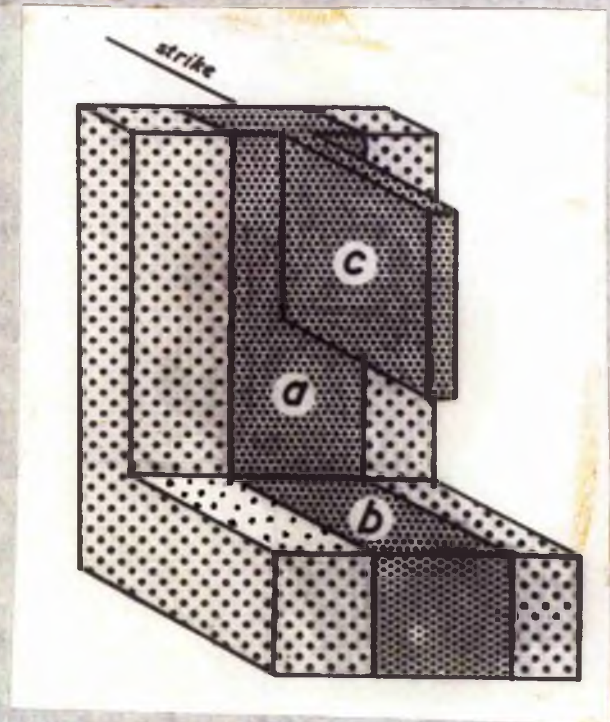


Fig. 149.

Fig. 150 i)

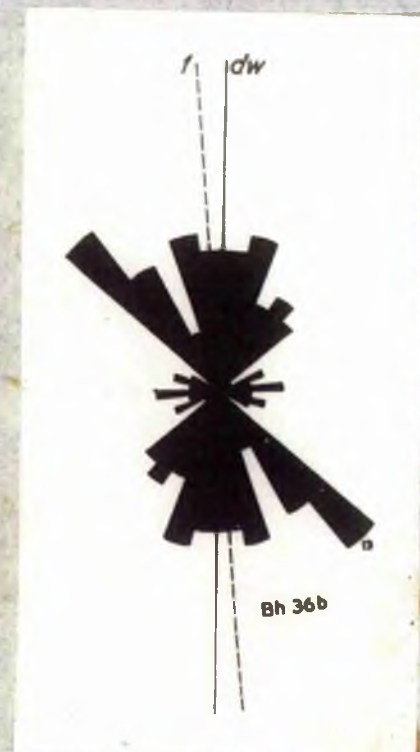


Fig. 150 ii)

Fig. 150.	iii)	Bh 36c =	L = 22.6% $p < .01$
	iv)	Bh 30b =	L = 18.2% $p < .04$
	v)	Bh 30a i)	L = 68.9% $p < 10^{-20}$
	vi)	Bh 30a ii)	L = 65.0% $p < 10^{-15}$

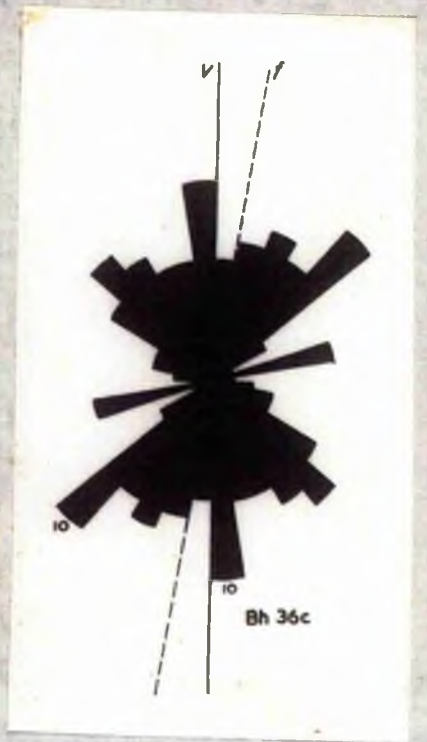


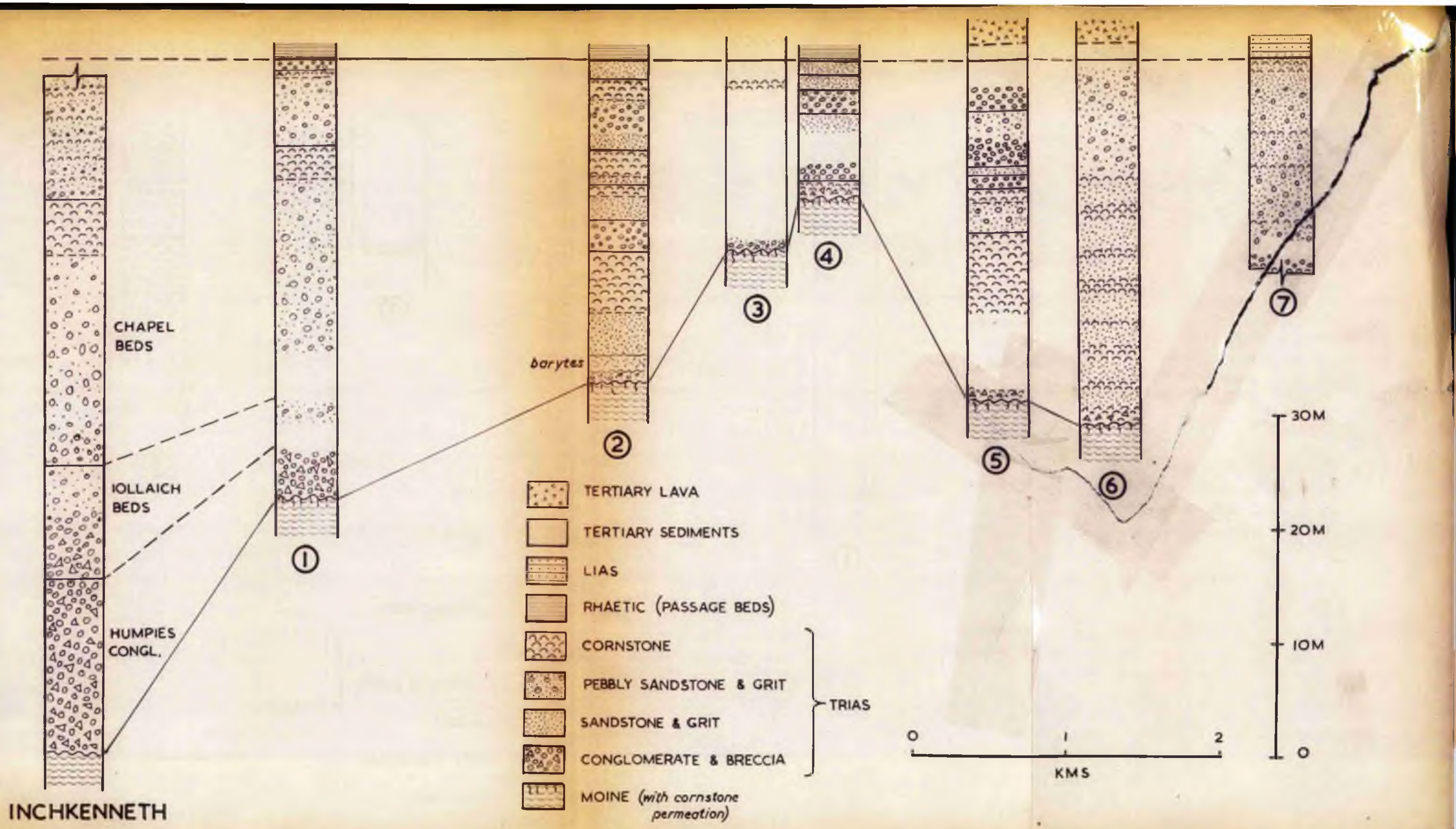
Fig. 150 iii) iv)

v) vi)

Fig. 151. Trias successions in Western Mull.

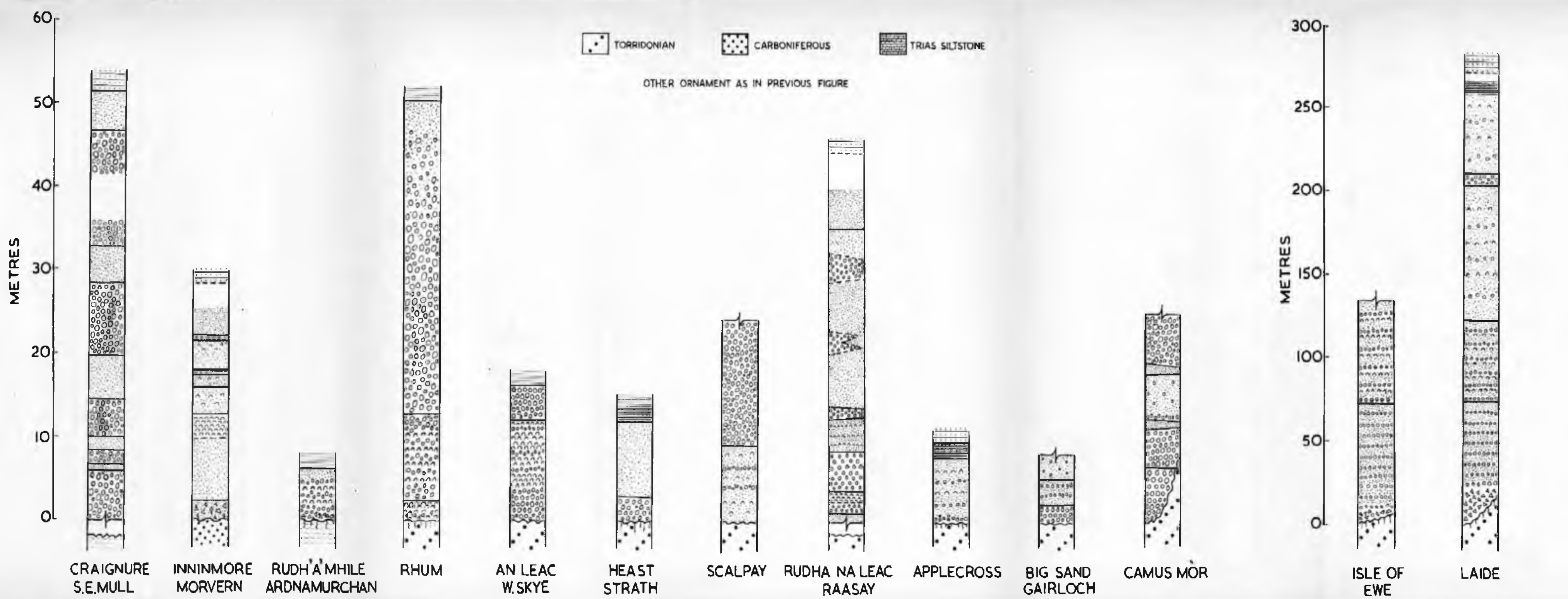
1. Allt na Teangaidh
2. Ath Dearg
3. Sloc nam Ban
4. An Dubh Allt
5. Allt na Leacainn
6. Lurg Bhriste-chridhe
7. Uamh nan Calman

