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SEDIMENTATION STUDIES IN THE SILURIAN ROCKS OF NORTH-WEST GALWAY, EIRE

Volume 1

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ABSTRACT

The Silurian rocks of north-west Galway are a clastic sequence at least 2700 m thick resting unconformably on Connemara Schist (Dalradian) in the south and on Ordovician rocks in the north-east. The full thickness of Silurian is not seen, as in the west it is overthrust by Ordovician strata, and in the east the younger beds have been removed by erosion.

The earliest Silurian rocks (Upper Llandoverian) were probably deposited under terrestrial and deltaic conditions, and were followed by a transgression during which fossiliferous shallow marine sediments accumulated. The overlying Wenlockian succession consists of basal boulder beds and a great thickness (approximately 1500 m) of graded sandstones, passing up into shallow marine fossiliferous siltstone and sandstone. The youngest beds are sparsely-fossiliferous red siltstones and mudstones.

The present study is limited to the Wenlockian rocks of the Killary Harbour area, i.e., those above the lowermost terrestrial and shallow marine deposits. The stratigraphy is revised, and new subdivisions proposed. The name Upper Owenduff Group (McKerrow and Campbell, 1960) is retained, but the upper limit of the group is redefined to exclude the upper fossiliferous shallow marine sediments and is divided into two new formations, the Lettergesh and the Glencraff, consisting dominantly of graded sandstones. A new group name, the Killary Harbour Group, is proposed for the uppermost shallow marine portions of the Wenlockian. It comprises the newly-defined fossiliferous Lough Muck Formation, and the Salrock Formation, with its characteristic red beds.

To facilitate study of the hydrodynamic processes involved in the deposition of the various sediment types the rocks are divided into fourteen distinct sedimentary facies,

which in turn are grouped into six associations of related facies which are considered to share the same environment of deposition.

(1) The Turbidite Association includes the whole of the Upper Owenduff Group and part of the overlying Lough Muck Formation; it contains conglomerates and massive sandstones interpreted as mass flow deposits, graded breccias and sandstones interpreted as turbidites, and units of silty mudstone interpreted as having been deposited largely from suspension. The pattern of thickness variation and dispersion of sole and internal current structures in several of the graded sandstone and breccia units suggests that much of the Turbidite Association was emplaced as submarine fans. In contrast, the palaeocurrent pattern calculated from cross-stratification azimuths shows little dispersion and over much of the thickness of the Turbidite Association shows little relationship to that indicated by sole and internal structures. It is suggested that traction currents, possibly geostrophic or tidal in origin, and capable of reworking sediment previously deposited by turbidity currents, were also active in the basin. The presence of traction currents would also explain the occurrence of cross-bedded breccias and coarse sandstones in association with the turbidites.

(2) The fossiliferous Siltstone Association, occurring above the Turbidite Association, comprises mainly massive or streaky fossiliferous mudstones and siltstones showing few signs of current activity. The presence of flow folding, slump overfolds, and rotational slumps in the facies, coupled with its stratigraphic position above turbidites and below shallow marine shelf sediments suggests that the association represents slope deposits. The concentration of slump scars and rotational slumps at the upper boundary between the Siltstone Association and overlying shallow marine deposits is interpreted as reflecting the change in gradient at the top of the slope, where failure

and slumping of semi-consolidated sediments is most likely to occur. A notable downslope and downcurrent thickening of the Siltstone Association can be explained by a basinwards advance of the shelf over older slope and basin-floor deposits.

(3) The Erosive-based Massive Sandstone Association both overlies and interfingers laterally with units of the Turbidite Association, and also forms lenticular bodies within the Siltstone Association. It consists of a mixture of facies but is dominated by erosive-based massive sandstones (sometimes with a basal concentration of fossils), slumped beds, massive or streaky siltstones and mudstones, turbidites, and thin-bedded parallel- or cross-laminated fine-grained sandstone beds. The lower units of the association immediately overlying and interfingering with the Turbidite Association are interpreted as proximal rise deposits formed at the foot of the slope represented by the Siltstone Association. The lenticular units within the Siltstone Association are considered to have formed in shallow valleys in the face of the slope.

(4) At the top of the Siltstone Association there is a rapid transition in most parts of the succession to strata arranged in Coarsening-upward Sequences, with mudstone or siltstone at the base and cross- or parallel-bedded medium sandstone, sometimes highly fossiliferous, at the top. The sequences are considered to represent off-shore bars developed in a shelf environment in which tidal currents were active. In other parts of the succession Coarsening-upward Sequences are not developed, the facies being the same as those of the sequences but arranged in apparently random order.

(5) The Coarsening-upward Sequences pass upwards into the sparsely fossiliferous Wave-rippled Association, consisting mainly of mudstones and siltstones and containing isolated wave-modified ripples of fine sandstone, interpreted as very shallow marine, possibly lagoonal.

(6) In the mainly fine-grained Red-bed Association the rare occurrence of the marine fossil Lingula, and the absence of any evidence of subaerial conditions such as mud-cracks, shows that the sediments are also marine. The red colouring is probably due at least in part to derivation of sediments from an oxidised source rock, but oxidation in situ in a restricted environment, probably lagoonal, may also have played a part.

The pattern of regional sedimentation changed considerably from Ordovician to Silurian times. The east-west-trending depositional trough (the South Mayo Trough) and southern positive area (the Connemara Cordillera) of Ordovician times had disappeared by the early Silurian. A new depositional basin developed, at least in part on the site of the earlier positive area, the source of sediments lying initially to the north-east and then to the north. A marine transgression across a subsiding shelf during which fossiliferous shallow marine strata of Upper Llandoverian age were deposited coincided with the development of small localised basins of deposition which received a great thickness of largely redeposited sediment of Wenlockian age.

Following on the disappearance by filling of the localised basins a coastline advancing first from the north-west or west-north-west and then from the west resulted in earlier-deposited turbidites being covered first by rise, then by slope and shelf sediments, the latter being affected by active offshore-onshore tidal currents. The sedimentational history of the rocks exposed in the area ended with fine-grained sediments being deposited in shallow lagoons protected from the open sea, probably by off-shore bars.

CHAPTER 1.

INTRODUCTION

1. Area Studied

The Silurian rocks of north-west Galway are a clastic sequence nearly 3000m thick resting unconformably on Connemara Schists (Dalradian) in the south and on Ordovician rocks in the north-east. They occur as a narrow strip approximately 4 km. wide extending about 35 km. from the Atlantic coast in the west to Lough Mask in the east (Fig. 1). West of Maam Valley the Silurian is overthrust by Ordovician strata; to the east the upper beds have been removed by erosion. Their greatest stratigraphic development occurs south of Killary Harbour, west of Maam Valley, and this study has been limited to that area.

The region described consists of dissected hill country, with elevations up to 600m. The area has been strongly glaciated, and the valley walls have been bared by ice, giving good exposure. Some ridge tops and most valley bottoms, however, are covered by bog and here exposure is minimal. Trees are absent except in some valley bottoms, and vegetation on the hill slopes is mainly restricted to tussock grass, with lichen covering some of the exposed rock. Small lakes have been developed in the valleys, particularly in the west, where Loughs Muck and Fee occupy the floor of the upper valley down which the Culfin River flows into the Atlantic.

Because of the interruption of outcrop by the presence of sandy beaches on the Atlantic coast, and the occurrence of bog, igneous intrusions, or faults inland, no complete succession through the Silurian sequence could be prepared. Instead, several composite or partially overlapping sequences have been measured.

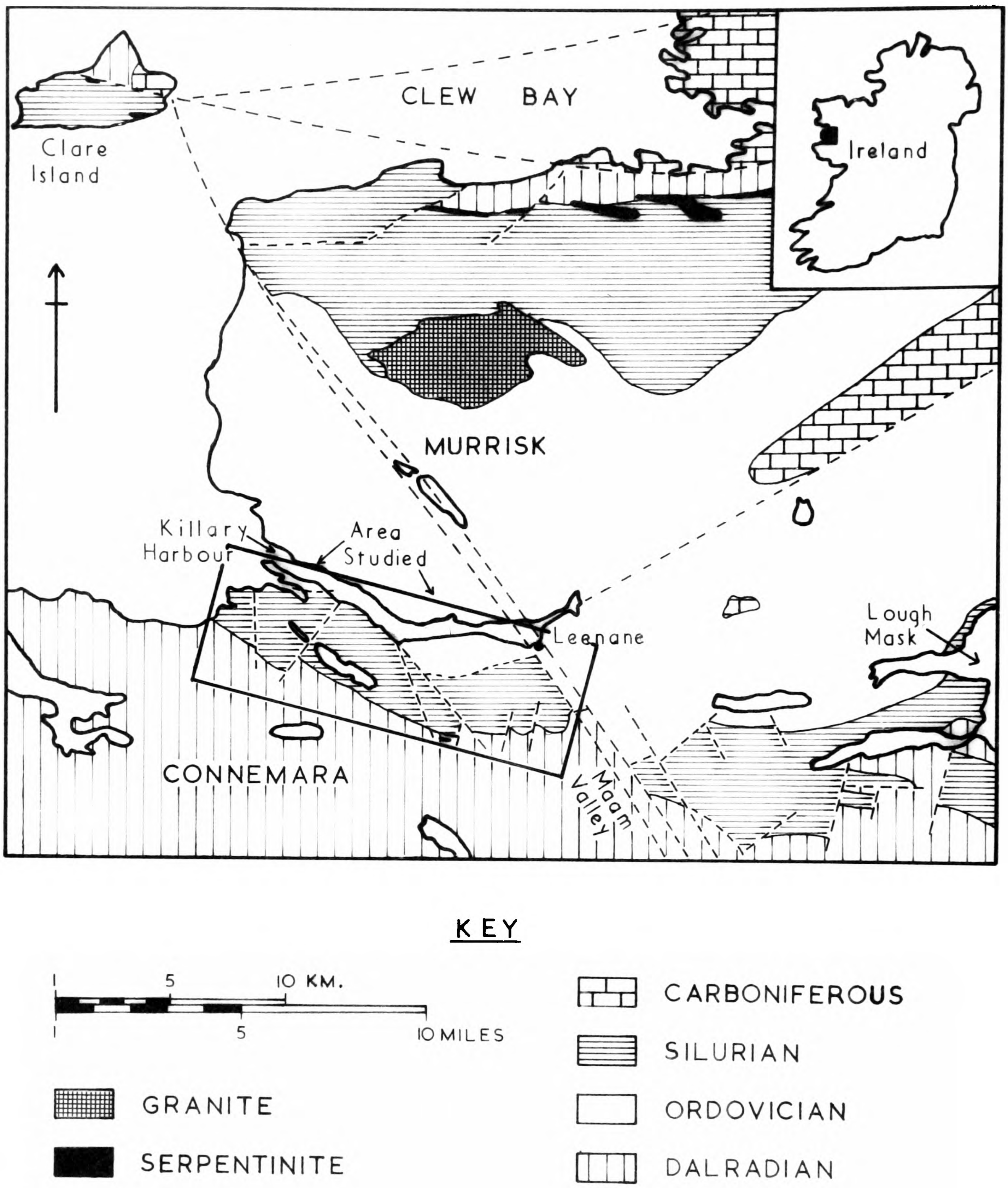

Fig. 1. **Locality Map.**

The area is shown on 6 inch to the mile maps (1 : 10,560) 10, 11, 12, 24 and 25 of County Galway, which were used as base maps from which the final geological map on a reduced scale was prepared (Fig. 2).

2. Previous geological work

Early workers such as Griffith (1838), Murchison (1854), Kelly (1860) and Harkness (1866) briefly touched on the geology of the area in their reports, but systematic work was not done until the area was mapped by the Geological Survey of Ireland (Kinahan, 1874, 1878: Kinahan et al, 1876, 1878). In the Geological Survey Memoir to accompany map sheets 93 and 94 (Kinahan et al, 1878), the Silurian rocks of the Killary Harbour area were divided into two units, the lower "Owenduff or Gowlaun Series", and the upper "Salrock Slates Series". The "Owenduff or Gowlaun Series" was defined to consist of "red, green, purple, grey and blue conglomerates, sandstones, grits, slates, and shales, with, towards the east, a bed of limestone, and in various places calcareous beds. On certain zones associated with these rocks are interstratified sheets of basic felstones, with tuffs and agglomerates". The "Salrock Slates Series" was separated from the lower series by the "Culfin River Fault" (not further discussed or shown on the geological map) and consisted at the base of principally green slates and thin-bedded grits, with red slates above, with in places thick quartzose grits and limestones.

A somewhat different nomenclature was used by Kinahan in his book "Manual of the Geology of Ireland" (1878). The Silurian rocks were classed under the "Culfin Group", which was subdivided as follows:

4. Salrock Series, consisting mainly of bright red shales and slates, with some green and red grits and shales.

3. Lough Muck Series, consisting mainly of alternations of grits and shales or slates.

2. Eurites and tuffs, made up of extruded rocks.

1. Gowlaun Series, consisting in the west of conglomerates with thick slates above alternating higher up with massive green grits. Further east the slates are replaced by alternations of grits and shales or slates; the conglomerate also splits up and becomes interstratified with shales.

Subsequent mapping and collecting by Kilroe (1901 and 1907) and by Carruthers and Muff (1909) caused some alterations and more accurate dating of Kinahan's succession.

Gardiner and Reynolds (1912 and 1914) working in the Kilbride and Lough Nafooey areas established a more detailed succession in that area, comprising:

6.	Doon Rock Grits.	Wenlock
5b.	Green-grey flags (L. Nafooey area only)	Tarannon
5a.	Purple sandy shale.	
4.	Finny School Beds (Calcareous flags).	Upper Llandovery
3.	Annelid Grits.	
2.	Red sandstones	
1.	Basal conglomerate.	

The Doon Rock Grits were regarded as equivalent to the grits and conglomerates in the Killary Harbour area, i.e., to the Lough Muck Series and to the upper part of the Gowlaun Series of Kinahan (1878), while the Finny School Beds (calcareous flags) were equivalent to the lower part of the Gowlaun Series, with lower units considered to be unrepresented in the Killary Harbour area.

The next modification of stratigraphic nomenclature was carried out by McKerrow and Campbell (1960) who recognised three major divisions of the Silurian, viz: the "Lower and Upper Owenduff Groups", which were separated by an unconformity; and the "Salrock Group", which followed the "Upper Owenduff Group". As a result of work carried out in the Killary Harbour area, McKerrow and Campbell were able to show that the lower portions of Gardiner and Reynold's succession could also be recognised to the west, and formed part of the Lower Owenduff Group. The following succession was established:

STAGE	GROUP	FORMATION	ZONE	THICKNESS
Wenlock	Salrock			3000 ft
	Upper Owenduff	Greywacke and siltstone	M. riccartonensis C. murchisoni	3,600 ft
		Conglomerate		0 - 400 ft
	------------ UNCONFORMITY ------------			
Upper Llandovery	Lower Owenduff	Purple Shale	C^{4-5}	0 - 300 ft
		Finny School Beds		0 - 400 ft
		Annelid Grit		0 - 700 ft
		Basal Beds		0 - 500 ft
	------------ UNCONFORMITY ------------			
		Connemara Schist		

The Doon Rock Grits of Gardiner and Reynolds (1912 and 1914) were included in the Upper Owenduff Group. Neither the Upper Owenduff nor Salrock Groups were formally subdivided into formations.

McKerrow and Campbell (1960) were the first to attempt to investigate the environment of deposition of the Silurian rocks. The Basal Beds were considered to have been deposited under terrestrial and deltaic conditions on the Connemara Schist landmass, continental sedimentation being followed by marine transgression during which the fossiliferous Annelid Grit and Finny School Beds were laid down.

The conglomerate, greywacke, siltstone, and shale which make up the greater part of the Upper Owenduff Group was interpreted to have been deposited by turbidity currents. The great majority of fossils occurred in the higher, finer-grained beds of the Upper Owenduff Group within 800 ft (240m) of the top. The base of the Salrock Group was defined by the lowest red shale horizon, above which level no truly marine fossils had been discovered.

It was suggested that a landmass, coinciding with much of the area now occupied by outcrop of Connemara Schist, existed to the south or south-west of the Killary Harbour area. The only current directions noted in the turbidites of the Upper Owenduff Group, based on the direction of overturn of flame structures, indicated currents flowing towards the west. These were interpreted to parallel a southern coastline.

Stanton (1960), writing primarily on the geology of south-west Murrisk to the north of Killary Harbour, considered that most of the Ordovician sediments had a southerly source area, and postulated a landmass of Connemara Schist lying to the south and east of south-west Murrisk in the Killary Harbour area. He noted, however, on petrologic grounds, the probability of a northern derivation for the unconformably overlying Lower Silurian sediments.

Dewey (1963), in a study of the lower Palaeozoic stratigraphy of central Murrisk, concluded that Ordovician and Silurian sediments were deposited in an east-west tectonically-controlled depression (the South Mayo Trough) underlain by Connemara Schist. He considered from palaeocurrent and petrologic evidence that Ordovician rocks were derived from the north, east, and south, and Silurian sediments from the north and east. Uplift in north Connemara during early Wenlock times was postulated to explain the occurrence of conglomerates at the base of the Upper Owenduff Group.

Subsequent more detailed investigations by Piper (1967) on the Upper Llandovery rocks of north Connemara disproved the existence of an intra-Silurian unconformity, and he also redefined the stratigraphy of the Lower Owenduff Group and also the lower part of the Upper Owenduff Group. The new nomenclature can be summarised as follows :

4. Gowlaun Formation. Includes part of the Purple Shales and the lower part of the Upper Owenduff Group of McKerrow and Campbell.

3. Tonalee Formation. Equivalent to the Purple Shale of McKerrow and Campbell.

2. Kilbride Formation. Equivalent to Annelid Grit and Finny School Beds of McKerrow and Campbell.

1. Lough Mask Formation. Equivalent to the Basal Beds of McKerrow and Campbell.

3. Problems investigated

McKerrow and Campbell (1960) had made brief reference to broad environments of deposition of the Silurian rocks of North-West Galway, but evidently there was great scope for more detailed enquiry into sedimentation of the strata. Although it was apparent that the Silurian succession passed from terrestrial deposits at the base into shallow marine, then deeper marine, and then up into shallow marine and possibly terrestrial once more, i.e., it was broadly a transgressive/regressive sequence, the nature of the transitions, the detailed environments of deposition, and the mechanism of emplacement of the sediments, was still unknown. Only passing reference had been made to current directions, and the hypothesis of a Connemara landmass to the south had not been tested. Furthermore, although the Llandoverian had been divided into lithological units, the Wenlockian had been classified only into broad groupings, and more detailed stratigraphic subdivision appeared to be justified.

The aim of the research carried out by the writer was to examine the environment of deposition of the deep basinal and regressive portion of the sequence, and study the nature of the transition into shallower water; to investigate the sedimentological processes involved in the deposition of different facies; and to deduce the palaeogeography of the area during Wenlock times. As a subsidiary aim a satisfactory detailed litho-stratigraphic nomenclature for the Wenlockian succession was to be devised.

Because of the great thickness of the succession and the wide variety of facies types present it was felt desirable to restrict the detailed study to the graded sandstones and overlying lithologies representing basin fill deposits. Mr. D.J.W. Piper is currently carrying out research on the transgressive portion of the sequence, including the partly time equivalent conglomerates and massive sandstones of the Gowlaun Formation (see above). Some work has however been carried out by the author on the conglomerates and massive sandstones immediately underlying the main basin-fill succession where necessary to elucidate the transition upwards into graded sandstones. The study was limited areally to the region south of Killary Harbour and west of the Maam Valley, where the greatest stratigraphic range is available. East of Maam Valley the upper portion of the Wenlock sequence involving the passage from deep to shallow marine sedimentation is absent because of erosion, and the beds in general are not so well exposed as those to the west. Reconnaissance study was, however, carried out in this sequence in order to compare it broadly with the detailed succession examined west of Maam Valley.

Because the primary aim of the study was sedimentological, no attempt was made to carry out a thorough remapping of the structure, and in general that illustrated on the map accompanying McKerrow and Campbell's (1960) paper has been accepted. However, in areas where detailed stratigraphic and facies studies were carried out faulting was carefully checked, and newly-discovered faults plotted and old ones redrawn where necessary.

In addition, no further study of the numerous igneous intrusions was made. The map published by McKerrow and Campbell (op. cit.) has been accepted, apart from minor boundary modifications, particularly in the case of the eastern end of the Benchoona Sill.

4. Structural Outline

The Silurian rocks of the Killary Harbour area crop out on the southern margin of an east-west trending syncline containing a maximum thickness of approximately 12,800 m of Ordovician and Silurian sediments.

East of Maam Valley the Silurian rocks have been folded into a series of anticlines and synclines with wavelengths of the order of one kilometre (Map, McKerrow and Campbell, 1960). In the Killary Harbour area, however, the only major fold occurs south-west of Leenane where lower Silurian rocks are synclinally folded. Elsewhere, the beds dip consistently northwards, apart from a few laterally impersistent buckles of small wavelength in the Salrock Formation south of Killary Bay Little, which McKerrow and Campbell (op. cit.) considered to be associated with movement along the Salrock Fault. The regional strike is east-south-east, although slight local variations occur.

Faulting in the area forms a complex pattern, but several major groupings can be discerned. The most important fault is that separating the Silurian beds from the Ordovician overthrust from the north. The trace trends approximately east-west. In the vicinity of Bencraff the plane dips northwards at between 40° and 70°, but at Salrock the northerly dip is only 20° to 30°. According to McKerrow and Campbell (op. cit.) the throw is approximately 7,500 ft (2,300 m).

Another major group of fractures is composed of north-west or north-north-west trending mainly dextral strike-slip faults, with a complimentary set of north-east mainly sinistral strike-slip faults. The dextral faults are dominant, the largest of them forming a double set passing down the Maam Valley and causing an apparent horizontal displacement of 5½ km. The latest recorded movement on the Maam Faults, however, was normal (Dewey and McKerrow, 1963).

Easterly-trending faults, many of them parallel to the sedimentary strike, are particularly common in the area between Glenglosh and Maam Valley. In most cases dislocation of strata is small, but they are often difficult to detect because of their parallelism to the regional strike. A large, previously-unrecorded strike fault occurs at the northern end of the peninsula north of the Culfin River estuary, and continues eastward, after offsetting by a north-west trending fault, along the line of the lower Culfin River until it is abruptly cut off by another north-north-west striking fault west of Lough Muck (Fig. 2). This fault accounts for the sudden and remarkable thickening of the outcrop of the Lough Muck Formation west of Lough Muck, and is responsible for the repetition of 120m of strata. All easterly-trending faults are affected by, and are therefore earlier than, the north-west and north-east trending faults.

In addition to these major groups of faults lesser fractures of mainly northerly trend also occur. Most of them have a displacement of the order of a few metres or less, and commonly die out laterally within the space of a few hundreds of metres. The sense of displacement varies apparently arbitrarily from one fault to another in the same group, and they are probably normal. Some of the north-west and north-east trending faults with apparent strike-slip movement in a direction at variance with the regional trend may also belong to this group.

As noted by McKerrow and Campbell (1960), with the exception of the earlier east-west faults, most of the structures in the area can be explained in terms of north-south compression prior to deposition of Lower Carboniferous deposits exposed to the north of the area and unaffected by the faults.

5. Acknowledgements

The writer wishes to record his gratitude to Dr. H.G. Reading, under whose supervision this work was carried out, and who has given constant encouragement and helpful advice and criticism throughout the period of study; and to Dr. W.S. McKerrow, who first drew attention to the problem, assisted with fossil identification, and has proved a continuing source of help and advice.

Stimulating discussions with and constructive criticisms from fellow sedimentological research workers are also gratefully acknowledged.

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Field work under sometimes depressing weather conditions was made considerably pleasanter by the friendliness and hospitality of the people of Connemara, and in particular by Miss J. Gibbons and Mr. and Mrs. R. King, of Leenane, Mr. and Mrs. O'Neill of Glencraff, and Mr. M. Coyne of Lettergesh.

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CHAPTER 2.

STRATIGRAPHY

1. Introduction

In geological mapping the basic lithological field unit is the formation, which has physical characteristics distinctive from the surrounding rocks, and which can be traced laterally for long distances. These criteria have been kept in mind when erecting stratigraphic terminology for the Middle and Upper Silurian of the Killary Harbour area, and only distinctive units which can be traced with certainty for the entire length of the area have been accorded formation status. Subordinate but lithologically distinctive units which are not laterally persistent throughout the area are treated as members: and associations of formations with similar lithological characteristics have been collected into groups.

The group names used for the lower and middle part of the sequence by McKerrow and Campbell (1960), i.e., Lower and Upper Owenduff, are retained, but with some modifications of the boundary between them following on Piper's (1967) redefinition of Lower Silurian formations. The "Salrock Group" of McKerrow and Campbell (1960) is not readily divisible into smaller units, and has therefore been reduced to formation status and included in the newly-defined Killary Harbour Group, which also incorporates the fossiliferous upper part of the old Upper Owenduff Group. The Lower Owenduff Group in the Killary Harbour area has already been subdivided into formations by the workers noted above, and the stratigraphy is therefore not discussed in detail here. The two higher groups are here subdivided into newly-defined formations and members (Table 1).

TABLE 1. STRATIGRAPHY OF SILURIAN, KILLARY HARBOUR AREA

SUPERGROUP	GROUP	FORMATION	THICKNESS	MEMBER	
CULFIN SUPERGROUP	Killary Harbour	Salrock	c.a. 817m		
		Lough Muck	200-280m	Upper	
				Middle	
				Lower	
	Upper Owenduff	Glencraff	65m		
		Lettergesh	c.a. 1520m	Letterettrin	3
					2
					1
				Benchoona	4
				"	3
				"	2
				"	1
				Garraun	4
				"	3
				"	2
				"	1
				Gowlaun	
	Lower Owenduff	Tonalee	c.a. 260m		
		Kilbride			
		Lough Mask			

------UNCONFORMITY------

Connemara Schist (Dalradian)

The three Silurian groups are referred to the Culfin Supergroup.

2. Culfin Supergroup

The name Culfin Group was used by Kinahan (1878) to include all the Silurian rocks of the Killary Harbour area and the region immediately to the east, and is here used in the same sense but the name is given supergroup status.

In the Killary Harbour area the base of the supergroup is defined by the unconformity on the Connemara Schist in the south: its top is not seen because of overthrusting of Ordovician sediments from the north. Its minimum thickness is approximately 2700 m.

The Culfin Supergroup is subdivided into three groups, the Lower and Upper Owenduff Groups, and the Killary Harbour Group (new name). Stratigraphic columns, which have been drawn for the upper two groups, are presented in Figure 3.

2.1. Lower Owenduff Group

This group, which comprises the oldest beds in the Silurian sequence, consists of three formations; the Lough Mask, Kilbride, and Tonalee Formations (Piper, 1967). These formations are absent south of Lough Fee, their place being taken by part of the interfingering and diachronous Gowlaun Member of the Lettergesh Formation. The base of the group is represented by the unconformity on Connemara Schist, and the top by the incoming of the Gowlaun Member (see below). The surface of the unconformity is highly irregular, an irregularity reflected by the varying thickness of the overlying group, which reaches a maximum of approximately 260 m for the Killary Harbour area at the head of Glenglosh. (Piper, pers. comm.).

The Lough Mask Formation consists of breccia, conglomerate, red sandstone, and interbedding siltstone and shale. No fossils are known. The Kilbride Formation consists mainly of calcareous sandstone and siltstone, sometimes highly fossiliferous. The Tonalee Formation is made up almost entirely of purple and red mudstones.

The age of the Lower Owenduff Group is taken from the fossiliferous Kilbride Formation, which has been dated by McKerrow and Campbell (1960) as Llandovery C_{4-5}. As noted by Piper (1967), red mudstones and siltstones are widespread in Britain at the top of the Llandovery in the M. Crenulatus zone (C_6), and the Tonalee Formation may therefore be uppermost Llandovery.

2.2. Upper Owenduff Group

The sediments comprising the group consist dominantly of graded sandstones in the middle and upper portion, with notable interbedded units of laminated silty mudstone. The lower portion comprises massive sandstones with some conglomerate horizons, particularly near the base, and with some well-developed mudstone units. The sediments are dominantly of the redeposited variety (see Chapters 3 and 4) and are sparsely fossiliferous. They thus contrast with both the overlying and underlying more highly fossiliferous sediments.

The Upper Owenduff Group is subdivided into two formations, the Lettergesh and the Glencraff, both of which are newly defined.

2.2.1. Lettergesh Formation (new name)

2.2.1.1. Name and distribution.

The name is derived from the settlement of Lettergesh at the Culfin River bridge, and is applied to breccia, sandstone and silty mudstone cropping out in the vicinity and to the east. The formation is best exposed on the southern and western slopes of Benchoona and on the northern side of Lough Fee, but extends from the coast near Lettergesh to Maam Valley, a distance of 17 km.

2.2.1.2. Type Locality and Type Section.

The type locality is defined as the vicinity of Benchoona and Lough Fee.

A continuous section could not be drawn because of interruption of the sequence by faults and igneous intrusions, so the type section presented (Table 2) is composite. It includes three separate but adjacent and overlapping sections, one measured between Altnagaighera and Benchoona (section 7, Figs. 2A and 3), another west of Illaunroe on the slopes of Letterettrin (section 21, Figs. 2A and 3), and the third north of the Owengar River (section 17, Figs. 2A and 3).

2.2.1.3. Members.

In the western half of the Killary Harbour area the Lettergesh Formation is divided into twelve members: the Gowlaun Member; The Garraun Members 1-4; the Benchoona Members 1-4; and the Letterettrin Members 1-3. To the east of Glencraff exposure is not so good, and although distinct members can be recognised correlation with those to the west is uncertain.

a) Gowlaun Member. (Previously "Gowlaun Formation" of Piper, 1967). This unit was originally given formational status by Piper, who described a type section north-south through Altnagaighera (reproduced as part of Table 2).

Piper noted that "the characteristic lithology is coarse and medium massive sandstone....with some interbedding conglomerates, mudstones, and siltstones". The base of the member is marked by the first appearance of these lithologies. The characteristic sandstones of the member are medium to coarse, occurring in thick

TABLE 2. TYPE SECTION OF THE LETTERGESH FORMATION

Where Measured		Thickness	Lithology	Letterettrin Members
(See section lines on Fig. 2)			GLENCRAFF FORMATION	
N. of Owengar River (Section 17)	y.	210m	Medium & fine-grained sandstone, with some thin silty mudstone units.	3
	x.	1.8m	Tuff.	
	w.	113m	Coarse & medium-grained sandstones with some graded fine breccia.	
	v.	10m	Silty mudstone containing thin beds of fine sandstone.	2
	u.	33m	Graded fine breccia.	
	t.	19m	Silty mudstones containing thin beds of fine sandstone.	
Southern slopes of Letterettrin, W. of Illaunroe. (Section 21)	s.	255m	Coarse, medium and fine-grained graded sandstone, with some thin silty mudstone units.	1
	r.	0.8m	Tuff	
	q.	121m	Coarse, medium & fine-grained graded sandstone with some graded fine breccia and thin silty mudstone units.	

Between summits of Altmagaighera and Benchoona. (Section 7)

Bed	Thickness	Lithology	Member	
p.	21m	Silty mudstone containing thin beds of fine sandstone.	4	Benchoona Members
o.	37m	Silty mudstone containing thin fine sandstone beds at base passing upwards into graded fine breccia.	3	Benchoona Members
n.	22m	Silty mudstone containing thin fine sandstone beds at base passing upwards into graded fine breccia.	2	Benchoona Members
m.	33m	Coarse, medium & fine-grained graded sandstone beds, with some thin silty mudstone units.	1	Benchoona Members
l.	36m	Silty mudstone with very thin beds of fine sandstone.	4	Garraun Members
k.	10m	Medium-grained graded sandstone. (Microgranodiorite sill - 96m)	3	Garraun Members
j.	67m	Coarse, medium & fine-grained graded sandstone.	3	Garraun Members
i.	46m	Silty mudstone containing very thin fine sandstone laminae.	2	Garraun Members
h.	100m	Coarse and medium-grained graded sandstone and graded fine breccia.	1	Garraun Members
g.	10m	Siltstone and mudstone.		Gowlaun Member (Section in Piper, 1967)
f.	120m	Massive coarse sandstones.		Gowlaun Member (Section in Piper, 1967)
e.	30m	Conglomerate and sandstones.		Gowlaun Member (Section in Piper, 1967)
d.	40m	Siltstone and mudstone with sills.		Gowlaun Member (Section in Piper, 1967)
c.	34m	Coarse & medium massive sandstones.		Gowlaun Member (Section in Piper, 1967)
b.	115m	Conglomerates and sandstones.		Gowlaun Member (Section in Piper, 1967)
a.	22m	Compact siltstone.		Gowlaun Member (Section in Piper, 1967)
	c.20m	No exposure.		Gowlaun Member (Section in Piper, 1967)
Total thickness	1526.6m	SCHIST.		

massive beds. They sometimes contain small pebbles, up to a few centimetres in diameter, and also mudstone clasts. Graded bedding is occasionally developed: where present it is of the "content graded" type (McBride, 1962), where the same range of grain size is found throughout a bed, but the proportion of the coarser grain sizes decreases upwards.

Piper did not give a formal definition of the top of the member, but provisionally recognised it by the first appearance of quite frequent beds of normally-graded medium-grained sandstone, in replacement of the thick massive-bedded content-graded coarse-grained sandstone.

Subsequent field work has however shown that in some areas the two sandstone types (i.e., massive-bedded content-graded coarse-grained sandstone and normally-graded medium-grained sandstone) are interbedded for considerable thicknesses, and sandstone intermediate in appearance between the two occurs. Accurate recognition of type is also dependant on good exposure, which is often lacking, particularly in the eastern half of the area. As the upper boundary of the Gowlaun "association" is often gradational and is evidently not readily mappable throughout the Killary Harbour area, it was considered desirable both by the present author and by Piper to reduce the Gowlaun "association" to the status of a member of the Lettergesh Formation.

The member extends throughout the Killary Harbour area, and also east of Maam Valley as far as Kilbride (Piper, op. cit.). Its thickness varies considerably, being thickest in the west near Altnagaighera where a maximum thickness of 391 m was noted, and thinnest (7.6 m) in the saddle between Glencraff and Glenglosh.

West of Lough Fee the junction between the Gowlaun Member and the immediately overlying strata can easily be followed as normally-graded sandstone beds rest sharply on the siltstone and mudstone unit which forms the top of the Gowlaun Member at the type section. Immediately east of Lough Fee the two sandstone types are separated by a gap of nearly 10m. In the vicinity of Lettershanbally and eastward to Maam Valley, however, the two sandstone types are often interbedded and sandstone of appearance intermediate between the two occurs; thus here the upper boundary of the Gowlaun Member is not clearcut.

Piper (op. cit.) specifically included in the Gowlaun "Formation" sandstone and thin conglomerate horizons cropping out at the summit of Lettershanbally, and on a sketch map included in it sandstone and thin conglomerate units to the north. However, the bulk of the sediments north of the summit are normally-graded sandstones more referable to overlying members. Further, a contact between mudstone and overlying sandstone and conglomerate immediately south of the summit of Lettershanbally can be traced westwards, and is the same as that between Garraun Member 4 mudstone and Benchoona Member 1 sandstone within the Lettergesh Formation (see later - also Fig. 3). The conglomerate and sandstone on the north of the summit of Lettershanbally is therefore laterally equivalent to the Benchoona Member 1 of the Lettergesh Formation, and is included in it. The upper boundary of the Gowlaun Member at Lettershanbally is therefore taken to be the top of the mudstone unit immediately south of the summit.

In the saddle between Glencraff and Glenglosh exposure is poor and the boundary is uncertain. However, it is tentatively taken at the top of the 7.6m thick unit of silty mudstone, containing a 1m thick bed of massive, ungraded pebbly sandstone, which separates the Tonalee Formation from a thick unit of graded and ungraded breccias and sandstones above (section 33, Fig. 3). The relative thinness of the mainly mudstone unit representing the Gowlaun Member here is compatable with the rapid eastward thinning of the member from a few hundred metres west of Lettershanbally (Fig. 3, sections 29, 30, and 31).

In upper Glenglosh the Gowlaun Member thickens, and south of the summit marked "1413 ft" is 71 m thick (Fig. 3, section 36). Here the upper boundary of the Gowlaun Member is taken at the top of a 25 m thick laminated silty mudstone unit which separates massive, ungraded coarse-grained wedge-bedded sandstone below from normally-graded parallel-bedded breccia and coarse sandstone occupying the summit. Further east poor exposure and apparent interbedding of massive ungraded and well-bedded normally-graded sandstones makes the precise positioning of the formational boundary impossible. The Member thickens eastwards from the head of Glenglosh (D.J.W. Piper, pers. comm.) and at Tonalee conglomerate beds occur within massive sandstone units (Fig. 3, section 38).

b) Garraun Members 1, 2, 3 and 4. These members are best exposed on the southern and western slopes of Garraun, where they attain their greatest thicknesses of 100 m, 46 m, 77 m and 36 m respectively (see Table 2 and Fig. 3). All four members have sharp upper and lower contacts with adjacent units. They all thin slightly to the east as far as the eastern shore of Lough Fee, and then more rapidly between there and Lettershanbally. The nature of the thinning is not clear because of bog cover, but 600 m west of Lettershanbally the silty mudstone of Member 2 has died out and a graded sandstone unit laterally equivalent to Members 1, 2 and 3 has diminished to a thickness of between 25-45 m. The sandstone unit thins rapidly eastwards until near the summit of Lettershanbally it has disappeared and only laminated mudstone is present.

Member 4 silty mudstone can be traced almost continuously with only minor breaks in exposure from within a kilometre of the coast to the summit of Lettershanbally. At the summit it merges into laminated mudstones which are the apparent lateral equivalents of Members 1, 2 and 3, and also of the Gowlaun Member. Although large breaks in exposure render correlation uncertain further east, it is probably partly equivalent to laminated mudstone (see earlier) overlying Tonalee Formation at the base of section 33 in the Glencraff/Glenglosh saddle and referred to the Gowlaun Member, and to laminated Gowlaun Member mudstone underlying graded sandstone and breccia immediately south of the summit "1413" in the headwaters of Glenglosh (Figs. 2A and 3).

c) Benchoona Members 1, 2, 3 and 4. These members are well-exposed on the southern slopes of Benchoona, and on the northern shore of Lough Fee.

Member 1 is the most persistent laterally, being exposed almost continuously with few breaks from the coast west of Lettergesh to the summit of Lettershanbally, a distance of 11 km. The member consists mainly of sandstone, which rests with sharp junction on the silty mudstone of Garraun Member 4. It thickens eastwards from a minimum of approximately 30m near the coast to a maximum of 220m at the summit of Lettershanbally, where the top of the member is not exposed. East of the summit there is almost no exposure for 1½ km., and correlation is doubtful, but the most likely equivalents are the graded breccias and sandstones above the uppermost mudstones of the Gowlaun Member in the saddle between Glencraff and Glenglosh and on the summit "1413" in Glenglosh (Figs. 2A and 3, sections 33 and 36). The member thus thins east and west of Lettershanbally, indicating that it probably reaches its greatest thickness in the vicinity of Lettershanbally. The region of maximum thickness coincides with the presence of lenses of conglomerate and fine breccia interbedded with sandstone, these coarser sediments being restricted to the vicinity of Lettershanbally.

Member 2, which is best exposed on the southern slopes of Benchoona, also reaches its maximum development here of 25m. It is a sharp-based unit, consisting of siltstone containing thin fine sandstone beds passing upwards into graded fine breccia. The member thins rapidly eastwards to a thickness of 14m just west of Illaunroe, and disappears under bog east of the eastern end of Lough Fee.

Member 3, also sharp-based and of similar lithology to Member 2, is well-exposed on the north shore of Lough Fee, and on the western and southern slopes of Benchoona, where the thick, weathering-resistant breccias of which it is largely composed cause it to form a prominent ridge. It crops out sporadically between Lough Fee and the main Leenane/Clifden road, and makes its last definite appearance just to the east of the road. To the east isolated outcrops of breccia and sandstone protrude through the bog, but correlation is uncertain. The member's greatest thickness of 38m is attained in the vicinity and west of Benchoona, and it thins slightly to the east, being 35m thick 100m east of Illaunroe.

Member 4 is also best exposed west and south of the summit of Benchoona and north of Lough Fee. It consists of silty mudstone with thin fine-grained sandstone beds resting sharply on Member 3. It is traceable from within one km. of the coast eastwards to just east of the main Leenane/Clifden road, a distance of 7½ km. It thins eastwards, from a maximum of 24m near the coast to approximately 10m east of Lough Fee.

d) Letterettrin Members 1, 2 and 3. Sediments belonging to the members are best exposed north of the Owengar River, a short watercourse joining Lough Fee and Lough Muck, and on the southern slopes of Letterettrin, after which hill the members ~~is~~ are named. All three members occur only in the western half of the area; from Glencraff eastwards Member 2 is not recognised, and the Letterettrin Member is not sub-divided.

The combined members are traceable from the coast near Lettergesh eastwards as far as Maam Valley. The total thickness is approximately 700 m in the Lough Fee area, where the upper and lower boundaries are clearly defined. Because of the uncertainty of correlation of the underlying Benchoona Members east of Lettershanbally the lower boundary of the Letterettrin Member 1 east of the main Leenane/Clifden road could not be accurately delimited, and therefore the thickness is uncertain. However, the total thickness of strata in the Glencraff section between Benchoona Member 1 and the Glencraff Formation is only 580 m, suggesting thinning of the combined Letterettrin Members to the east.

Member 1 is dominated by coarse and medium-grained graded sandstones, with graded fine breccia units at the base, resting sharply on the silty mudstone of Benchoona Member 4. A tuff horizon, 0.8 m thick, occurs 121 m above the base of the member north of Illaunroe, Lough Fee, where it is traceable laterally for approximately 100 m. Itcould not be located in other sections examined to the east and west.

Member 2 is well-exposed on the lower hillslopes north of the Owengar River, and also to the east, south, and west of the summit of Letterettrin. In these localities it consists of three units, a lower and an upper unit consisting of silty mudstone containing thin fine sandstone beds, separated by a thick unit of fine breeccia.

The lower mudstone unit has a sharp junction with the top of the Letterettrin Member 1 exposed below, but has a gradational contact with the breccia unit above. The upper mudstone unit has sharp upper and lower contacts with the surrounding beds. The member reaches its greatest thickness of 62 m north of the Owengar River, where the central breccia unit also reaches its maximum development of 33 m.

The member is traceable eastwards as far as the main Leenane/Clifden road, beyond which exposure is limited by bog for approximately 4 km. Further east it could not be recognised and apparently dies out laterally. West of the Owengar River a thick silty mudstone unit correlated with the member occurs in one locality south-west of Lough Muck on the northern slopes of Benchoona, but could not be traced further west (Figs. 2A and 3, section 13). At this locality the central breccia unit is absent, its equivalent being 0.6 m of coarse sandstone bounded by mudstone units. Here the thickness of the member has diminished at the expense of all three units to 14 m, and may indicate westward lensing out of the member.

Member 3 like Member 1 consists dominantly of coarse and medium-grained graded sandstones, with some graded fine breccias developed towards the ~~top~~ base. Where Member 2 is developed, it is overlain sharply by Member 3.

A tuff unit, varying in thickness between 1.8 m and 3.2 m, occurs 113 m above the base of the member in the western part of the Killary Harbour area, where it can be traced laterally discontinuously for 4½ km. It could not be located east of the main Leenane/Clifden road.

e) Members east of Glencraff. At least four silty mudstone members in section 36 (Glenglosh) and at least three in section 38 (Tonalee), the thinnest 10 m, and the thickest 25 m, separating thick members composed mainly of coarse, medium and fine-grained sandstone, occur above conglomerate or massive sandstone of the Gowlaun Member (Fig. 3). Both mudstone and sandstone members are similar in lithology to members further west, but because of intervening poor exposure cannot be correlated with certainty either between the two sections or with western members. In some cases mudstone members apparently correlate laterally with part of a sandstone member, suggesting that rapid lateral facies changes occur.

2.2.1.4. Lithology and thickness.

The typical lithology of the formation is coarse and medium-grained sandstone, but conglomerate, breccia, and fine-grained sandstone and silty mudstone occurs to a subordinate extent. Thin section study shows the sandstones and breccias to be poorly-sorted (Appendix, B), and to consist mainly of angular grains of quartz and feldspar, with a lesser proportion of lithic constituents, and the matrix making up approximately 20% of the rock (Appendix, A). According to the classification of Williams et al. (1955) they are arkosic greywackes.

The conglomerate clasts consist dominantly of white and red quartzite (approximately 40-50%), sandstone and siltstone (approximately 30%) and basic or intermediate volcanic rocks (approximately 15%), the remainder comprising mainly jasper and serpentinite. The matrix is mainly of angular medium to coarse sand-sized fragments of quartz and feldspar.

Thin sections of the tuffs show angular fragments of quartz and feldspar set in an altered sericitic matrix in which the outlines of glass shards are usually recognisable. A small number of altered ferromagnesian minerals are usually present, and, more rarely, rounded fragments of quartzitic and volcanic rock. The composition suggests an acid or intermediate vitric tuff.

There is no systematic lateral variation in grain size throughout the formation, but the coarser facies are best developed in the western portion of the area. In the broadest sense the formation fines upwards, with conglomerates being located only near the base, and coarse lithologies becoming rare towards the top. In particular, the Letterettrin Member 3 shows an unsystematic but definite decrease in grain size upwards, finer-grained sandstone units and siltstone units becoming more common towards the top.

The formation has its greatest development at its type section, where it is approximately 1520 m thick. Lateral variation in thickness is difficult to assess because of poor exposure and the difficulty of correlation of individual members from east to west, but the formation appears to diminish in thickness eastwards from Lough Fee, at the expense both of its basal members and the upper ones, being thinnest at the head of Glencraff, where the apparent thickness is 727 m. However, at least two faults of uncertain but probably small displacement interrupt the succession, and this value is only approximate. East of Glencraff the formation evidently thickens once more, as the Gowlaun Member shows a marked increase in thickness. Some thinning probably occurs west of the Owengar River, mainly at the expense of the Letterettrin Members.

2.2.1.5. Relationship to Underlying beds.

The base of the formation is diachronous. Piper (1967) noted that the Gowlaun Formation (now the Gowlaun Member) "in the west rests on schist or Lough Mask Formation, south and east of Lough Fee it comes within the Kilbride Formation, and east of Lettershanbally the base is at the top of the Tonalee Formation".

2.2.1.6. Palaeontology and Age.

Apart from two unidentifiable coral fragments in sandstone beds of the Letterettrin Member[1] on the southern slopes of Benchoona, and unidentifiable coelenterate fragments in mudstones of the Gowlaun Member exposed on the coast, fossils have been discovered at only one locality in the Lettergesh Formation. They were collected by Dr. W.E.A. Phillips of Trinity College, Dublin, from within Benchoona Member 1, and identified as Monograptus flemingii (Salter) by Dr. R.B. Rickards of the Sedgwick Museum, Cambridge. This graptolite represents an age range from middle to upper Wenlockian (rigidus - lungrini Zones) (Dr. R.B. Rickards, pers. comm.). However, in view of the occurrence in the Lough Muck Formation nearly 1000 m higher in the sequence of Monoclimacus flumendosae (Gortani), which Dr. R.B. Rickards (pers. comm.) considers is indicative of middle Wenlockian (i.e., rigidus - ellesae Zones), the Lettergesh Formation cannot be younger than middle Wenlockian in age.

2.2.1.7. Correlation.

East of Maam Valley graded sandstone beds, with subordinate siltstone, breccia and conglomerate units overlying the Tonalee Formation, have been correlated by McKerrow and Campbell (1960) with the Upper Owenduff Group, and the lithologies indicate equivalence with the Lettergesh Formation. The top of the formation is not seen because erosion has removed overlying beds.

2.2.2. Glencraff Formation (new name)

2.2.2.1. Name and Distribution.

The name is derived from the large, east-trending valley east of the main Leenane/Clifden road. The formation is well-exposed on the northern side of the upper valley, and also on the hillslope north of Owengar River. It can be traced sporadically from near the coast north of the Culfin River estuary eastwards to the northeastern slopes of Bunnaviskaun, beyond which outcrop is lacking.

2.2.2.2. Type Locality and Type Section.

The type locality of the formation is taken at its outcrop 440m north of the Owengar River outlet of Lough Fee, where the most complete section occurs.

The type section consists of 60m of thin fine-grained graded sandstone beds, with thin included units of mudstone containing thin laminae of fine sandstone, overlain by 5m of cream-weathering thin-bedded tuff.

2.2.2.3. Lithology and thickness.

The lithology of the strata comprising the formation shows no observable change laterally. It is dominated by thin fine-grained sandstone beds averaging approximately 10 cm in thickness and separated from each other by thin layers of silty mudstone. Thin section study shows that the sandstones are arkosic greywackes as in the Lettergesh Formation (Appendix, A). Thicker units of silty mudstone up to 2m thick and containing thin beds and laminae of fine sandstone occur in the sequence, particularly near the base.

The tuff is fine-grained and occurs in thin layers generally between 10 and 30 cm thick, but up to a maximum of 80 cms thick. It has a typical conchoidal fracture and weathers a distinctive cream colour; in thin section it appears identical to the tuffs of the Lettergesh Formation.

The thickness of the formation varies little, reaching 65m in the west, north of Owengar River, and 64m in the east in Glencraff. The slight change in thickness is attributable to the thinning of the tuff horizon from 5m in the west to 4m in the east.

2.2.2.4. Relationship to underlying beds.

The Glencraff Formation rests conformably on the Lettergesh Formation. At the type locality the base of the formation is defined as the last appearance of associations of thick (> 20 cm) sandstone beds. Thick sandstone beds are present in parts of the Glencraff Formation, but they occur as isolated beds and are rare. At the type locality the change from coarse or medium-grained thick-bedded sandstone to silty mudstone or thin-bedded sandstone is abrupt. In most other localities, however, the boundary is either obscured or poorly exposed, and the contact cannot with certainty be shown to be sharp. Nevertheless, the gradation from one lithology into another takes place within about one metre. The presence of a tuff unit at the top of the formation acts as a time horizon, and it is evident from the uniform thickness and lithology of the sediments beneath it that the lower contact is not notably diachronous, and no observable lateral facies change takes place within the Killary Harbour area.

2.2.2.5. Palaeontology and Age.

The only fossils seen in the Glencraff Formation were rare specimens of *Orthoceras* occurring in tuff at the top of the formation north of the eastern end of Lough Muck. These are not indicative of a precise age, but the age of the Glencraff Formation must be middle Wenlock like the under and overlying beds (see under Lettergesh Formation and Lough Muck Formation).

2.2.2.6. Correlation.

No correlatives are known. Strata of Wenlock age extend east of Maam Valley to Lough Mask, but all beds above the correlative of the Lettergesh Formation have been removed by erosion.

2.3. Killary Harbour Group (new name)

The sediments which make up the group are dominantly fine-grained, with prominent thick units of siltstone or mudstone. Where beds of sandstone are present they are ungraded, and often cross-bedded. Fossils of benthonic organisms are relatively numerous, and this, together with the lack of redeposited sediments, suggests shallower water conditions than those prevailing for the Upper Owenduff Group.

The upper limit of the Upper Owenduff Group of McKerrow and Campbell (1960) has been redefined on the basis of lithological and faunal criteria; the fossiliferous, generally fine-grained upper two to three hundred metres of the old Upper Owenduff Group is now included in the Killary Harbour Group.

The group is divided into two formations: the Lough Muck Formation (new name), and the Salrock Formation.

2.3.1. Lough Muck Formation (new name)

2.3.1.1. Name and distribution.

The name is derived from Lough Muck, a small lake west of Lough Fee and drained by the Culfin River. The formation is particularly well-exposed north of Lough Muck and on the southern slopes of Knockraff. It extends from the coast north-west of Lettergesh eastwards as far as Maam Valley.

2.3.1.2. Type Locality and Type Section.

The type locality of the formation is at its outcrop north of Lough Muck, between Salrock School and the road from Lough Muck to Killary Bay Little, where an almost complete section through the formation occurs. This is taken as the type section, which is reproduced in Table 3.

TABLE 3. TYPE SECTION OF LOUGH MUCK FORMATION

Thickness	Lithology	Member
	SALROCK FORMATION	
3.2m	Unseen	
12m	Mudstone, with occasional thin beds of medium-grained sandstone.	
39.5m	Mudstone containing thin lenses of fine-grained sandstone or siltstone. Frequent intercalations of medium-grained cross-bedded sandstone.	Upper
37m	Mudstone and siltstone, with frequent thick units of cross-bedded medium-grained sandstone.	
29m	Laminated siltstone and very fine-grained sandstone.	
3m	Unseen.	Middle
62m	Massive mudstone and siltstone.	
4m	Massive and banded siltstone with several slump horizons.	
3m	Medium-grained sandstone.	
2m	Siltstone with slump balls of fine-grained sandstone.	
0.5m	Sandstone.	
2m	Massive siltstone.	
8.5m	Banded siltstone with several slump horizons.	
3m	Massive siltstone and mudstone with thin sandstone beds.	Lower
1.5m	Medium-grained sandstone.	
2m	Siltstone with slump balls of medium and fine-grained sandstone.	
1.3m	Medium-grained sandstone.	
2.9m	Siltstone with slump balls of fine and medium-grained sandstone.	
4m	Laminated siltstone.	
2.4m	Laminated siltstone with slump balls of fine and medium-grained sandstone.	
1.2m	Thin-bedded fine sandstone alternating with thin layers of mudstone.	
Total 224.0m		
	GLENCRAFF FORMATION	

The Lough Muck Formation is divided into three members, a Lower, a Middle and an Upper Member, which are recognisable throughout the Killary Harbour area.

a) <u>Lower Member</u>. This member, which is relatively well-exposed throughout the area, consists of fine and medium-grained sandstone beds, both massive and thin-bedded, massive or laminated siltstone, and siltstone beds containing slump balls of medium or fine-grained sandstone. In the western half of the area slumped beds and massive sandstone units are common; to the east they are uncommon, their place being taken by thin-bedded fine-grained sandstone beds alternating with mudstone, which is a lithology indistinguishable from that common in the underlying Glencraff Formation.

The member is extremely variable in thickness from locality to locality, varying from a minimum of 23m at the west coast to a maximum of approximately 50m north of Owengar River and on the south slopes of Knockraff.

b) <u>Middle Member</u>. This member, because of its finer grain size than the members above and below tends to weather as depressions and hence is the least well-exposed of the three. It consists mainly of massive or laminated mudstone and siltstone. In the area ~~west~~ east of Letterettrin and in a few other localities, however, complex lenticular bodies of massive, medium-grained sandstone up to 7m thick, are also present.

The member increases markedly in thickness to the east, varying from 85m at the coast to 130m at Knockraff.

c) <u>Upper Member</u>. This member, like the Lower Member, comprises a variety of rock types. In the lower part of the member cross-bedded or parallel-laminated medium-grained sandstone is common, alternating with siltstone units. In the upper half of the sequence mudstone or siltstone containing thin lenses of fine sandstone or siltstone, with occasional thin interbeds of cross-bedded or parallel-laminated medium-grained sandstone, is dominant. In some localities, e.g., the type locality near Salrock School, thick units of massive or laminated mudstones occur at the top of the sequence.

The Upper Member varies slightly and irregularly in thickness throughout the area, from a minimum of 90m to a maximum of approximately 110m.

2.3.1.3. Lithology and Thickness.

As noted above, many different lithologies occur in the Lough Muck Formation. The dominant lithologies, however, are fine-grained, and siltstone or silty mudstone is present either in very thick units as in the Middle Member, or alternating with coarser lithologies in thinner units. This contrasts with the sandstone-dominated lithology of the underlying Glencraff and Lettergesh Formations.

Thin section study shows that the sandstones are arkoses, most showing much better sorting and better grain rounding than those in the Upper Owenduff Group. The massive sandstones of the Middle Member are exceptions showing in thin section angular grains of quartz and feldspar "floating" in an abundant matrix.

There is no regular pattern of vertical lithological change, but it is notable that the fine-grained portions of the formation, i.e., the Middle Member and the upper half of the Upper Member pass with rapid transition into their bordering coarser lithologic units. The formation as a whole has a higher proportion of finer-grained material towards the east because of the increasing thickness of the Middle Member in this direction.

The thickness of the formation as a whole varies considerably throughout the area, largely because of the lateral thickness variation of the Middle Member, and thickens eastwards from a minimum of 200 m at the coast to approximately 290 m on Knockraff.

2.3.1.4. Relationship to Underlying Beds.

The basal beds of the Lough Muck Formation rest conformably on the tuffs which form the topmost beds of the Glencraff Formation. At nearly all localities the beds immediately overlying the tuffs are thin-bedded fine-grained sandstones closely-similar to those underlying the tuffs. The main lithological change occurs between one and ten metres above the topmost tuff horizon, in most cases consisting of a slumped bed or a massive sandstone. However, because of the variety in lithologies and in their stratigraphic position at the base of the Lough Muck Formation, it was considered most convenient to take the top of the tuff as a formational boundary.

2.3.1.5. Palaeontology and Age.

All three members of the Lough Muck Formation contain a relatively high proportion of fossils, in contrast to the underlying formations of the Upper Owenduff Group. They mainly occur scattered sporadically throughout siltstone or mudstone units, or concentrated towards the base of thick massive sandstone complexes in the Lower and Middle Members, or at the top of thick cross-bedded sandstone units in the Upper Member. No fossils were found in the upper fine-grained portion of the Upper Member. Benthonic forms dominate the fauna.

The fossils collected include:

Lower Member: Eocoelia sulcata, "Petraia", Orthoceras, dalmanellids, generically unidentifiable graptolites, gastropods, bivalves, and crinoids.

Middle Member: Monoclimacus flumendosae (Gortani), Encrinurus, Plectodonta, Leptaena, dalmanellids, and generically unidentifiable bivalves, gastropods, corals, trilobites, and a chonetid.

Upper Member: Encrinurus, Leptaena, Acaste, Dalmanites, dalmanellids, and generically unidentifiable gastropods, crinoids, bivalves, and coelenterates.

Only Monoclimacus flumendosae (Gortani) is sufficiently restricted in time range to define the age of the rocks within narrow limits. This graptolite represents a middle Wenlock age (rigidus - ellesae Zones) (Dr. R.B. Rickards, pers. comm.)

2.3.1.6. Correlation.

No correlatives are known in the vicinity of Killary Harbour, as the belt of Silurian rocks east of Maam Valley represents older formations (see earlier). Possible correlatives of the Lough Muck (and Lettergesh) Formation occur however on Clare Island, 20 km. to the north of Killary Harbour, where conglomerates, sandstone, tuff, and laminated red and greyish siltstone of probable Wenlock age crop out (see Fig. 1).

2.3.2. Salrock Formation

2.3.2.1. Name and Distribution.

Kinahan (1878) and Kinahan et al. (1878) first used the name "Salrock Series" or "Salrock Slates Series" in reference to the dominantly red-coloured fine-grained rocks occurring in the upper part of the Silurian sequence. McKerrow and Campbell (1960) first defined the beds formally as the "Salrock Group", and drew the base at "the lowest red shale horizon". As the rocks are not readily subdivisible at the formational level the "Salrock Group" of McKerrow and Campbell (op. cit.) has been redefined as the Salrock Formation. The lower boundary is defined as the first appearance of laterally persistent red-colouration in the upper part of the Silurian sequence.

The Salrock Formation can be followed laterally from the coast around Killary Bay Little in the west, where it is particularly well-exposed, to the north-eastern slopes of Bunnaviskaun in the east. East of this it is faulted out.

2.3.2.2. Type Locality and Type Section.

The type locality is taken as the area between Salrock School and Killary Bay Little, where the formation is best exposed. The type section, drawn from this locality, is reproduced in Table 4.

2.3.2.3. Lithology and Thickness.

The Salrock Formation is dominated by fine-grained lithologies, mainly massive or laminated mudstone and siltstone, but coarser lithologies consisting of arkosic sandstone are also present. In the area south and immediately to the east of Killary Bay Little the formation is dominated by red beds, but these progressively give way to grey-green-coloured beds towards the east until in the Knockraff area red-coloured strata make up only about one third of the sequence. The lowermost 110 m throughout the region is almost entirely red-coloured. The red colour occurs mainly in fine-grained lithologies, but many sandstone beds are also red-coloured,

TABLE 4. TYPE SECTION OF THE SALROCK FORMATION

Thickness	
	TOP UNSEEN - KILLARY BAY LITTLE
48 m	Red mudstone and siltstone.
12 m	Thick green sandstone beds and thin interbedded red siltstone.
63 m	Red mudstone and siltstone with some thick green-grey sandstone beds.
0.1 m	Tuff.
63 m	Red mudstone and siltstone with some thin red sandstone beds.
4 m	Tuff.
19 m	Red mudstone with a 2 m unit of green-grey sandstone near the base.
3 m	Tuff.
7 m	Massive red mudstone.
8.4 m	Mainly green-grey sandstone, with some interbedded red mudstone.
13.3 m	Massive red mudstone with some thin beds of fine sandstone.
6.5 m	Unseen.
96.5 m	Massive red mudstone with occasional thin beds of green-grey sandstone.
5.6 m	Unseen (summit of gravel road between Salrock and Lettergesh).
32.5 m	Red medium-grained sandstone with thin interbeds of red mudstone.
39.0 m	Mudstone with some thin beds of fine sandstone. Mainly red, but with some red and grey alternations in the basal 6 m.
18.2 m	Grey-green medium-grained sandstone.
31.3 m	Alternating mudstone and medium-grained sandstone beds. Mainly red-coloured, but with red and grey alternations in the basal 7 m.
36.6 m	Mainly red massive mudstone with thin fine-sandstone beds. Alternating grey and red colouration in the basal 6 m.
2.6 m	Unseen.

13.2 m	Mainly red massive mudstone with some thin sandstone beds. Some grey and red alternations.
10.2 m	Mainly grey laminated siltstone with some thin sandstone beds. Some grey and red colour alternations.
13.8 m	Massive red mudstone, the colour grading into grey-green sediments above and below.
30.5 m	Mainly massive grey mudstone, with thin beds of fine-grained sandstone.
3.4 m	Grey mudstone and siltstone with thin lenses of fine-grained sandstone.
	SILL
44.5 m	Alternating grey mudstone and siltstone, with some thin lenses of fine-grained sandstone.
1 m	Tuff.
10.7 m	Grey mudstone and siltstone with thin lenses of siltstone or fine-grained sandstone.
55.6 m	Grey siltstone with thin beds of fine sandstone.
32.8 m	Laminated red siltstone and mudstone, with thin beds of fine sandstone.
6.8 m	Red, medium-grained sandstone.
24.2 m	Massive red mudstone with some thin fine sandstone beds. Some red and grey colour alternations near the top.
9.1 m	Mainly red-coloured fine-grained sandstone in thin beds.
	SILL
17.8 m	Alternations of mainly red coloured fine-grained sandstone and siltstone or mudstone.
2 m	Unseen.
5.5 m	Red mudstone.
1 m	Tuff.
13 m	Laminated red siltstone and mudstone with thin fine sandstone beds.
Total 814 m	
	SILL
	LOUGH MUCK FORMATION

especially in the lower half of the sequence. Frequently, vertical gradational changes from red to grey-green-coloured beds, particularly in the case of mudstones or siltstones, occur, usually over a range of a few tens of centimetres, and with no detectible change in lithology.

The grey-green-coloured beds consist mainly of mudstones and siltstones, and mudstones with lenses of siltstone or fine-grained sandstone similar to the lithology of the beds in the upper part of the Lough Muck Formation. In the upper half of the Salrock Formation in the Salrock School area most sandstones are also grey-green in colour. These are distinguished from the red-coloured sandstones lower in the sequence by being notably more quartzitic and containing much less matrix.

Five tuff horizons occur in the sequence south of Killary Bay Little, but only the lowest one could be traced throughout the Killary Harbour area. This varies irregularly in thickness from 50 cm to 120 cm, and occurs between 8 and 15m above the lowest red-beds. Most of the higher tuff beds can be traced for approximately 2 km. in the Salrock School area, but could not be recognised east of Killary Bay Little. They range in thickness from 10 cm to 4m. All weather a distinctive cream colour which contrasts strongly with the surrounding red-coloured sediments. In thin section they are identical in appearance with the tuffs of the Lettergesh and Glencraff Formations.

Kinahan et al. (1878) recorded lenses of limestone from the uppermost part of the "Salrock Slates Series", but these were not located during the course of the present study. However, limestone lenses occur or have been quarried in the past (Dr. W.S. McKerrow, pers. comm.) from the Ordovician sediments immediately overlying the Salrock thrust and possibly these may have been included inadvertently in the Silurian by Kinahan and his co-workers.

2.3.2.4. Relationship to Underlying Beds.

The boundary between the Salrock and Lough Muck Formation is everywhere conformable and gradational. The incoming of red colouration in the sediments is gradual, and there are fluctuations from one colour to another in a transition zone which may extend from a few centimetres to a metre or more. Hence a firm demarcation line cannot always be drawn between the two formations. The tuff unit occurring a few metres above the base of the Salrock Formation can be taken as a convenient time plane, and its approximately constant level above the first incoming of red beds can be taken as indicating almost synchronous initial red-bed formation throughout the Killary Harbour area.

2.3.2.5. Palaeontology and Age.

The present author collected only *Lingula* sp. and unidentifiable gastropods from the Salrock Formation, but Carruthers and Muff (1909) recorded *Lingula symondsii* and *Modiolopsis complanata* from the Salrock Formation. The former ranges from Upper Llandovery to Lower Ludlow in age, but is commonest in the Wenlockian beds of Shropshire; and the latter has been previously recorded only from Ludlovian and Downtonian beds (McKerrow and Campbell, 1960, p.41), although, as noted by these authors, a favourable environment for this organism was lacking in older sediments and it is quite possible therefore that its time range extends down into the Wenlockian.

Since Middle Wenlock fossils occur only 150m below the base of the Salrock Formation it is probable that most, if not all of the formation was deposited during Wenlock times.

2.3.2.6. Correlation.

No fine-grained Silurian red-beds are known in the region surrounding Killary Harbour, and, as noted earlier, all upper Silurian beds east of the Maam Valley have been removed by erosion. However, twenty kilometres to the north of Killary Harbour on Clare Island, green and red laminated siltstones and buff-coloured sandstones of the Toormore and Knackaveen Groups range in age from Wenlock (on fossil evidence) to Ludlow (radiometric dating) (Phillips, 1965), and thus at least part of this succession can be correlated with the Salrock Formation. The Clare Island sequence also contains many tuff horizons.

CHAPTER 3

FACIES

1. Facies A: Ungraded Conglomerate

1.1. Description

On the summit and western slopes of Lettershanbally ungraded conglomerate occurs in units varying from one pebble to about 3m in thickness. No individual bed can be traced for more than a few tens of metres laterally, some being lenticular and others wedging out, thinning being accompanied by splitting into thinner layers separated by massive or pebbly sandstone (Plate 1). All beds have sharp, often erosive, bases and, generally, sharp tops, although occasionally the top grades rapidly upwards into massive or pebbly sandstone. Pebbles larger than about 3 cm are invariably well-rounded, and in some beds boulders reach a diameter of 40 cm. Commonly the larger clasts "float" in a matrix of much finer angular breccia or sandstone, but occasionally they occur densely packed (Plate 2). In one place poorly developed imbrication occurs with pebbles dipping to the north-east, but usually the boulders lie with their long axes in the plane of the bedding. Pockets of pebbles sometimes occurring within otherwise massive sandstone beds (Plate 3) may indicate that some of the sandstones interbedded with the conglomerates are amalgamated (Walker, 1966), pebble-filled scours being the only remaining evidence of interbed erosion. Four hundred metres west of the summit of Lettershanbally all conglomerate horizons have disappeared, and the rocks are dominated by facies C graded breccias and sandstones, interbedded with some facies B massive sandstones.

In the sequence studied in detail this facies occurs only in the Benchoona Member 1 of the Lettergesh Formation, although it is a relatively common constituent of the Gowlaun Member. In the Benchoona Member 1 it is restricted areally to the western slopes and summit of Lettershanbally.

1.2. Interpretation

Although this facies is apparently laterally equivalent to, and in some places is interbedded with strata probably deposited from turbidity currents, a different mechanism seems to be required to account for its emplacement. The deposits are much coarser than those normally associated with turbidity currents, and lack grading and lamination. In addition, apart from the one instance of pebble imbrication seen, there is no evidence for any other type of current activity. The most likely means of transport was by some mechanism such as the "inertia flow" described by Bagnold (1954), where grains move under the tangential attraction of gravity independently of any fluid flow. Flow and creep of sand have been observed to take place in submarine canyons off the Californian coast, the sand often carrying large amounts of man-made junk (Shepard and Dill, 1966, p.107). These authors recorded sand flows only on slopes in excess of 20°, but more recent observations on the sediment fill of submarine canyons (Trumbull and McCamis, 1967), and on submarine fan sediments (Shepard and Dill, op. cit.), suggest that movement of sand supporting large blocks may take place at much lower angles of slope.

2. Facies B: Thick Massive Sandstone and Pebbly Sandstone

2.1. Description

The sandstones, which typically are of medium grain size, are thick-bedded (up to 10 m) sharp, sometimes erosive-based, and show little or no internal structure, although sometimes an illdefined, irregular, often anastomosing lamination marked by faint dark lines is present throughout an individual bed. In some instances weathering has emphasised the laminae so that they stand out as minute ridges on the outcrop surface. This type of irregular ridge relief, although also occurring rarely in facies C breccias and sandstones, appears to be characteristic of Facies B sandstones. Occasionally fine parallel lamination occurs in the top few centimetres of the massive sandstones. Grading, which sometimes occurs, is usually of the "content graded" type (McBride, 1962), where the same range of grain size is found throughout a bed, but the proportion of the coarser grain sizes decreases upwards. This is shown particularly well in some of the pebbly sandstone beds where angular pebbles ranging in size up to 3 cms, occur widely scattered in a matrix of coarse sandstone (Plate 4). Normal grading is uncommon, but occasionally a few centimetres of breccia grading rapidly upward into medium sandstone may be present at the base of a bed. Grading also sometimes occurs within the top few centimetres of a bed. Thin section study (Appendix, A, B) shows the sandstones to be notably poorly sorted with abundant matrix. No bed can be traced laterally for more than a few tens of metres, and some beds can be seen to wedge out rapidly or terminate abruptly (Plate 5). Inclusions of mudstone, the largest up to 1 m long, sometimes occur near the top or base of a bed.

Some massive sandstones, not included in this facies, are associated with graded sandstones higher in the sequence, but these never exceed 3m and are generally less than 1m thick.

Facies B is most typically developed in the lower part of the Benchoona Member 1 in the Lettershanbally area, and is commonly found in association with Facies A ungraded conglomerates. It is also relatively common in the underlying Gowlaun Member, where the sandstones are also associated with conglomerates.

2.2. Interpretation

Rarity of grading, sharp bases, limited lateral extent and rapid wedging out of individual beds, poor sorting, and absence of readily identifiable current structures in Facies B sandstones indicate that, like Facies A, they were probably emplaced by a mass flow mechanism. Laminated tops to some beds may have resulted from the activity of sea-floor traction currents reworking and redistributing material at the top of a bed. The poorly-defined irregular or anastomosing lamination sometimes developed resembles that described by Stauffer (1967) as "dish-structure", and interpreted by him to be typical of grain-flow deposits. However, it also bears a superficial resemblance to internal structures developed in deposits of high flow regime currents (Middleton, 1965), and the presence of such lamination cannot in this case be used to support unequivocally a mass flow hypothesis.

3. Facies C: Graded Sandstone and Fine Breccia

3.1. Description.

This facies is the one most commonly developed in the Upper Owenduff Group, and consists of breccias and sandstones showing common normal grading, and notably poor sorting (Appendix, B). Individual beds are also characterised by having sharp bases and generally parallel bases and tops. Beds are normally laterally persistent and can be traced for the length of outcrop (up to 200 m). In rare cases individual beds can be traced for up to 3 km laterally. A variety of sole structures is also present.

To emphasise the distribution of various sedimentary properties between coarse-grained thick beds and finer-grained thin beds, and to assist in lithological mapping, it was found convenient to subdivide the sandstones and breccias into three sub-facies, C1, C2 and C3, which have gradational lateral relationships with each other. There is also a gradation in bedding types and in sedimentary structures between the sub-facies. These are summarised in Tables 6 and 7.

Sub-facies C1 beds are arbitrarily defined as those which contain grains whose maximum size is in excess of 2 mm reaching a maximum of 3 cm in diameter. Breccias of the sub-facies occur most commonly in units up to 30 m thick comprising several beds, and particularly where they are bounded above and below by a mudstone facies as in the Benchoona Member or in Letterettrin Member 2 they stand out as readily mappable topographic features (see Plate 6). Beds are typically between approximately 0.5 - 1 m thick. Thicker beds up to 3 m occur, but amalgamation is common and some of these thicker units may be composite. Beds which weather as one unit and show no internal stratification not infrequently on close inspection are seen to consist of as many as 10 individual units distinguished from each other only by a slight change in grain size at the base of each, or an interruption in normal grading.

Amalgamation would make it impossible to distinguish successively deposited massive ungraded beds of closely similar grain size. In most cases of amalgamation the bases of individual beds are erosive into the bed below and show an undulating

TABLE 6. BEDDING TYPES IN FACIES C BRECCIAS AND SANDSTONES

Bedding Type	Sub-facies		
	C 1	C 2	C 3
A (Graded)	43%	60%	51%
A (Ungraded)	20%	4%	2%
A (Reverse graded)	7%	4%	0%
AB	22%	20%	17%
ABC	6%	3%	6%
AC	0%	4%	1%
B	1%	1%	11%
BC	0%	1%	6%
PGU	0%	3%	6%
Cross-bedding	1%	0%	0%

Symbols represent bedding types equivalent to the intervals of Bouma (1962), i.e., A = structureless interval; B = lower parallel-laminated interval; and C = cross-laminated interval. PGU = perfectly graded unit.

TABLE 7. GENERAL SEDIMENTARY FEATURES OF FACIES C

Feature	C 1	C 2	C 3
Sharp bases	X	X	X
Erosional bases	X	X	-
Channels	X	X	-
Amalgamation of beds	X	X	Rare
Mudstone or siltstone inclusions	X	X	Rare
Loads	X	X	Rare
Grooves	X	X	X
Flutes	X	X	-
Prods	-	Rare	Rare
Streaked out ripples (base of bed)	X	X	Rare
Sheet Structures	X	X	-
Brush marks	-	Rare	Rare

X Present - Absent

basal profile. Upper surfaces of beds are either erosion surfaces overlain by a succeeding breccia bed, or they form a sharp contact with a thin mudstone unit, rarely more than 5 cm thick and often no more than a thin parting.

This sub-facies makes up much of the Benchoona Members 1, 2 and 3 and Letterettrin Member 3 of the Lettergesh Formation, and also forms a minor portion of the remainder of the Lettergesh Formation.

Sub-facies C2 is arbitrarily distinguished from sub-facies C1 by its finer grain size (Maximum grain size less than 2 mm). Beds of thickness less than 30 cm but greater than 5 cm are included in sub-facies C3. The sandstones of sub-facies C2 form the dominant lithology in the Lettergesh Formation (Plate 7). Amalgamation in sub-facies C2 is common, but not as frequent as in sub-facies C1, and often a thin layer of mudstone separates one bed from the next.

The sandstone beds of sub-facies C3 range in thickness between the arbitrary limits of 30 cm and 5 cm. They normally consist of medium or fine-grained material, the sandstone beds commonly being separated by layers of silty mudstone, the sandstone/mudstone ratio being approximately 2/1. Sub-facies C3 sandstones and mudstones form the bulk of the Glencraff Formation, and also occur to a minor extent in the Lettergesh Formation. (Plate 8).

3.1.1. Sole structures

Sole marks are uncommon in all three facies and consist of grooves and associated tool marks, flutes, loads, streaked-out ripples (flame-structures), and burrows.

3.1.1.1. Grooves, prods, and brush-marks.

Grooves on sub-facies C1 breccias are extremely rare, and are almost invariably isolated and large, up to 10 cm wide and with bottom relief up to 3 cm.

Those on sub-facies C2 sandstones are more gregarious and have smaller dimensions. Grooves on Facies C3 sandstones are often very thin and frequently resemble striae. Prods and brush marks are extremely rare and occur only on the soles of sub-facies C2 and C3 sandstones (Plate 9).

3.1.1.2. Flutes.

Flutes occur on the soles of some sub-facies C1 and C2 beds but are rare. They are often large, up to 20 cm long and 10 cm wide.

3.1.1.3. Flame structures and transverse ripples.

Flame structures (Walton, 1956) or streaked-out ripples (Sanders, 1960) occur frequently at the base of sub-facies C1 and C2 breccias and sandstones, the height of the 'flames' being greatest in the thicker coarser-grained beds. Normally, underlying mudstone is deformed into flames no more than a few centimetres high, the direction of overturning, with few exceptions, being constant for any one horizon. Sometimes, however, siltstone and laminated fine sandstone is also deformed into flames which can reach heights of up to 30 cm (Plate 10).

The exposed bases of beds containing flame structures display asymmetrical ripple-like forms (Plates 11 and 12) with their axes normal to the direction of overturn of the flames. The ripples are often straight-crested and continuous for short distances, but on a long expanse of bedding plane are seen to consist of rounded, highly elongate but discontinuous ridges and troughs. The amplitude of a ripple set is the same as the height of the "flames" associated with it, and varies widely from bed to bed; the wavelength also varies considerably up to a maximum of 15 cm. Grain fabric study of a thin section cut parallel to and within two or three centimetres of the rippled base of a sandstone bed indicates that there is a strong preferred alignment of the long axes of sand grains normal to the ripple axes (Fig. 4).