(See Map 2)



CHAPEL BEDS
IOLLAICH BEDS
HUMPIES CONGL.
INCHKENNETH
barytes
1
2
3
4
5
6
7
TERTIARY LAVA
TERTIARY SEDIMENTS
LIAS
RHAETIC (PASSAGE BEDS)
CORNSTONE
PEBBLY SANDSTONE & GRIT
SANDSTONE & GRIT
CONGLOMERATE & BRECCIA
TRIAS
MOINE (with cornstone permeation)
0
1
2
KMS
30M
20M
10M
0

Fig. 152. Trias successions in the remainder of the West Highland area.

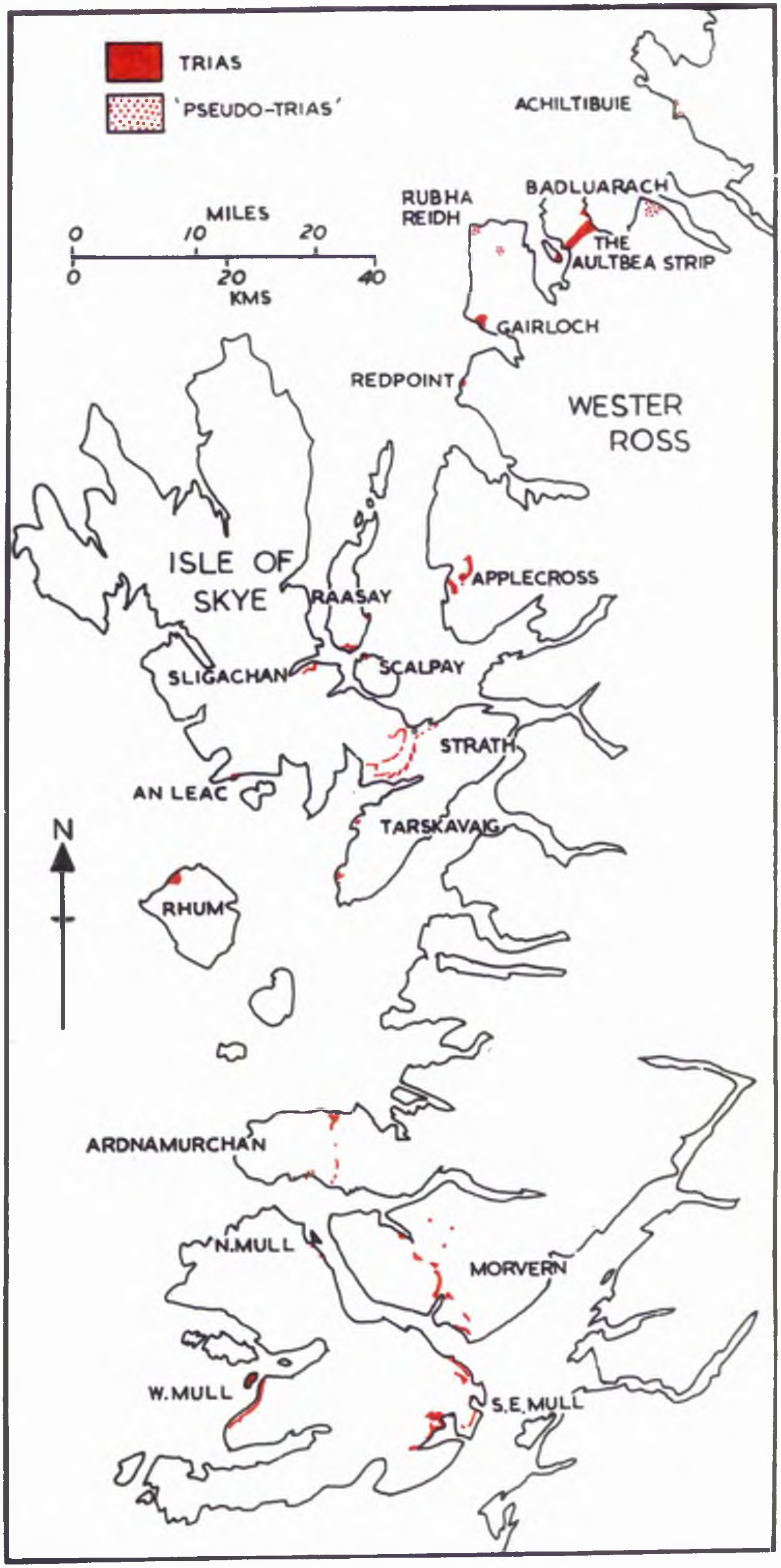


TORRIDONIAN
CARBONIFEROUS
TRIAS SILTSTONE
OTHER ORNAMENT AS IN PREVIOUS FIGURE
METRES
60
50
40
30
20
10
0
300
250
200
150
100
50
0
CRAIGNURE S.E.MULL
INNINMORE MORVERN
RUDH'A'MHILE ARDNAMURCHAN
RHUM
AN LEAC W.SKYE
HEAST STRATH
SCALPAY
RUDHA NA LEAC RAASAY
APPLECROSS
BIG SAND GAIRLOCH
CAMUS MOR
ISLE OF EWE
LAIDE

MAPS.

MAP 1

General map of the West Highlands and Inner Hebrides, showing the locations of rocks described in this thesis.



TRIAS
'PSEUDO-TRIAS'
ACHILTIBUIE
MILES
0
10
20
0
20
40
KMS
RUBHA
REIDH
BADLUARACH
THE
AULTBEA STRIP
GAIRLOCH
REDPOINT
WESTER
ROSS
ISLE OF
SKYE
RAASAY
APPLECROSS
SCALPAY
SLIGACHAN
STRATH
AN LEAC
TARSKAVAIG
N
RHUM
ARDNAMURCHAN
N.MULL
MORVERN
W.MULL
S.E.MULL

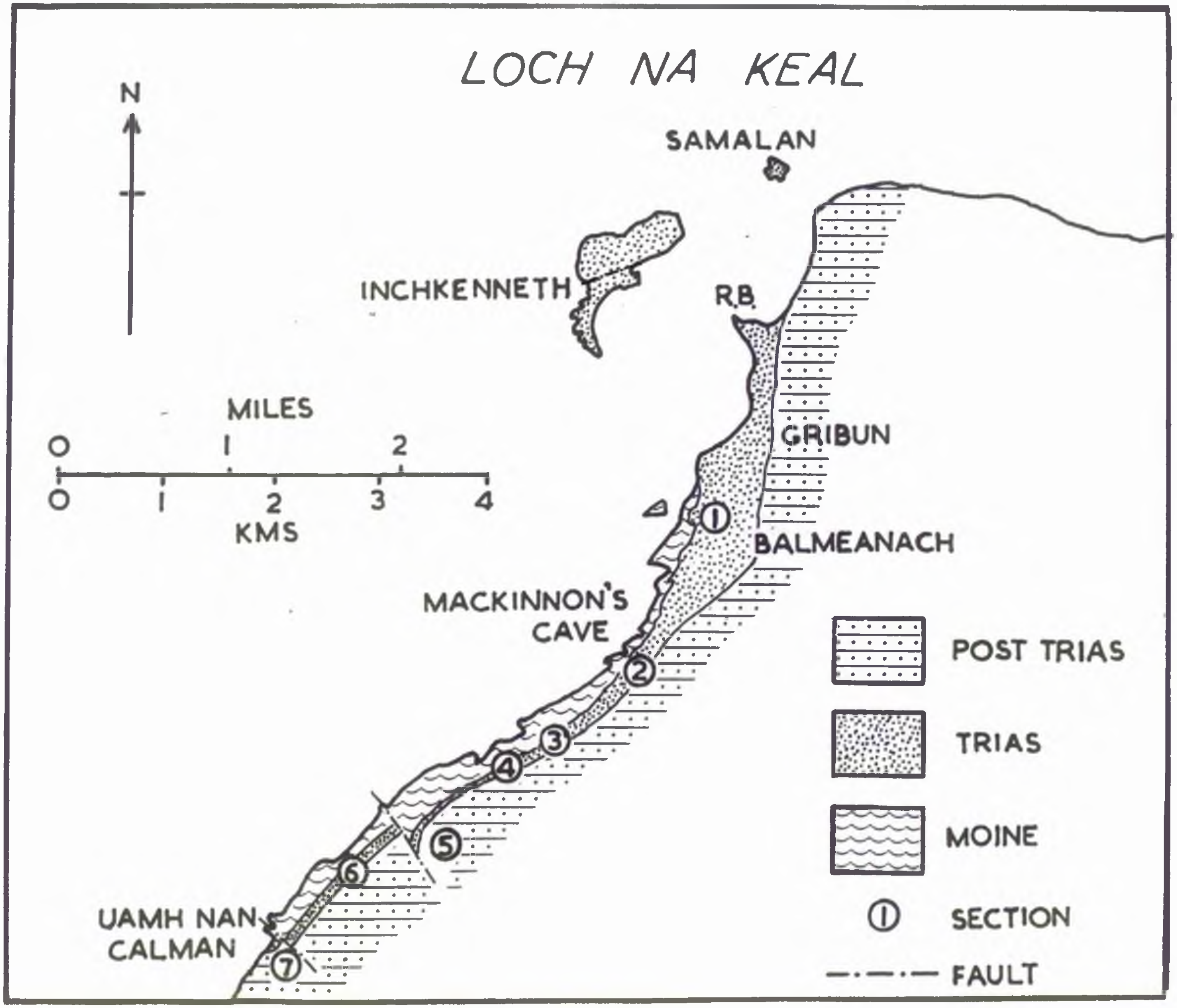
MAP 2.