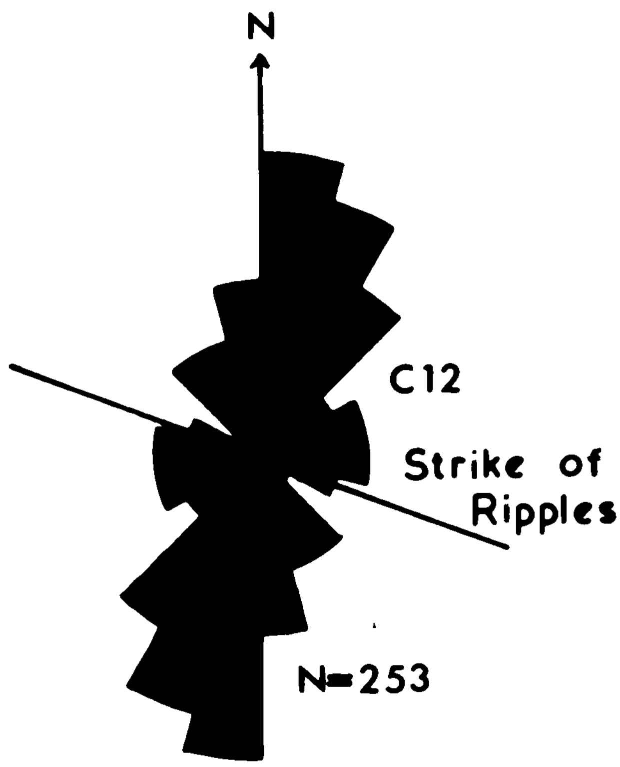


Fig. 4. Rose diagram of grain-length orientation parallel to the bedding immediately above ripples (Plate 11), showing a preferred grain alignment at right angles to the ripple trend.

Published experimental studies on grain fabric (e.g., Rusnak, 1957; Hampton and Colburn, 1967) show parallelism of long axes of grains to depositional current direction, and the result above thus confirms the impression that the features are current-generated ripples and are transverse to the generating current direction.

Sanders (1960) described the mechanism of formation of such ripples in the light of experimental work by Bagnold (1956). They were considered to arise in a bed as a spontaneous response to a current in an attempt to balance a deficiency of shearing resistance in the bottom with respect to that imposed by the fluid flow.

3.1.1.4. Loads.

Loads are common in both sub-facies C1 and C2, but are almost completely absent in sub-facies C3. In some cases (particularly in sub-facies C1) the sediment-laden currents appear to have followed each other so rapidly that expulsion of pore water and compaction did not have time to occur before deposition of a subsequent bed. Occasionally adjacent beds have become intricately mixed and "swirl" structures developed, such structures suggesting lateral flowage within an extremely wet sediment-water mixture (Plate 13). The demarcation surfaces between successive beds are often amalgamated and irregular, but are frequently without apparently eroded bases. The contact in these cases is closely analogous in appearance to the interface between two immiscible liquids (Plate ~~14~~ 13).

Other structures suggest vertical loading from above into an unconsolidated bed, such as in the two breccia beds illustrated in Plate 14. Here either the shock of arrival of a new deposit on a water-saturated bed below has caused sudden expulsion of pore water and sinking of lobes of breccia from the bed above to compensate, or differential static loading from the bed above caused expulsion of water in a volcano-like form.

3.1.1.5. Basal Scours.

Scoured bases to beds are particularly common in sub-facies C1 breccias. The erosion surfaces usually penetrate only a few centimetres into the bed below (Plate 15), but some scours are as deep as 20 cm. Most scours are shallow depressions, but some have steep walls and evidently acted as traps for sediment of coarser grain than that of the adjacent basal parts of the bed (Plate 16).

3.1.1.6. Channels.

Channels (for the purpose of this discussion) are differentiated from scours on the basis of their larger dimensions (minimum depth approximately 0.5 m), generally steeper walls, and their generally more complex history of cut and fill. Channels are commonly developed in and below sub-facies C1 breccias, and less commonly in sub-facies C2 sandstones; they have not been observed in sub-facies C3 sandstones.

One large channel, 9 m deep, was seen within the Letterettrin Member 2 between Lough Fee and Lough Muck. It was cut into sub-facies D1 mudstones and filled by sub-facies C1 breccias. The western boundary of the channel is concealed beneath the waters of Lough Muck; towards the east the channel cuts through sub-facies D1 mudstone to the underlying Facies C unit with which it merges. Lack of exposure prevented tracing of the eastern boundary. The basal contact between breccia and underlying mudstone, exposed at two points by digging, erosively cuts across laminae in the mudstone. The walls of the channel slope at a very low angle (approximately 5°). The channel-filling breccia beds are notably variable in thickness and wedge out towards the channel wall. Some slumping of beds away from the channel wall is also evident, the apparent axis of overfolding being approximately parallel to widely-separated grooves on the base of the lowest breccia bed of the fill.

Fig. 5 indicates the complexity occasionally attained in cut and fill of smaller channels. At least six stages of channel erosion are developed in a unit approximately 1.5 m thick, almost all showing a multistage history of fill (four separate sedimentation units in "g", Fig. 5). The curved layers of breccia

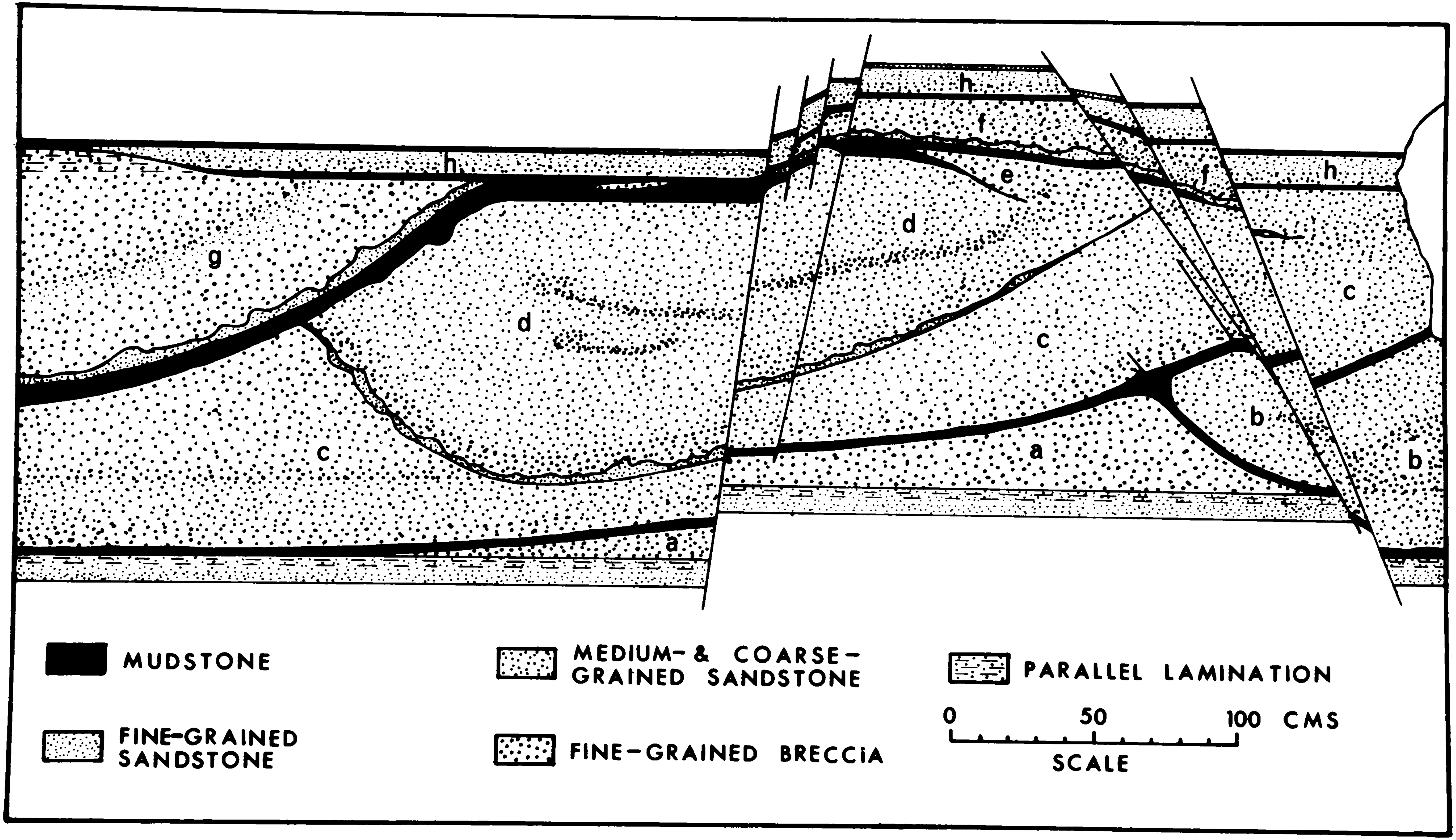


Fig. 5. Channel complex in breccias and coarse sandstones of Facies C. Locality is thirty metres north of Owengar River, section 17 (Fig. 2A).

halfway up the fill in channel "d" may represent amalgamation of two (or more) separate fills, and the history of filling of several other channels may be more complex than immediately apparent. Most erosion surfaces of channels shown in Figure 5 are immediately overlain by mudstone, suggesting that a considerable period of negligible current activity occurred following the channel erosion, allowing fine material to settle. In ~~the~~ Section 3 two channels, one 60 cms, and the other one metre deep eroded in sub-facies C2 sandstone are infilled entirely by sub-facies D2 mudstone. Evidently in all these cases the eroding current had passed on without depositing sediment.

3.1.2. Internal Structures

3.1.2.1. Nature of bedding.

Table 6 summarizes the different types of bedding developed and the distribution of types between sub-facies C1, C2 and C3. The most notable point is that 70% of sub-facies C1, and approximately 90% of sub-facies C2 and C3 show normal grading, which is thus one of the most typical features of the facies. Where internal lamination is present the normal upward sequence is: graded unit - parallel laminated unit - cross-laminated or convoluted unit (Plate 17). There are however important exceptions. Over a quarter of the beds in sub-facies C1 and 8% of those in sub-facies C2 show either no discernable grading or show reverse grading. In the former, more common, case, the beds typically have sharp, parallel bases and tops and show no internal structure. In the rarer case of reverse grading the nature of the unit is variable. A few beds (Plate 18) show a perfect uninterrupted reverse grading from fine or medium-grained sandstone to breccia without noticeable internal lamination. One example of complex grading was seen showing the sequence:

reverse grading - normal grading - reverse grading - normal grading, in one apparently uninterrupted depositional unit. The most common type of reverse grading however is of the symmetrical type, in which a fine or medium-grained sandstone at the base grades upwards into a coarse-grained sandstone or breccia towards the centre, from which point upwards normal grading occurs. Frequently parallel lamination is present below the reverse-graded portion (Plates 19 and 20).

3.1.2.2. <u>Internal Scours.</u>

In one coarse sub-facies C2 sandstone bed 1.5 m thick internal scours were noted in parts of the basal "massive" portion. The bed can be traced laterally for approximately 50 m and except for a lateral interval of about 10 m shows a normal sequence from the base of graded coarse sandstone - parallel-laminated medium sandstone - cross-laminated fine sandstone - mudstone, without any noticeable internal interruptions in sedimentation. Within the abnormal 10 m faint laminations sub-parallel to the base of the bed and to each other occur, frequently cut by internal scours up to 20 cm deep (Plate 21). The widely-spaced laminations appear to represent discontinuities in deposition of the sediment as there are frequently changes in grain size across the laminae (c.f. Facies B). There is no overall grading within the lower 90% of the bed, but fine and coarse layers alternate, with some reverse grading apparent. In some parts of the bed there seems to be a rhythmic alternation of fine and coarse layers with diffuse boundaries, sometimes dipping at a low angle to the base of the bed and resembling cross-bedding (Plate 22). In the few centimetres below the top parallel laminated portion of the bed gently-curved arcuate structures, concave upwards sometimes occur (Plate 21). They bear a superficial resemblance to the "dish structures" figured by Stauffer (1967).

3.1.2.3. Parallel Lamination.

A parallel-laminated division which occurs in many Facies C beds normally lies above the massive or graded portion of the bed. Usually the division consists of alternating coarse and fine layers with diffuse boundaries with each other, showing a progressive general upwards overall decrease in grain size. An apparent break in sedimentation sometimes occurs between the massive lower portion and the overlying parallel-laminated division (Plates 20 and 21). Occasionally, where the basal or upper surface of an individual layer is exposed, parting lineation, which Allen (1963, 1964) considered indicative of an upper flow regime, is visible. Parallel lamination also frequently occurs at the base of symmetrically-graded beds (see p.58), and occasionally a crude parallel lamination is developed throughout coarse, non-graded beds.

3.1.2.4. Cross Lamination.

A cross-laminated division, where present, invariably occupies the uppermost finest-grained portion of a bed. In plan view the surface of most beds containing cross-laminae contains nearly straight-crested asymmetric transverse ripples, although in rare cases the bed form is made up of linguoid ripples. Sometimes a sharp change in grain size occurs from the parallel-laminated division to the cross-laminated division. The ripples may be climbing or non-climbing, but normally only one cross-laminated set, averaging 3-4 cm in thickness, is present (Plate 23). Occasionally (Plate 24), however, cosets up to 20 cm thick occur. In the thicker cosets it is common for individual cross-laminated sets to be interstratified with thin parallel-laminated units of similar grain-size (Plate 24). Units consisting of alternating parallel and cross-stratified laminae are normally of medium or fine grained sandstone, and grading is generally absent.

Plots of cross-lamination azimuths show that the current directions deduced from them often bear little relationship to the direction of sole marks from the same group of beds, and in some cases the two current directions vary by nearly 180° (see later). Current azimuths plotted from cross-lamination also show considerably less variability than sole marks (Fig. 24).

3.1.2.5. Convolute Lamination

Closely associated with divisions of cross-lamination are various kinds of disturbance which can be conveniently termed convolutions. In many instances disturbance is limited to the over-steepening of cross-lamination foresets (Plate 15), while in others the tops of cross-laminated sets are overturned in the same direction as the dip of the cross-laminations (Plate 26). Sometimes parallel rather than cross-lamination appears to be disturbed, in which case it is common for a series of discontinuous ridges and furrows to occur on the surface of the bed (Plate 27). The ridges and furrows may be symmetrical or asymmetrical : if the latter, the ridges are bent over in the same direction as the dip of foresets in associated cross-laminated beds. Their axes are parallel to the axes of current ripple-marks in surrounding beds, and these convolutions also are considered to be current generated. Other forms are laminated throughout and their distorted synclinal shape suggests that they are loaded into the bed below, in similar fashion to the ripple-load convolutions described by Dzulynski and Slaczka(1965) (Plate 28). However, unlike the examples quoted in that paper the convolutions appear to be an integral part of the whole bed and form part of a normally-graded sequence without a mudstone parting beneath the convolutions. The tops of the convolutions are frequently truncated, indicating post-deformational erosion. Possibly they represent foundering of the upper layers of a bed in response to expulsion of pore water from sediment in the lower portion.

Another rarer type consists of complexely distorted laminae with truncated tops

(Plate 29), the top surfaces usually showing isolated cones and hollows with no preferred overall orientation. Convolutions of this type may represent the result of extreme current deformation, downhill creep of plastic sediment which deforms the upper laminae, or the effect of pure loading in water-saturated sediment.

3.1.2.6. Cross-bedding.

Cross-beds, in single sets up to 30 cm thick, occur associated with the graded or massive breccias and sandstones of Facies C. They most commonly occur interbedded with sub-facies C1 breccias (Plates 30, 31 and 32). In almost all cases cross-bedded sets are separated from underlying and overlying massive or graded units by a marked erosion surface: rarely they pass downwards into almost horizontally parallel laminae (Plate 31). Cross-bedded units are commonly lenticular in cross-section and individual sets can rarely be traced for more than a few metres laterally, although isolated scour pockets containing cross-bedding can sometimes be traced for some tens of metres along the same horizon. Very occasionally trough cross-bedding is developed, but this appears to be restricted to the infill of deeper scours. Most exposed top surfaces show wavy but parallel crest-lines. Rarely, cross-beds can be traced laterally into parallel-laminated beds, which also have sharp tops and sharp, erosive bases. The average grain size within the sets is similar to that of the surrounding massive or graded beds, and reaches a maximum of about 5 mm. No cross-bedding in sediments whose maximum grain size is less than 1 mm has been observed. Thin section study shows that much less matrix is present, and the sediment is much better sorted in the cross-beds than in associated graded beds of approximately the same median range of grain size (Appendix, A and B).

Plots of cross-bedding azimuths show close agreement with cross-lamination azimuths from associated beds (Fig. 24), but often show considerable variation from current directions indicated from sole marks from the same units. In one case only was a cross-bedding direction in the directly opposite sense noted, and it was separated by erosion surfaces from two beds whose sole marks indicated a current direction at right angles to that determined from the cross-bedding. The angle of cross-bedding averages between 20-25° and is of the avalanche type, showing a marked tendency to coarsen downwards.

3.1.2.7. Sheet Structures.

These structures, limited to the lower massive unlaminated portion of a bed, are relatively common in the graded breccias and coarse sandstones of sub-facies C1 and C2.

In vertical cross-section the features appear as slightly sinuous subparallel mainly vertical streaks, distinguished from the surrounding rock by their lighter colour and greater resistance to weathering. In plan view they show a rectilinear or slightly wavy, sub-parallel pattern (Plate 33) and thus have a sheet-like three-dimensional form. They occur as swarms of individuals averaging about 1 cm apart. Each sheet averages about 1 mm - 2 mm thick, the height varying from approximately 1 cm to 50 cm.

The bearings of sheets in plan vary considerably from one bed to another; in one case where six out of eight consecutive graded breccia beds contained well-developed sheet swarms bearings ranged through 90°. Most sheets are normal to the bedding, but a small percentage dip steeply (Fig. 38), or follow a highly-sinuous wave-like path upwards (Plate 20). Occasionally sheets branch downwards (Plates 34 and 35). The features may start at any point within the massive portion of a bed, usually beginning indistinctly and terminating upwards abruptly, either at the top of a bed or at an internal erosion surface (Plate 20). No sheets have been observed to penetrate into laminated sediments, and only a very few can be traced from the base of a bed. They occur only in the coarsest beds, none being observed in beds whose maximum grain size is less than 0.5 mm.

Microscopic study shows that the differences between sheet and interstitial material are very subtle. The light-coloured sheets have slightly less matrix and include slightly larger grains of quartz and feldspar than the inter-sheet material.

Grain-fabric studies were carried out on six specimens collected from the upper portion of sheet-bearing beds to determine the relationship, if any, between long-axis orientation of grains and the strike of the sheets. In all of the samples a pronounced preferred orientation of the long axes of the grains parallel to the bearing of the sheets occurred (Fig. 6). In order to check the nature of the grain orientation two vertical thin sections were cut from one sample, one section parallel to the preferred grain orientation, and the other at right angles to it. The latter showed no imbrication, while the one cut parallel showed a strong preferred dip of long axes of grains to the south (Fig. 7).

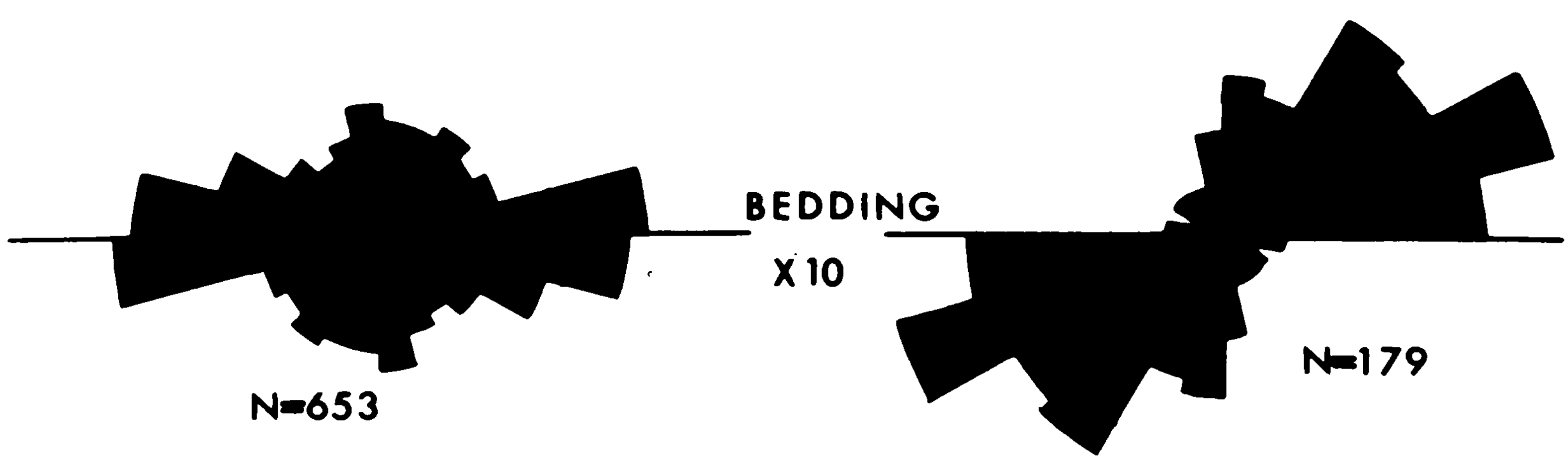


Fig. 7. Rose diagrams of long axis orientation of grains in thin sections perpendicular to bedding. A. Section perpendicular to long axis orientation. No imbrication is apparent. B. Section parallel to long axis orientation, showing strong grain imbrication.

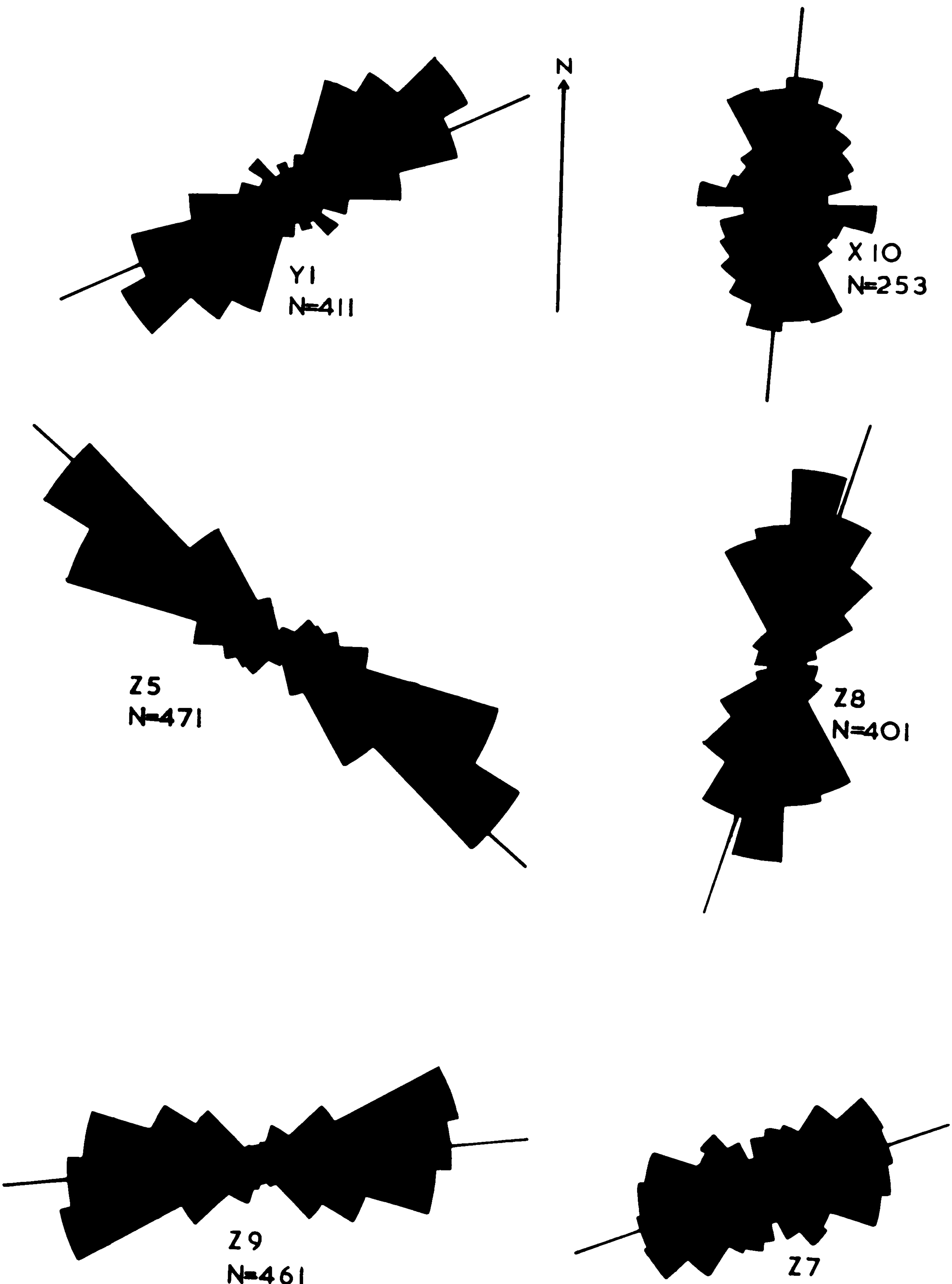


Fig. 6. Rose diagrams of long-axis orientation of grains in thin section parallel to bedding, from specimens taken from the top of beds containing sheet structures. The bearing of sheets seen in plan is indicated by a line through each rose, and in each case shows parallelism with grain orientation.

This suggests that the fabric is primary and reflects deposition of grains by a current.

Apparently identical sheet-like structures were described by Wood and Smith (1958) from the Silurian Aberystwyth Grits of Wales. These authors noted that the strike of the sheets was parallel to the strike of the bedding and of the cleavage, and considered that the structures were tectonic in origin. They believed that earthquakes or early tectonic movements disturbed the packing of grains and caused injection of the coarser and more water-laden layers into overlying finer less-mobile ones, a process they termed "auto-injection".

A tectonic origin for the sheet-structures examined by the author must however be discounted on the grounds of the wide variability of horizontal bearings of sheets from bed to bed and the lack of relationship to strike of beds, faults, or cleavage. The parallelism of the sheets to grain fabric, and the fact that they are circumscribed by bed boundaries and are often topped by an internal erosion surface, suggest that they were formed during or shortly after sedimentation of a bed and before a subsequent bed was deposited. The notable imbrication of grains parallel to the preferred long-axis orientation indicates that the observed grain fabric is of primary current origin, and not induced by sheet structure formation. Furthermore, the sheet structures follow discrete paths and apparently do not disturb the intervening sediment. If re-orientation of grains had occurred subsequent to deposition of the sediment fabric rose diagrams of a mixture of disturbed and undisturbed sediment should show in most cases a bimodal distribution of grain long axes, which is not apparent in the specimens studied.

A strikingly similar root-like pattern permeating sediment was obtained by Kuenen (1968) during experiments on the settling of sediment suspensions in water. In high density clay suspensions settling convection caused the formation of open branching tubes, up which clear water washed clay flakes, sometimes depositing them on the surface in a cone-like form similar to the sand volcanoes developed on slumps. In suspensions containing sand, veins of clean sand instead of open tubes were produced.

The similarity between the branching sheet structures occurring in the Silurian rocks and the tubes produced experimentally by Kuenen is so close that it is reasonable to assume that they had a similar origin, i.e., by settling convection. The sheet-like rather than tube-like form developed in the ancient sediments is probably a reflection of the larger grain size, the high proportion of grains with the length of the a axis greatly in excess of the length of the b and c axes, and the pronounced preferred orientation of the long axes in a horizontal plane, in these deposits.

Tube-like water escape routes initially developed around the grains would tend to coalesce into the sheets now preserved, and any surface expression would therefore be a ridge rather than the cone developed in finer or equant-grained material. By analogy with the formation of the tubes described by Kuenen each sheet represents the path taken by the upwelling portions of two adjacent convection cells, while the interstitial material between the sheets represents the path taken by the downward moving portions of adjacent cells (Fig. 8).

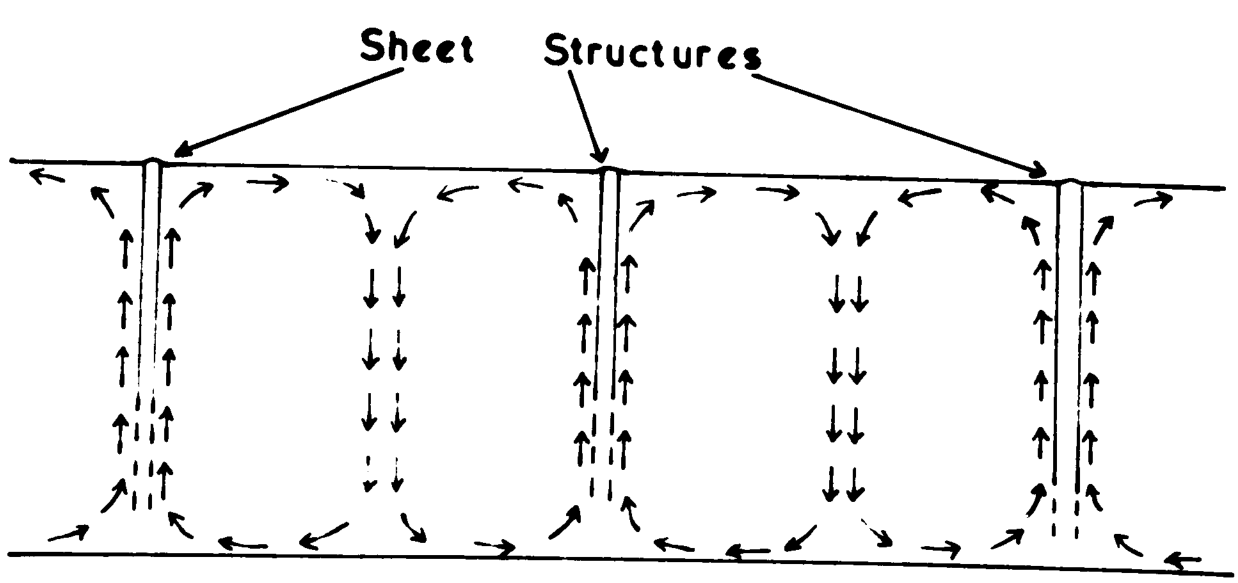


Fig. 8. Convection cells formed during the settling of grains from suspension. Sheet structures tend to form where there are upward-moving currents.

In the ascending portions of cells finer material would be carried upwards leaving a matrix-deficient residue in the sheets. Coarser grains, if not actually carried upwards, would at least have a hindered rate of settling compared with grains in the adjacent downward-convecting parts of cells. Thus at any particular level within a settling suspension coarser, better-sorted grains would occupy the ascending portions of convection cells.

Because the orientation of the sheet structures reflects grain fabric, the features can be used as a palaeocurrent indicator in a similar way to parting lineation. In instances where the sheets branch they may also be used as "a way-up" criterion, as the sheets invariably branch downwards.

Further support for the hypothesis that the sheets are developed parallel to the depositing current direction is given by the general parallelism of the bearings of sheet structures and of sole marks in associated beds, particularly in the Benchoona Member 2 of the Lettergesh Formation, where there is apparently little spread of palaeocurrent directions, and a direct comparison of sole marks and sheet structures can be made. It is noteworthy also that in the case of the Aberystwyth Grits groove casts on the base of associated beds are nearly parallel to the strike of the sheets (Wood and Smith, 1958).

3.1.2.8. Sandstone Dykes.

These occur only in the upper parallel or cross-laminated portion of sub-facies C2 graded sandstone. The dykes occur infrequently, but when they are present tend to form densely-packed swarms. The height of individual dykes varies, but is rarely greater than a few centimetres; the width varies from less than 1 mm to approximately 5 mm. Most vary considerably in thickness throughout their height and are sinuous in cross-section (Plate 36). The geometry, lack of internal structure, and the fact that sections through the dykes parallel to the bedding show them to be elongated in plan view serve to distinguish them from organic burrows, to which some of them bear a superficial resemblance. That the dykes have penetrated upwards from below is indicated by the updoming of overlying laminae in some cases. The dykes are interpreted to be the result of a reduction in pore space in thin sandstone layers resulting in expulsion of interstitial water which carried sand grains upwards with it.

3.1.2.9. Inclusions of sandstone and mudstone.

Sandstone or mudstone inclusions commonly occur in sub-facies C1 and C2, and much more rarely in sub-facies C3. The great majority of smaller inclusions occur near the top of the graded or massive division of a bed, just below the division of parallel lamination if present. Less common are beds with inclusions near the base or near the centre, generally with their long axes parallel to the bedding and occupying the same horizon. In some cases mudflakes near or at the base of a bed when traced laterally can be seen to occupy the same horizon as a continuous mudstone layer lying below the sandstone bed, and evidently the mudflakes resulted from erosion and fragmentation of this layer by the shearing effect of the sand-bearing current passing over it. Mudflakes at other horizons within an otherwise apparently homogeneous bed can also sometimes be shown to be laterally equivalent to a mudstone layer separating two sandstone units, and represent a surface of amalgamation. Some mudstone and sandstone inclusions are surrounded by a shell, up to 1 cm thick, of sandstone of similar grain size but of lighter colour than that surrounding (Plate 37). This difference could be due to slightly less matrix in the shell of the inclusion, or could be attributed to ionic exchange between mudstone and sandstone during diagenesis. A similar lightening in colour of sandstone is also sometimes evident where a bed rests directly on mudstone, while no change in grain size is evident between the lighter-coloured layer and dark-coloured sandstone above. Stanley (1964), in discussing similar "shelled" inclusions in sandstones, concluded that they were first formed by muddy fragments being torn up from the bottom by a turbulent viscous flow and then rolled along the bottom, grains of sand adhering to the still soft mud fragments as they rolled. The great length to thickness ratio of some of the inclusions (the largest seen was 110 cm long, 5 cm thick), and the lack of internal distortion of lamination which should be expected if rolling had taken place, render this explanation unlikely in the present case. The diagenatic explanation is therefore considered to be the more feasible.

Some large inclusions, particularly in breccias of sub-facies C1, are of medium or coarse sandstone commonly containing internal lamination, which frequently shows that the clasts have been contorted or rolled into balls (Plate 38). The large inclusions appear to represent ripped-up fragments of earlier deposited units, and occasionally stages in the disruptive process can be seen. Sometimes the inclusions reach very large dimensions; one raft of Facies D mudstone 2 m long was seen near the top of one thick coarse sandstone bed.

3.2. Interpretation

Three possible mechanisms can be considered for the emplacement of breccias and sandstones of Facies C:

3.2.1. Deposition from turbidity currents.

This mechanism is supported by features which are characteristic of the overwhelming majority of the beds such as a) sharp bases with occasional directional structures, b) normal grading, with a sequence of internal structures typical of a waning flow regime, c) parallel top and bottom surfaces with lateral continuity of individual beds, and d) poor sorting coupled with a high proportion of matrix.

It is more difficult to explain on the turbidity current hypothesis the occurrence of almost unidirectional cross-bedding in association with graded beds; unidirectional cross-lamination often apparently unrelated in direction to sole structures in the associated beds; massive ungraded beds; reverse or symmetrically graded beds; the rare presence of internal scours and dish-structures in the massive basal portions of graded sandstones, and the occasional separation of coarse grains in erosional pockets.

(i) Perhaps the major argument against the turbidity current hypothesis is the presence of cross-bedding associated with graded beds, although occasional instances have been recorded in the geological literature.

Poorly-developed cross-beds associated with graded units in the Ventura Basin of California have been noted by Natland and Kuenen (1951), and by Dott (1963). More recently Morey (1967) recorded relatively common trough cross-bedding associated with turbidites in the Precambrian Rove Formation. In the latter case the cross-bedding in general gave an average current direction approximately parallel to that indicated by flutes and grooves in surrounding beds. Hubert (1966) recognised cross-bedding in graded Ordovician sandy limestones in the Girvan area of Scotland, and suggested that it developed as part of a sequence of internal current structures formed by a waning flow. The cross-beds rested on an erosion surface, but were conformably overlain by first cross-lamination, then parallel lamination followed by a pelitic division forming the upper part of the typical graded turbidite sequence described by Bouma (1962). Current directions determined from cross-bedding azimuths corresponded with those calculated from flutes on the limestone soles.

Large-scale cross-bedding also occurs in Llandoverian and upper Bala turbidites in central Wales (Dr. G. Kelling, pers. comm.). Some of the cross-beds occur in megaripples which are often isolated within shale sequences. The current direction deduced from cross-bedding was often at variance with that calculated from sole marks from associated turbidites, and Kelling concluded that the cross-beds "were created by tractional currents which operated independently of any turbidite flows in that area".

It is difficult to accept the cross-bedded units in the Killary Harbour succession as part of a modified Bouma sequence of deposition from a turbidity current because of the rarity of either upwards or downward gradation into the next member of the Bouma sequence, and because of its usual appearance as isolated lenses in scour pockets. Possibly the flow regime was such that only the dune bedform was developed, but in many, if not most instances, a sequence of structures showing a waning current should be developed, which is not the case. That it is not upper flow regime antidune cross-bedding is shown by the steep dip of the foresets, which is typical of angle of repose of avalanche cross-bedding.

(ii) Extremely difficult to explain on the turbidity current hypothesis is the fact that both cross-bedding and cross-lamination current azimuths are mutually consistent in direction for great thicknesses of strata, but, in many units bear no obvious relationship to the direction of sole structures in associated beds; in many cases directions derived from sole structures are partially opposed to directions obtained from cross-stratification. Kuenen (1967) attempted to explain minor deviations between current directions derived from sole marks and those from cross-lamination by several mechanisms, but none could solve the problem of major differences in current direction.

Scott (1967) recorded considerable variations in paleocurrent directions within individual sandstone beds in a Silurian flysch succession in the Southern Uplands of Scotland. Here also a large minority of readings obtained from small-scale cross-stratification diverged more than 90° from those obtained from sole markings. Scott considered that the causes of variation included: changing resolution of gravitational forces and forces applied by fluid energy, where the current flow is other than directly downslope at a point; turbulence in association with irregular bottom topography resulting in spatial variation; interactions between turbidity currents and normal ocean currents; and multidirectional sources of turbidity currents or of normal currents depositing a single composite bed.

(iii) The presence of massive ungraded beds in otherwise normally graded turbidites sequences has been explained by Walker (1965) and by Walton (1967) as the deposits of immature turbidity currents, where no significant vertical grain sorting has had time to occur.

(iv) Reverse graded beds where the average grain size increases systematically upwards could perhaps be explained (Walker, 1965) as the result of high grain concentration and high rates of shear. Bagnold (1954) recorded that when grains of mixed sizes were sheared together the larger grains tended to drift towards the zone of least shear strain, i.e., towards the free upper surface. This could also be used to explain symmetrically graded beds, but it is more difficult to account for the normally graded top on a grain shearing hypothesis. Possibly some symmetrically graded beds are composite units, with a reverse graded lower unit and a separate normal graded upper one deposited later. Others, however, show no apparent internal discontinuity, and Walton (1967) has suggested that such a unit could represent sedimentation in the "metastable" phase of an immature turbidity current. The frequent presence of parallel lamination in the lower part of the symmetrically graded unit could be explained (Walton, op. cit.) by early deposition in the "stable" field, i.e., where deceleration of a current is sufficiently slow to allow a traction carpet with appropriate bed-form to develop. Walton (op. cit.) noted that this lowermost division of parallel lamination lying below the massive graded portion of a turbidite is not uncommon in many successions. (It occurs for instance in the Hell's Mouth Grits of Wales - Dzulynski and Walton, 1965.)

It is also of interest to mention in this context Schmincke's (1967) paper on Miocene-Pliocene lahar deposits. It has been observed that lahars are able to carry large boulders in suspension (Kuenen and Migliorini, 1950, p.122), and enormous blocks are known to have been transported by lahars over distances of at least 80 km (Gregg, 1960, p.54), and the transport mechanism is perhaps comparable to that of turbidity currents. Schminke showed that the lahar deposits of the Ellensburg Formation consist of a thin, fine-grained vaguely-stratified basal zone of sand which grades upward abruptly into a central massive zone forming the bulk of the deposit. The central zone consists of subangular to subrounded coarse sand granules and pebbles, sometimes graded and usually supported by a framework. The central and basal zones together closely resemble the symmetrically graded basal portions of the Irish Silurian Facies C breccias and sandstones.

(v) Internal scouring, dish structures, and faint anastomosing lamination, which are all extremely uncommon, could possibly have formed during the antidune phase of deposition (Middleton, 1965) from a turbidity current. The features occur only within the basal massive portion of beds where high flow regime structures would be expected. The gently-dipping laminated infill of the scours, irregular anastomosing lamination beneath them, and poorly-developed dish structure are all similar to features described and drawn by Middleton (op. cit.) in deposits formed from a current during the antidune phase of activity. Alternatively, the internal scours, together with their fill, could possibly represent separate episodes of cutting and deposition, but the lateral gradation into one apparently homogeneous or faintly laminated unscoured bed renders this explanation less likely.

(vi) The presence in scour pockets of grains much coarser than those on the adjacent unscoured base of the bed is difficult to explain on a suspension current hypothesis, as if a turbidity current had reached the depositional phase, grains of equal size would have been deposited both in the scour and on the adjacent unscoured floor. Sanders (1965) pointed out that such coarse-grained infillings must represent entrapment of coarser grains being transported as bed load.

To summarize, the bulk of strata comprising Facies C can be explained as being the deposits of turbidity currents, with the exception of features such as coarse-grained fill of scour pockets, cross-bedding, and the large discrepancy between current directions derived from sole marks and those deduced from cross-stratification.

3.2.2. Deposition by traction currents

This mechanism would explain the presence of cross-bedding, which is a common feature of traction current deposits. It could also provide an explanation for scouring, and for the infill of some scours with coarse material which could represent trapped traction current deposits. Parallel and cross-laminated beds within the sequence could also be individually explained by traction currents, and also the presence of some sole structures. However, on this hypothesis alone it is difficult to explain the rhythmic succession of graded beds showing internal features indicative of a declining flow regime; the poor sorting of sediments; the presence of massive unstratified beds; the presence of large included clasts; and the fact that all beds are sharp-based.

3.2.3. Deposition by a mass flow mechanism, such as sand flow or sand creep

Dill (1964[a]) and Shepard and Dill (1966) have noted present-day occurrences of sand flow and creep taking place in submarine canyons, which appears to occur on slopes only in excess of 20°, but elsewhere (op. cit., p.114) they recorded from a fan valley, sloping less than 7°, beyond the mouth of a canyon, a core in which the upper part was graded and overlay about 120 cm of ungraded clean sand containing scattered gravel. Such deposits they considered may have been formed by processes other than turbidity currents. Trumbull and McCamis (1967) recorded the presence of large talus blocks resting on sand on the horizontal floor of a submarine canyon. The blocks were angular and were up to 100 m distant from the nearer side wall of the canyon, and rolling from the walls seems unlikely. The authors considered that down-axis mass transport of sediment had taken place.

Stauffer (1967) considered that many deposits in the Lower Tertiary of the Santa Ynes Mountains, California, were emplaced not by suspension currents but by mass movement of sediments which he termed grain-flow. The features he interpreted as being typical of such deposits were the presence of outsize clasts; thick, ungraded, sharply-bounded beds, commonly massive except for diffuse, flat lamination; dish structure; peculiar types of sole markings; and lack of typical turbidite or traction current features. Similar features are typical of many of the massive beds included in Facies C breccias and sandstones, which could therefore be the result of a similar process.

Stauffer (op. cit.) citing Bagnold's (1956) experiments on grain flow considered that granular material under only slight dispersion would flow spontaneously on a slope of 18° provided only that it could maintain its dispersion. The initial dispersion could be accomplished by initial sliding on a steep slope, and the flow once dispersed would be self-sustaining on lesser slopes. There is abundant evidence in the sequences comprising Facies C breccias and sandstones of the presence of some slope, as slumping and pull-apart of beds is very common (see under "Slumps", p.97).

An apparent break in sedimentation occasionally occurs between the massive lower portion of graded beds and the overlying division of parallel lamination (see p.59 and Plates 20 and 21), and it is notable that sheet structures invariably terminate at the upper boundary of the massive division (see p.63). This supports Sanders (1965) view that the lower portion of some beds was emplaced by a mechanism different from that which deposited the overlying stratified sequence. Sanders argued that such cases may indicate a combination of inertia-flow bed load deposits not necessarily connected with turbidity current deposition, and an overlying turbidity current deposit showing traction with fallout features. Such a distinction is often difficult or impossible to make, however, especially as many of the features considered by Sanders to be typical of bed-load deposits may be produced by immature turbidity currents.

Although the action of some type of mass flow mechanism could explain many of the massive relatively featureless beds included in the three facies, it still fails to explain both the very common occurrence of graded bedding, often with internal structures suggesting a waning flow throughout deposition of the bed, and the common presence of traction current features such as cross-stratification.

3.2.4. Conclusions

It has been shown above that deposition by turbidity currents, traction currents, or mass flow mechanisms can individually explain many of the features common to Facies C sediments, but not all. Of the three mechanisms considered the turbidity current hypothesis best fits the facts, and can account without difficulty for the emplacement of the overwhelming majority of the beds. It is possible that mass flow also played a part in the deposition of the thicker, massive beds, but as Walton (1967, p.314) pointed out it is extremely difficult to distinguish between deposits of the two types of mechanism, and no attempt to do so will be made here, particularly as in some cases the deposits of one appear to pass laterally without break into the deposits of the other. As it is difficult to explain the presence of coarse cross-bedding and the lack of relationship between cross-stratification in general with sole structures it seems necessary to invoke traction current activity at least for the formation of much of the cross-strata. Reworking or transport of some sediment by traction currents offers an explanation for abrupt breaks or changes in grain-size often apparent between the lower massive portion of a bed and the upper cross- or parallel-laminated division.

In summary, therefore, it is considered that the great bulk of beds were deposited by turbidity currents, perhaps associated in some instances with sand flow or creep on the steeper slopes. The tops of many of the turbidites were then reworked by traction currents.

4. Facies D. Mudstone or siltstone with intercalated thin sharp-based sandstone beds.

4.1. Description

This facies is found interlayered with the graded sandstones and breccias of Facies C in units varying from a few centimetres to a maximum of 120 m in thickness.

It consists of siltstone or silty mudstone with thin intercalations of fine-grained sandstone varying in thickness from a little less than 5 cm to laminae one grain thick.

To assist in a study of the distribution of the facies and in regional mapping, the mudstones were subdivided into two sub-facies, D1 and D2. Sub-facies D1 consists of mudstone containing sandstone beds between one and five centimetres thick, the sandstone/mudstone ratio being approximately 1/1. Beds 5 cm or more thick are included in sub-facies C3. This distinction is not as arbitrary as it appears, as the great majority of the sandstones in the sub-facies average approximately 2 - 3 cm in thickness. Sub-facies D2 comprises mainly mudstone containing thin beds or laminae of fine or very-fine-grained sandstone.

The sandstone beds of sub-facies D1 are notably parallel-bedded with sharp bases and tops, and are usually laterally continuous for the length of outcrop (i.e., up to 100 m). Grading is rare, and is restricted to the thicker beds. The majority of the sandstone beds are parallel- or cross-laminated (Plate 39), the cross-lamination occurring in single sets. Current directions shown by the cross-laminations are consistent within any one facies unit (except for some extremely rare reverse directions - see Chapter 4, p.125), and are normally consistent with those from surrounding Facies C sandstones. Convoluted tops to beds are common, the axes almost always being parallel to the axes of ripples in adjacent beds.

The thin sandstone beds of sub-facies D2 are structureless, parallel-laminated, or, more rarely, cross-laminated, and are frequently disturbed by loading into the underlying mudstone. In wave-washed coastal exposures mudstone units are seen often to be finely laminated and banded light and dark grey (Plate 40), the colour differentiation reflecting slight differences in grain size. The finer-grained bands sometimes have diffuse bases and tops, are parallel-bedded, and laterally continuous, at least over the extent of outcrop.

Sole marks, which are extremely rare in both sub-facies, consist of fine grooves (some less than 0.5 mm wide) and brush marks, which occur on the base of beds as thin as 6 mm.

Some horizons in both sub-facies show evidence of bioturbation, and sometimes horizontal burrows and trails are present. The only fossils found consisted of a broken coral fragment and comminuted pieces of a coelenterate.

Facies D mudstone units are found in all members of the Lettergesh Formation, in the Glencraff Formation, and in the lower part of the Lower Member of the Lough Muck Formation. They commonly occur in units of a few tens of centimetres or less, but some units are up to 120 m thick and are accorded member status. Sub-facies D2 is found in thick units only near the base of the studied succession, and comprises part of the Gowlaun Member, and Garraun Members 2 and 4 of the Lettergesh Formation. Sub-facies D1 makes its appearance higher in the sequence, and comprises Benchoona Member 4, much of Benchoona Members 2 and 3, and also most of the Owengar Member.

4.2. Interpretation

The close association of the facies with the turbidite facies C, the sharp bases of most of the sandstone beds, their lateral continuity and the occasional presence of grooves, suggest that at least some of these sandstones also accumulated from turbidity currents. However, the overwhelming majority of the sandstones of sub-facies D1 are non-graded and are generally either parallel- or cross-laminated, suggesting traction current activity. This is also indicated by the parallelism of cross-lamination azimuths with those of the surrounding Facies C sandstones which are regarded to be reworked by bottom traction currents (see p.77). The lack of climbing ripples also supports traction current activity, as it indicates that the ripples were not being fed by sand from suspension during their formation (Kuenen, 1967). Probably both turbidity and traction currents were active, the deposits of turbidity currents being later reworked by bottom traction currents.

The general scarcity of current-generated structures in the thin sandstone beds of sub-facies D2 suggests a quiet environment of deposition, probably deep basinal, where fine-grained material was able to accumulate largely from suspension beyond the zone of strong current activity. Similar banded mudstones are found in the deepest parts of present-day basins on the continental borderland off the coast of California (Gorsline and Emery, 1959).

5. Facies E. Massive fossiliferous mudstones and siltstones

5.1. Description

In appearance Facies E is superficially similar to sub-facies D2, but in contrast to it the mudstones and siltstones are completely structureless. Some horizons occupying several metres are horizontally or sometimes vertically burrowed, the burrows being filled by slightly coarser material than that surrounding. Fossils of benthonic organisms (mainly gastropods and brachiopods) occur scattered throughout individual units. The facies is restricted to the Lough Muck and Salrock Formations, and is particularly well-developed in the Middle Member of the Lough Muck Formation.

5.2. Interpretation

The absence of coarse material and of current structures suggests that the fine sediments of the facies were deposited from suspension. The relative prevalence of burrows, the presence of fossils of benthonic organisms and its limitation stratigraphically to a position above the turbidites of the Lettergesh Formation, suggest an environment of no great depth.

6. Facies F. Mudstone or siltstone with discontinuous laminae and streaks of fine sandstone ("Silty Streak")

6.1. Description

Facies F grades vertically and probably laterally into massive mudstones and siltstones of Facies E. It consists of fine or very fine sandstone laminae varying from about 1 mm - 5 mm thick in a matrix of siltstone or mudstone. Some laminae are continuous throughout an outcrop, but most die out rapidly laterally within a few centimetres and give a streaky appearance to the rock (Plate 41). Rare laminae show a wavy form and fine cross-lamination is occasionally present. The thicker fine sandstone laminae have gradational bases. Burrows are often present and body fossils, mainly gastropods and brachiopods, also occur. The facies differs from sub-facies D2 mudstones in the absence of turbidites and sandstone beds or laminae with sharp bases, and in the streaky, discontinuous nature of the laminae. In appearance Facies F closely resembles the Silty Streak Facies described by de Raaf et al (1965) from the Carboniferous of North Devon. The facies is restricted to the Lough Muck and Salrock Formations and is particularly common towards the top of the Middle Member of the former formation.

6.2. Interpretation

The general absence or only rare occurrence of cross-lamination and the gradational bases of sandstone laminae suggest generally quiet depositional conditions with weak traction currents bringing in occasional coarser sediment, while most of the finer material was deposited from suspension. The alternations of siltstone and fine sandstone suggest fluctuating sediment supply or current activity, and in general suggest a slightly more active environment than that in which Facies E mudstones and siltstones were deposited.

7. Facies G. Mudstone or siltstone with bundles of fine sandstone laminae ("Oscillatory Facies")

7.1. Description

The facies consists of alternating units of coarse and fine material often giving a rhythmically banded appearance to the rock. The finer beds consist of mudstone or siltstone with streaks or fine laminae of fine or very fine sandstone (i.e., Facies F), and grade rapidly into the coarser beds which are made up of bundles of fine sandstone laminae or streaks, each about 1 mm thick (Plate 42). Occasional wavy or cross-lamination may be present in the coarser units. Burrows are often present, but no body fossils have been found. In appearance the facies is closely similar to the Oscillatory 2 Facies described by de Raaf *et al* (*op. cit.*). It has a gradational vertical relationship with Facies F. The facies is relatively uncommon and is best developed in the upper part of the Middle Member of the Lough Muck Formation north of Lough Muck, although it also occurs in the Salrock Formation.

7.2. Interpretation

The higher proportion with respect to Facies F of sandstone relative to siltstone and mudstone suggests either greater current activity or a more constant source of supply. The sediment is fine-grained however and cross-lamination is very uncommon, suggesting that currents were still relatively weak. The common rhythmic banding could perhaps be explained either by rhythmically fluctuating currents or sediment supply, or both. The rhythms could be introduced by seasonal variations in supply, or by the influence of storms or tidal currents elsewhere on sediment supply.

8. Facies H. Siltstone or mudstone with thin parallel- or cross-laminated beds of fine sandstone

8.1. Description

The facies comprises thin fine-grained laterally discontinuous irregular sandstone beds parallel or cross-laminated throughout, separated by mudstone or siltstone. Individual beds commonly have gradational bases, and average about 2 cm in thickness (Plate 43). The cross-laminae occur as single sets which occasionally form isolated ripples. The facies superficially resembles both Facies F and D1 but differs from the former in that the sandstone units are thicker and cross-lamination is much more abundant. The sandstones differ from those of sub-facies D1 in lacking sharp bases, in irregularity of form, and in lateral discontinuity. Both vertical and horizontal burrows are relatively common. The facies sometimes has gradational relationships with Facies F beds, but more commonly occurs in association with massive channel sandstones of Facies I. No body or trace fossils have been observed. Facies H occurs in the Salrock Formation and in the Lower and Middle Members of the Lough Muck Formation.

8.2. Interpretation

The high proportion of cross-lamination and coarse sediment suggests stronger and more prevalent currents and a more continuous sediment supply than in Facies F or G. A relatively active, shallow water environment is indicated.

9. Facies I. Massive erosive-based sandstone

9.1. Description

The facies comprises medium to fine-grained arkosic greywackes with notably poor sorting (Appendix, A and B). Groups of beds occur in units up to 7 m thick, and are ungraded and massive apart from occasional very faint lamination or a diffuse banding (Plate 44). This banding often has erosive contacts with the unit below, suggesting amalgamation of two beds. A break in sedimentation is also occasionally demonstrated by a laterally continuous film of mudstone within a thick, otherwise apparently homogeneous unit (Fig. 9). Individual beds occur up to 1 m thick, but the average thickness of the layers separated by the banding is 15 - 20 cms. Beds can rarely be traced for more than a few metres laterally, as they commonly wedge out or are cut out by erosion from above.

The bases of sandstone units are sharp, notably irregular, and sometimes loaded, but without directional sole structures. In some cases the base is seen to be sharply cross-cutting (Plate 45). Smaller sandstone bodies lie in shallow channels in underlying finer-grained sediments, as in Fig. 9. In this example the bearing of the channel wall could be measured, the width/depth ratio being 10. Other channels, although seen only in outcrop face, also appeared to have a similarly high width/depth ratio. Internal erosion and channelling within sandstone complexes is also very common (Plate 46). Some sandstone bodies wedge or lens out rapidly without apparent erosion of the underlying strata, and in rarer instances thin and merge imperceptibly with laminated siltstones of Facies H. Although not obviously erosively based these sandstones are in all other respects identical with those above erosion surfaces, and are included in Facies I.

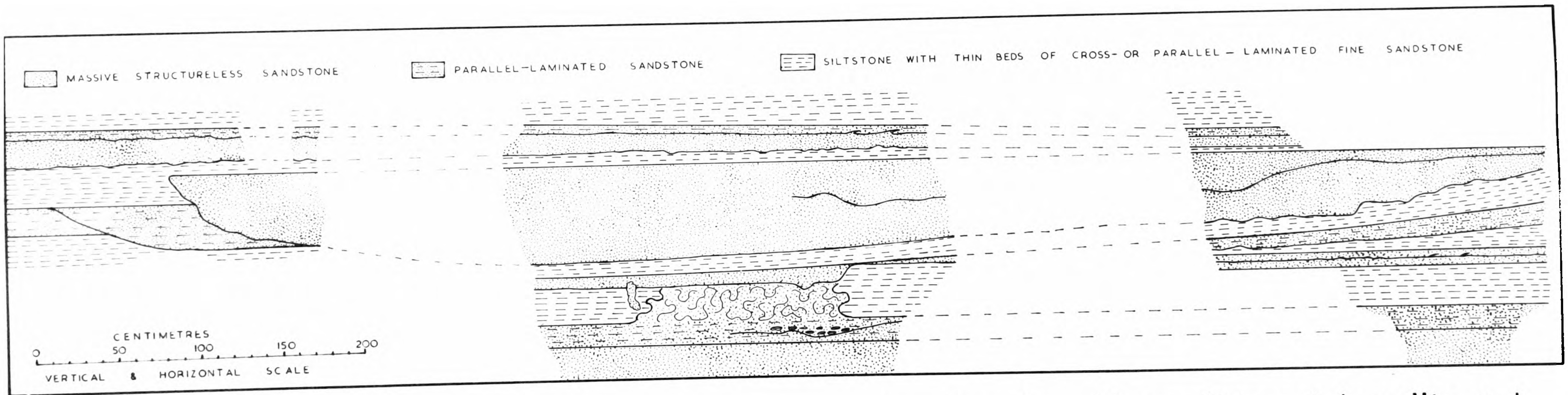


Fig. 9. Massive sandstone beds of Facies I filling shallow channels. Note the multi-stage history of channelling and filling, and indications of amalgamation of beds to form thick units in the case of the upper massive channel-fill sandstone and the lowest parallel-laminated sandstone bed. Note also the lateral thinning of the topmost massive sandstone bed. Lower Member, Lough Muck Formation (Section 17, Fig. 2A).

The base of the lowermost sandstone bed of a unit sometimes contains mudflake breccia, concentrations of fossils (dominantly brachiopods), or very occasionally quartz granules (Plates 47 and 48). Less commonly mudflake breccias and fossil horizons occur higher in a sandstone complex, and these also when traced laterally are usually seen to lie within the erosive base of a separate sandstone bed. In rare instances fossils are also concentrated in siltstone or mudstone immediately underlying a massive sandstone bed with fossils at its base. No fossils were noted in growth position.

The sandstones of this facies are restricted to the Lough Muck Formation. They occur commonly in the Lower Member of the Formation, and sporadically throughout the Middle Member. They are rare in the eastern half of the Killary Harbour area where they occur only as thin units in the Lower Member of the Lough Muck Formation.

9.2. Interpretation

Possible mechanisms of deposition of the massive sandstones can be grouped under four headings: traction currents, turbidity currents, slumping, and mass flow mechanisms such as sand flow or creep.

9.2.1. Traction current deposition

The presence of fossils, mudflakes, and sometimes granules at the base of some of the sandstones invites comparison with traction current deposits filling channels in estuarine and fluviatile environments, where such coarse fragments constitute a basal lag (e.g., Oomkens and Terwindt, 1960). However, the lack of a sequence of internal structures suggesting a waning flow regime common in traction current deposits filling channels, and the absence of current lamination argues against deposition by traction currents. Further, the massive sandstones are much more poorly sorted than undoubted traction current deposits higher in the sequence (Appendix, B). The traction current hypothesis is therefore considered extremely unlikely.

9.2.2. Turbidity current deposition

The occurrence of channels and of sharp and erosive bases to beds could all be accounted for by turbidity current erosion. Although no internal structures are apparent in most beds the sediment could have been deposited from turbidity currents under upper flow regime conditions too rapidly for bed forms and the accompanying sedimentary structures to develop. The poor sorting and greywacke texture of the sandstones is typical of turbidites and compares closely with that shown by fine-grained turbidites lower in the succession (Appendix, B). The presence of quartz granules at the base of some beds may reflect crude grading during deposition from an immature turbidity current, and absence of grading and of lamination is considered by some authors, e.g. Walker (1965) to be characteristic of such units.

However, it is more difficult to explain on this hypothesis the commonly highly irregular bases of beds, common channelling, lateral impersistence of individual beds, and lack of lateral gradation from massive sandstones into recognisable turbidites. The graded beds which occasionally occur in association with massive sandstone complexes are distinguished from the latter by having sharp, flat bases sometimes bearing sole marks, parallel bedding, lateral persistence, lack of channelling, and frequent occurrence of parallel lamination above the massive interval perhaps indicating a declining flow regime.

9.2.3. Slumping

In one instance a massive sandstone bed resting erosively on underlying sediments

contained rare sandstone inclusions which could represent slump balls. Recognisable slumps, showing all variations between local overfolds with one limb still in situ to massive siltstones containing unassimilated slump balls of fine sandstone, are occasionally associated with the massive sandstone beds, and it is possible that the massive sandstone beds represent completely homogenised slumped material.
Many of the "channelled" surfaces could represent slump scars, although this is unlikely as most of the surfaces are irregular indicating erosion.

9.2.4. Sand flow or sand creep

Deposition by sand flow or sand creep could explain the sharp bases and tops of beds, rapid lateral wedging out, and more particularly their structureless nature. The lack of sorting of grains is comparable with that shown by sandstones (Facies B) believed to have been deposited by some such mechanism (Appendix, B). As earlier mentioned, sand flows have only been observed to take place on relatively steep slopes, but there is evidence that the facies was deposited in a slope environment (see Chapter 4, p.132). Stauffer (1967) described channels floored with mudflake breccia in deposits which he considered to have been emplaced by mass movement of grains, and Dill (1964) cited evidence suggesting that the glacier-like creep of sand in some present-day submarine canyons has considerable erosive power. Clearly, therefore, sand creep could have been responsible for the high degree of channelling and the irregularity of bedding characterisitc of the facies. The hypothesis however does not explain the occasional concentration of quartz granules at the base of beds.

9.2.5. Conclusions

It is difficult to reach a definite conclusion on the mechanism involved in deposition of beds of this facies as they bear no close resemblance to any described from the literature.

None of the mechanisms considered above completely explain all the features exhibited by the massive sandstones, and particularly difficult to explain is the association of massive sandstones with undoubted traction current deposits, slump deposits, and possible turbidites. It is considered that deposition by sand creep or by immature turbidity currents are the most likely possibilities, but until further studies have been carried out on modern deposits known to have been emplaced by this means certainty is not possible. Recent oceanographic work (e.g., Shepard and Dill, 1966) has shown that in some restricted environments, e.g., submarine canyons, several transport mechanisms operate at different times, and therefore an association of mass flow, traction current, turbidity current, and slump deposits often occurs.

10. Facies J. Sandstone with medium-scale "herring-bone" cross-bedding

10.1. Description

This facies consists of medium-grained, well-sorted cross-bedded sandstone with little matrix (Appendix, B). The cross-beds occur as isolated lenses or as continuous beds in mudstone or siltstone, commonly forming cosets between 0.5 - 3 m thick. Each coset comprises several cross-beds between 10 cms and 30 cms in individual thickness, often arranged in a herring-bone pattern with azimuths falling on two opposed modes (Fig. 10, and Plate 49). Groups of isolated sets also normally show a bimodal distribution of current directions which holds good for the Lough Muck Formation throughout the area. (Fig. 19). Occasionally, especially near the base of the uppermost member of the Lough Muck Formation, sets of unidirectional cross-beds also occur, but as they are indistinguishable in appearance from the bimodal sets they are included in this facies.

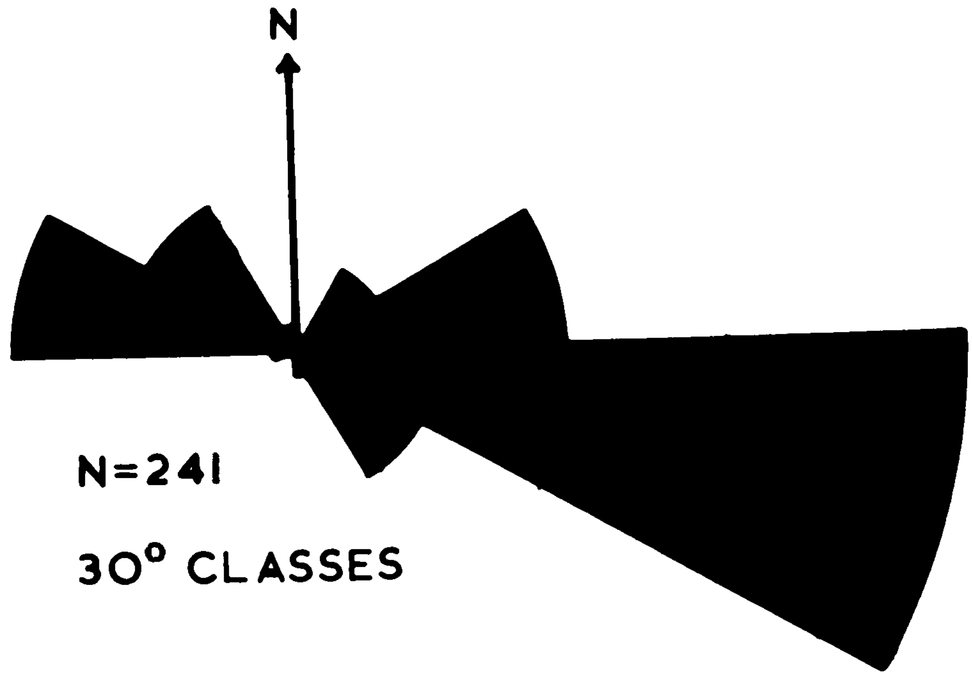


Fig. 10. Current rose diagram of cross-bedding azimuths in Facies J, Upper Member, Lough Muck Formation, showing bimodal distribution.

Frequently, when cosets of two or more units are present individual sets are separated from their neighbours by clay laminae 1 - 2 mm thick, each lamination being draped over the underlying cross-bed. The bases of beds are flat-lying and relatively sharp-based. The angle of cross-stratification varies, but averages between 20 - 25°. Exposed top surfaces of units show that the cross-beds are straight-crested. Brachiopods, crinoid fragments, and vertical and horizontal burrows are sometimes present.

The facies is very common in the Upper Member of the Lough Muck Formation, and also occurs in the Salrock Formation.

10.2. Interpretation

The abundance of cross-bedding indicates a highly-active environment in which currents were of sufficient competence to move medium-grained sand in dunes across the sea floor. The bimodally-opposed distribution of current directions suggests a current which at times reversed its direction, and the frequent occurrence of clay drapes between cross-bedded sets suggests a period of cessation or near-cessation of current activity. The most likely explanation for such features is the action of tidal currents along a shallow sea floor.

11. Facies K. Sandstone with small-scale cross-bedding of variable direction ("Knitted beds")

11.1. Description

The facies consists of medium to fine-grained well-sorted sandstone units ranging in thickness from approximately one metre to a maximum of six metres. Units are cross-stratified throughout, the cross-stratified sets ranging widely in thickness from approximately 0.5 cm to 10 cm, but sets usually average 1 - 2 cm. The cross-stratification changes abruptly in direction from bed to bed, and sets with opposed current directions, separated by scours, commonly occur at the same horizon. Frequently the cross-lamination direction changes several times within a few centimetres at the same horizon giving sandstones of this facies a "knitted" appearance, and making it quite distinct from the herring-bone cross-bedded sandstones of Facies J into which it sometimes grades. Sorting is good, but not as marked as that of Facies J (Appendix, B). Occasionally, small symmetrical scours, usually less than one centimetre deep, are present within the sandstone unit, and in such cases the crests of the ripples are also symmetrical (Plate 50). In some instances a thin sandstone lamina is draped over the crest of a ripple originally asymmetrical in form and apparently current-derived, to result in a symmetrical final form. Vertical and horizontal burrows are relatively frequent in this facies. Clay drapes are occasionally present.

The facies is restricted to the upper portion of the Upper Member of the Lough Muck Formation, and to the Salrock Formation.

11.2. Interpretation

The abundance of cross-stratification suggests a high energy environment, and the abrupt changes in direction of the cross-stratification within short distances suggests currents of extremely variable direction. The relative absence of clay laminae indicates that fine-grained material, if originally present, was unable to settle because of continued agitation. The most likely agent is considered to be wave action in shallow water which would account for the rarity of clay drapes, the presence of small scoops, the symmetrical form of many of the ripples, and the variability of the cross-lamination directions. Some of the larger, more continuous cross-stratified sets may have originated as current ripples, but have subsequently undergone modification by wave-action.

12. Facies L. Parallel-bedded sandstones, parallel-laminated throughout

12.1. Description

This facies consists of medium to fine-grained sandstones interbedded with mudstone and siltstone. The beds occur in association with cross-bedded sandstones of Facies J in the Upper Member of the Lough Muck Formation and in the Salrock Formation, and also occur as isolated beds within Facies M Spaghetti Beds. Beds average between 10-30 cms in thickness, and are strongly parallel-laminated throughout. No parting lineation was seen on exposed top or bottom surfaces. Bases may be either relatively sharp or gradational. Individual units have parallel tops and bases and are laterally continuous for considerable distances without significant change in thickness (Plate 51). Burrows, both vertical and horizontal, are sometimes present and also some body fossils, consisting of brachiopods, trilobites, or crinoid fragments. Clay partings are also sometimes present between two adjacent beds, but beds showing this feature are almost entirely restricted to the Lough Muck Formation. Most sandstones (referred to sub-facies L1) are well-sorted, the sorting being closely comparable to that shown by Facies J cross-bedded sandstones (Appendix, B). Exceptions are members of the facies which occur in units 5-7 metres thick limited to the Upper Member of the Lough Muck Formation in the Knockraff area (sub-facies L2). These beds are finer-grained and the degree of sorting is notably poorer than in other developments of the facies (Appendix, B).

12.2. Interpretation

The internal lamination and absence of parting lineation suggests that the beds were deposited by currents in the lower part of the lower flow regime. The occasional presence of clay drapes and the common association of the sub-facies with the tidally-deposited Facies J in the Lough Muck Formation indicates that in these instances it was also probably deposited by tidal currents. In the Salrock Formation, where clay drapes are rare in association, non-tidal traction currents must have been involved.

13. Facies M. Mudstone with lenticles or isolated lenses of fine sandstone ("Spaghetti beds")

13.1. Description

The facies is dominantly fine-grained, with fine sandstone or siltstone lenses separated by mudstone laminae averaging 1 mm thick, giving an anastomosing pattern in cross-section (Plate 52). The irregular, wavy pattern of the mudstone laminae gives outcrops of the facies a distinctive, spaghetti-like appearance. Microscopic study of the siltstone lenticles reveals that they are cross-laminated and appear to be isolated current ripples. The cross-lamination appears in cross-section to be bi- or poly directional. Ripple trains sometimes show a symmetrically undulating upper surface of average wavelength about 5 cm and amplitude 1 cm or less, underlain by variably-directed cross-laminated sandstone similar in appearance to the "knitted" sandstones of Facies K (Plate 53). Small scours, generally less than 1 cm deep, are also sometimes present. Poorly preserved gasteropods were found in one locality and an isolated Lingula at another in this facies; vertical and horizontal burrowing, although present, is not common. Units of cross-bedded sandstone (Facies J) and parallel-laminated sandstone (Facies L) occur as isolated interbeds within the Spaghetti Beds.

The facies is restricted to the upper part of the Upper Member of the Lough Muck Formation, and to the Salrock Formation. It makes up a large portion of the latter formation in the east of the area, but the facies thins to the west, and near the coast it occupies a thickness of only 70 m near the base of the formation.

13.2. Interpretation

The presence of cross-laminated sandstones suggests a moderately high-energy environment, with currents of sufficient competancy to transport fine sand. The occurrence of the sandstone bodies as isolated ripples indicates a paucity of sediment supply. The symmetrical wave form of the surfaces of the isolated ripples, the abrupt change in cross-lamination direction within a single lens, and the presence of small scours suggests wave activity (c.f. Facies K), although in this case the action of waves was not sufficient to erode mudstone already deposited, and presumably wave activity was sufficiently intermittent to allow muddy sediments time to settle. The relative lack of sediments coarser than fine sand, and the rarity of organic remains coupled with the presence of Lingula suggests that the facies represents a restricted environment of sedimentation in an embayment or lagoon probably protected from the open sea. The evidence of wave activity on a small scale indicates very shallow water conditions.

14. Facies N. Tuff

14.1. Description

Vitric tuff beds of acid or intermediate composition occur in the Lettergesh, Glencraff, and Salrock Formations, eight horizons being recognised. As noted earlier (Chapter 2, p.27), in thin section most tuffs are seen to have a vitroclastic texture with angular fragments mainly of quartz and feldspar with rare rounded exotic lithic clasts of quartzite and volcanic rock, in an altered sericitic matrix. Units, comprising several beds, range in thickness from 10 cm to 6 m, individual beds varying in thickness from a few centimetres to 50 cm. Because of their relatively structureless nature tuff beds are hard to recognise in the field, and even when recognised are difficult to follow laterally. Occasionally surfaces weather a distinctive cream colour which serves to differentiate the tuffs from surrounding grey or orange weathering sandstones or siltstones. Beds are usually very fine-grained and have a conchoidal fracture. Tuff horizons appear and disappear abruptly in the sedimentary column, individual beds have parallel, sharp bases and tops, and most are laterally continuous for at least several kilometres (see Chapter 2). The lowest tuff unit in the Salrock Formation is notable in varying unsystematically in thickness laterally from 50 cm to

120 cm, although it can be traced continuously (apart from breaks in exposure) throughout the area. No sole structures have been seen except for occasional loads.

Most tuffs are structureless, but some coarser beds occasionally show grading from coarse to fine upwards, and a few are parallel-laminated either throughout their thickness or in the upper portion only. Three of the tuff horizons in the Salrock Formation differ from the others in showing complex internal distortion with beds deformed into elongate lobes which sometimes penetrate horizontal tuff beds below like loads (Plates 54 and 55). Beds with these structures are sandwiched between tuffs showing parallel lamination and occasionally cross-lamination. Body fossils and burrows are absent, except for one locality, where casts of *Orthoceras* are present in the tuff marking the top of the Glencraff Formation.

14.2. Interpretation

The normally graded nature of some of the tuffs can be explained by different settling velocities of ash particles of different sizes falling through water. Parallel lamination can be attributed to current activity during or immediately after the ash fall reworking the ash. The sharp bases of individual beds and the abrupt incoming of tuff horizons reflects the spasmodic nature of volcanic eruptions and resulting ash falls. The apparently randomly varying thickness of one of the tuff units may be explained either by deposition on an irregular sea floor topography with ash tending to drift into hollows, or post-depositional erosion of the tuff. The lobe-like internal distortions of some beds perhaps represents loading of coarser into finer horizons, possibly with the effects of some downslope movement superimposed, and the ptygmatic folding occasionally present may be likened to flame structures generated by loading. The disturbances also somewhat resemble the "quicksand structures" described by Selley et al (1963) from the Torridonian of Skye and Raasay and believed by them to have been formed in very shallow water. All tuffs were probably deposited under aqueous conditions as shown by occasional grading, the presence of rare rounded exotic clasts, parallel and cross-lamination, the latter two points suggesting reworking by aqueous currents, and the tuffs of the Glencraff Formation were evidently deposited under marine conditions as indicated by the marine fossils.

15. Slumps

15.1. Introduction

Although slumps are not a facies they are an environmental indicator and are therefore best considered in the context of sedimentary facies. Because folding due to loading is sometimes confused with slump folds the latter are here defined as gravity-induced folds whose lateral component of movement exceeds in magnitude any vertical component.

Slump structures occur throughout most of the stratigraphic column and are represented in all formations except for the Salrock. They may occur as rotational slumps, slump overfolds, or be represented by beds containing detached folds and balls of sandstone.

15.2. Beds with slump overfolds or detached folds and balls

In the turbidite facies C slumps of this nature are relatively common and usually involve a single bed only which is overlain and underlain by undisturbed sediment. Slump folds are generally detached and tightly curled (Plate 56). Although folding is often relatively complex, fold axes within any one bed are commonly subparallel to each other. Direction of slope cannot be obtained in the case of detached folds, but where axial bearings of folds are reasonably consistent within a bed they are taken as an indication of the palaeostrike at the time of sedimentation (see Chapter 4, p.122).

The fine-grained Facies D is also frequently slumped, the slumps taking the form of either attached or detached folds. Also relatively common are slurried Facies D horizons, the chaotic fragments of sandstone and mudstone often passing laterally into undisturbed beds of the same thickness.

Slumped beds make up a considerable proportion of the Lower Member of the Lough Muck Formation, where they are interbedded with a variety of facies. Most slump horizons here are represented by thick siltstone units with scattered hooks and balls of laminated fine sandstone (Plate 57), although a few overfolds with one limb attached may also be present.

The coarser laminated facies making up the Middle Member of the Lough Muck Formation (Facies F, G, and H) often also show slump structures. These range from ptygmatic-type plastic folds suggesting slow downslope creep of unconsolidated sediment, to local overfolds in otherwise undisturbed strata (Plate 58). A horizon of slump overfolds occurs just within the base of the Upper Member of the Lough Muck Formation in the Knockraff area (Plate 59). These involve several metres of strata and numerous individual beds. The slumps are apparently of local extent only, as they are seen to pass laterally westwards into undisturbed Facies J and L sandstones near Knockraff, and were not seen east of Bunnaviskaun.