WEST MULL.

Figures refer to sections given in Fig. 151:

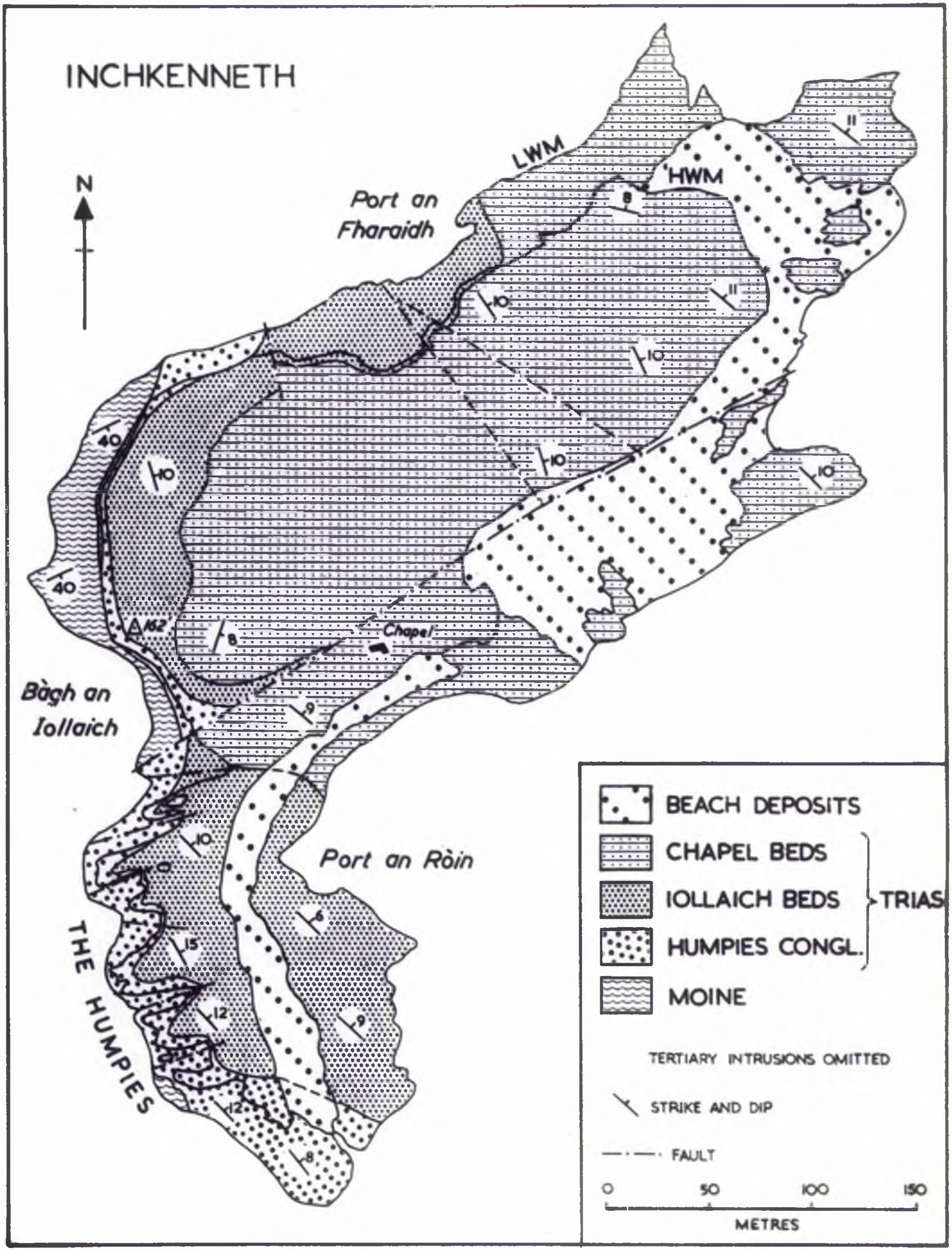
1. Allt na Teangaidh
2. Ath Dearg
3. Sloc nam Ban
4. An Dubh Allt
5. Allt na Leacainh
6. Lurg Bhriste-chridhe
7. Uamh nan Calman

R.B.: Rudha Baile na h-Airde


LOCH NA KEAL
N
SAMALAN
INCHKENNETH
R.B.
MILES
0
1
2
0
1
2
3
4
KMS
GRIBUN
BALMEANACH
MACKINNON'S
CAVE
UAMH NAN
CALMAN
POST TRIAS
TRIAS
MOINE
1 SECTION
FAULT

MAP 3

<u>INCHKENNETH.</u>

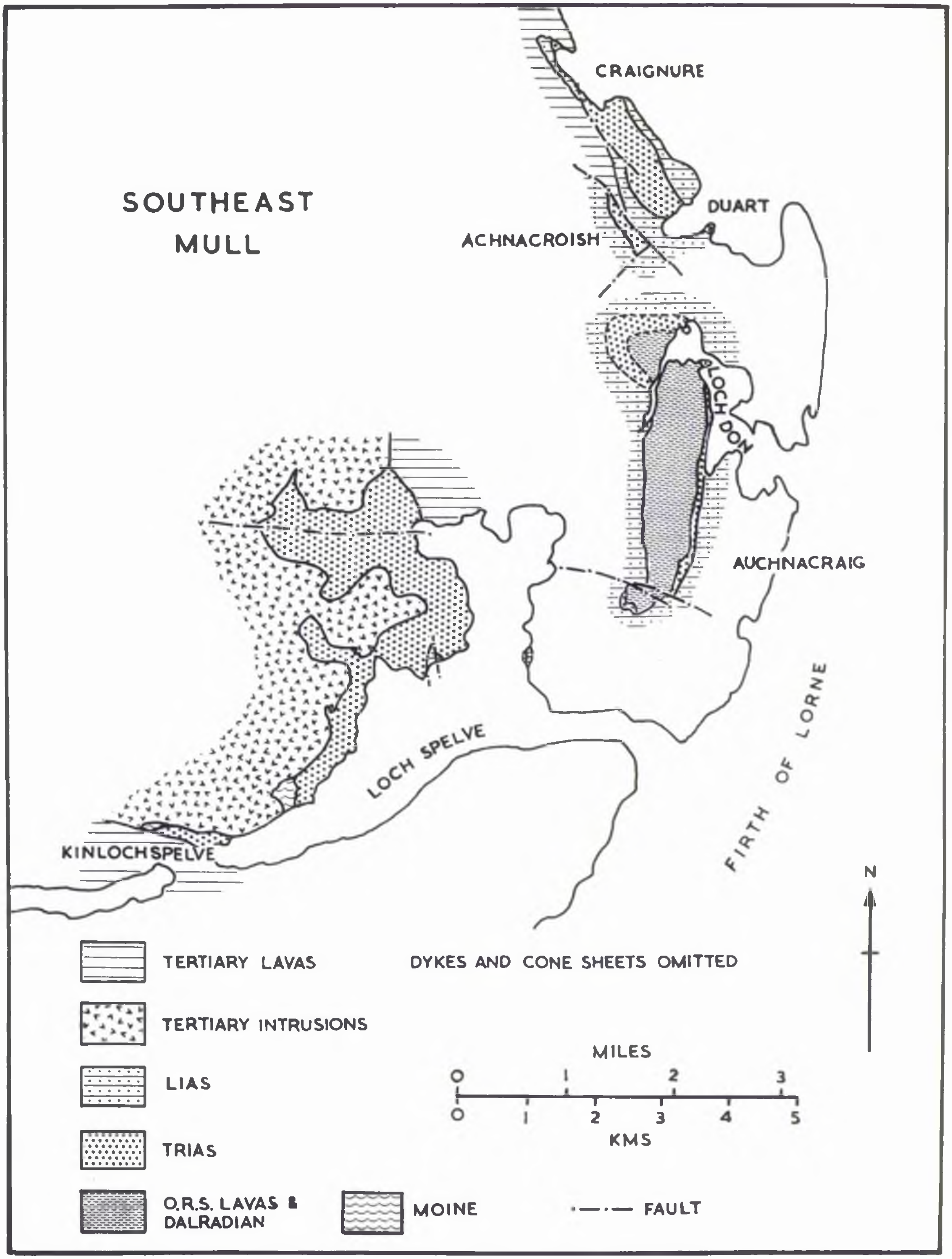


INCHKENNETH
N
LWM
HWM
Port an Fharaidh
Chapel
Bàgh an Iollaich
Port an Ròin
THE HUMPIES
BEACH DEPOSITS
CHAPEL BEDS
IOLLAICH BEDS
HUMPIES CONGL.
TRIAS
MOINE
TERTIARY INTRUSIONS OMITTED
STRIKE AND DIP
FAULT
0
50
100
150
METRES

MAP 4

SOUTHEAST MULL

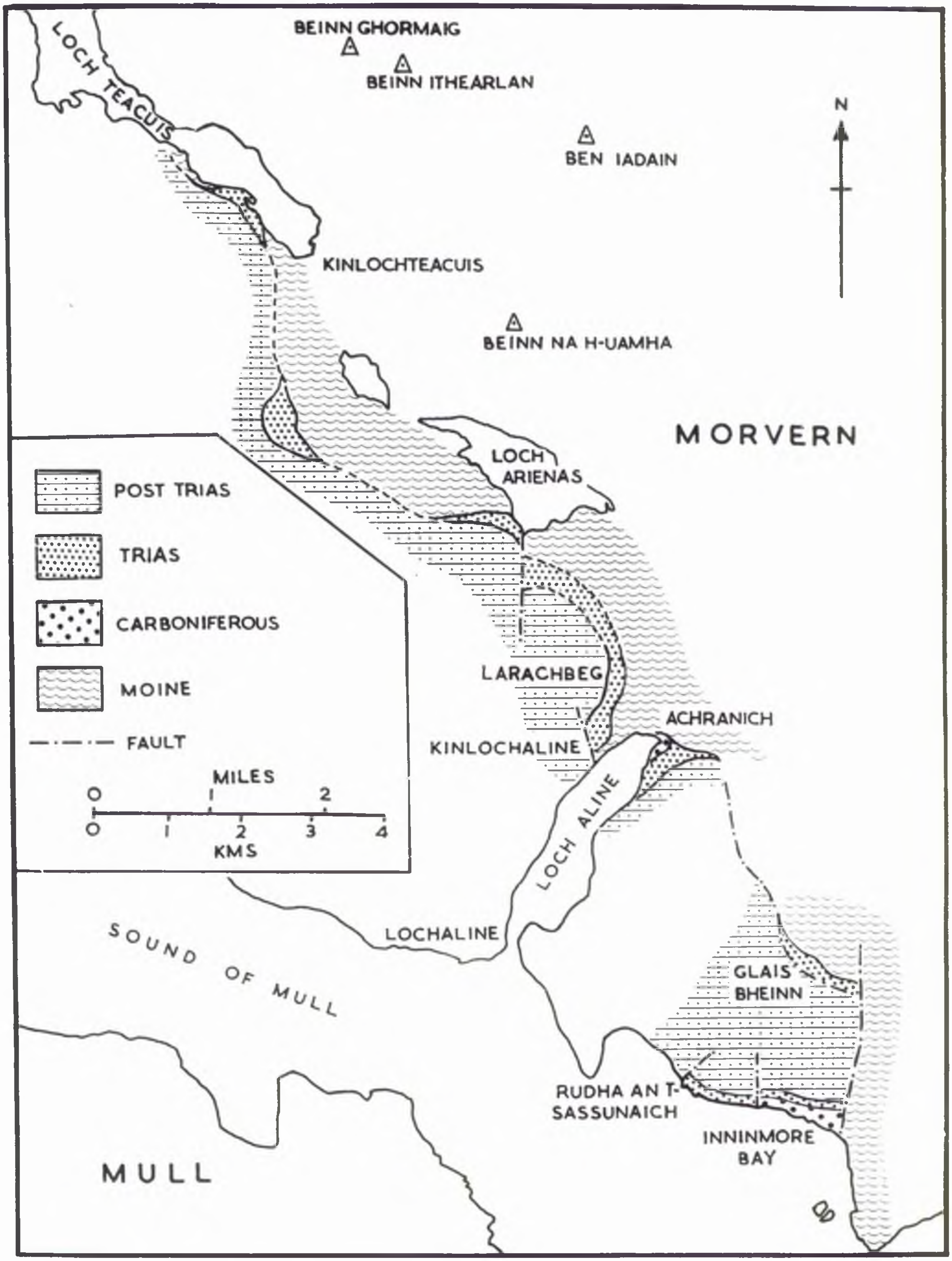
(Mainly based on the Geological Survey Sheet 44)



SOUTHEAST
MULL
CRAIGNURE
DUART
ACHNACROISH
LOCH DON
AUCHNACRAIG
FIRTH OF LORNE
LOCH SPELVE
KINLOCHSPELVE
N
TERTIARY LAVAS
DYKES AND CONE SHEETS OMITTED
TERTIARY INTRUSIONS
MILES
0 1 2 3
LIAS
0 1 2 3 4 5
KMS
TRIAS
O.R.S. LAVAS & DALRADIAN
MOINE
FAULT

MAP 5

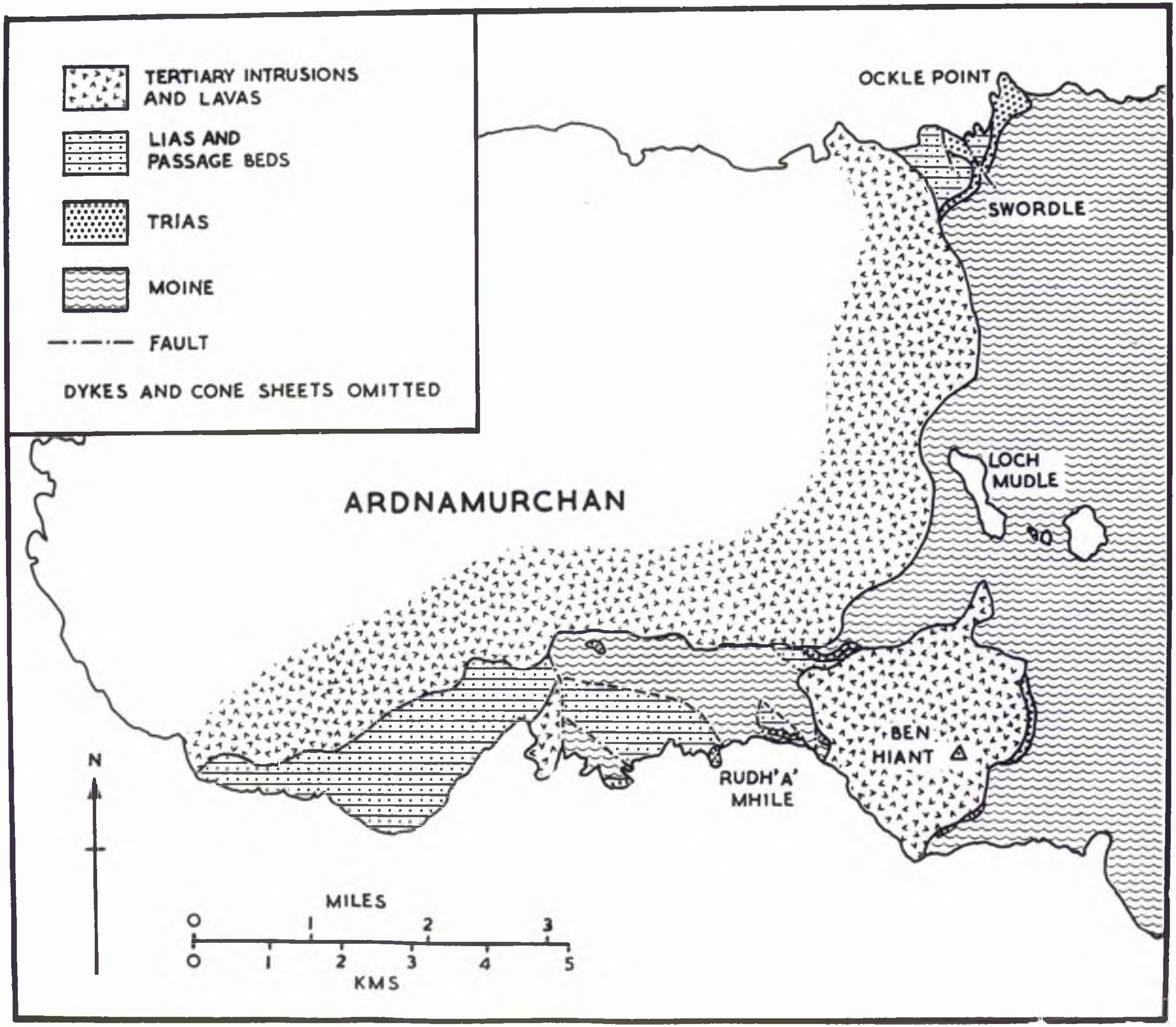
MORVERN.


LOCH TEACUIS
BEINN GHORMAIG
BEINN ITHEARLAN
BEN IADAIN
N
KINLOCHTEACUIS
BEINN NA H-UAMHA
MORVERN
LOCH ARIENAS
POST TRIAS
TRIAS
CARBONIFEROUS
MOINE
FAULT
MILES
0
1
2
0
1
2
3
4
KMS
LARACHBEG
ACHRANICH
KINLOCHALINE
LOCH ALINE
LOCHALINE
SOUND OF MULL
GLAIS BHEINN
RUDHA AN T-SASSUNAICH
INNINMORE BAY
MULL

MAP 6

ARDNAMURCHAN.