No slumps were seen at higher stratigraphic levels in the Lough Muck Formation, or in the Salrock Formation.

15.3. <u>Rotational slumps</u>

Curved, commonly dish-shaped, discordant surfaces occur near the top of the

Middle Member of the Lough Muck Formation. They are almost entirely limited to the stratigraphic interval 20 metres below the transition to cross-bedded sandstone which marks the base of the Upper Member, the greatest concentration being found in the top few metres of the Middle Member.

15.3.1. Description of discordances

The more important characteristics of the discordances are:

a) The outcrop traces are invariably smooth, planar or gently curved, concave upwards, with a maximum gradient of 30° with respect to the regional attitude of the surrounding strata. The lowest portion of a discordance is either gently concave upwards or planar, following a bedding plane for some distance, often several metres. A part of one discordant surface seen in three dimensions was smoothly curved without polishing or slicken-siding. The thickness of strata intersected by the surfaces is commonly between 1 - 2 metres, but in rare cases is up to 5 metres.

b) Strata contained within the curved surface of a discordance are invariably identical in lithology to that of the surrounding or immediately overlying sediments.

c) Contained strata fall into one of two categories. Either beds form drapes subparallel to the discordant surface, each bed thickening towards the centre and decreasing in concavity upwards until the beds become horizontal (Plate 60), or the contained strata form a packet of beds resting at an angle to the base and margins of the feature (Plates 61 and 62). The former type occurs at the coast (section 9, Fig.2A), while the latter category appears to be restricted to a strip 150 metres long north of Lough Muck (section 15, Fig.2A; and Fig.11).

d) Packets of dipping strata are often cut by internal planar or slightly curved discordant surfaces. Matching of beds above and below the discordances almost

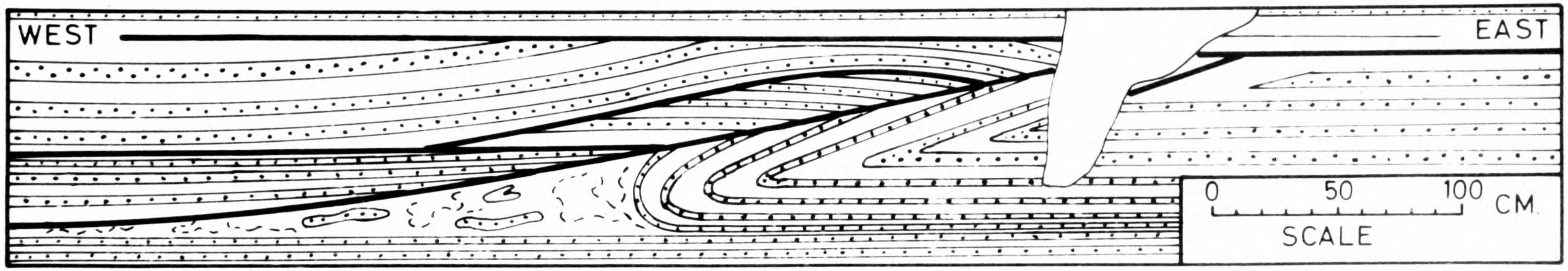


Fig. 13. Strata folded by slump packets overriding towards the right of the figure (see Fig.11,1). Legend is the same as for Fig.12.

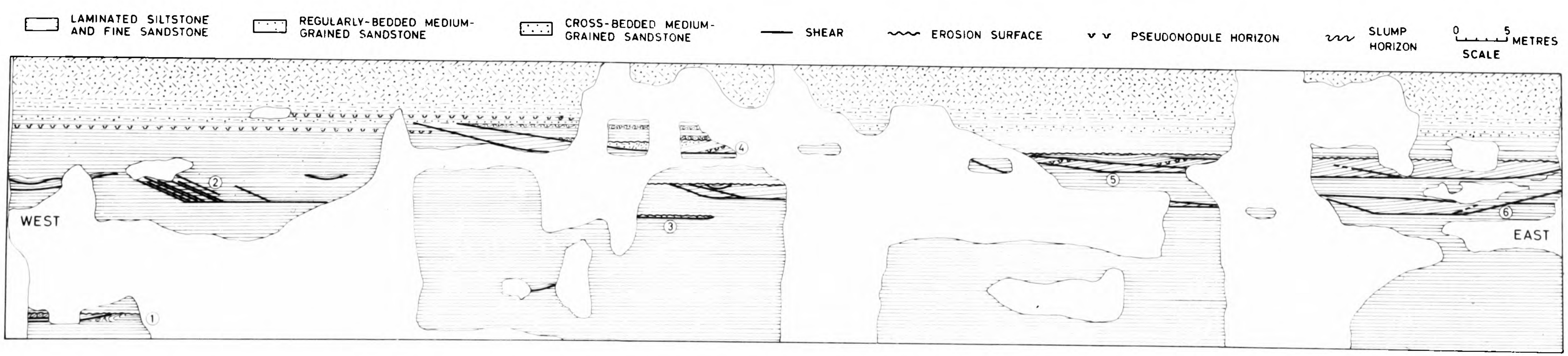


Fig. 11. Field relationships of discordances in the Lough Muck area. Areas left blank represent no exposure.

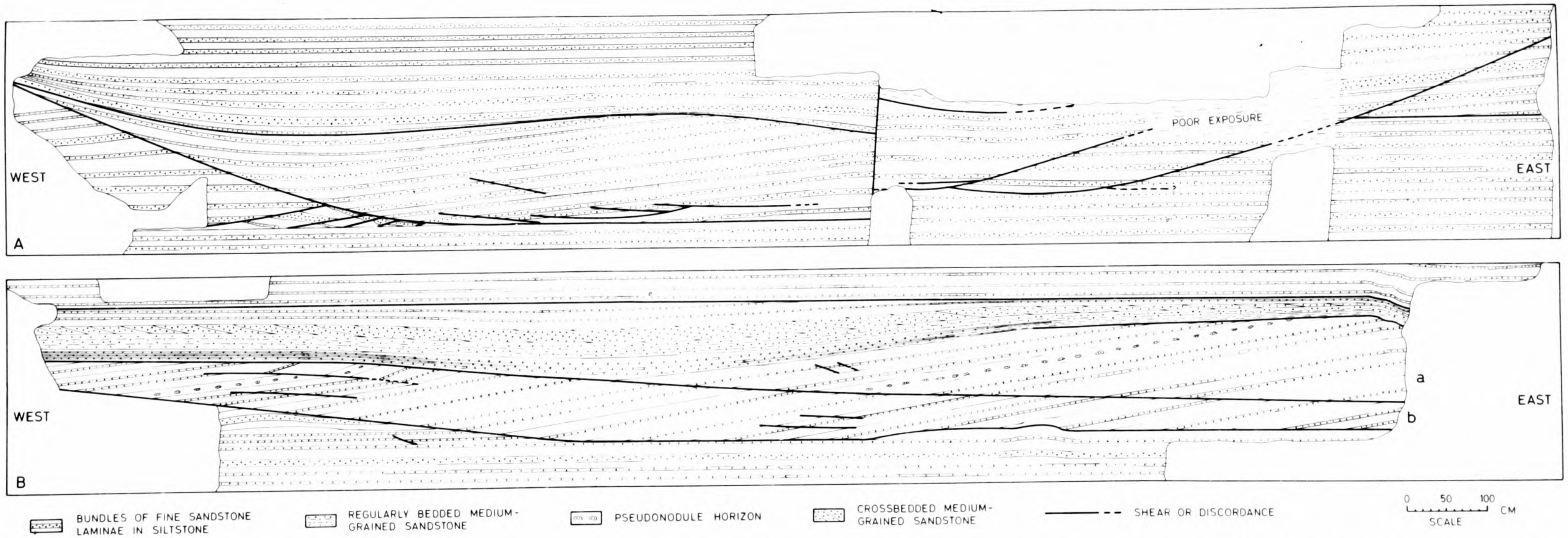


Fig.12. A. Rotational slump with well-developed internal shears near the base of the packet, the upper strata showing drag effects (see Fig.11,6). Note also the thrusts below the base of the shear surface indicating movement in the same sense, i.e. towards the right of the figure.

B. Double slump (see Plate 62, and Fig.11,5). Slump packet a has moved to the right relative to the packet b below, an indication of the relative amount of movement being given by the displacement of the dislocated pseudonodule horizon. The hole left by movement of a to the right contains draped fill indicating that dislocation was syndepositional.

invariably indicates that the upper strata have moved eastwards relative to those below (Figs. 12 A and B). In one case (Fig. 12B) where a pseudonodule horizon is cut by an internal discordant surface relative lateral displacement across it is of the order of several metres.

e) Strata immediately above a surface of discordance frequently show drag effects (e.g., Fig. 12A), the direction of drag always suggesting movement from west to east. In the exposure shown in figure 12A the effects of drag increase upwards from nil near the base of the dipping packet until near the top approximately 4 metres of bedding plane are affected. In the same figure strata immediately beneath the surface of discordance show thrust effects indicating drag from above in an easterly direction.

f) The dip of strata within packets contained by the discordant surfaces is, with very few exceptions, in the same direction, i.e., towards the west.

g) The top bounding surface of packets is often planar overlain by horizontal strata. In other instances the top surface is gently curved, concave upwards, with overlying sediments draped over the top.

h) In one example (Figs. 13 and 11, no. 1) subjacent strata are overfolded by a small overriding packet, indicating movement of the packet to the east.

i) Low angle faults of small displacement (up to 12 cm) occur (Fig. 11, no. 2), with the direction of displacement also to the east. All of the small faults die out abruptly below at the same horizon. The faults also die out upwards but the nature of the transition is not seen because of poor exposure.

15.3.2. Origin of the discordances

Tectonic movements as an origin for the discordances must be ruled out, for although they could account for angular discordance and lateral displacement along surfaces of shear, the fact that anomalously-dipping packets of beds and surfaces of discordance are overlain by draped sediment indicates that the processes involved were contemporaneous with deposition of strata.

The dish-shaped cross-sections of the discordances superficially resemble those of erosion channels, and the presence of such channels has been recorded from similar fossil sedimentary environments (e.g., Seilacher and Meischner, 1965). However, channels typically show an irregular outline indicating erosion, and commonly contain fill with sedimentary structures showing evidence of the activity of a higher depositional flow regime than the sediments into which the channels were cut. The invariably smooth margins of the features coupled with the lithological identity of strata inside and outside the curved discordant surfaces renders an erosive origin of the features unacceptable. Although lateral accretion deposits in channels typically have a low sedimentary dip, there is no evidence of a change in flow regime sufficient to erode a channel and deposit high flow regime sediments. The nature of the strata indicates that the flow regime has not changed significantly from that existing before formation of the discordant surfaces.

All of the characteristics described above are compatible with contemporaneous slumping, the dipping packets of strata representing beds rotated during movement along curved shear surfaces, and the dish-like features with draped sedimentary fill representing slump scars. The overwhelming weight of evidence suggests that movement has occurred in a generally easterly direction. The slump packet illustrated in figure 12A shows fracturing at the base and drag effects against the shear plane increasing upwards. Otherwise deformation of bedding within each slump packet is small, and it is unlikely that the packets have moved far. This is corroborated by the presence of a pseudonodule horizon in three of the rotated slump packets which can probably be matched with the lower of two undisturbed similar horizons to the west and stratigraphically above the packets (see Fig.11). Both horizons die out laterally within about 20 metres, and it is therefore likely that the slump packets are of extremely local origin.

15.3.3. Stages in the development of the rotational slumps

The above described features have many characteristics in common with contemporaneous subaerial downslope movements under gravity variously called "slumps" and "structural-break slides" in which blocks show rotation suggesting movement along a basal shear surface (e.g., MacDonald, 1915; Becker, 1916). The close similarity between the observed features of subaerial rotational slips and the Silurian slumps suggests a similar mechanism and sequence of events. An attempt to reconstruct the probable process of slumping is given in Figure 14. The first stage is the appearance of tension cracks, usually gently curved, and small step faults at the upslope end. The mass then slides slowly forward causing low-angle shears and thrusts to develop at the downslope end. Rotation about the curved shear surface develops, the upper end of the packet subsiding and the toe rising. The part of the toe protruding above the surface may either shear and continue to move downslope independently or be slowly eroded. If the toe of the slide continues downslope as a discrete mass it may rotate and the packet may apparently dip upslope (see Fig.11, no.3). At the upper end of the packet the hole left by slumping is slowly filled in by draping sediment.

15.3.4. Genesis of the slumps

Most previous authors writing about the genesis of slumps have tended to

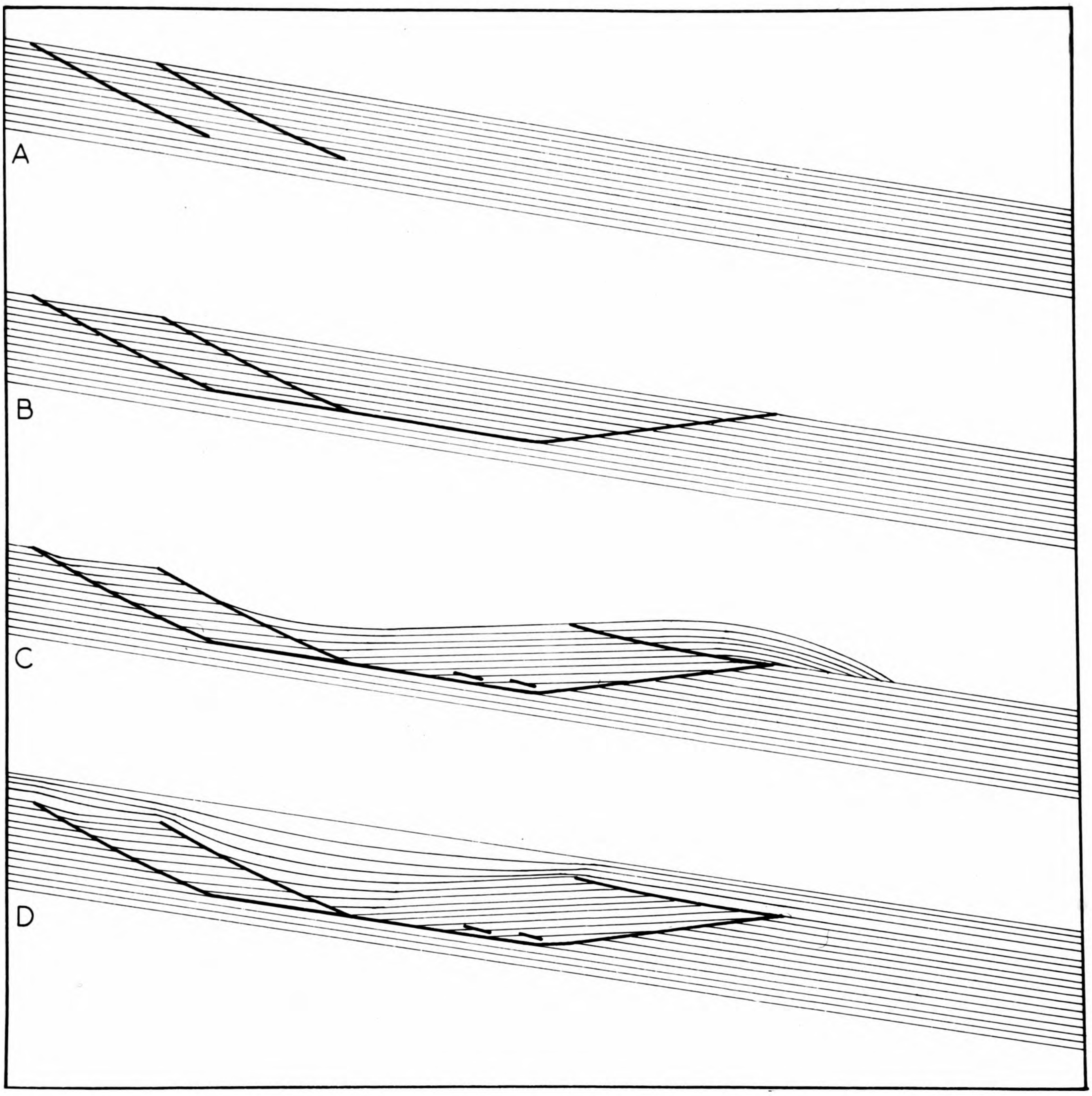


Fig. 14. Theoretical reconstruction of slumping history.

A. Tension cracks develop.

B. Slow downslope movement begins, step-faulting occurs and low-angle cracks develop downslope.

C. The whole mass slides forward and rotates, the upper end of the packet subsiding and the toe rising. Adjustment to rotation takes the form of plastic drag folding and of fracture. The part of the toe protruding above the sediment surface may shear and move downslope independently.

D. The hole left by sliding is slowly filled in by draping sediment.

consider thixotropic mixtures in a metastable state, failure being induced by a variety of external factors which disturb the internal structure sufficiently to cause slumping (e.g., Dott, 1963). However, it is evident in the case under discussion that the rotated slump packets were in at least a semi-consolidated state by the time slumping was initiated. This suggests that the sediments were laid down under stable conditions on a sea floor whose slope was not sufficient to cause spontaneous slumping. A catastrophic event such as an earthquake, sudden sedimentary loading, unusually vigorous impact of waves or tidal currents, tectonic tilting of the sea floor, or removal of support by undercutting of slopes seems to be required. The latter has in fact been suggested as the cause of rotational slumping in the Carboniferous of western Pennsylvania (Williams et al, 1965), where slumping occurred as a result of slope failure on the banks of fluviatile channels. Slump packets under these conditions bear a symmetrical relationship to each other across the original channel, being rotated in opposite directions. The Irish rotational slumps however indicate slumping from one direction only; neither is there any evidence in the surrounding strata of wave activity. However, any of the other possibilities can be seriously entertained.

15.3.5. Discussion

Without the presence of associated rotated slump packets it would, in many cases, be very difficult to prove that dish-shaped discordances with draped fill represent slump scars. It is probable that in some parts of the stratigraphic record elsewhere such features have in fact been mistaken for channels. The criteria listed in Table 8 may serve to aid in distinguishing the two.

TABLE 8. COMPARATIVE FEATURES OF CHANNELS AND SLUMP SCARS

	Slump scars	Channels
1.	The walls and floor are in general smoothly curved, but may follow a bedding surface in part.	The walls and floor are irregular and show evidence of erosion.
2.	The fill is similar in lithology and facies to the sediment immediately surrounding and overlying the scar.	The fill is often different in lithology and facies from the sediment in which the channel is cut. A lag deposit may be present at the base.
3.	The fill normally consists of layers of sediment draped into the scar, the concavity of the drapes increasing upwards until the layers become horizontal.	The fill may be horizontal (vertical accretion) or dip at a low angle (lateral accretion), both types being cut off abruptly against the channel wall. If however the eroding current has not deposited sediments, the fill may be draped as for a slump scar.
4.	Small shears or contortions which do not affect the infilling sediments may be present in strata immediately beneath the scar as a result of drag by the sliding packet above.	Disturbances, if present, are likely to affect both fill and surrounding sediments.

15.4. Environmental significance

Slumps may occur in almost any environment which contains a floor with sufficient slope for sliding of sediment to occur. This may occur on slopes of less than 1° (Shepard, 1955), given the right grade of sediment and conditions of sedimentation, but on the other hand unconsolidated modern sediments are known to rest at slope angles of up to 18° (Moore, 1961), or even 35° - 40° (Trumbull and McCamis, 1967). The occurrence of slumping in the geological record is therefore an indication of the presence of a palaeoslope only, and does not give information on the magnitude of such a slope.

It is possibly significant that slumps occur in all formations up to and including the Middle Member of the Lough Muck Formation, but are absent from the Upper Member and from the Salrock Formation. Perhaps sediment making up the former group of formations and members was deposited on slopes, while sediment deposited to form the upper Lough Muck and Salrock Formations was deposited on a flat or nearly flat floor. Although such an interpretation must be approached with caution in view of evidence quoted above that unconsolidated sediment can rest in a stable position at high slope angles, an environmental change occurring at the junction between the Upper and Lower Members of the Lough Muck Formation is also supported by trace fossil evidence (see next section).

16. Trace Fossils

16.1. Introduction

Trace fossils, like slumps, are not a facies in themselves but being of great environmental significance they are also treated in association with sedimentary facies.

16.2. Horizontal trails

These occur sparingly on the soles of graded sandstone beds of Facies C and more commonly on the exposed soles of beds of Facies F, J, and L. In the case of turbidite beds trails commonly occur as sinuous rounded ridges of low relief, of maximum width 2 cm but generally much less. Trails on the bases of beds of Facies L, M, and O are typically rectilinear with many separate trails crisscrossing, and of maximum width about 2 mm (Plate 63).

16.3. Horizontal burrows

These occur throughout most of the stratigraphic column. They are particularly well-exposed on the soles of sandstones of Facies C and D, and on the bases of Facies E and F siltstones. Although horizontal burrows occur higher in the sequence in the Lough Muck and Salrock Formations they are not as common as vertical burrows. The majority of horizontal burrows resemble Granularia (Plate 64), which is a branching burrow very commonly found in some flysch sequences (Seilacher, 1962), and was regarded by that writer to be a postdepositional burrow. It is found on the base of beds up to one metre in thickness, but is most common on the soles of beds belonging to Facies D where in some localities almost every unit within a vertical interval of several metres displays the burrow. The only other type of horizontal burrow seen was short and cigar-shaped, the width averaging about 0.5 cm and the length 2 cm (Plate 65). On rare occasions where burrows and current-derived sole marks occur on the same sole the burrows disturb the current structures (Plate 65), indicating that the burrows were postdepositional. Some thick units of massive or striped mudstones and siltstones (Facies E and F) in the Middle Member of the Lough Muck Formation, and also the siltstones of Facies D, contain numerous horizontal burrows throughout which give the rock a distinctive mottled appearance (Plate 66).

16.4. Vertical burrows

Vertical burrows are almost limited in stratigraphic extent to the Upper Member of the Lough Muck Formation and to the Salrock Formation, although rare isolated vertical burrows also occur in the Lower Member of the Lough Muck Formation. Their first major appearance is with the incoming of herring-bone cross-bedded sandstones (Facies J) or parallel-bedded sandstones (Facies L), and from here upwards in the stratigraphic succession vertical burrows predominate over horizontal ones. Vertical burrows are never numerous enough to mottle the host rock as with horizontal burrows, and they occur only as widely separated individuals. They never exceed more than a few centimetres in height, and generally have a diameter of 5 mm or less.

16.5. Environmental significance

Little environmental significance can be attached to the presence of horizontal burrows throughout the bulk of the succession. The dominant type of branching burrow occurs on the soles both of turbidite sandstones and of fossiliferous mudstones and siltstones of probably relatively shallow-water origin, and this type of trace fossil cannot therefore be used as an environmental indicator. The change from horizontal to dominantly vertical burrowing, however, is significant in the context of environment. Seilacher (1967) showed that there was a gradation from vertical burrows in the shallowest to horizontal and increasingly patterned burrows in the deepest deposits. This he attributed to vertical burrows being formed by suspension feeders in a zone of agitated water, and to horizontal burrows being formed by sediment feeders in quieter, deeper water. The change from horizontal to dominantly vertical burrows occurs at the base of the Upper Member of the Lough Muck Member with the incoming of sediments regarded to be deposited by tidal currents, and corroborates the other evidence of a change to shallow-water conditions.

CHAPTER 4

FACIES ASSOCIATIONS

1. Turbidite Association

1.1. Description

This association consists of Facies A (ungraded conglomerate), Facies B (thick massive or pebbly sandstone), Facies C (graded breccias and sandstones), and also Facies D siltstones. It forms the whole of the Upper Owenduff Group and part of the overlying Lower Member of the Lough Muck Formation. The broad facies relationships are shown in Fig.15, with more detailed relationships involving the Benchoona Members indicated in Fig. 16.

Piper (1967) has shown that massive sandstones of the Gowlaun Member of the Lettergesh Formation wedge out eastwards into mudstones and siltstones in the vicinity of Lettershanbally. In the west of the area, between Lough Fee and the coast, conglomerate amd massive sandstone units of the Gowlaun Member pass laterally westwards into Facies D siltstones containing thin turbidites. The area of facies change on the western slopes of Altnagaighera is concealed by bog, but lateral transition between the two lithological units evidently occurs within the space of approximately 100 m. Such an abrupt change could be explained either by channelling of one facies into the other, or by interfingering of the two. In view of the rapid wedging out of conglomerates and sandstones into mudstones and siltstones shown to occur near Lettershanbally (Piper, op.cit.) this explanation is preferred to the possibility of channelling.

Above the Gowlaun Member, the occasional interbedding of thick units of Facies D siltstone or tuff horizons between turbidite successions enables the otherwise relatively homogeneous mass of sandstones and breccias to be divided into mappable sequences, in each of which lateral facies changes can be followed. The units which can be traced most easily in this manner are the four Benchoona Members.

Facies A and B in the Benchoona Member 1 of the Lettergesh Formation interbed with and pass laterally into one another. Conglomerate wedges out very rapidly into massive or pebbly sandstone, and where lateral exposure is good is often seen to form lenticular bodies within Facies B sandstone. Units of Facies A and B pass rapidly both vertically and laterally by interfingering into units of Facies C on the summit of Lettershanbally. To the west, the thickness and number of interbedded turbidite units increases until approximately 600 m west of the summit almost all of the stratigraphic column is taken up by turbidites (Fig.17).

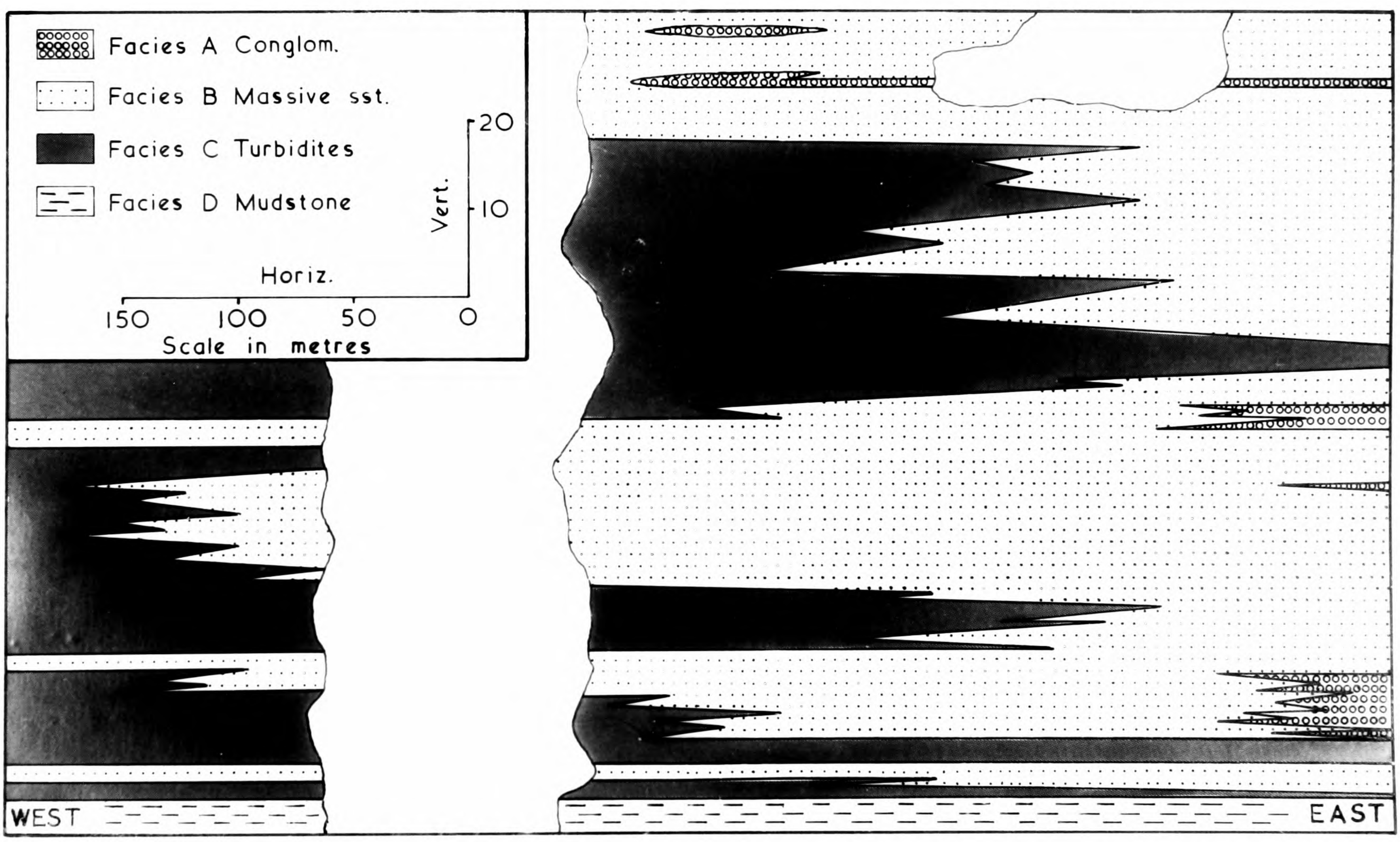


Fig.17. Lateral and vertical relationships between facies A, B, and C in the Lettershanbally area. Note the lenticular and wedge-shaped nature of the conglomerate bodies which die out westwards into massive sandstones, and the increasing proportion of turbidites to the west. The summit of Lettershanbally lies in the south-east corner of the figure.

Concomitant with the westward increase in proportion of turbidites to massive sandstones and conglomerates is the systematic and rapid decrease in thickness of Benchoona Member 1, which reaches its greatest thickness on Lettershanbally, where conglomerates and massive sandstones of Facies A and B also achieve maximum importance. East of Lettershanbally turbidites also interbed with massive sandstones of Facies B at the top of the Gowlaun Member in Glenglosh and on Tonalee.

The westward thinning of the Benchoona Member 1 occurs in conjunction with a westward diminution of grain size from conglomerates of Facies A on Lettershanbally through breccias and then sandstones of Facies C. With increasing distance to the west, also, the member contains more siltstones of Facies D (Fig.16). The Member has sharp upper and lower contacts with Facies D siltstones.

Directional sole marks and cross-laminated tops of sandstones both show currents from a generally easterly direction between Lettershanbally and Lough Fee, with a progressive swing in direction west of this to a north-easterly direction. Current data east of Lettershanbally are scarce: one measured cross-lamination dip showed currents derived from the north, a direction supported by other cross-laminated beds seen in cross-section only.

The upper three Benchoona Members are well-exposed only over a maximum distance of 5½ km., from the western slopes of Benchoona to the eastern end of Lough Fee. However, even in this short distance the second and fourth members show considerable lateral variation in thickness and facies, and some is also evident in Member 3 (Fig.16).

In general Member 2 coarsens upward from siltstone of Facies D with upward increasing thickness of interlaminated fine sandstone beds into sandstones and then fine breccias of Facies C. East of Benchoona there is a rapid thinning from approximately 24m to 14m over a distance of about 2 km due to a decrease in the proportion of sub-facies C1 breccias and a general decrease in grain size.

Current directions derived from grooves, grain orientation studies, and slump axes are sparse, but when coupled with the eastward thinning suggest currents from the north-north-west to north-west in the westernmost exposures, from the north-west to west in the vicinity of Benchoona, and from the west near Illaunroe. Thus from the limited current data available and the pattern of thinning it appears that there is a systematic eastward swing in current direction from north-north-west to west.

Member 3, like Member 2, is in its lower portion composed of Facies D siltstones, and inthe upper portion of massive breccias of Facies C, but the tendency to coarsen upwards throughout the Member, although present, is not nearly so marked as in Member 2. It is sharply overlain by the alternating siltstones and fine sandstones of Member 4.

The member remains at a nearly constant thickness of approximately 37m for the western half of its well-exposed outcrop, but east of Benchoona (Section 7, Fig.2A) it thins slightly so that at Illaunroe (Section 21B) it is 33m thick. The slight eastwards thinning apparently occurs as the result of thinning of the coarser beds, for although immediately east of Illaunroe (Section 22) the member as a whole is slightly thicker the coarser upper portion is thinner than immediately west of Illaunroe (Section 21B), which in turn is thinner than that at Garraun. The eastward thinning is accompanied by a general eastward fining of units. Finer-grained facies interbedding with Facies C breccias are more common in the Illaunroe sections (Sections 21A and 22) than in those to the west. Also, the breccia units are on the average coarser-grained in the Garraun and Benchoona sections than in sections both east and west of them.

Current directions obtained from grooves, flutes, prods, parting lineation, sheet structures, and basal transverse ripples indicate currents from the western quadrant in the east of the area. In the vicinity of Benchoona ~~some~~ directions from the north and north-east, occur ~~occur with ones from the west and north-west~~, while in sections to the west (sections 3 and 4, Fig.2A), although western or north-western derived current directions are still present, some currents evidently originate from the north-east. This fan-shaped pattern of current directions supports the lateral variation in grain size of the coarser sediments already noted.

Member 4 consists of alternating siltstones and fine-sandstones of Facies D. It shows a marked eastward thinning from 24 m in the west to just over 10m in the east.

The apparent fan-shaped distribution and at least partly northern source of the palaeocurrents determined from sole marks from Members 2 and 3 is not reflected by directions obtained from cross-stratification. Not only the fine-grained Facies D sandstones of Members 2, 3, and 4, but also the cross-laminated tops of Facies C turbidites, and cross-bedded breccias indicate persistent currents from the west. Cross-bedding has a sporadic regional distribution, but occurs most commonly in the vicinity of Benchoona in Benchoona Members 2 and 3. There is a greater concentration towards the top of each member in all cases where cross-bedding is present.

A further example of lateral thickness changes is given by Letterettrin Member 2 of the Lettergesh Formation (Fig.15). Like Members 2 and 3 of the Benchoona Formation, the lowest one third consists of alternating sandstone and siltstone of Facies D, which passes up rapidly through a small thickness of turbidites of sub-facies C2 and C3 into Facies C1 breccias. The upper third consists once more of fine-grained beds of Facies D which rest abruptly on the breccias. The member reaches a maximum thickness of approximately 65 m near the Owengar River (section 17, Fig. 2A, and Fig. 15), and thins both eastwards and westwards from this point. To the west the member is exposed only at one locality, and here it has thinned to 15 m at the expense of both coarse and fine-grained facies. The thick breccia unit occupying the central portion of the member to the east is represented to the west by 65 cm of medium-grained sandstone of Facies C. To the east of the Owengar River the member thins largely at the expense of the lower fine-grained portion. No notable change in grain size of the central coarse-grained unit is evident eastwards. Apart from the much greater thickness of the member at the Owengar River, it is characterised at this locality by possessing a channel, 9 m deep and filled with breccia, cut into Facies D beds above the central coarse unit. Rare grooves on the base of breccia beds filling the channel indicate a north-south current direction, which is corroborated by readings taken from the wall of a small channel cut into breccia infill. Current directions derived from cross-laminated sandstones both above and below the breccia however indicate a current from the west (Fig. 15). Units of cross-bedded breccia, limited to the upper part of the breccia unit beneath the large channel in the Owengar River section, although seen only in cross-section, also suggest a westerly current.

Above Letterettrin Member 2 another unit can be distinguished bounded below by Letterettrin Member 2 and above by a tuff horizon. This unit is approximately 120 m thick north of Lough Fee (section 17 and 24, Fig. 2A), but thins rapidly westwards to approximately 20 m west of Lough Muck (section 13, Fig. 2A). This rapid thinning is accompanied by westward fining of sediments, as breccias of Facies C, common in the two eastern sections, are absent in the western one. The unit is poorly exposed east of section 24, and the tuff horizon could not be traced, so it is impossible to determine any lateral variation to the east. Current directions, derived both from sole markings and cross-laminations, all indicate a northern source.

Lateral relationships within other units are [redacted] difficult to assess because of poor exposure in critical areas or because of lack of satisfactory marker horizons. Facies D beds in the Glencraff Formation show no systematic lateral variation in total thickness or in facies throughout the Killary Harbour area. The Garraun Members of the Lettergesh Formation show a general eastward thinning. This appears to be at the expense of both sandstone and siltstone units. No sole marks were seen on any sandstone beds, but cross-laminated tops of turbidite units indicate currents derived from the north-east.

In summary, the palaeocurrent pattern shown by the Turbidite Association indicates a direction from the northeast for the Garraun Members and for Benchoona Member 1 of the Lettergesh Formation. Current directions determined from the soles of turbidites from above Benchoona Member 2 to the top of Letterettrin Member 2 show a wide spread from west through north to east, while cross-stratification indicates almost unidirectional currents from the west, with little spread. From the coarse facies of Letterettrin Member 2 upwards to the base of the Glencraff Formation sole structures indicate that currents are from the north, a pattern echoed by current directions obtained from cross-lamination. Current directions obtained from sole marks (no cross-lamination directions could be measured) show that a swing to the north-west occurs in the Glencraff Formation, a pattern continued into the base of the Lough Muck Formation, although a slightly more westerly pattern is evident from the Knockraff area (Fig.16).

1.2. Relationship to other Facies Associations

The lower boundary of the Turbidite Association coincides with the junction between the Lettergesh and older formations. As noted earlier the base of the Lettergesh Formation rests unconformably on Connemara Schist in the west, interfingers with the fossiliferous Kilbride Formation in the central portion of the Killary Harbour area, and rests on the red mudstones and siltstones of the Tonalee Formation in the east.

The upper boundary of the association is transitional into units of the Erosive-based Massive Sandstone Association and is dealt with in detail in connection with that association.

1.3. Interpretation of Environment

Although detailed study was not carried out on the Gowlaun Member sandstones and conglomerates, the interfingering of units of Facies A and B into units of sub-facies D2 siltstones both near Lettershanbally and the coast suggests a lens or wedge-like body of sediment intruding into an otherwise quiet environment where pelagic deposition was typical. All the coarse material in the upper Gowlaun Member appears to have been transported in the form of a series of sand flows along the bottom as indicated by the abrupt wedging out of beds without any transition into siltstones. That it was only a temporary interruption of quiet conditions is suggested by the fact that siltstones of sub-facies D2 not only interfinger with but blanket the wedge of coarse sediment, at least west of Lough Fee.

The main episode of turbidity current activity began with the deposition of the Garraun Members in the western half of the area only, followed by the regional influx of turbidity current deposits represented by the overlying Benchoona Members. The lenticular shape of Benchoona Member 1 and the wedge shape of Members 2 and 3 in cross-section, coupled with associated lateral facies changes and a fan-like distribution of current directions determined from sole structures in Member 3, suggests that at least Members 1, 2, and 3 have been deposited as submarine turbidite fans. The conglomerates and massive sandstones occurring in Benchoona Member 1 at Lettershanbally probably represent the proximal portion of a fan. Such environments are known to contain associations of conglomerates with massive structureless sandstone and interbedded turbidites, and have been recorded to pass laterally into turbidites in the median and more distal portions of fans (Shepard and Dill, 1966). This provides a logical explanation for the extremely local development of conglomerates, and the striking thinning both eastwards and westwards from Lettershanbally of Benchoona Member 1.