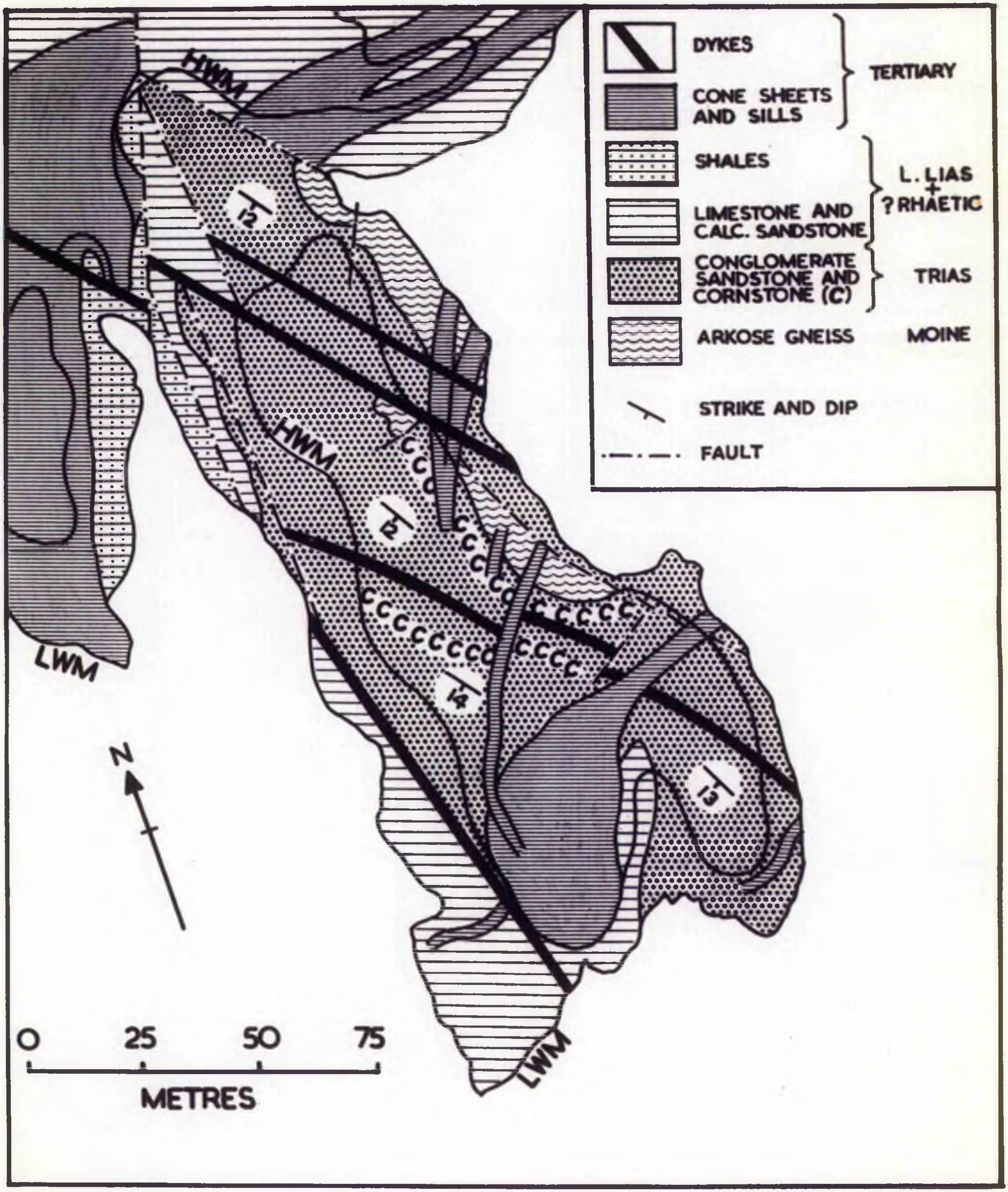
(After Richey 1961, Plate VII)


TERTIARY INTRUSIONS AND LAVAS
LIAS AND PASSAGE BEDS
TRIAS
MOINE
FAULT
DYKES AND CONE SHEETS OMITTED
ARDNAMURCHAN
OCKLE POINT
SWORDLE
LOCH MUDLE
BEN HIANT
RUDH'A' MHILE
N
MILES
0
1
2
3
0
1
2
3
4
5
KMS

MAP 7

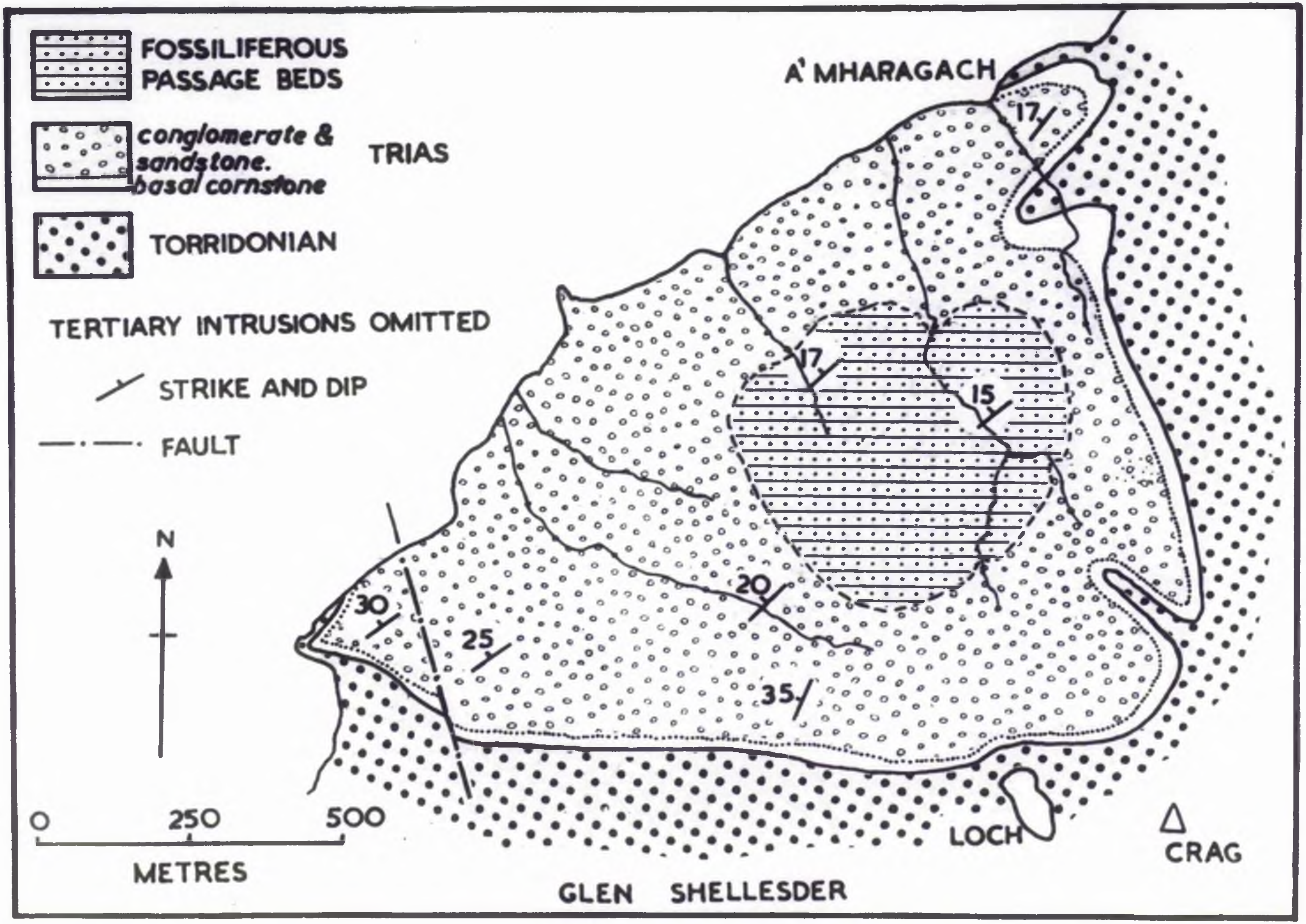
RUDH'A' MHILE, ARDNAMURCHAN

(After Richey and Thomas 1930, Fig. 23, with modifications)


DYKES
CONE SHEETS AND SILLS
TERTIARY
SHALES
LIMESTONE AND CALC. SANDSTONE
L. LIAS + ? RHAETIC
CONGLOMERATE SANDSTONE AND CORNSTONE (C)
TRIAS
ARKOSE GNEISS
MOINE
STRIKE AND DIP
FAULT
HWM
HWM
LWM
LWM
12
12
14
13
N
0
25
50
75
METRES

MAP 8

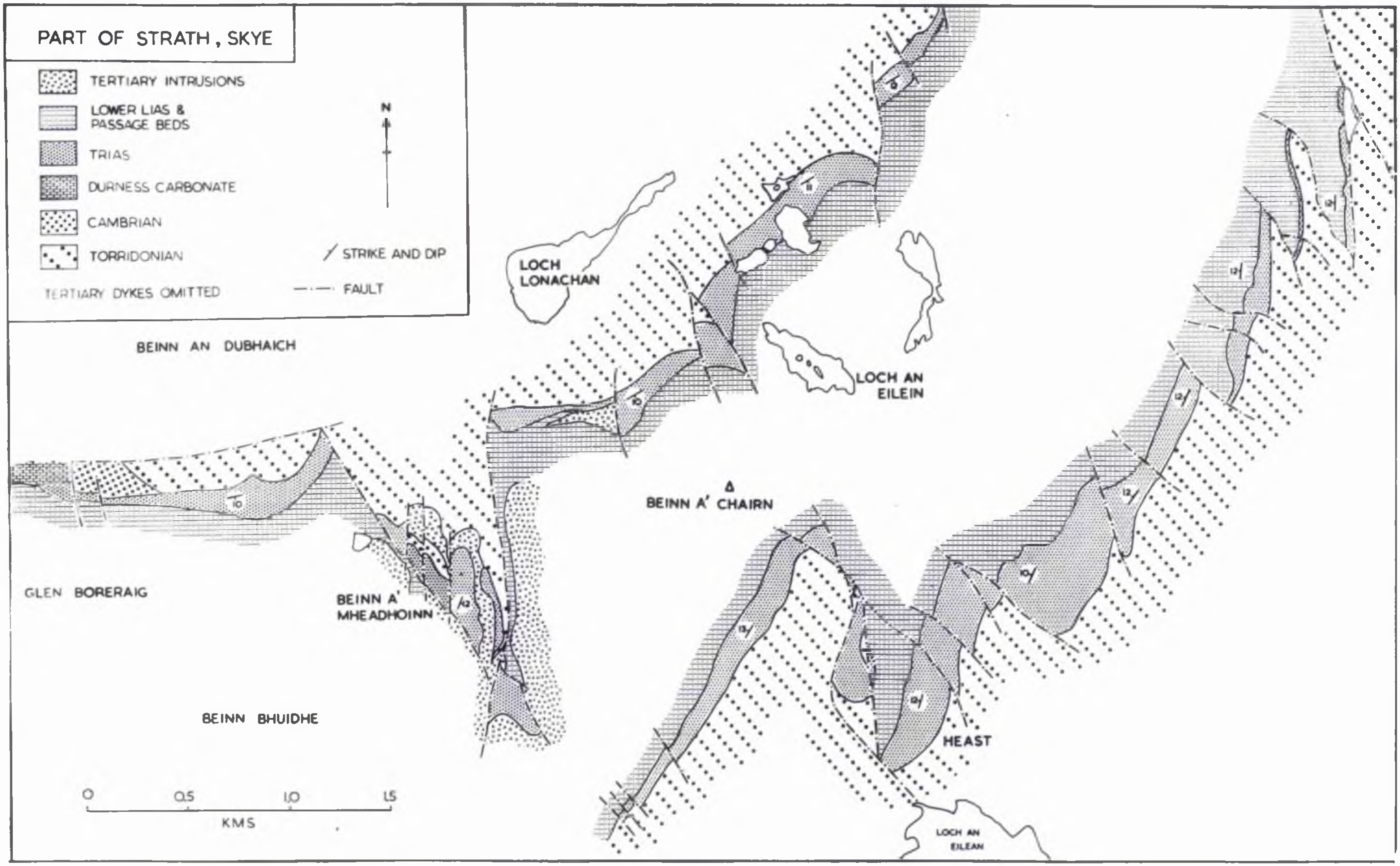
RHUM.


FOSSILIFEROUS PASSAGE BEDS
conglomerate & sandstone. basal cornstone
TRIAS
TORRIDONIAN
TERTIARY INTRUSIONS OMITTED
STRIKE AND DIP
FAULT
N
0
250
500
METRES
A' MHARAGACH
17
17
15
20
30
25
35
LOCH
CRAG
GLEN SHELLESDER

MAP 9

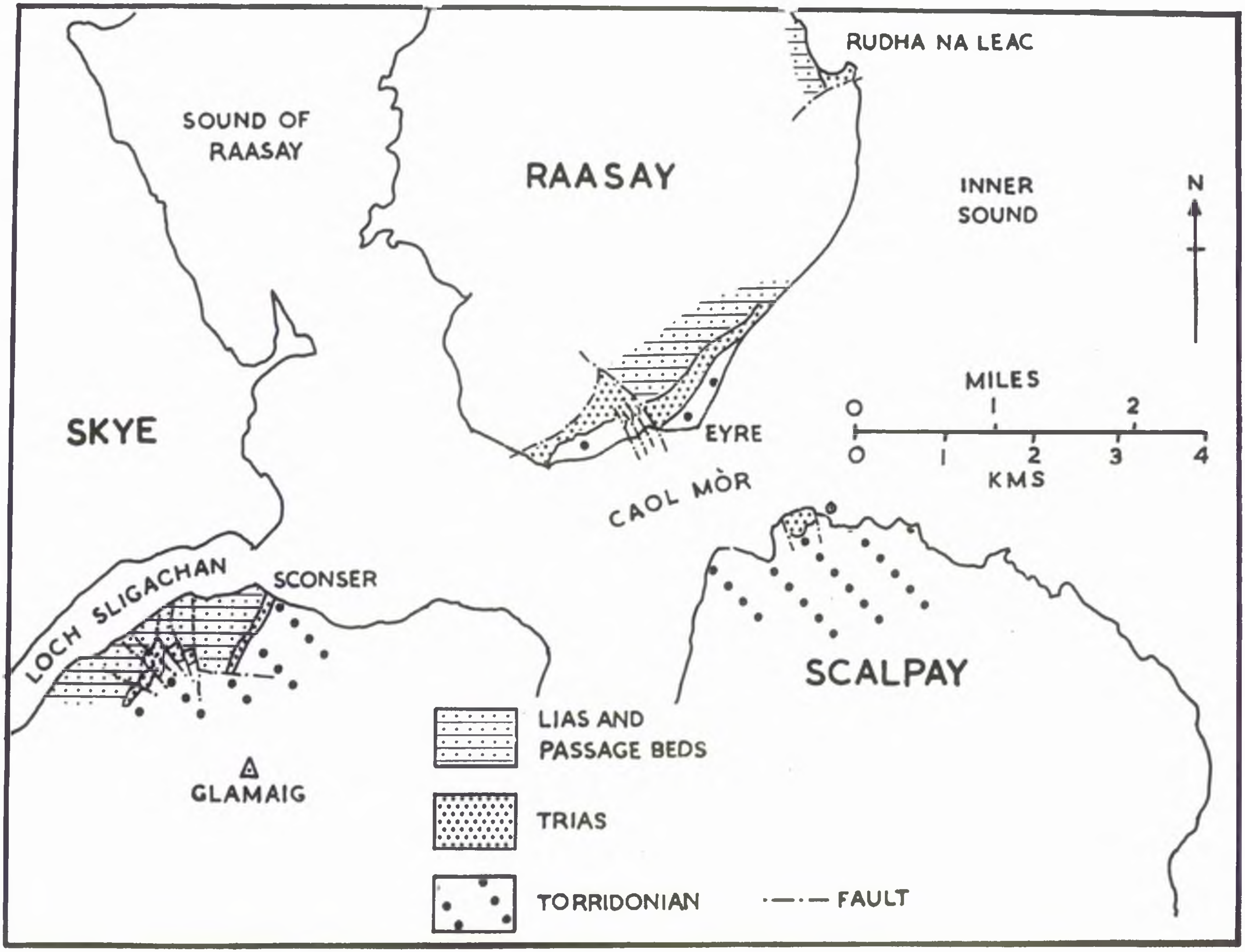
PART OF STRATH, SKYE.

Loch Buidhe is the most easterly of the three lochs north of Loch an Eilein. Allt na Pairte follows the main N-S fault east of Beinn a Mheadhoinn.


PART OF STRATH, SKYE
TERTIARY INTRUSIONS
LOWER LIAS & PASSAGE BEDS
TRIAS
DURNESS CARBONATE
CAMBRIAN
TORRIDONIAN
TERTIARY DYKES OMITTED
N
STRIKE AND DIP
FAULT
BEINN AN DUBHAICH
LOCH LONACHAN
LOCH AN EILEIN
BEINN A' CHAIRN
GLEN BORERAIG
BEINN A' MHEADHOINN
BEINN BHUIDHE
HEAST
LOCH AN EILEAN
0
0.5
1.0
1.5
KMS

MAP 10.

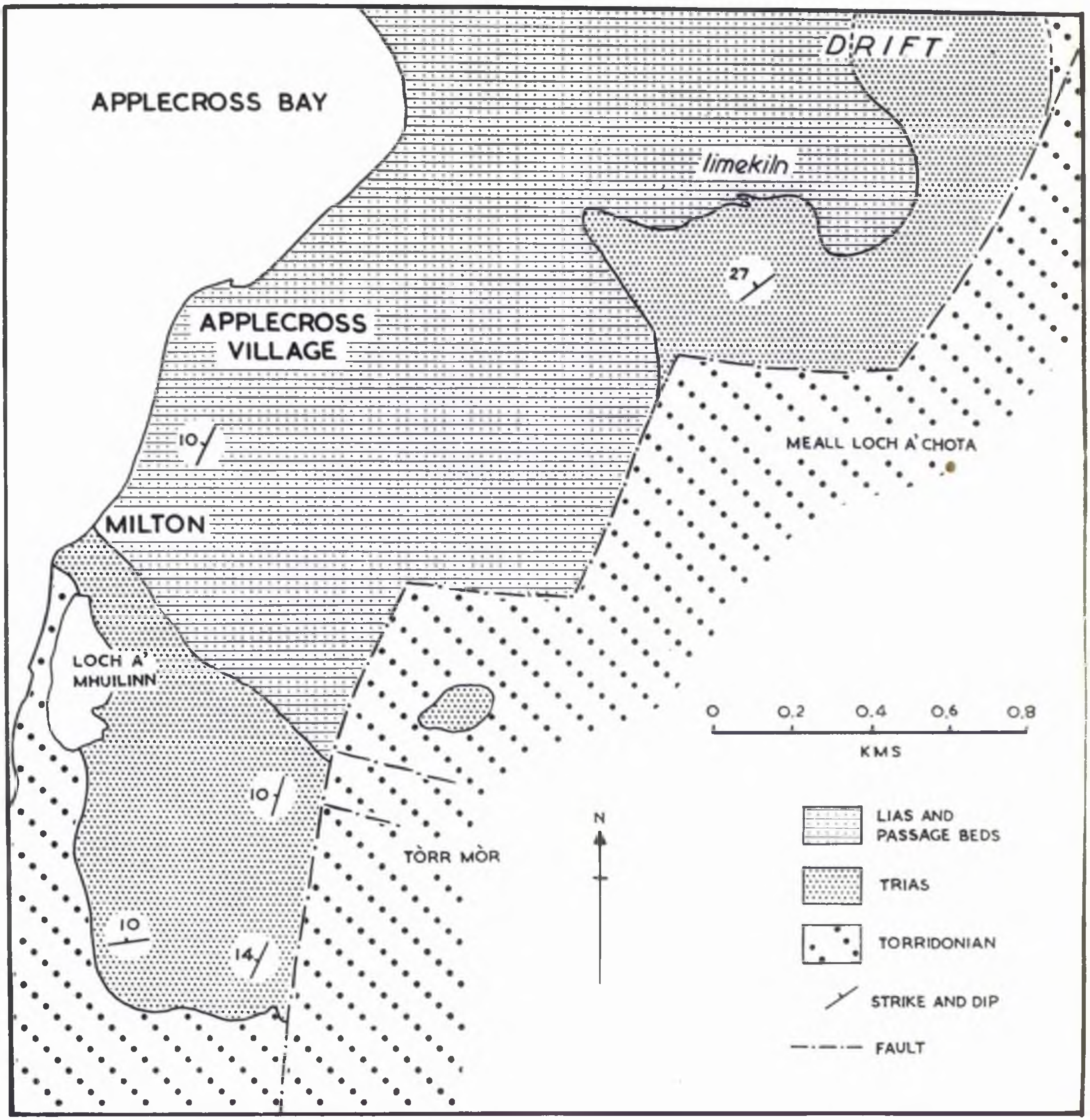
SCONSER, SCALPAY AND RAASAY.