The submarine fan hypothesis is further strengthened by the tendency of Members 2 and 3 to coarsen upwards. Although in the few cases where coarsening upwards turbidite sequences have been discussed their origin has usually been attributed to tectonism (e.g., Ksiazkeiwicz, 1960; Neef, 1964), it is also likely that they represent normal vertical accretion on a submarine fan, which can be likened to the outbuilding of a delta. Fig.18 represents an ideal case where turbidity currents of equal density and thickness follow one another in succession on to a horizontal sea floor. The first current will begin to deposit when the angle of slope decreases to a certain value. The one following will begin to deposit its coarsest sediment at approximately the same place, but because the slope has been built out slightly by the deposits of the first current, the less coarse deposits tail out more and overlap

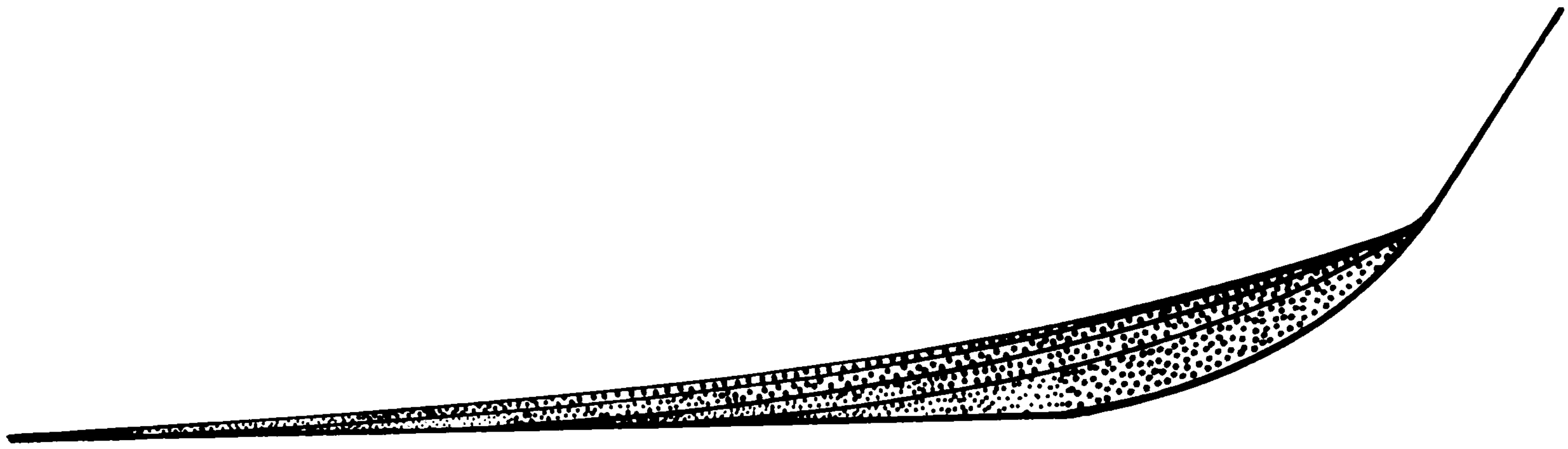


Fig. 16. Cross-section through an idealised submarine turbidite fan. (for discussion see text).

beyond the deposits of the first current. In consequence, particularly towards the distal portion of the fan, there will be a tendency for relatively coarse sediment to be carried a little further than for the preceeding current, and there will be overlaps of successively coarser sediment. Any vertical section through the more distal portions of an ideal fan will therefore show a coarsening upwards sequence. The lower three Benchoona Members are likely therefore to represent transverse or oblique cross-sections through successive submarine fans. The lateral variation in thickness of the finer-grained Member 4 may possibly be attributed to infill largely from suspension of an interfan depression. The deposits of the three fans forming Benchoona Members 1, 2 and 3 therefore represent lateral supply to a basin, probably from a northerly direction.

By analogy, Letterettrin Member 2 probably also represents a submarine fan deposit, again with a northerly origin. The same is probably true for the turbidites between Letterettrin Member 2 and the tuff horizon above. The rapid wedging out westwards of both of these turbidites and those of Letterettrin Member 2 suggest either thinning out distally of the respective fans or wedging out of turbidites against a basin margin or local "high". The thick turbidite association between Benchoona Member 4 and the Letterettrin Member 2 is probably made up of several interdigitating fans because of the wide spread of current directions. Other evidence of fan formation is the implied palaeoslope direction given by the axes of slumps in two horizons stratigraphically only 8 m apart but separated laterally by 2 km. Slump axes from an horizon in section 21B north of Lough Fee imply an east-south-east directed palaeoslope, while those from the nearly equivalent horizon in section 7 south of Benchoona suggest a palaeoslope directed to the south-south-west (see Fig. 15). The slumps in the two horizons have moved away from each other in a mutually perpendicular direction and may represent slumping down the opposite slopes of the same fan.

The abrupt vertical change in sedimentation from coarse turbidites to fine-grained sediments (in the case of Benchoona Members 1, 2, and 3 and Letterettrin Member 2 of the Lettergesh Formation) may reflect deflection of supply of sediment from one feeder canyon to another, allowing material to accumulate largely from suspension over the top of the abandoned fan until an adjacent outbuilding fan increasingly overlaps the area. This situation is very likely to have arisen in the transition from the fan represented by Member 1 to that represented by Member 2, where the directions of sediment supply are so markedly different. It was probably more common, however, for sediment supply never to be completely deflected from a canyon, and consequently units of several fans would interleave allowing little or no time for any thick continuous build-up of fine-grained sediment. This situation probably prevailed throughout most of the Turbidite Association.

A notable problem is the disparity between current directions given by sole marks and those implied by cross-stratification in the middle portion of the Turbidite Association. An associated problem is the presence of cross-bedding in the coarser facies, already discussed in Chapter 3 (pp. 61 and 62). Directional divergence between sole and internal structures in turbidites is not uncommon, and various explanations have been suggested. These include a) the possibility of erosion by one turbidity current and deposition from another (e.g., Crowell, 1958), b) erosional and depositional structures both being formed by the same turbidity current but external factors, e.g., bottom topography, increasingly influencing the directional properties of structures during deposition (e.g., Kelling, 1964), and c) reworking of the upper finer-grained portions of turbidites by bottom currents (e.g., Hsu, 1964).

Mechanism a) is unlikely in this case, because depositional features such as parting lineation and grain orientation show parallelism to erosional sole structures, and other internal features such as slump folds and basal transverse ripples associated with flame structures show the expected distribution approximately at right angles to the erosional structures.

Kelling (1964) and Scott (1967) produced evidence in support of the operation of some factor, other than the turbidity current itself, which influenced the deposition of the finer portions of beds. Kelling (op. cit.) recorded the presence of periodic transverse flow affecting deposition and suggested that such cases might be due to the reflection in a different flow direction of turbidity current-generated surge-waves. Scott (op. cit.) recorded similar deflections of current directions during deposition, some examples showing increasing upwards deflection in the same sense, corresponding with an upward decrease in grain size. He attributed this variation to the changing resolution of gravitational forces and forces supplied by fluid energy where the current flow was other than directly downslope at a point.

However, the evidence of post-depositional slump fold axes from the few horizons where they could be measured indicates that sole marks are approximately parallel to the dip of the palaeoslope, while the cross-stratification directions show currents parallel to the strike of the palaeoslope. Also, if the turbidites were being deposited on fans the assumption that the cross-lamination azimuths reflect the palaeoslope would require that the azimuths when plotted would possess a fan shape, instead of the almost unidirectional trend they exhibit. For these reasons (b) is considered unlikely.

The possibility of ocean-bottom current reworking of turbidites seems plausible, as the presence of bottom traction currents of high velocity has been firmly established (e.g., Heezen and Hollister, 1964). These authors in a review of current measurements obtained from passages between islands and continents noted a maximum velocity in excess of 100 cm/sec in the Straits of Gibraltar and velocities in other passages of between 10 and 60 cm/sec. On the Blake Plateau current velocities up to 0.94 knots (48.4 cm/sec) were recorded by Pratt (1963), while on abyssal plains measured or calculated velocities do not exceed 20 cm/sec. A graph constructed by Sundborg (1956) showing the experimentally-derived relationship between current velocity 1 m above a river bottom and grain movement of uniform material indicated that the minimum current velocity necessary to transport grains 5 mm in diameter (the maximum grain size seen in the cross-beds of the Lettergesh Formation) is 80 cm/sec. The figures quoted above indicate that sea-floor currents of sufficient magnitude to transport fine breccia are available in at least some restricted present-day environments. Such currents acting in the Killary Harbour area must have maintained constant direction for prolonged periods of time, but were not continuously active, as finer-grained silts and muds were able to settle and form interbeds between the rippled or parallel-laminated fine sandstone beds in Facies D. In the Killary Harbour area they apparently flowed approximately at right angles to the direction of sediment supply and parallel to the strike of the local slope of the sea floor, a slope still significant as suggested by the relatively common presence of slump folds in surrounding strata. At certain times they increased their strength enormously, or were augmented by similarly directed currents capable of transporting particles of small pebble size. Rarely, but significantly, complete current reversals occurred, without any intermediate current bearings.

Possible dynamic models for such a situation include currents constricted within straits, wave induced currents, tidal currents, and geostrophic contour currents.

(i) Heezen and Hollister (1964) cited several examples of high current velocities in straits (see above). However, in the case under discussion there is no evidence for a source of sediment supply other than from a generally northerly direction. Although it is possible that the current laminated deposits were resting on the northern slope of a wide strait and thus were out of reach of sediment-carrying currents from the southern side, it is unlikely in this case that the currents, strongest at the centre of the channel, would have sufficient competance to rework coarse sediment on the flanks.

(ii) The second possibility, that of reworking by wave-induced currents, could only fit a situation where a relatively shallow sea was affected by prevailing winds. Hadley (1964) and Draper (1967) considered that the sea bed is affected by the passage of surface waves as far out as the edge of the continental shelf, i.e., at least as deep as 600 ft (183 m). Draper calculated that occasional particle velocities of up to 2.8 ft/sec (85.4 cm/sec) could occur at a depth of 500 ft (152 m) to the west of Ireland. Higher velocities were reached in shallower depths. It is possible that the cross- and parallel-laminated sandstones of Facies D and the rippled tops of turbidites therefore represent periods of medium wind activity, and the interbedding siltstones periods of atmospheric calm. The large-scale scouring and infilling cross-bedding could have resulted from infrequent storms which generated more active currents. The association of the cross-bedding and scouring with breccia units might indicate that surface storms not only increased erosion in the source area but initiated turbidity current flows of the collected materials down canyons onto the fans, and then reworked the resultant turbidite.

Several objections can be raised, perhaps the main one being the common assumption of considerable depth for turbidity current deposition, at least below normal wave base. However, there is no evidence of bathymetry in the Turbidite Association, and much of the sediment may have been deposited in a shallow basin whose floor was higher than wave base. Although the succession from the base of the turbidites up to very shallow water conditions (a few metres ?) is approximately 1300 m this is probably a maximum figure for basin depth as the floor may well have been subsiding during sedimentation. A more serious objection is the fact that the current directions shown by cross-laminations are almost unidirectional with much less scatter than could be expected from a wind system blowing for a time probably counted in millions of years. Also, if the currents are solely wave-induced they are oscillatory, and therefore wave-action alone cannot cause appreciable net sediment transport. The absence of oscillation ripples and of bi- or polymodal current azimuths on the cross-stratification therefore renders it unlikely that surface wave-action by itself accounts for the paleocurrent pattern. Also, in a steadily shallowing basin, as is probably the case at least during the time of deposition of the upper portion of the Turbidite Association, it would be logical to expect increasing influence of waves up the stratigraphic sequence, which is not the case.

(iii) The action of tidal currents could explain many of the more puzzling features of the cross-stratification pattern. An important fact is that tidal currents are pulsating, fluctuating from a maximum velocity during ebb and flow to a minimum or even nil velocity during low and high tides. There are also larger period fluctuations in current velocities connected with the monthly neap and spring tides. Although a characteristic of tidal currents is the twice diurnal reversal of direction, Stride (1963) has shown that it is common for one mode, i.e., that of ebb or flow, to dominate, and cause net sediment transport along the dominant modal direction. Present-day ocean floor currents attributed to tidal action have been recorded from depths as great as 4300 m (Isaacs et al, 1966), and in shallower water (1300 m) with speeds of up to 40 cm/sec (Doebler, 1967) which, according to the graph reproduced by Sundborg (1956) would be capable of transporting coarse sand. As the observations quoted by Doebler (1967) were made only over a 5 month period it is probable that on occasions his maximum recorded velocity is exceeded, particularly if high tidal current velocities are coupled with surface storms, and much coarser material could sometimes be transported. Kuenen (1967) has shown that no transport even of clay is maintained in sea water below a current velocity of 10 cm/sec, and silt is deposited at 20 cm/sec. Hence, as most deep ocean tidal currents are likely to fall below 20 cm/sec (Doebler, 1967, recorded an average speed of 4.5 cm/sec over a 5 month interval) for most of the time silt and clay will be deposited, while deposition and reworking of coarser grades will occur only at times of peak current velocities.

There is thus no substantial objection to the nearly unidirectional palaeocurrent pattern of part of the Irish Silurian having been formed by tidal current reworking of sediments originally deposited by turbidity currents, the east-directed azimuths showing the net transport direction, and the rare directly opposing directions representing occasions when the weaker mode was preferred.

However, as with the postulate of wave-induced currents, it is hard to understand why if the sediments are reworked by tidal currents the degree of reworking does not increase upwards in the stratigraphic column with increasing shallowing. Possibly downwarping of the basin under normal conditions kept pace with sedimentation, and only when sediment supply outstripped basin sinking was the level of the sea floor raised sufficiently for strong currents to effect reworking of coarse material. In this respect it may be significant that medium-scale cross-beds are common only towards the top of thick, probably rapidly-deposited breccia units.

(iv) Geostrophic contour currents have only recently been recognised and their role in sediment transport and deposition is still imperfectly understood (Heezen et al, 1966; Schneider et al, 1967). They are deflected by the Coriolus force against the side of an oceanic basin and flow parallel to it. In the only example so far studied (Western North Atlantic) a geostrophic current forms a south-flowing undercurrent flowing in the opposite direction to the surface Gulf Stream. The current readings form an almost unidirectional southerly pattern, but extremely rare northerly currents, attributed (Schneider et al , 1967) to the Gulf Stream itself, at certain locations intermittently scour the sea floor. The highest contour current velocity so far recorded has been 70 cm/sec (Emery and Ross, 1968), which is sufficient to transport grains up to 4 mm in diameter (Sundborg, 1956, Fig. 23). Higher velocities are evidently possible. Schneider et al, (1967) note that silt layers are often cross-bedded with good sorting, and cores contain interbeds of lutites, which suggests that the current velocity often falls to a level where fine-grained sediments could be deposited.

Thus the activity of geostrophic contour currents could be invoked to account for the more outstanding characteristics of the palaeocurrent pattern, namely, the mainly unidirectional mode parallel to the palaeoslope, and the occasional complete reversals which could be caused by infrequent scouring of a surface countercurrent.

1.4. Summary and Conclusions

Most, if not all, units of the Turbidite Association were deposited by turbidity currents on submarine fans spreading from a generally northerly direction. In at least the central part of the Association pulsating bottom currents of sufficient strength to erode and transport sand-sized particles, and occasionally small pebbles were active and were responsible for reworking both thin beds of fine sandstone and the fine-grained tops of turbidites. These bottom currents trended approximately parallel to the strike of the regional palaeoslope, and were most likely to have been generated either by tides, or by the Coriolus force. Occasional scouring and cross-bedding in the coarser beds may have resulted from the coupling action of infrequent surface storms on already existing bottom currents.

2. The Siltstone Association, Middle Member, Lough Muck Formation

2.1. Description

The association consists of the fine-grained Facies E (massive mudstones and siltstones), F (silty streak), and G (oscillatory beds). Although Facies E and F also occur in the Salrock Formation, their most widespread development and association is in the Lough Muck Formation, where they form the bulk of the Middle Member (Fig. 19). These two Facies pass gradationally into each other both laterally and vertically in apparently unpredictable sequence locally, but silty streak occurs much more commonly in the upper part of the member than do massive mudstones and siltstones. The alternating siltstone and bundles of fine sandstones which comprise Facies G are limited in their extent to the area north of Lough Muck, and occur only in the top twenty - thirty metres of the member. Thus there is a tendency throughout the region to coarsen upwards, a tendency particularly marked immediately below the first appearance of cross-bedded sandstones. There is however no recognisable systematic lateral variation in grain-size throughout the Killary Harbour area. Body fossils (gastropods, graptolites, and brachiopods) and horizontal burrows occur relatively frequently throughout the association. The most striking variable parameter is that to thickness, which increases eastwards from approximately 85 m near the coast to approximately 130 m near Knockraff.

Another characteristic of the association is the occasional presence of laminated siltstone beds containing plastic flow folds, particularly in the eastern half of the region. In the Lough Muck region rotational slumps occur within oscillatory beds close to the top of the member, and here as well as elsewhere slump scars are recognised (see Chapter 3, pp. 98-107). Unfortunately no axes of slumps within the association of facies could be measured because of surface planation, but the rotational slumps appear in cross-section to have a strong eastwards component of movement (see p.102). This is supported by the E.S.E. direction of dip of cross-laminated beds comprising part of the "erosive-based massive sandstone association" within the Middle Member of the Lough Muck Formation (see next section), a similar direction of slope implied by a slump overfold within this latter association, and two measurements from a slump horizon immediately above the Middle Member on Knockraff.

2.2. Relationship to other facies associations

The Siltstone Association has the same external boundaries as the Middle Member of the Lough Muck Formation. Its lower contact is with the erosive-based massive sandstone association of the Lower Member. The uppermost unit of the Lower Member Association varies from locality to locality and is usually either a slump bed or a massive sandstone, but the contact in most cases is abrupt.

Similarly, the upper boundary of the association is the transition to the Upper Member of the Lough Muck Formation. The transition, normally from silty streak or oscillatory beds into parallel-bedded sandstone or herring-bone cross-bedded sandstones is rapid, occurring within a few metres. The cross-bedded sandstones first appear at very approximately the same horizon throughout the area (with respect to the tuff horizon near the base of the Salrock Formation), but there are some oscillations as in the coastal section, where the association passes abruptly upwards into several metres of unidirectional cross-beds, and then rapidly back into several more metres of silty streak before herring-bone cross-bedded sandstone makes its appearance.

This transition must mark an important environmental boundary since only rare vertical burrows occur below it, while above it vertical burrows predominate over horizontal ones. Also, as noted in Chapter 3 (p. 108), with the exception of one horizon on Knockraff immediately above the top of the Middle Member of the Lough Muck Formation, no slumps occur higher in the sequence, whereas they are relatively common below the boundary.

2.3. Interpretation of Environment

The presence of occasional slump overfolds, rotational slumps, and flow folds strongly suggests that this combination of facies was deposited on a slope. Experimental studies (e.g. Rettger, 1935) have shown that fine-grained sediments on a slope tend to creep or flow downslope under the tangential component of gravity forming plastic folds. The flow folds sometimes seen in siltstones within the association are therefore further evidence of the presence of a slope and of downslope creep of sediment. Furthermore, strong evidence to suggest that the relatively abrupt change from the Siltstone Association to one dominated by herring-bone cross-bedded sandstones represents a change from slope to shallow shelf conditions is given by the rapid transition from massive or laminated mudstones, siltstones and fine sandstones indicating deposition from suspension or by weak currents and lack of supply of coarse material to one of plentiful coarse sediment supply dominated by strong tidal currents. Additional support is provided by the change at this boundary from sediments containing mainly horizontal burrows to one dominated by vertical burrows; the common presence of slumps or plastic flow folds below the boundary and the lack of such structures above it; and the concentration of rotational slumps and slump scars just below the boundary. Penecontemporaneous faults resembling slump slip surfaces occur on the present-day shelf edge and upper slope (Moore and Curray, 1963), and large-scale rotational slumps have also been recorded from a similar palaeogeographic position in the Tertiary of Louisiana (Dickey _et al_, 1968). The rotational slumps at the boundary between the Middle and Upper Members are similarly interpreted to occur at the change in gradient between slope and shallow marine shelf, where failure and slumping of semi-consolidated sediments is most likely to occur.

The notable thickening of the Siltstone Association to the east occurs downcurrent and downslope, and can probably be explained by the eastward or south-eastward basinward advance of the shelf over older slope and basin-floor deposits, akin to deltaic advance into a sea or lake.

3. Erosive-based massive sandstone association

3.1. Description

Erosive-based massive sandstones of Facies I are found both in the Lower and in the Middle Members of the Lough Muck Formation (Fig. 19). They almost invariably occur in association with thin parallel or cross-laminated beds of fine sandstone in siltstone (Facies H), massive siltstones or mudstones (Facies E), thin turbidites (Facies C), and with slumped beds. Less commonly they are also associated with silty streak (Facies F) and (in one case only) with cross-bedded sandstones (Facies J). The distinct associations in the Lower and in the Middle Member differ only in the higher proportion of turbidites and slumped beds in the Lower Member Association, the greater lateral extent in the Lower Member, and in the spatial separation of the two associations.

Turbidites forming part of the massive sandstone associations are in most cases closely similar to those of Facies C (sub-facies C3) and show normal grading, the Bouma sequence of internal structures (although they rarely contain the cross-laminated division), and sharp bases with occasional sole structures (flutes, prods, and grooves). They differ, however, in that few beds can be traced for more than a few tens of metres laterally, most thinning and wedging out into massive siltstone or siltstone with thin sandy laminae. In some localities (particularly in the vicinity of Knockraff) in the Lower Member only, thicker beds of sandstone up to 60 cm occur, usually massive or poorly graded, or with parallel lamination throughout. These, like the sub-facies C3 turbidites lower in the stratigraphic sequence, have parallel and sharp bases and tops, and occasionally bear sole structures.

Erosion surfaces, which are extremely common beneath the massive sandstones, also frequently cut through several beds to form channels up to one metre deep. Usually the deeper channels are infilled by massive sandstone, but frequently a thin drape of massive siltstone is present between the erosion surface and an overlying sandstone bed, and on one occasion a channel was completely infilled by beds of Facies H.

As noted earlier (Chapter 3, p.86) Facies I sandstones sometimes contain a concentration of mudflakes and/or fossils in the basal few centimetres of a bed, the fossils occurring almost always at the base of an erosive-based massive sandstone complex. At three localities a concentration of fossils occurs in massive silty mudstone immediately underlying the erosive base of a sandstone with a basal fossil and mudflake concentration.

In order to analyse the relationships between the various facies in detail, transition matrices were constructed for the associations to represent statistically the probabilities of transition from one facies to another. The theory and application of transition matrices to geological problems has been discussed by many authors (a good summary and review is given by Potter and Blakely, 1968) and need not be considered further here. Only well-exposed sections where transitions between facies could be clearly seen were utilized for this purpose. Separate matrices were constructed for the Lower and Middle Member Associations in order to determine differences in association if any (Tables 9A and 9B). Erosion surfaces were also plotted as one element of each matrix in order to determine their relationship to various facies. A surface was regarded as an erosion surface if it was seen to clearly cut strata below, or, in the case of a massive sandstone overlying unlaminated massive siltstone, if the undersurface of the sandstone was notably irregular. Surfaces overlain by massive sandstones with a layer of mudflakes at or near the base were not included with erosion surfaces unless the base was seen to cut into the bed below. In addition, many beds could be followed laterally for only a few metres, and probably the true proportion of erosion surfaces underlying massive sandstones is considerably higher than the figures used in the tables.

Several notable relationships are indicated by the transition matrices. Although an erosion surface may cut into any facies, it is usually overlain by Facies I massive sandstone, a relationship obvious in the field. The massive sandstone, in turn, is most commonly overlain by more massive sandstone, an erosion surface, or massive siltstone.

In order to explore the facies relationships further two-step or higher order matrices are necessary. In a two-step process it is desired to know not only the probability of an event given a preceding event, but also to know the probability of the next succeeding event occurring. This can be done by constructing a three-dimensional cubic matrix, but this method raises practical difficulties in representation. A compromise was reached by fixing the intermediate event (facies) and determining the probabilities of the preceding and succeeding events for a two-dimensional matrix. For n events (facies) n separate matrices would need to be constructed. In this case,

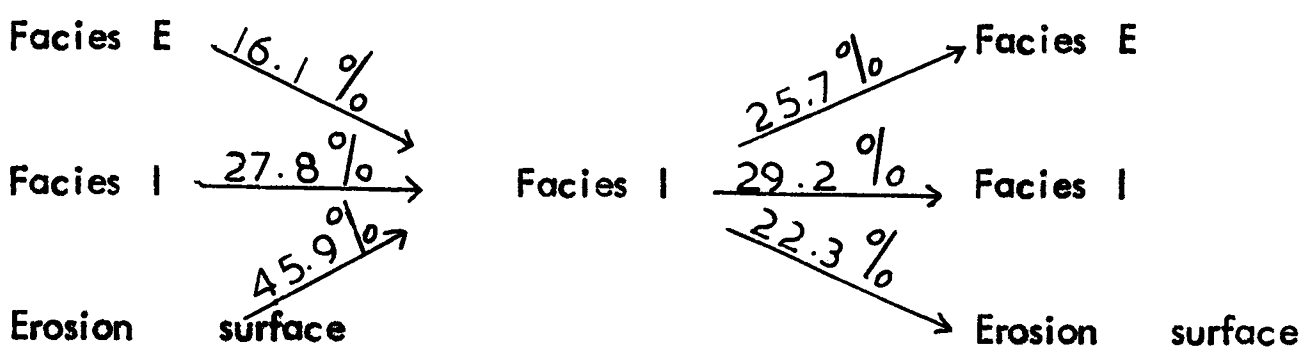
TABLE 9A. TRANSITION MATRIX FOR EROSIVE-BASED MASSIVE SANDSTONES LOWER MEMBER, LOUGH MUCK FORMATION. (300 ELEMENTS)

	I	S	E	C	H	F	X	No. of Facies elements counted
I	0.30	0.11	0.22	0.02	0.10	0.04	0.21	82
S	0.10	0	0.31	0.12	0.16	0.12	0.19	32
E	0.21	0.13	0	0.30	0.11	0.02	0.23	47
C	0.04	0.09	0.21	0.37	0.17	0.06	0.06	52
H	0.10	0.17	0.20	0.20	0	0.06	0.27	30
F	0.25	0.25	0.17	0.17	0.08	0	0.08	12
X	0.87	0.02	0	0.09	0.02	0	0	45

TABLE 9B. TRANSITION MATRIX FOR EROSIVE-BASED MASSIVE SANDSTONES, MIDDLE MEMBER, LOUGH MUCK FORMATION. (152 ELEMENTS)

	I	S	E	C	H	F	J	X	No of Facies elements counted
I	0.27	0.02	0.27	0.04	0.10	0.02	0.02	0.27	66
S	0	0	0	0	0.67	0	0	0.33	3
E	0.56	0	0	0.04	0.12	0	0	0.28	25
C	0	0	0.20	0.20	0.40	0	0	0.20	5
H	0.39	0.11	0.17	0.05	0	0	0	0.28	18
F	0	0	0	0	1.00	0	0	0	1
J	0	0	0	0	0	0	0	1.00	1
X	0.85	0	0.06	0	0.09	0	0	0	33

the relationship of the massive sandstone only with respect to underlying and overlying facies was investigated. A matrix showing the probabilities expressed in percentages of the total number of transitions counted is given in Table 10. Apart from the still obvious close association of massive sandstones with other massive sandstones or erosion surfaces, it is apparent that the next most probable arrangement is for massive siltstones to overlie and underlie massive sandstones. This result is emphasized by summing the percentages of rows and columns which indicates that the only significant transitions involving massive sandstones of Facies I are:



3.2. <u>Relationship to other Facies associations</u>

The erosive-based massive sandstone association with the Middle Member of the Lough Muck Formation passes both laterally and vertically into units of the Siltstone Association. The vertical transition is usually abrupt, particularly if the lower or upper boundary is formed by a massive sandstone. The association is present in several discrete units distributed throughout most stratigraphic horizons of the Middle Member, and occurs in most sections throughout the region. There is a notable concentration in the area east of Letterettrin, where at least seven separate units of the association occur. No one association exceeds 7 m in thickness, and

TABLE 10. MATRIX FOR COMBINED EROSIVE-BASED MASSIVE SANDSTONE ASSOCIATIONS, SHOWING PERCENTAGES OF TWO-STEP PROCESSES INVOLVING MASSIVE SANDSTONES

	i I	i S	i E	i C	i H	i F	i J	i X	Total % for rows
I i	12.5	0	6.9	1.4	1.4	0.7	0	4.9	27.8%
S i	0.7	0	0	0	0	0.7	0	0	1.4%
E i	4.9	1.4	5.6	0	2.8	0	0	1.4	16.1%
C i	0.7	0	0.7	0	0	0	0	0	1.4%
H i	2.8	0	1.4	0	1.4	0	0	0	5.6%
F i	0	0.7	0	0	0	0.7	0	0.7	2.1%
J i	0	0	0	0	0	0	0	0	0
X i	7.6	4.9	11.1	1.4	4.9	0	0.7	15.3	45.9%
Total % for columns	29.2%	7.0%	25.7%	2.8%	10.5%	2.1%	0.7%	22.3%	

I = Massive sandstone

S = Slumped beds

E = Massive siltstone or mudstone

C = Turbidites

H = Parallel and cross-laminated fine sandstone in siltstone.

F = Silty streak

J = Cross-bedded sandstone

X = Erosion surface

none could be traced more than 400 m in lateral extent. When mapped, associations were found to be lenticular or broadly dish-shaped in cross-section (Fig.20). While some obvious channelling occurs both within and at the base of associations, some individual associations gradually die out laterally by thinning (4 and 5 in Fig.20). In this case it is noteworthy that the massive siltstone separating the associations 4 and 5 also wedges out in the same direction.

The few indications of current direction or direction of sediment transport are based on direction of dip of cross-laminae in beds of Facies H, one slump overfold, and preferred grain orientations from the bases of two massive sandstone beds. Directions of palaeoslope or of current vary between north-south and east-south-east (Fig.21A).

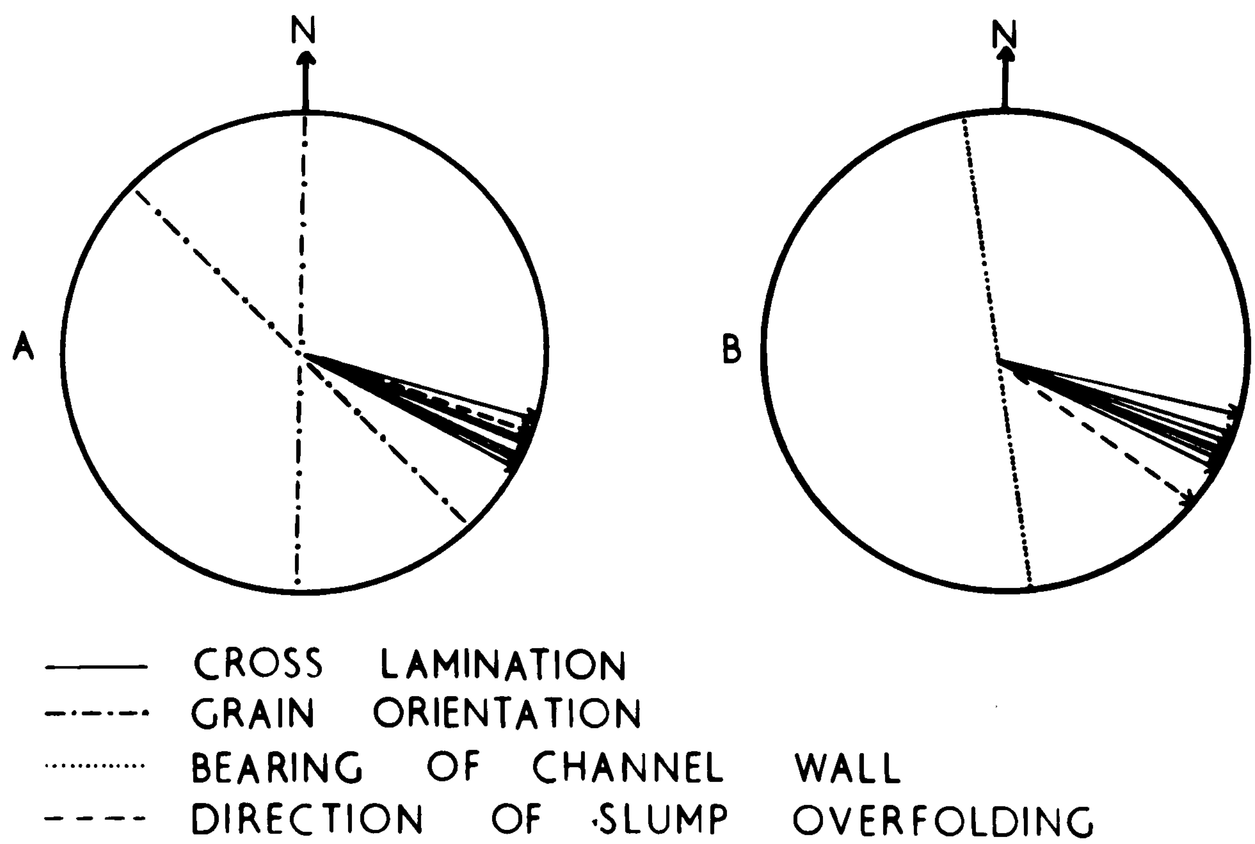


Fig.21. Plots of palaeocurrents and palaeoslope in the Erosive-Based Massive Sandstone Association, in the Lough Muck Formation. A. Associations in the Middle Member. B. Associations in the Lower Member.

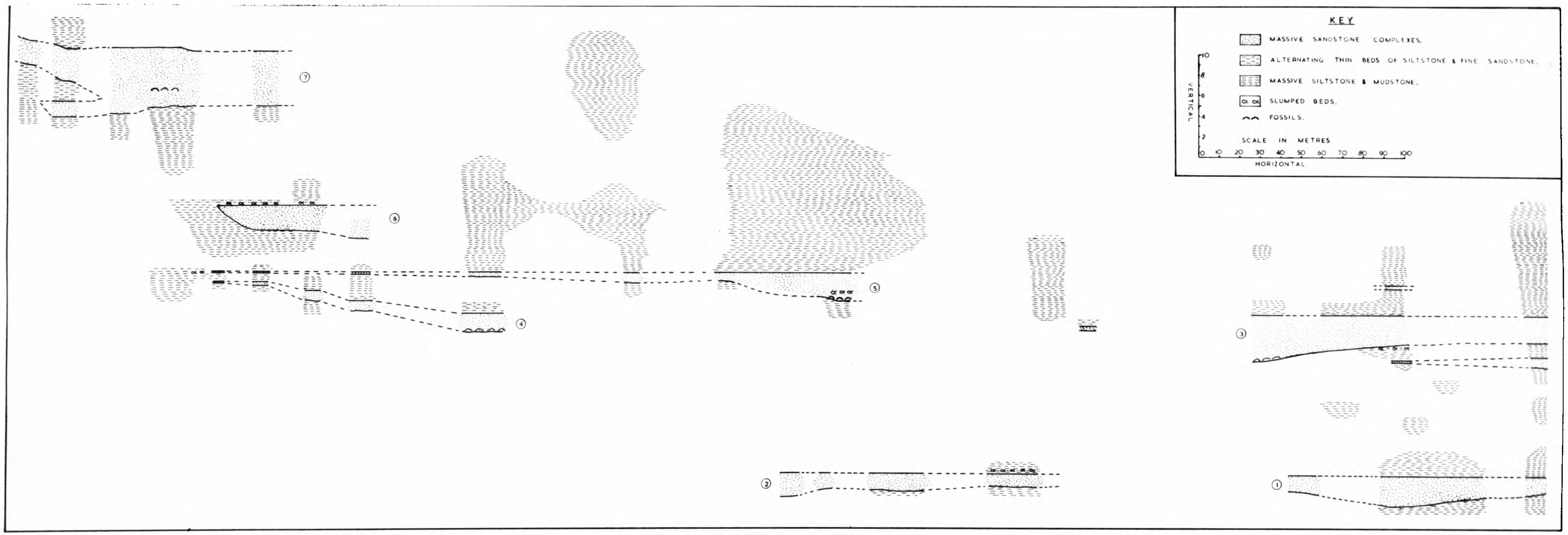


Fig. 20. Erosive-based Massive Sandstone complexes east of Letterettrin. Note the lateral wedging or channelling out of the complexes.

Because of the wide spread of current directions it is not possible to calculate the true lateral extent of the discrete associations, so the lateral extent in outcrop must be considered a maximum value. Calculations are also complicated by the fact that in no instance were both lateral limits of an association exposed.

In the Lower Member the upper boundary of the association is represented by the abrupt transition to the Siltstone Association: the lower boundary is taken as the incoming of the first massive sandstone, and varies somewhat from one locality to another. Usually the association rests on thin sub-facies C3 turbidites. Massive sandstones notably occupy a greater thickness of the stratigraphic column in the Lough Muck/E. Letterettrin region than near the coast and in the vicinity of Knockraff. Laterally, there is a slight increase in the proportion of thin turbidites from Letterettrin towards the east, and they predominate in the Knockraff region, the Erosive-Based Massive Sandstone Association apparently wedging out into or interfingering with turbidites to the east.

Current direction readings for the association in the Lower Member, derived from interbedded and immediately underlying turbidites in the western half of the area, from cross-laminated beds of Facies H, from a slump axis, and from the walls of a channel show variations between almost north-south and east-south-east (Fig.21B). The laterally equivalent beds in the eastern half of the region are turbidites whose sole marks show east-south-east directions.

3.3. Interpretation of Environment

In the Middle Member, the broadly dish-shaped cross-section of units, the limited lateral extent and the wedging out not only of some adjacent units of the association but of massive siltstone in between suggests that both the associations and the intervening thick units of siltstone were deposited in shallow depressions or valleys in the surface of the slope now represented by the Siltstone Association. The concentration of the units in certain areas may indicate a tendency for a valley once formed to persist in the same area for a long time: two separate systems evidently occurred in the areas east of Letterettrin and north-east of Lough Muck. The increasing shift to the west up the stratigraphic column shown by the associations in Fig.20 suggests that the valleys migrated laterally with passage of time.

The Erosive-Based Massive Sandstone Associations occurring in the Lower Member require a somewhat different explanation as although locally and on a small scale units of the association occupy channels, on the large scale they are traceable laterally for much greater distances, and they contain a much higher proportion of slumped beds and thin turbidites, than those occurring within the overlying Siltstone Association. Another significant difference is that while these latter associations pass laterally and vertically into massive siltstone or silty streak, those of the Lower Member pass upward from and are laterally equivalent to turbidites. The most likely explanation is that these associations are rise sediments deposited at the foot of the slope represented by the generally fine-grained strata of the Siltstone Association. These have spread out fan-wise over earlier-deposited basin floor turbidites. The high proportion of slump horizons and thin turbidites in the Lower Member, and their comparative rarity in the Middle Member associations is explained by the probability that the gradient of the slope was too steep for deposition of these facies, which however piled up at the base of it. This would also explain the presence of some thick, massive turbidites in the association which could be interpreted as the deposits of dense, immature turbidity currents whose load could no longer be maintained in suspension when current momentum was lost due to the flattening of slope. The general increase eastwards of turbidites interbedding with the associations in the Lower Member reflects the interfingering with and feathering out of the fan material downslope and downcurrent into normal basin floor sediments.