RUDHA NA LEAC
SOUND OF
RAASAY
RAASAY
INNER
SOUND
N
MILES
0
1
2
0
1
2
3
4
KMS
SKYE
EYRE
CAOL MÒR
LOCH SLIGACHAN
SCONSER
SCALPAY
GLAMAIG
LIAS AND
PASSAGE BEDS
TRIAS
TORRIDONIAN
FAULT

MAP 11

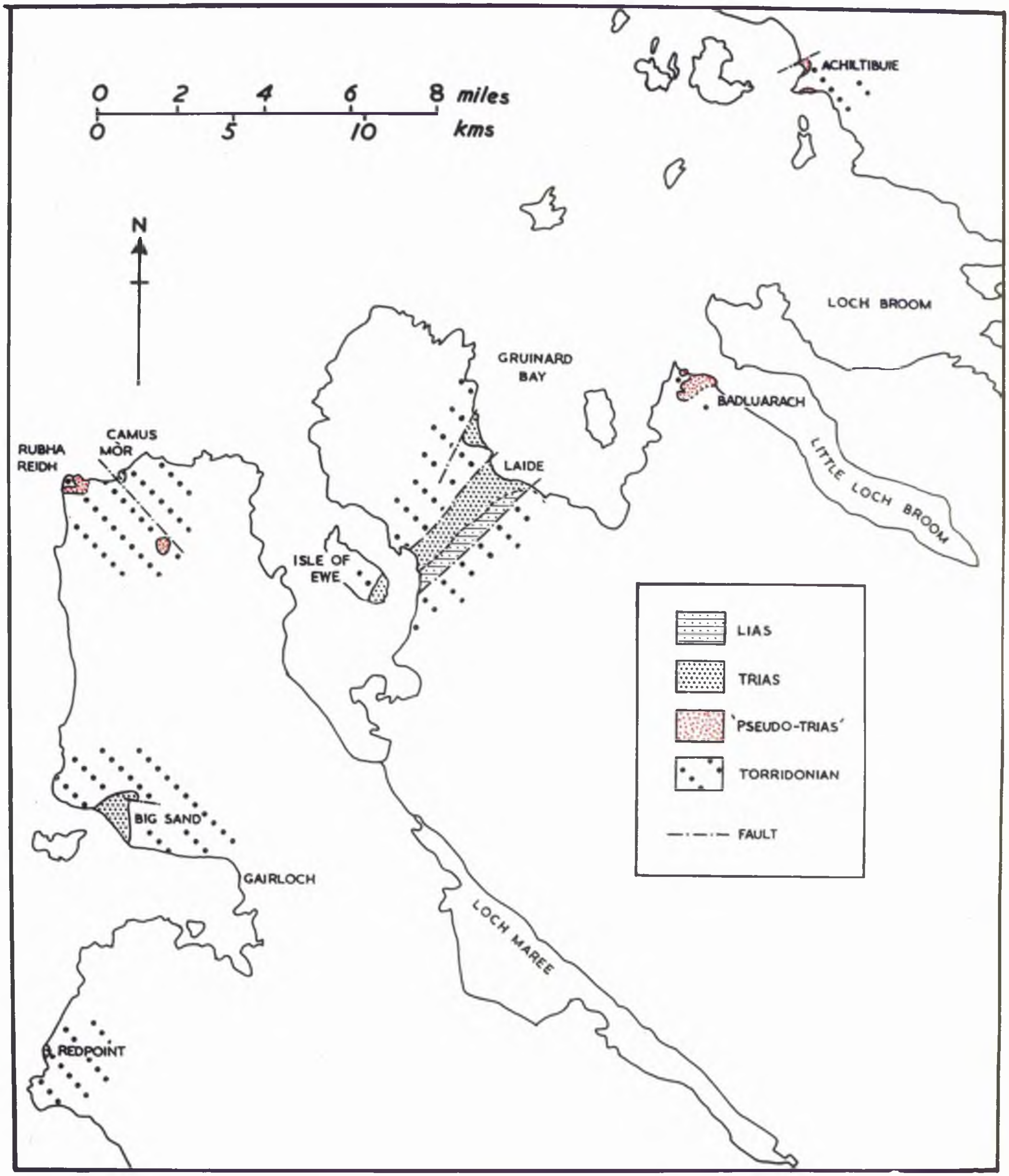
APPLECROSS.



APPLECROSS BAY
DRIFT
limekiln
27
APPLECROSS VILLAGE
10
MEALL LOCH A' CHOTA
MILTON
LOCH A' MHUILINN
0 0.2 0.4 0.6 0.8
KMS
10
N
TÒRR MÒR
LIAS AND PASSAGE BEDS
TRIAS
TORRIDONIAN
STRIKE AND DIP
FAULT
10
14

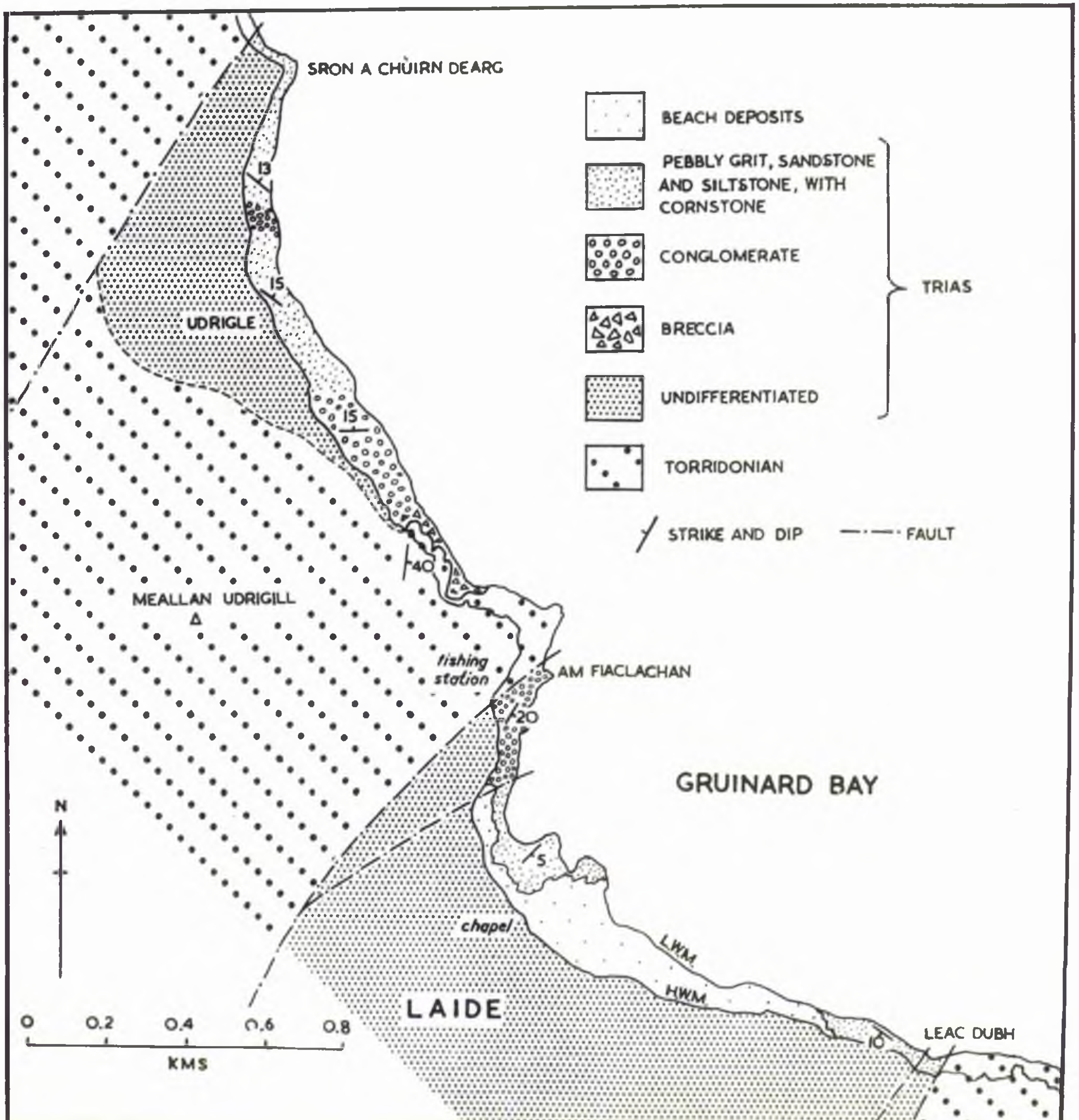
MAP 12

GENERAL MAP OF WESTER ROSS.


0 2 4 6 8 miles
0 5 10 kms
N
ACHILTIBUIE
LOCH BROOM
GRUINARD BAY
BADLUARACH
LITTLE LOCH BROOM
LAIDE
RUBHA REIDH
CAMUS MÒR
ISLE OF EWE
LIAS
TRIAS
'PSEUDO-TRIAS'
TORRIDONIAN
FAULT
BIG SAND
GAIRLOCH
LOCH MAREE
REDPOINT

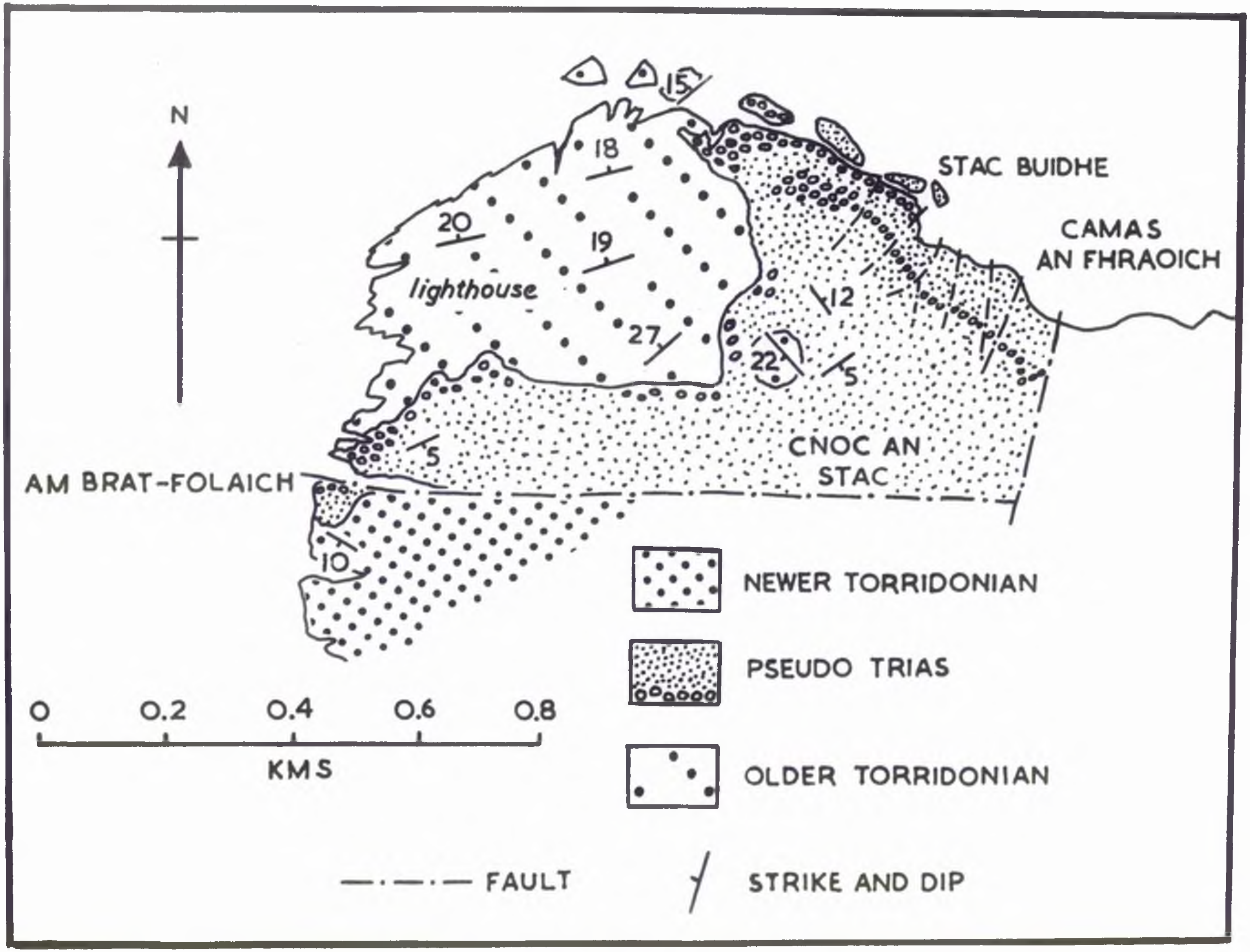
MAP 13

LAIDE, GRUINARD BAY.


SRON A CHÙIRN DEARG
BEACH DEPOSITS
PEBBLY GRIT, SANDSTONE AND SILTSTONE, WITH CORNSTONE
CONGLOMERATE
BRECCIA
UNDIFFERENTIATED
TRIAS
TORRIDONIAN
STRIKE AND DIP
FAULT
UDRIGLE
13
15
15
40
MEALLAN UDRIGILL
fishing station
AM FIACLACHAN
20
GRUINARD BAY
N
5
chapel
LWM
HWM
LAIDE
10
LEAC DUBH
0
0.2
0.4
0.6
0.8
KMS

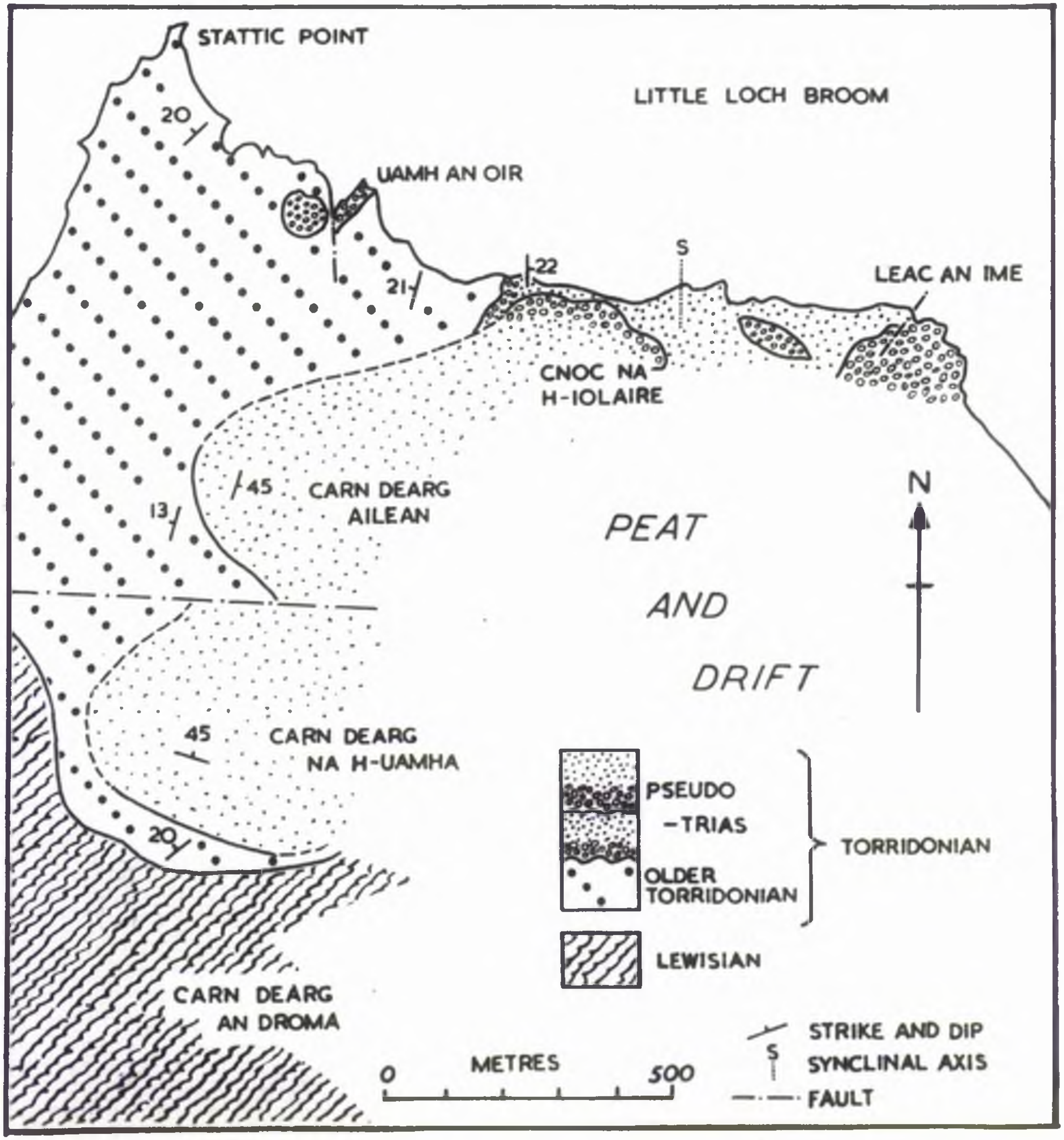
MAP 14

RUBHA REIDH.


N
STAC BUIDHE
CAMAS
AN FHRAOICH
lighthouse
CNOC AN
STAC
AM BRAT-FOLAICH
18
20
19
27
15
12
22
5
5
10
0
0.2
0.4
0.6
0.8
KMS
NEWER TORRIDONIAN
PSEUDO TRIAS
OLDER TORRIDONIAN
FAULT
STRIKE AND DIP

MAP 15

BADLUARACH.



STATTIC POINT
LITTLE LOCH BROOM
UAMH AN OIR
LEAC AN IME
CNOC NA H-IOLAIRE
CARN DEARG AILEAN
CARN DEARG NA H-UAMHA
CARN DEARG AN DROMA
PEAT AND DRIFT
N
20
21
22
S
45
13
45
20
PSEUDO -TRIAS
OLDER TORRIDONIAN
TORRIDONIAN
LEWISIAN
STRIKE AND DIP
SYNCLINAL AXIS
FAULT
0 METRES 500