Study of the transition matrices drawn from the associations reveals no strong Markov Dependance between different facies, and it appears that the facies were deposited in random order with the main exception that the erosive-based massive sandstone beds tend to occur together. The minor relationship between massive sandstone beds and massive siltstones suggests that the massive sandstones tend to be introduced abruptly following quiet conditions of sedimentation largely from suspension, and they tend to be followed by quiet conditions, rather than being associated with traction current activity implied by the deposition of Facies H. The massive sandstones therefore appear to have been deposited by isolated events separate from the "normal" pattern of sedimentation. Evidently conditions in the valleys and on the fans were frequently quiet for a length of time sufficient for benthonic organisms to establish themselves before being destroyed and eroded by sand flows, as the presence of highly fossiliferous pockets in massive siltstone below erosive-based fossiliferous sandstone indicates.

Several different transport mechanisms were evidently acting in close association with each other, namely, deposition from suspension (Facies E), traction currents (Facies F and H), turbidity currents (Facies C), slumps, and probably sand flow. It is interesting to note that all of these mechanisms have also been observed to be active in modern submarine canyons (Shepard and Dill, 1966; Stanley, 1967). Stanley (op. cit.), who compared ancient and modern submarine canyon sediments recorded wedge-shaped bundles of strata, lenticularity and limited lateral extent of beds, erosional bases, mud pellets, slumped beds, and discontinuous sheets of graded and cross-laminated silt and sand strata as well as inter-bedded muds. All of these features are present in the Erosive-Based Massive Sandstone Association in the Killary Harbour area, strengthening the hypothesis that units of the association were deposited in restricted depressions such as submarine valleys.

Probably quiet conditions were represented by Facies E, F, and H, while storms or the sudden failure of unconsolidated sands built up over a period of time at a valley head resulted in slumps, flows of sand, or turbidity currents down the valley axis and out on to the basin floor.

4. Coarsening Upwards Sequences

4.1. Description

For much of the thickness of the Upper Member of the Lough Muck Formation the facies of which it is composed appear to follow one another in random order. However, at many localities a definite ordered sequence, in which each facies is followed by a coarser one to form a coarsening upwards sequence occurs. These sequences are restricted to the lower half of the Upper Member of the Lough Muck Formation, and may consist of some or all of the following facies: massive mudstone or siltstone (Facies E), silty streak (Facies F), cross-bedded sandstone (Facies J), knitted beds (Facies K), parallel-bedded sandstone (Facies L), spaghetti beds (Facies M), and parallel and cross-laminated sandstones in siltstone (Facies H).

The commonest occurring sequence begins with massive mudstone or siltstone at the base and ends with herring-bone cross-bedded sandstone at the top, which in turn is sharply overlain by massive mudstone or siltstone. Sequences range in thickness from 1 m to a maximum of approximately 25 m. The thickest and most striking coarsening upwards sequences occur in the east of the Killary Harbour area in the vicinity of Knockraff. To the east of this none were recognised: to the west they are thinner and often occur in cyclic sequences of up to twelve units. The smaller ones are best developed in the Salrock School Owengar River area and on the coast, while in the areas intervening they are either absent or poorly developed. Fig. 22 illustrates typical examples of both thin simple sequences, and thick, more complex, ones. A striking feature of some of the thicker, more complex sequences (e.g., Fig.22b) is the presence of a shelly bioturbated layer of sandstone at the top of the unit. The fossiliferous layer is usually limited to a thickness of less than 10 cm, but in one case extended to 1 m below the sharp top of the sandstone. Fossils are concentrated towards the top and rapidly decrease in abundance downwards. Where the upper layers of sandstone are bioturbated or fossiliferous, fossils also usually occur in the lowest few centimetres of the fine-grained sediment immediately overlying. The fauna is often rich and varied, and consists of crinoid fragments, trilobites, brachiopods, gastropods, bivalves, and coelenterate fragments. In one case quartz granules up to 5 mm in diameter occur widely scattered on the upper surface of the topmost sandstone bed of the sequence.

The uppermost coarsening upwards sequence in the west Knockraff section (Fig.22c) is much more complex than other units, and although it coarsens upwards on the average it is made up of a number of small scale oscillations from fine to coarse and then back to fine again. Sub-facies L2 fine-grained parallel-bedded sandstone and Facies K knitted bed make up a significant portion of the sequence, which is also an

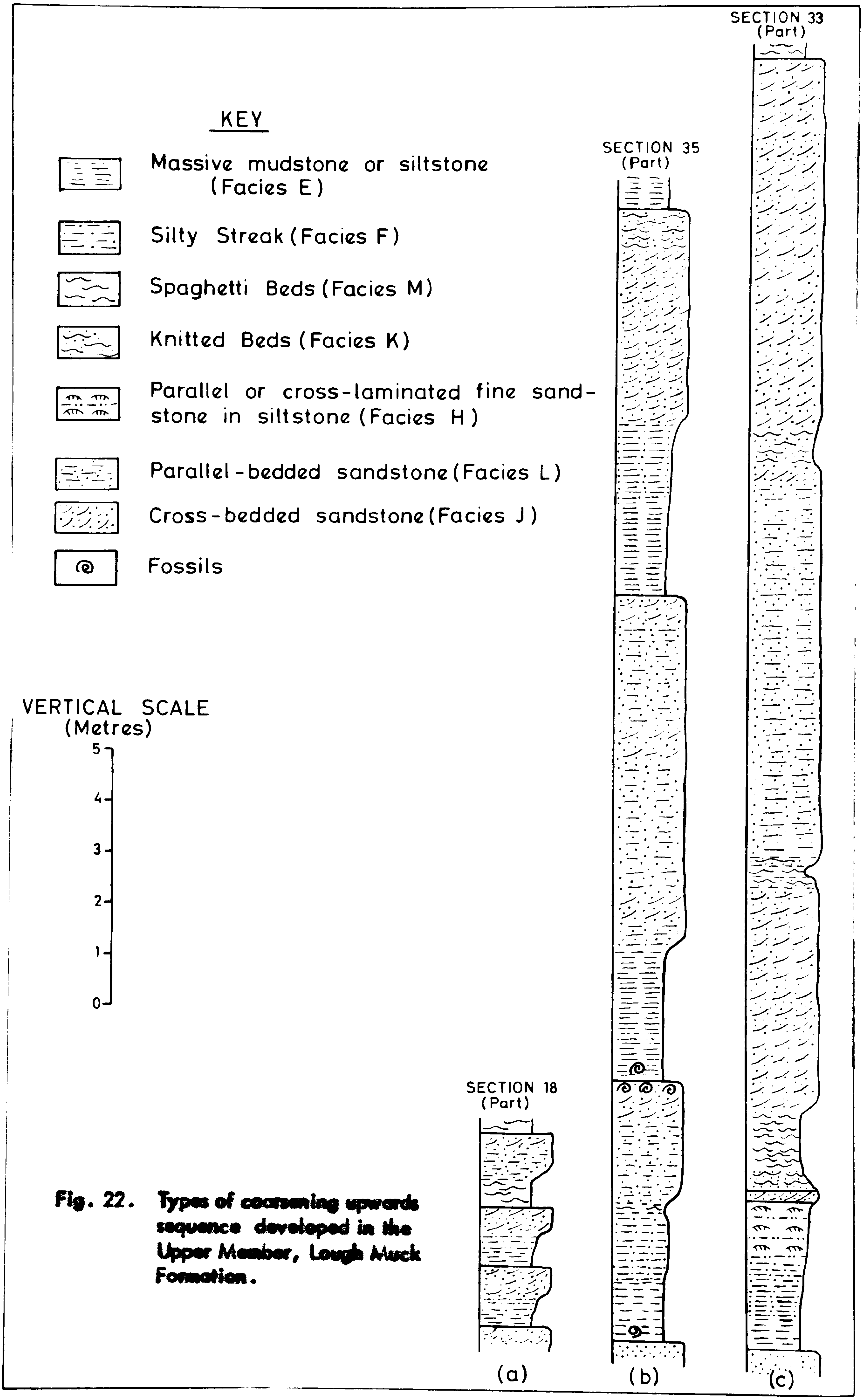


Fig. 22. Types of coarsening upwards sequence developed in the Upper Member, Lough Muck Formation.

unusual feature. To the east of this section much of the sub-facies L2 sandstones pass into cross-bedded sandstones of Facies J. The sub-facies L2 sandstones rest gradationally on spaghetti beds, and pass gradationally upwards into knitted beds and then into thick cross-bedded sandstones, which are overlain abruptly by a great thickness of spaghetti beds marking the vertical limit of the coarsening upwards sequences.

Individual sequences are difficult to correlate laterally. In the Knockroff area where the sequences are thick and the upper portions are marked by thick sandstone bodies some units can be traced laterally with reasonable precision for distances up to 1500 metres (see Fig.19). As a result of such efforts at correlation it was shown that the units changed in thickness very rapidly laterally, and appear lenticular in cross-section. In the western half of the area where coarsening upwards sequences are thinner, great difficulty was experienced in lateral tracing of units, and in most cases units could not be correlated from one section to another largely because of offsets by inter-vening faults, poor exposure, and poor development of sequence, and probabl y also because of rapid lateral change of thickness.

Cross-bedding in Facies J sandstones in all coarsening upwards sequences is of the bimodal, herring-bone type.

4.2. Relationship to other facies associations

As noted earlier, coarsening upwards sequences do not occur in every section investigated, and they appear to lens out laterally into units containing the same facies but in random order.

The lower boundary of the association approximately coincides with the top of the Middle Member of the Lough Muck Formation, although, as noted under the

Siltstone Association (p.130), the tendency to coarsen upwards gradually throughout this latter association is particularly marked near the upper boundary of the Middle Member, and consequently the lower limits of the lowest coarsening upwards sequences cannot be precisely delimited.

The upper boundary usually coincides with the sudden incoming of thick Facies M spaghetti beds above the top sandstone unit of the highest coarsening upwards sequence, but often the uppermost sequences in a section include spaghetti beds as part of the sequence, and so the boundary again is hard to limit precisely.

4.3. Interpretation of Environment

The vertical change in average grain-size and facies types within the coarsening upwards sequences suggests that current velocities and sediment supply progressively increased during the deposition of each unit. The change from swift currents to quiet waters at the beginning of each sequence appears to have been sudden, and to have been accompanied by the colonization of the sea bottom by burrowing benthonic organisms in many cases. The presence of concentrations of fossils and occasional pebbles at the top of the sequences may alternatively have been caused by the presence of swift currents allowing deposition only of coarse material and resulting in a low rate of sedimentation.

The presence of the herring-bone cross-bedded Facies J sandstones shows that tidal currents were active. The cross-bedding azimuths, taken in conjunction with the palaeoslope direction determined for the immediately underlying Siltstone Association, indicate that the tidal currents acted perpendicular to the shoreline, with the dominant mode offshore, i.e., to the east.

Several palaeocurrent patterns indicating net transport offshore have been previously described. Unimodal offshore palaeocurrents in the Triassic of British Columbia (Pelletier, 1965) were considered to have been formed in response to uplift in the source area, and palaeoslope attitude was the dominant regional control for the sedimentary trends. Bipolar cross-bedding with the major mode directed seaward in the Salem Limestone of Indiana (Seminar, 1966) was considered to be developed under the action of oscillating tidal currents on a shallow marine shelf.

On the other hand, some ancient deposits attributed to offshore bar complexes have either polymodal palaeocurrent patterns (Wermund, 1965) or bimodal onshore (Selley, 1967). In the latter case bimodal offshore patterns were associated with estuarine channels, for which there is no evidence in the Killary Harbour sequence. Although the dominant palaeocurrent mode in the offshore bars described by Selley (op.cit.) is onshore, the secondary offshore mode is very strong, and evidently little change in the sedimentary balance would be necessary to cause the offshore mode to dominate.

The lenticular shape in two-dimensions of many of the coarsening upwards sequences in the Killary Harbour area, the tidal environment and bimodality of the current system, and the increase of grain size and of current velocity upwards, all support the interpretation of the coarsening upwards sequences as deposits on offshore bars. The grading from fine sediment at the base to coarsest at the top is characteristic of such formations (Van Straaten, 1961).

The unique appearance of sub-facies L2 parallel-bedded sandstones in the topmost coarsening upwards sequence in the Knockraff area could possibly represent a beach deposit, particularly as it is closely associated above and below with sediments showing structures associated with wave activity indicating very shallow-water conditions. However, the fineness of grain compared with associated facies, and the poorer sorting, render this explanation unsatisfactory. Possibly the facies represents fine-grained material swept over the surface of a bar into quieter waters, leaving coarser material to settle in the wave-agitated waters on top of the bar. This would explain the higher degree of sorting and coarser grain size in Facies K sandstones compared with that of sub-facies L2 sandstones.

The cyclic occurrence of many of the coarsening-upwards sequences could be explained by one of several models. a) Periodic slow elevation of the sediment source area resulting in increasingly coarser material being made available, interspersed with periods of tectonic calm during which fine-grained sediments were deposited; b) intermittent subsidence of the whole area, resulting in shoreline retreat by drowning during rapid subsidence, and slow advance seaward during times of stability, causing seaward extension of coarser and coarser sediments; c) eustatic rises of sea level, causing abrupt retreat followed by slow advance of the shoreline; d) fluctuating supply of sediment from the source area for sedimentological reasons.

Models b) and c) would explain the sudden cut-off of sediment supply and of reduction in current velocity because of increase in depth and shoreline retreat. The bioturbated and fossiliferous sandstone forming the top layer of many sequences could be equivalent to the layer of sand overlying present-day delta sequences, and formed by reworking of the underlying deltaic sediments as the sea transgresses across the subsiding area. However, regional changes in sea level would cause regional changes in sedimentation patterns which would result in the same number of coarsening upwards sequences occurring at the same horizons throughout the Killary Harbour area. As the number of coarsening upwards sequences vary considerably from locality to locality and are absent from some, and no one horizon can be traced throughout the whole area, models b) and c) must be rejected. The possibility of very localized differential subsidence between one part of the area and another, e.g., along faults, is unlikely and there is no evidence to support it.

Model a) would likewise be expected to show a regional rather than localized change in sedimentation pattern, and is therefore unsatisfactory.

Model d) could arise in several ways, such as by temporary diversion of sediment by changes in current pattern or by crevassing and diversion of sediment in a feeder delta distributary.

5. Wave rippled Association (Spaghetti beds and Knitted beds)

5.1. Description

This association, which consists of Facies M (Spaghetti Beds) and Facies K (Knitted Beds), occurs only in the upper part of the Upper Member of the Lough Muck Formation and in part of the Salrock Formation.

In the Lough Muck Formation both elements of the Association are present in the uppermost coarsening upwards unit in the Knockraff area, where they pass gradationally into one another vertically. Elsewhere knitted beds are not common, but occur occasionally within spaghetti beds above the highest coarsening upwards units and occur as individual beds within massive mudstones in the lower 10 m of the Salrock Formation. The most important development of the association is at the top of the Lough Muck Formation, between the topmost coarsening upwards sequence and the lowest red-beds of the Salrock Formation. There is also a strong development of spaghetti beds occupying a thickness of approximately 60 m of strata 170 m above the base of the Salrock Formation. No further spaghetti beds occur higher in the two western

Salrock Formation sections, but the facies reappears in the eastern section at the 370 m level where it occupies a thickness of at least 25 m. The facies occurs only within intercalations of green or grey-coloured strata within the red-bed sequence.

Locally, both within the Salrock and Lough Muck Formations, the association is divided by thick cross- or parallel-bedded sandstone units or by units of massive mudstone or siltstone. Particularly in the western half of the Killary Harbour area units of the association change in thickness from section to section and pass laterally into massive mudstones or siltstones.

As noted in Chapter 3, trace fossils are uncommon and are limited to isolated vertical burrows. The only body fossil found was one specimen of _Lingula_.

Current azimuths from cross-beds interstratified with the association in the Lough Muck Formation show a similar bimodal pattern to that of the azimuths calculated for the coarsening-upwards sequences below, indicating that the palaeoslope and source direction have not changed from one association to the other.

5.2. Relationship to other facies associations

In the Lough Muck Formation the association is normally bounded below by, or is interlayered with coarsening upwards sequences. Less commonly, when coarsening upwards sequences are locally absent, there is a gradual passage downwards into massive siltstones and cross- or parallel-bedded sandstones. The upper boundary is formed in most cases by the incoming of the lowermost red siltstone bed of the Salrock Formation, but in the Salrock School area is formed by gradational upward passage into massive siltstones or mudstones or silty streak of Facies E and F.

In the Salrock Formation spaghetti beds pass vertically transitionally into silty streak or massive siltstones and mudstones of Facies E and F.

5.3. Interpretation of Environment

Somewhat similar facies consisting of isolated ripples of fine sandstone in siltstone or mudstone have been described from diverse environments, including deltaic (Coleman & Gagliano, 1965), estuarine (Oomkens & Terwindt, 1960), tidal flats (Van Straaten, 1954), marine embayments (Reineck, 1967; Reineck & Singh, 1967), and deep ocean in association with turbidites (Hsu, 1964). The absence of associated turbidites and the wave modification of ripples eliminates a deep ocean environment, while the lack of associated fluviatile sediments, the presence of the marine fossil Lingula, and the variable direction of cross-lamination renders a deltaic environment improbable. Estuaries and tidal flats are characterised by extensive channelling, which is lacking in Facies M, and by a variety of rapidly changing sedimentary types and structures.

The change from a high energy tidal current regime implied by the herring-bone cross-bedded sandstones making up much of the coarsening upwards sequences to one with few strong currents but common signs of wave activity, coupled with the change from predominantly coarse sediments to ones of much finer grain, suggests that the area in which the Wave-rippled Association was deposited was partially protected from the open sea, perhaps by off-shore bars such as those probably represented by the underlying coarsening upwards sequences. That protection was only partial is shown by the still common presence of herring-bone cross-bedded sandstones within the association, and clay drapes in the spaghetti beds, both of which suggest access to the area of deposition by tidal currents.

The presence of Lingula suggests shallow water, as modern Lingulids are not commonly found in water deeper than 10 fathoms (approximately 20 m) and are particularly common on muddy tidal flats (Craig, 1952). The ubiquitous occurrence of small wave-generated ripples and the occasional presence of Lingula as the only generically identifiable fossil in the association therefore indicate very shallow water depth, perhaps only a few metres. The association was probably deposited in a shallow marine embayment or lagoon partially protected from the open sea.

6. Red Bed Association

6.1. Description

This association is limited to the Salrock Formation, whose lower boundary is defined (see Chapter 2) by the first appearance of red-beds. This lower boundary, although irregular, is apparently not notably diachronous within the Killary Harbour area, since a tuff horizon traceable throughout the length of the area appears at approximately the same stratigraphic level above the lowest red horizon.

The red colouration, due to the presence of iron oxide in the fine-grained matrix of the sediments (see Chapter 2), occurs in both fine and coarse-grained facies, but it is common, particularly towards the upper part of the Salrock Formation, where clean sandstones occur, for the sandstones to be green-grey in colour, while interbedded finer sediments are red coloured. Vertical colour changes, although sharp when a sharp change from a fine to coarse facies is involved, are transitional in the finer-grained facies. Sequences of silty streak or massive siltstone commonly alternate in colour from grey to red rhythmically over a thickness of tens of metres without any noticeable change in facies or current direction.

In thin section, most of the iron oxide appears to be restricted to the fine-grained matrix, although occasionally grains rimmed by iron oxide occur. In the cleaner, green-grey sandstones, some red colour is always visible under the microscope in interstitial material between grains, but the grains themselves do not have red rims.

The facies present cover a wide range, and consist of Facies E (Massive mudstones and siltstones), F (silty streak), H (parallel or cross-laminated beds of fine sandstone in siltstone), J(herring-bone cross-bedded sandstones), K (knitted beds), L (parallel-bedded parallel-laminated medium-grained sandstones), and N (tuffs). Facies M (spaghetti beds) also occasionally occurs in close association with red-beds but is never red in colour. No facies are unique to the Red-Bed Association, which is dominated by massive or streaked siltstones throughout most of its thickness although parallel-laminated parallel-bedded sandstones are also common, particularly towards the base of the formation. With these minor exceptions, facies appear to be arranged in random order. No mud-cracks or flat-topped ripples suggesting emergence or near-emergence were noted, and facies showing signs of wave activity are rare.

The lowermost 110 - 140 m of the Salrock Formation is red coloured throughout, but is followed by approximately 180 m of mainly grey-green sediments in the two western sections, and by 250 m of the same colouration in the eastern section, where the red colouration is absent to the top of the exposed section (Fig.23).

The palaeocurrent pattern for cross-bedded sandstones is similar to that shown by the same facies in the Coarsening Upwards Sequences and in the Wave-rippled Association, i.e., bimodal E-W, with the dominant mode directed to the east (Fig.24). The palaeocurrent pattern shown by cross-laminations (plotted separately: Fig.24) shows a noticeable difference from that shown by the cross-bedding. Currents on the average were directed towards the south-east, and show a much wider spread.

Discordances, dish-shaped in cross-section, are occasionally locally present.

They are up to 1.5 m deep, with walls sloping at angles of less than 30° to the horizontal, concave upwards in their lower portions and flattening out to horizontal at the top. The outcrop width does not exceed 4-5 metres. The walls and floor are generally smoothly curving, but sometimes show irregularities on a small scale suggestive of erosion. The infilling sediments, which are similar in lithology to those surrounding the discordances, form drapes which rapidly die out vertically until they are horizontal. The only examples seen occurred as individuals, widely separated spatially and stratigraphically, and were not limited to any specific groups of facies.

Body fossils are rare, and are limited to Lingula (found both in red and grey-green coloured beds) and unidentified gastropods (found in green-grey sediments). Trace fossils are more common, and occur both in red and in grey-green beds. Most consist of vertical burrows occurring as widely-scattered individuals.

6.2. Relationship to other facies associations

The red-bed association is bounded below mainly by elements of the wave-rippled association, into which it passes gradationally over a few centimetres. In one area only, that of Salrock School, does it pass downwards into silty streak or massive mudstones or siltstones similar in lithology to the red coloured beds above.

Between one hundred and sixty and one hundred and seventy metres above the base of the Salrock Formation the Red Bed Association passes upwards into 60 m of members of the Wave-rippled Association on each of the three sections measured (Fig.23). The change is transitional from grey-green massive or streaked siltstones into spaghetti beds, with increasing thickness of spaghetti beds upwards. The sequence is interbedded with thick massive or silty streak units and dies out upwards in similar transitional fashion. Spaghetti beds also occur higher in the sequence in the eastern section only, but contacts with the Red Bed Association are not exposed.

6.3. Interpretation of Environment

A pervading red colouration in rocks, due to disseminated ferric oxides, indicates either strongly oxidising conditions at the place of deposition, or a sediment source area dominated by red beds. Red beds are to be expected most frequently in non-marine environments that are at least periodically dry and oxygenated (Williams et al, 1955). Evidently this is not necessarily the case, however, as some modern marine sediments are red. Red clay is widespread in the open ocean, and red terriginous mud occurs near shore in a large area off the mouth of the Amazon River where it is however probably derived from red soil on the continent (Dunbar and Rodgers, 1957). Reddish-brown and brick-red glacial marine sediment was deposited in the Laurentian Channel during the Late Pleistocene (Connelly et al, 1967), and red lutites occur in modern sediments of the lower continental rise in the Western North Atlantic (Schneider et al, 1967) where they are attributed to southern transport from the St. Lawrence region.

The evidence from other red beds, ancient and modern, shows that the oxidation producing the red pigmentation could have taken place either after deposition or the red beds themselves could have been derived. Both conditions may have pertained in the Solrock Group red beds. The occasional presence of grains rimmed with iron oxide suggests derivation of red beds from a red-coloured source area, but fluctuations in colour occur throughout some otherwise homogeneous fine-grained units where there is no evidence of a changing source of supply to account for the red colour which may indicate reddening in situ. In other cases where facies changes occur, e.g., in a change from massive siltstone to parallel-bedded sandstone the colour often remains red, the main exception being changes from finer-grained facies to clean sandstones which rarely appear red in hand specimen, presumably because iron minerals occur in a secondary mineral suite only found in the fine-grained matrix.

There is no evidence such as mud-cracks or flat-topped ripple marks to suggest emergence, and the marine fossil Lingula has been found in red coloured beds, suggesting that the red beds of the Salrock Formation represent a continuation of marine conditions upwards from the underlying Wave-rippled Association. The red colouration indicates an oxidising environment, however, and the water was probably very shallow. The general lack of evidence of tidal currents, except sparingly in the lower portion of the association, suggests that access to the sea was limited, and the environment was probably a brackish lagoon in which mainly fine-grained sediment was deposited. The relatively sudden appearance of spaghetti beds 110 m above the base of the Salrock Formation probably represents a change to truly marine conditions, perhaps induced by the temporary disappearance of a seaward barrier bar or by a eustatic rise in sea level to bring about tidal activity again. The commoner occurrence of grey-green sediments and spaghetti beds to the east is an indication of increasingly marine conditions in that direction. The large dish-shaped discordances are a little harder to explain, but may represent scoops caused by storms scouring the shallow sea bottom.

CHAPTER 5

HISTORY OF SEDIMENTATION

1. Provenance

1.1. Palaeocurrent pattern

A simplified palaeocurrent pattern for the Wenlockian is shown in Fig. 24. It is evident that the direction of sediment transport changed considerably throughout the period of basin fill.

No current directional structures were seen in the Gowlaun Member of the Lettergesh Formation. In the overlying Garraun Members no directional sole structures were seen, but cross-lamination directions recorded from the tops of beds show a direction consistently from the north-east throughout the lateral development of the members (Fig.24, 1). This direction is in keeping with the tendency for the grain size to coarsen to the east. The north-easterly current pattern is continued into the Benchoona Member 1, with directional sole structures showing a similar trend to cross-lamination azimuths (Fig.24, 2).

A considerable change occurs above this horizon, with sole structures showing palaeocurrents coming from both north-west and north-east quadrants. None come from the south, although in rare cases a slight southerly component is evident. The palaeocurrent pattern determined from cross-bedding and cross-lamination directions, in contrast to the sole structures, is almost consistently from the west, with rare exceptional currents from the reverse direction (see Fig.24, 5B). This poly-directional pattern persists from the top of Benchoona Member 2 up to the base of

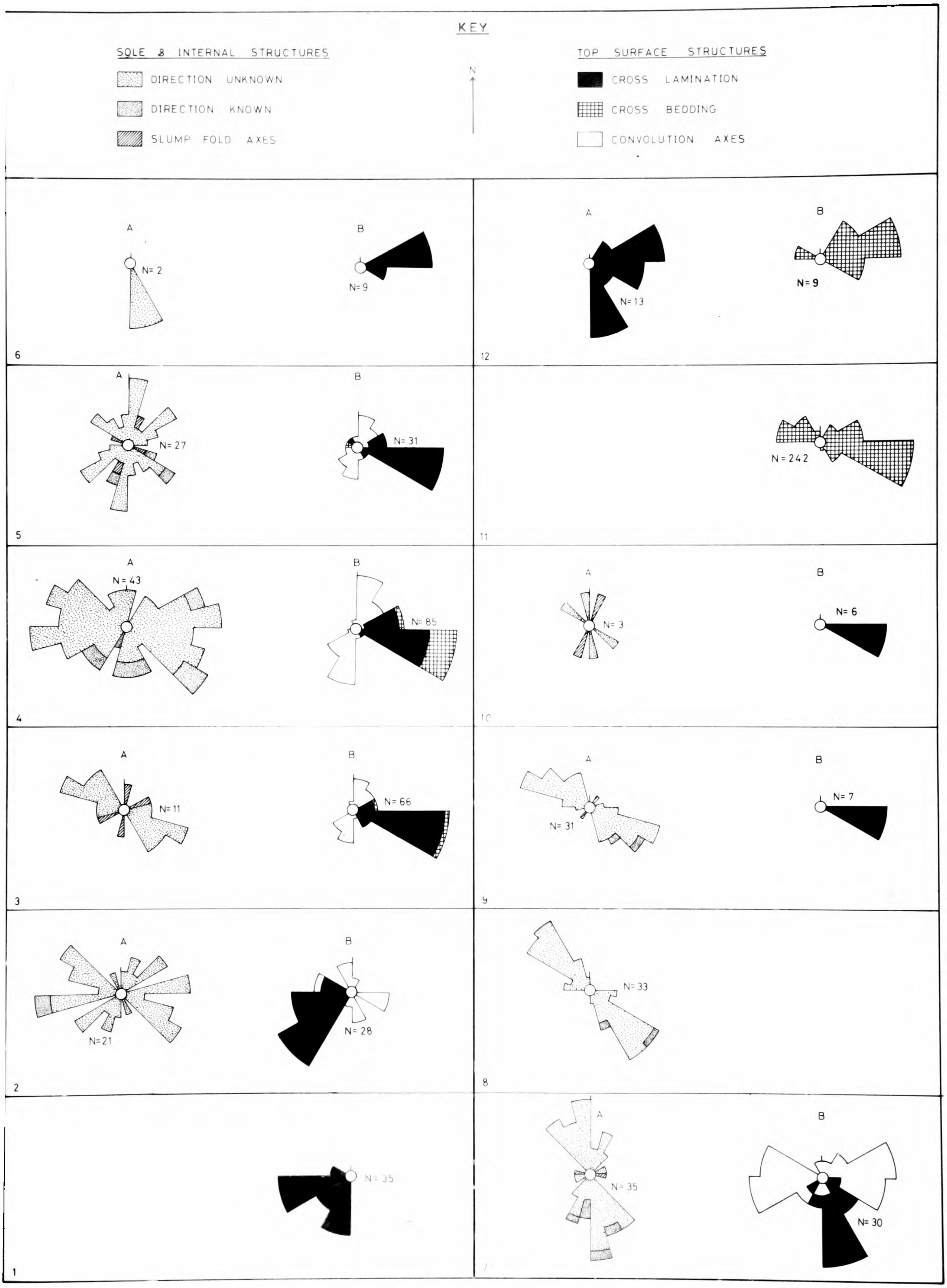


Fig.24. Summary of palaeocurrent trends throughout the Wenlockian. The current roses are arranged in pairs contrasting sole and internal structures (15° classes) in the left hand columns (except no. 12), with top surface structures (30° classes) in the right hand columns. 1) Garraun Fmn. 2) Benchoona Member 1. 3) Benchoona Member 2. 4) Benchoona Member 3. 5) Benchoona Member 4 and Letterettrin Member 1. 6) Letterettrin Member 2. 7) Letterettrin Member 3. 8) Glencraff Fmn. 9) Lower Member, Lough Muck Fmn. 10) Middle Member, Lough Muck Fmn. 11) Upper Member, Lough Muck Fmn. 12) Salrock Fmn.

Letterettrin Member 2.

The western origin of traction currents continues throughout this member, but the included unit of breccia and sandstone appears from scant evidence (one groove and one channel wall) to come from the north (Fig.24, 6). In Letterettrin Member 3 all current indicators suggest a northern origin (Fig.24, 7), with a swing to a direction from the north west in the eastern part of the area.

In the Glencraff Formation a further swing in current direction (determined from sole marks) to one from the north-west is evident (Fig.24, 8), the swing being slightly greater in the Glencraff area than in the west.

Turbidites within the Lower Member of the Lough Muck Formation continue to show a current direction from the north-west in the west of the area, and a direction from the west-north-west in the Glencraff area (Fig.24, 9A). Thus there is a systematically increasing westerly component of current direction shown by turbidite sole structures from the base of Letterettrin Member 3 to the Lower Member of the Lough Muck Formation. In both the Lower and Middle Members, slump overfolds and cross-lamination azimuths continue to indicate a current and palaeoslope direction from the west-north-west, although grain orientation studies (two) and the strike of a channel wall show directional variation from north-west to north-south (Fig.24, 9 and 10).

In the Upper Member current azimuths measured from cross-bedding are bimodal with opposed modes, the stronger mode indicating currents from the west or west-north-west, and the minor mode showing derivation of currents from the east or east-south-east (Fig.24, 11).

Only a few current readings could be taken from the Salrock Formation, but cross-bedding azimuths show a similarly asymmetrical opposed bimodal plot, the main mode showing current derivation from between west and west-south-west (Fig.24, 12B). A separate plot of cross-lamination directions is more complex, giving two strong modes, one indicating currents from between west and west-south-west as for the cross-bedding azimuth plot, and the other currents from between north and north-north-west (Fig.24, 12A). Possibly the difference in current directions is due to the influence of surface waves on the ripples.

1.2. Petrography

Boulders in Benchoona Member 1 of the Lettergesh Formation consist of three main lithological types: volcanic, sandstone or siltstone, and quartzite. The clasts of volcanic rocks are basic to intermediate in composition. Most clasts are too fresh to be attributed to the Dalradian and correspond closely with Ordovician volcanics. They may also be connected with contemporaneous Silurian volcanic activity, as tuffs of intermediate composition are found higher in the Wenlockian.

The sandstone and siltstone clasts are indistinguishable from similar lithologies interbedded with the conglomerates, but are equally likely to be derived from the Ordovician. The quartzites in outcrop are commonly reddened, although this colour is not apparent in hand specimen. This lithology resembles both Dalradian and Ordovician quartzites.

Other lithologies found much less abundantly are jasper and serpentinite. The jasper was probably derived from the Ordovician (Lough Nafooey Group - Dewey, 1963), but the source of the serpentinite is more likely to be from intrusions into the Dalradian. Serpentinites intrude Dalradian rocks both in Connemara and along the Highland Boundary Fault on the southern shore of Clew Bay, where there is evidence that they are pre-Wenlockian (W.E.A. Phillips, pers. comm.). The serpentinite in Benchoona Member 1 is not found among the larger pebbles and in thin section appears as frayed fragments, unlike the well-rounded quartzites, volcanics, and siltstones. The friability of the serpentinite suggests that it could not have travelled far, and its occurrence in only two samples collected suggests derivation from a local source only.

All Wenlockian sandstones examined in thin section are highly arkosic, some with more than 60% feldspar content, and most with an excess of feldspar over quartz. No systematic variation in major mineral content was noted throughout the Upper Owenduff and Killary Harbour Groups, with the exception of the clean green-white sandstones in the upper Salrock Formation which are notably more quartzitic (some over 60% quartz) than surrounding red-coloured more feldspathic sandstones.

Many of the arkosic greywackes making up the bulk of the Lettergesh Formation have a high proportion (up to 25%) of lithic clasts consisting mainly of quartzite and a basic or intermediate volcanic rock.

The petrologic data is more consistent with a northerly than with a southerly source. During most of Ordovician times Connemara is believed to have formed an emergent area (Stanton, 1960; Dewey, 1963) and is unlikely therefore to have provided a source of Ordovician detritus during Silurian times. All lithologies occurring in the conglomerates and sandstones occur in Ordovician or Dalradian rocks to the north, and rocks specifically suggesting a southerly origin (such as granite from the pre-Wenlockian Oughterard Granite or schists from the Connemara Schist) are absent. A northern source area is not only consistent with the palaeocurrent directions, but it is there that abundant volcanics occur in the Ordovician sediments.

2. Depositional History and Palaeogeographic Interpretation

The depositional history of the area began in Upper Llandovery times with first fluviatile and then shallow marine sedimentation. There is evidence (D.J.W. Piper, in press) for a transgression from the south over a northern or north-eastern land area. The basal fluviatile deposits have a palaeocurrent pattern generally directed towards the south-west, and in the marine deposits deeper-water shelf facies occur southwards and are replaced by the deeper "basin facies" of the Gowlaun Member to the west (Piper, 1967; Piper, in press).

Palaeocurrent evidence is lacking in the Gowlaun Member, but petrological data is consistent only with a generally northern source (Piper, in press). In the upper part of the Member, examined briefly by the present writer, the interfingering of coarse sandstones with siltstones both west near the present coastline and east at Lettershanbally suggests either a generally northerly or generally southerly source. The eastward coarsening of the sandstones indicates either north-easterly or south-easterly provenance, only the former being compatible with palaeocurrent directions from both older and younger rocks. Piper (1967) suggested that the facies change in the Gowlaun Member at Lettershanbally occurred at the eastern margin of a basin accumulating coarse allochthonous sediments. The poor sorting of the sandstones and presence of boulder beds with well-rounded clasts in association with graded beds is evidence for resedimentation, and probably much of the coarse facies of the Gowlaun Member was deposited by means of sand flows and boulder slides down a steep-walled basin margin into an area in which quiet-water mainly pelagic sedimentation was occurring.

The overlying sandstones of the Garraun Members indicate that resedimentation was a continuing process, but that sand flow and sand creep was giving way to deposition by turbidity currents, the change in sedimentation mechanism perhaps reflecting the decrease of basin margin slopes below the angle required to maintain significant mass movement of sediment. A north-easterly source direction was maintained as indicated by the palaeocurrents, and all Garraun Members thin and wedge out in the vicinity of Lettershanbally indicating persistence of a basin margin in that area. On the western slopes of Altnagaighera the two lowermost Garraun Members thin to the west before being obscured by bog, possibly indicating the proximity of the western margin of the basin.

East of Lettershanbally, in the saddle between Glencraff and Glenglosh, all Garraun Members have disappeared and the Gowlaun Member attains its minimum thickness of 7.6 m. East of the saddle the Gowlaun Member thickens consistently towards Maam Valley. The area at present between Lettershanbally and the saddle thus probably constituted a local positive area between two depositional basins. On this positive area only fine-grained deposits accumulated, largely from suspension, while the basins on either side accumulated mainly resedimented material. Corroborative evidence for the existence of a basin to the east of the Glencraff/Glenglosh saddle comes from the Lower Owenduff Group (Piper, pers. comm.). The eastern basin continued to accumulate mass flow deposits while later deposition in the western basin consisted mainly of turbidites.

The Benchoona Member 1 represents a north-easterly or easterly derived submarine fan with its axial region close to or immediately east of Lettershanbally. The fan evidently spilled over into both basins. A period of quiescence followed before turbidity currents built out fans once more. The history of basin fill in the eastern basin is obscure, because of the difficulty of correlating stratigraphic sections from one part of the basin with another. In the western basin it is evident that two clear-cut episodes of turbidity current deposition followed not long after the emplacement of the fan material of Benchoona Member 1. These two succeeding fans (Benchoona Members 2 and 3), separated from each other by periods of little current activity, in contrast to the Benchoona Member 1 fan have a provenance mainly from the west or north-west. The turbidites which follow show directions varying from nearly west, through north, to nearly east, until the deposition of Letterettrin Member 2. The central coarse unit of this Member appears to represent part of a turbidite fan from the north, and all succeeding turbidites have a northerly direction of origin until the deposition of the Glencraff Formation. The thinning out not only of the coarse facies of Letterettrin Member 2 and part of Member 3, but also of the fine-grained non-turbidite sediments of Member 2 towards the west possibly indicates thinning against a basin margin, and suggests that the western basin persisted at least until this time. The sequence above Benchoona Member 1 also thins eastward from the Benchoona/Lough Fee area to the Glencraff/Glenglosh saddle, corroborating the persistence of a basin margin in this area also.

Bottom traction currents were active in addition to turbidity currents, at least in the western basin. Initially they approximately paralleled the direction of turbidity current flows, and may have been generated by the turbidity currents. A dramatic change occurred after the deposition of the fan representing Benchoona Member 1. Whereas cross-laminated thin sandstone beds are rare in siltstone units below this horizon, they become common above it, and show a persistent current direction from the west. The cross-laminated top surfaces of the turbidites also show the same current direction, which is often at variance with associated sole structures. Evidently bottom traction currents independent of penecontemporaneous turbidity currents were active in the western basin. Their nature is uncertain, but they were probably tidal or geostrophic contour currents. These currents were responsible for the reworking of much of the material brought in initially by turbidity currents. Above Letterettrin Member 2 the traction current pattern swings abruptly through ninety degrees to one from the north and again parallels the direction of turbidity currents determined from sole marks. Evidently the geostrophic or tidal currents were deflected suddenly from the area of the basin or ceased to act, leaving only lateral traction and turbidity currents active.

The impression thus gained from the palaeocurrent and slump fold evidence in the Lettergesh Formation is of turbidity currents building out fans of coarse material laterally from the basin margins, the fans originating from the north-west, north, and north-east, implying the existence of a generally northern source area (Fig.25).

By the time deposition of the Lettergesh Formation had ended both eastern and western basins had ceased to exist as topographic depressions, and the Glencraff Formation was laid down as a mat of uniform thickness over the whole area. The sudden change from the coarse turbidites of the Lettergesh Formation to the fine-grained beds of the Glencraff Formation indicates a change in depositional conditions, emphasized by a change in provenance from north to north-west. The northerly source of coarse-grained turbidites evidently either ceased to be active or the turbidity currents generated from it were suddenly deflected to another area of deposition. The north-westerly-derived fine-grained turbidites were probably being deposited at the same time as the coarse-grained ones, but the palaeocurrent pattern of the earlier deposits

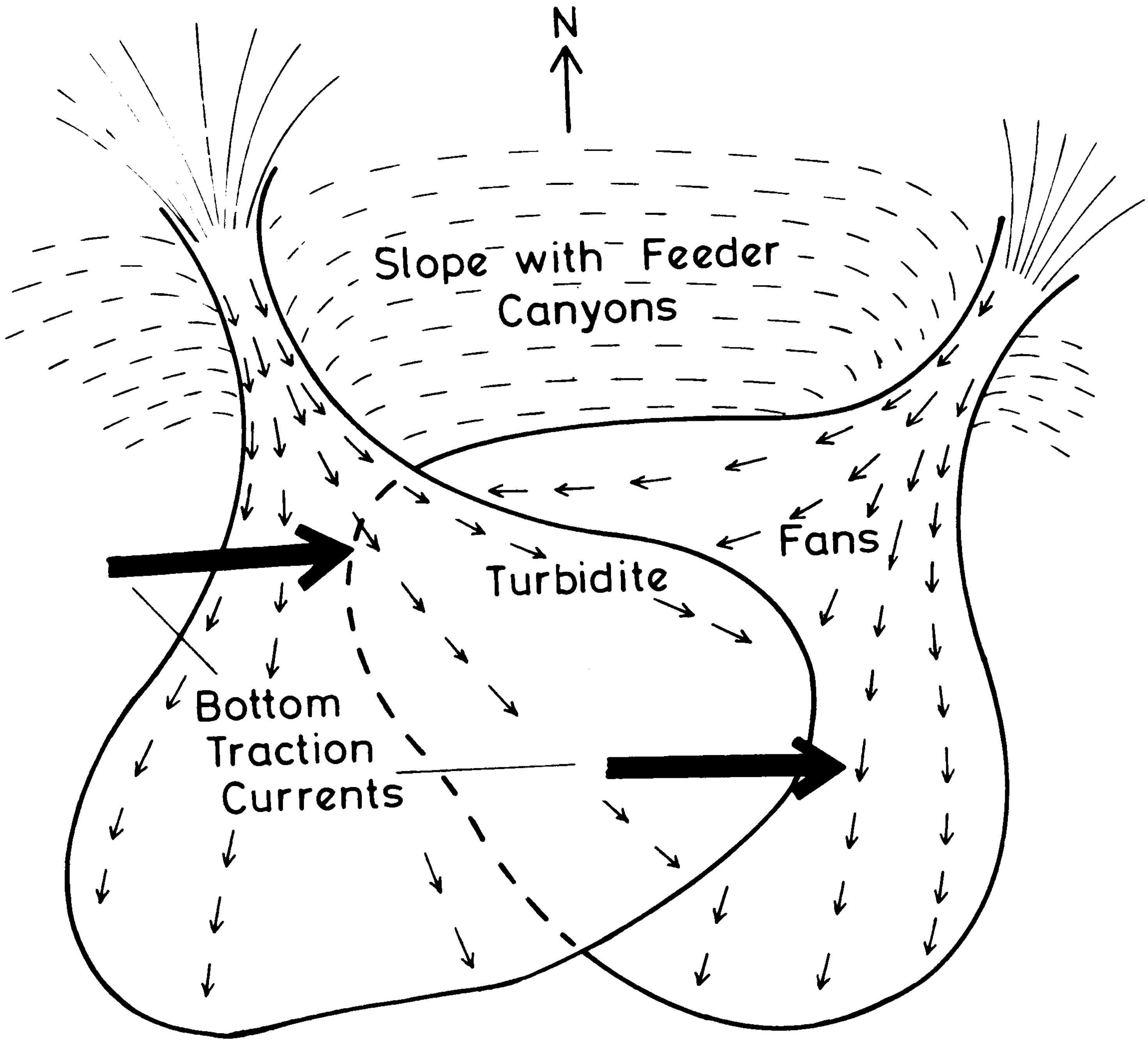


Fig.25. Lateral derivation of turbidite fans and reworking by bottom traction currents moving parallel to the slope during the deposition of the Lettergesh Formation.

may have been masked by more frequent deposition of coarse-grained beds.

Another possible explanation for the sudden decrease in grain size and bed thickness is the occurrence of a rapid transgression with consequent retreat of the shoreline and deposition of finer, more distal turbidites than those preceeding.

Turbidity currents continued to be deposited from the north-west or west-north-west in early Lough Muck times, but in the west these were soon supplanted by rise deposits consisting mainly of massive sandstones emplaced by sand creep or flow or representing the deposits of immature turbidity currents, and by slumped beds, with minor fine-grained turbidites and massive siltstones. These had been channelled down shallow valleys in an adjacent slope and spread out fanwise over earlier-deposited turbidites. Downcurrent to the east and therefore in the distal portions of the fans a higher proportion of turbidites was deposited, the massive sandstones and slumps being mainly restricted to the proximal fan area. Slope deposits represented by the Middle Member of the Lough Muck Formation were built out over earlier deposited rise sediments in the form of a basinwards thickening wedge. Possibly the basinwards building out of the shelf was responsible for the earlier deflection of supply of the thick coarse-grained northerly-derived turbidites of Letterettrin Member 3, the fine-grained north-westerly-derived turbidites of the Glencraff and Lower Member of the Lough Muck Formations representing finer-grained shelf-derived material channelled down slope valleys and deposited in the basin beyond the proximal rise deposits.

The basinward-building shelf advancing from the west-north-west eventually covered these earlier rise and deeper basinal deposits and a shallow marine environment dominated by offshore-onshore tidal currents obtained, the shoreline being directed approximately north-south or north-north-east south-south-west. In some localities, particularly in the east of the Killary Harbour area, offshore bars developed, behind which quieter fine-grained sedimentation under lagoonal conditions occurred. The water by this time had become shallow enough for wave action to be important in the resorting of sediments. Fig.26 represents a reconstruction of the palaeogeography during Lough Muck times.

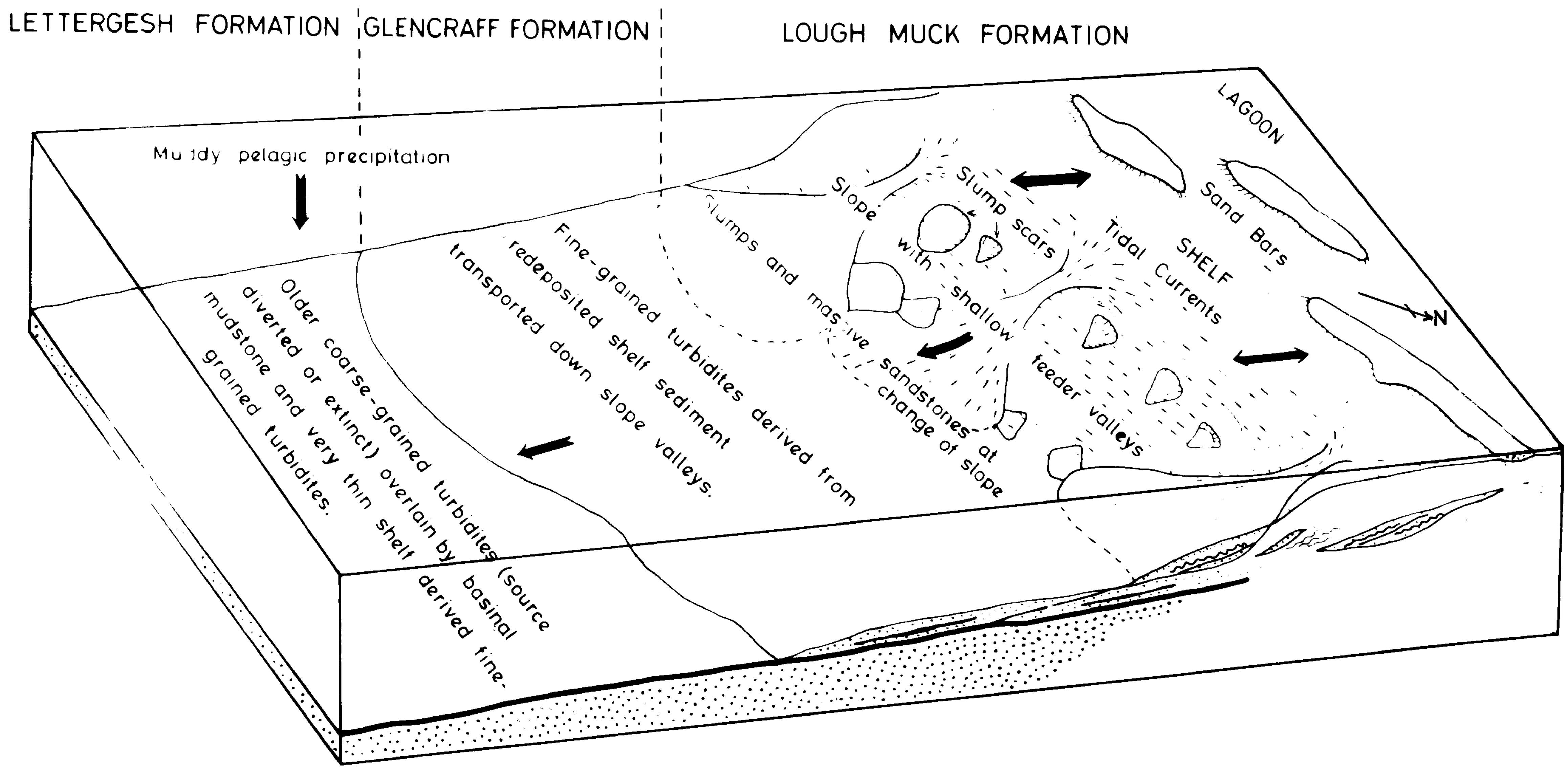


Fig. 26. **Palaeogeography of the Killary Harbour area during deposition of the Lough Muck Formation (middle Wenlockian).**

By Salrock times, the water may have shallowed sufficiently to allow oxidation of iron compounds to occur and tint the sediments red, but probably the red colouration was at least in part due to the erosion of red sediment in the source area. The accumulation of a thickness in excess of 800m of mainly red-coloured shallow marine sediments suggests near-balance between rate of sediment supply and rate of downwarp of the basin of deposition for a considerable period of time. That minor fluctuations in base level may have occurred, however, is suggested by the sudden appearance and persistence for a short while of tidal influence approximately 170 m above the base of the Salrock Formation. The persistence of a north-south oriented shoreline to the west of the area into Salrock times is suggested by a continuation of the east-west bimodal tidal current pattern, which in the Lough Muck Formation represented offshore-onshore currents, and by the decreasing proportion eastwards of red beds implying less oxidising conditions in that direction.

3. Regional Considerations

The pattern of regional sedimentation changed considerably from Ordovician to Silurian times. During most of the Ordovician period sedimentation in the Connemara-Murrisk area occurred in an east-west-trending trough (the South Mayo Trough), defined to the north by a normal fault and to the south by a rising Cordillera in Connemara (Dewey, 1963).

By the beginning of Silurian sedimentation the tectonically controlled South Mayo Trough had ceased to be an active feature, and the Connemara Cordillera had disappeared. A marine transgression from the south slowly covered a northern or north-eastern land area. As the land subsided small, localized basins of deposition developed on the shelf, and received a great thickness of largely redeposited sediment. The situation at this time was probably analogous to the present-day continental borderland off the Southern Californian coast where small sedimentary basins are now collecting turbidites and pelagic material (Gorsline and Emery, 1959).

While turbidite deposition continued in the Killary Harbour area, shallow marine deposits were accumulating in Central Murrisk (Dewey, 1963) and littoral and fluviatile sedimentation occurred on the site of Clare Island and on the southern shore of Clew Bay (Phillips, 1965). The northern deltas provided abundant sediment for deposition in the basins on the continental borderland, and slowly spread south and east causing the submarine portions of the deltas to advance basinward over earlier-deposited turbidites and pelagic sediments. The Middle and Upper Members of the Lough Muck Formation thus probably represent the foreset slope and topset plain (Dunbar and Rodgers, 1957) of the marine part of a delta, while the Salrock Formation represents near-shore lagoonal deposits close to the subaerial part of the delta. The slope valleys which served to concentrate the basinwards flow of sediment may have represented the seaward extension of delta distributaries.

APPENDIX

A. Point Counts

Approximately 100 thin sections were made from rocks collected throughout the stratigraphic column. From these nine cut from the coarser facies were selected for point counting in order to decide the general composition, and to determine whether or not there was any significant compositional difference throughout the sequence (Table A1).

Quartz and feldspar always form the dominant clast constituents. "Other minerals" consist mainly of chlorite, mica, and a dark ore. Rock fragments consist of volcanic rocks, sandstone or siltstone, and quartzite, in varying proportions. Material which could not be resolved was assigned to the category of matrix.

TABLE A1. POINT COUNTS FROM 9 THIN SECTIONS

Slide	Facies	Formation	Member	Quartz	Feldspar	Other Min.	Rock Frags.	Matrix
13	B	Lettergesh	Gowlaun	24.4%	34.5%	7.8%	12.4%	21.0%
G1	C_1	"	Benchoona No.2	13.9%	42.2%	3.8%	18.2%	22.0%
X10	C_1	"	Benchoona No.3	28.1%	27.8%	2.0%	11.4%	30.8%
X13	C_1	"	"	23.3%	47.4%	2.4%	7.7%	19.2%
b1	C_2	Glencraff		5.2%	62.3%	2.6%	-	30.3%
S3	I	L. Muck	Middle	24.1%	45.0%	11.6%	-	19.4%
020	J	"	Upper	30.8%	43.4%	2.0%	12.2%	11.7%
Z10	L	Salrock		27.3%	53.1%	4.9%	-	14.6%
Z12	L	"		61.5%	30.8%	2.2%	-	5.5%

B. Grain Size Analysis.

Lithification renders disaggregation of the sediments impracticable, and hence thin section analysis of selected facies was undertaken. The apparent long diameters of all resolvable grains with clear outlines were measured, using a one centimetre sample grid over a 'Shadomaster' screen on to which an image of the thin section was projected at known magnification. Grains falling on more than one grid point were counted for each point to give a closer approximation to a weight distribution. The measured grains were allocated to Ø classes and plotted as cumulative percentage curves (Fig. B1).

No corrections were applied to the curves, as Friedman's 1958 corrections apply only to well-sorted highly quartzitic sandstones, and manipulation of the calculated curves could well lead to misrepresentation in the case of the dominantly poorly-sorted arkosic sandstones of the Killary Harbour area.

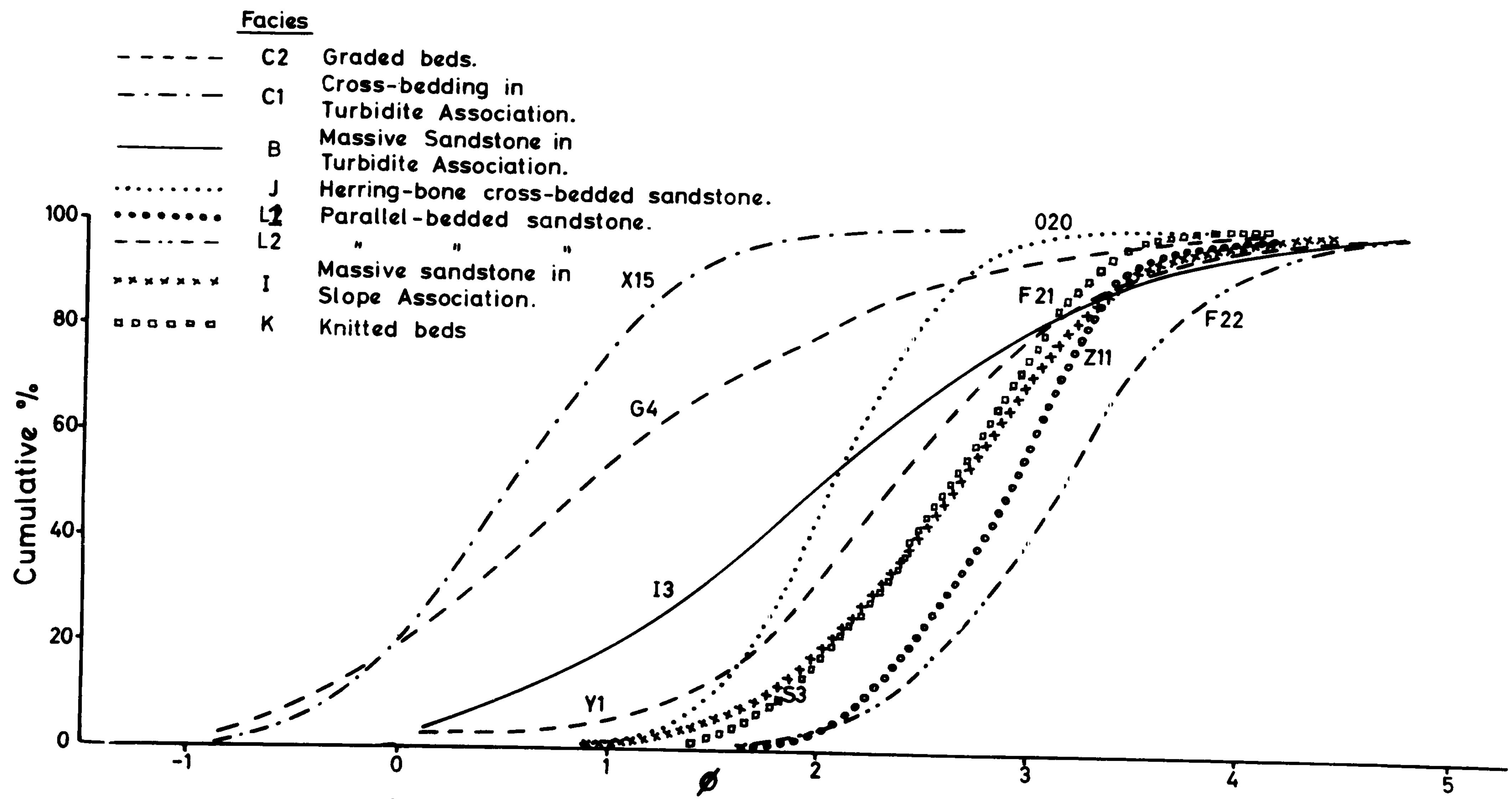


Fig.B1. Cumulative grain size frequency curves

C. Fossil Localities

Collection no.	Formation & Member	Stratigraphic Section (Map 2A)	Location	Fossils
A20	Glencraff (tuff bed)	Between 15 & 17	1730 m at 285° from Letterettrin.	Orthoceras
A21	Lough Muck, Lower Member.	17	1630 m at 286° from Letterettrin.	Orthoceras
B1	" "	15	2230 m at 291° from Letterettrin.	Graptolites, gastropods
F24	" "	33	300 m at 202° from Knockraff	Eocoelia sulcata, "Petraia", dalmanellids bivalves, crinoids.
A32	Lough Muck, Middle Member	17	1630 m at 287° from Letterettrin.	Plectodonta
A33	" "	Between 15 & 17	1680 m at 286° from Letterettrin.	Leptaena, dalmanellids
X7	" "	17	1620 m at 287° from Letterettrin.	Monoclimacus flumendosae (Gortani)
B3	" "	15	2240 m at 291° from Letterettrin.	Gastropods
B4	" "	Between 14 & 15	2470 m at 293° from Letterettrin.	Bivalves, gastropods
B5	" "	14	2600 m at 293° from Letterettrin.	Leptaena, Orthoceras dalmanellids, corals, bivalves.
B6	" "	14	2600 m at 293° from Letterettrin.	Trilobites, bivalves.
Q1	" "	12	3300 m at 288° from Letterettrin.	Encrinurus, gastropods, dalmanellids.

S2	Lough Muck, Middle Member	18	1270m at 294° from Letterettrin.	Leptaena, chanetid, trilobite, gastropod.
T1	" "	24	550m at 79° from Letterettrin.	Leptaena, coral, dalmanellids
X2	" "	25	800m at 93° from Letterettrin.	Leptaena, dalmanellids.
X3	" "	25	800m at 93° from Letterettrin.	Leptaena, dalmanellids.
X5	" "	Between 25 and 26	1000m at 94° from Letterettrin.	Leptaena, dalmanellids.
U1	Lough Muck, Upper Member	East of 26	1700m at 95° from Letterettrin.	Crinoids.
R1	" "	9	5650m at 293° from Letterettrin.	Coelenterates
R2	" "	9	" "	Encrinurus
R3	" "	9	" "	Trilobite
F18	" "	33	350m at 225° from Knockraff.	Acaste, Dalmanites, gastropods
O1	" "	35	700m at 117° from Knockraff.	Bivalves, crinoids
O22	" "	35	" "	Leptaena, dalmanellid, gastropods, crinoids
O23	" "	34	600m at 142° from Knockraff	Leptaena, dalmanellids.
O24	" "	34	" "	"
F30	Salrock	33	450m at 0° from Knockraff.	Gastropods.
B7	"	14	2450 m at 301° from Letterettrin.	Lingula

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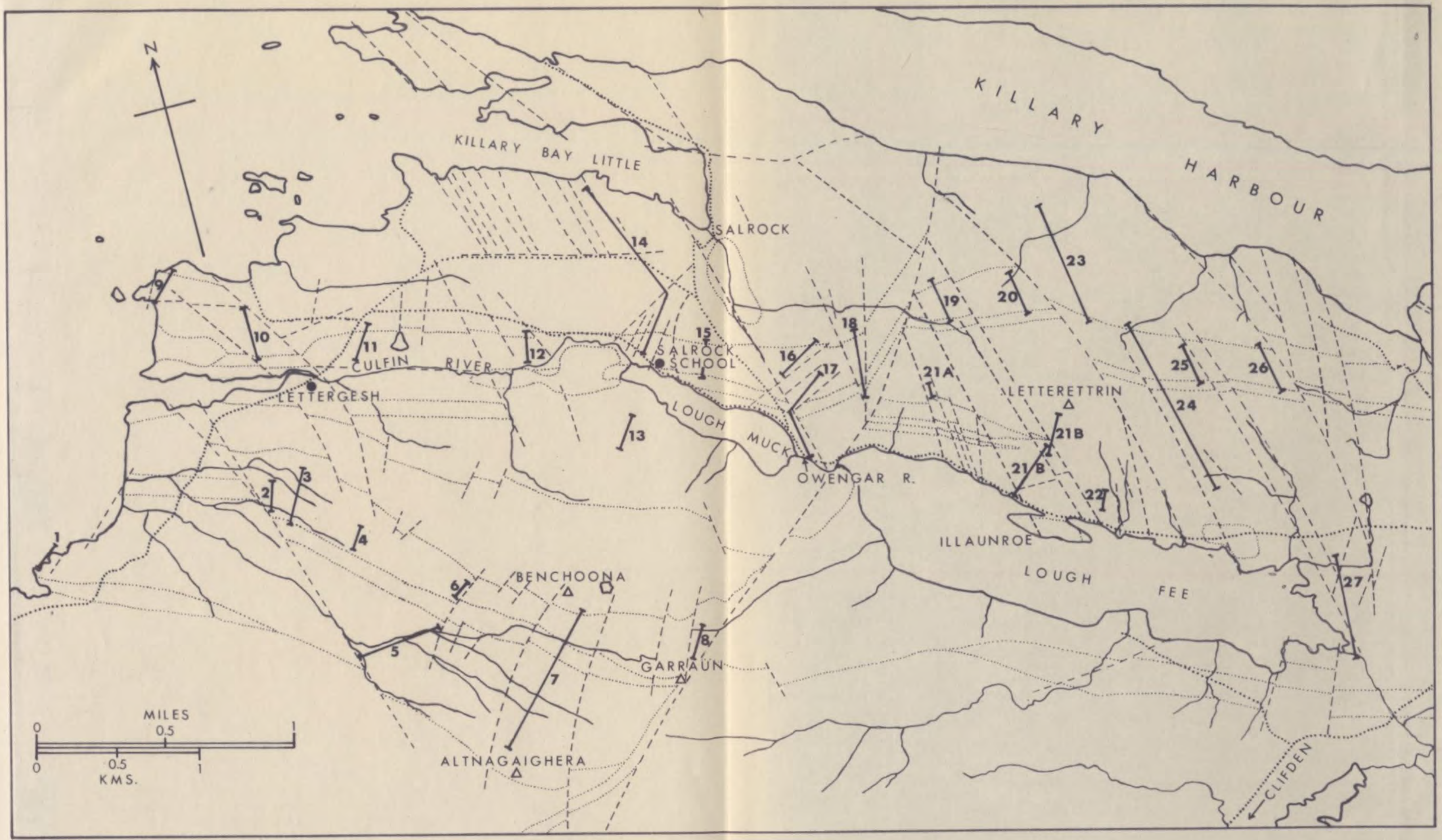
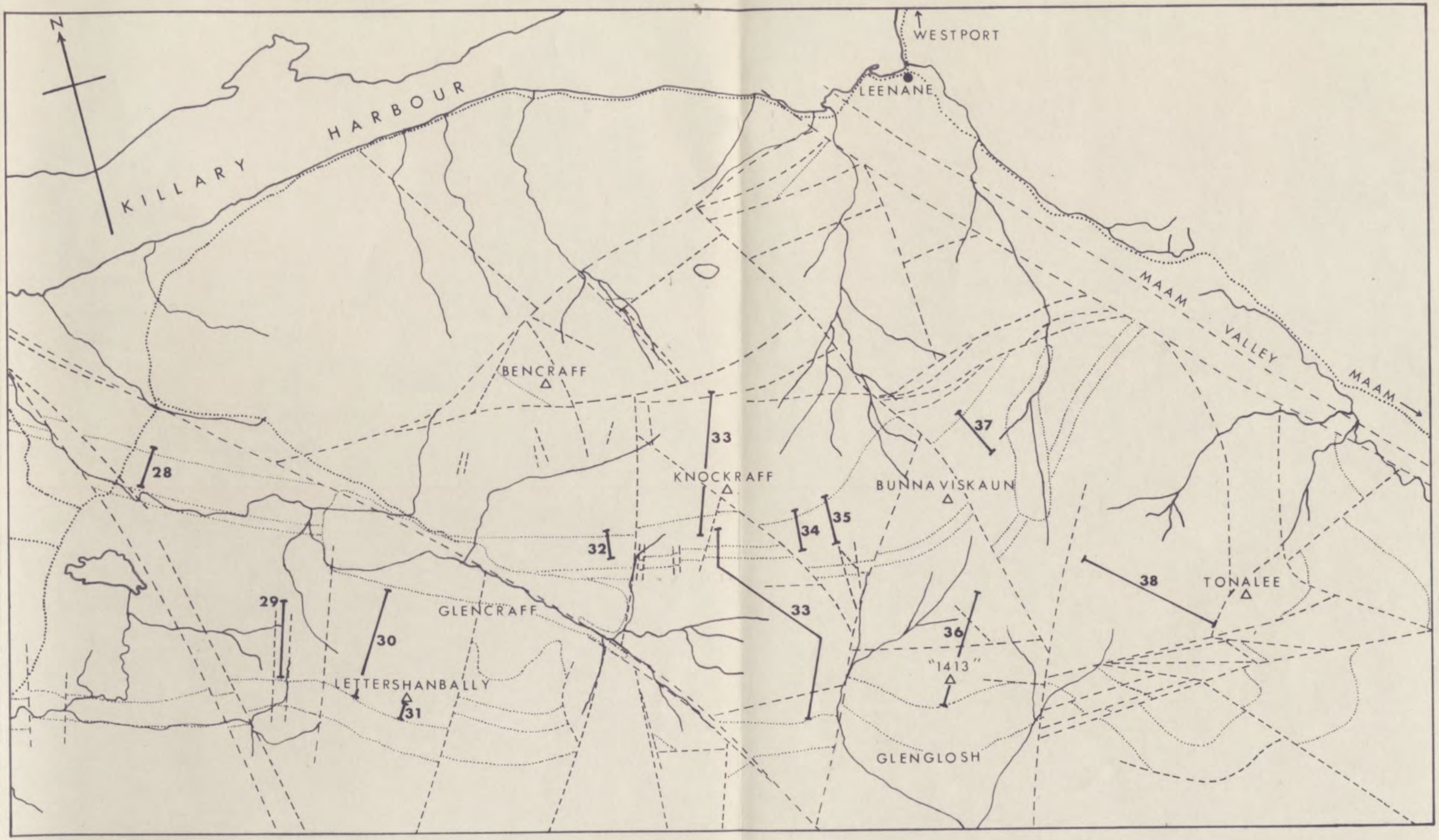


FIG. 2A TOPOGRAPHICAL AND LOCATION MAP OF THE KILLARY HARBOUR AREA



STRATIGRAPHIC SECTION ⊢7⊣ GEOLOGICAL BOUNDARY ············

FAULT - - - - - - ROAD ············

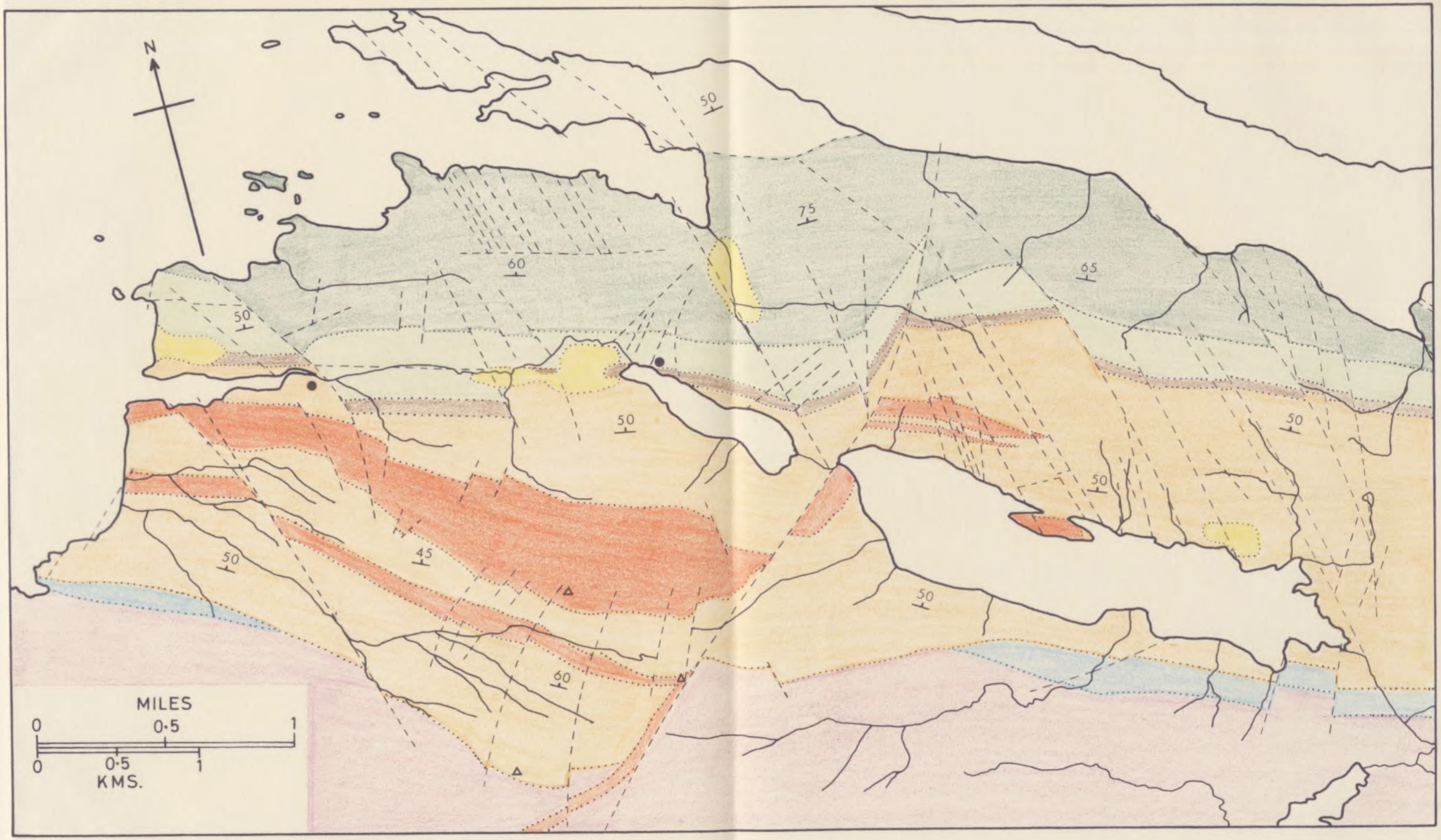
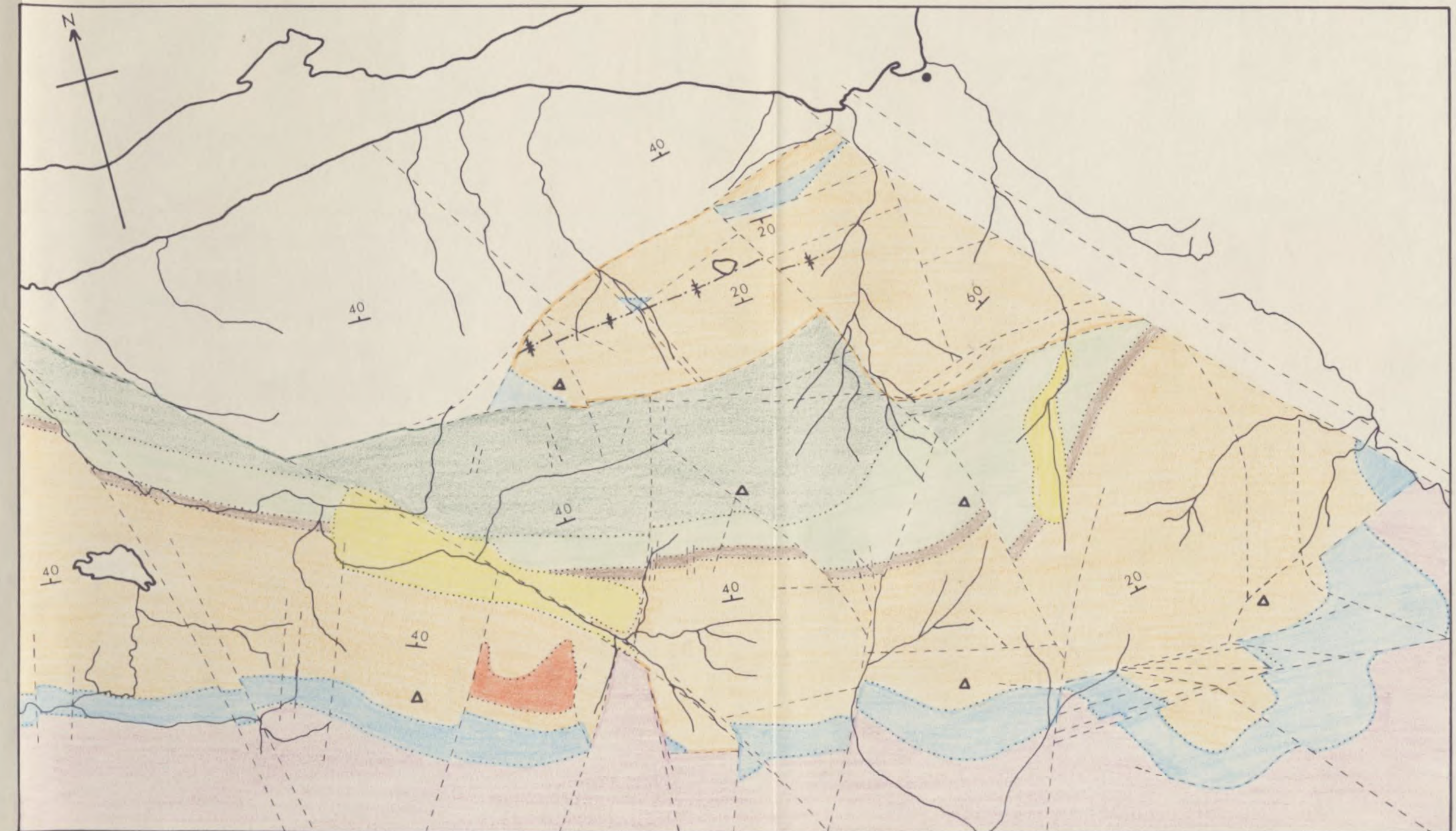


FIG. 2B. GEOLOGICAL MAP OF THE KILLARY HARBOUR AREA



SALROCK FMN.	KILLARY HARBOUR GROUP	LOWER OWENDUFF GROUP	BOG AND ALLUVIUM
LOUGH MUCK FMN.		ORDOVICIAN	SYNCLINE
GLENCRAFF FMN.	UPPER OWENDUFF GROUP	CONNEMARA SCHIST	STRIKE AND DIP
LETTERGESH FMN.		IGNEOUS INTRUSIONS	FAULT