RECENT CARBONATE SEDIMENTS OF THE WEST COAST OF SCOTLAND BETWEEN ARDNAMURCHAN AND ISLAY

by

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DECLARATION

I have been a member of a research group which included Dr. Terence P. Scoffin of the Department of Geology, The University of Edinburgh and Dr. George E. Farrow and Mr. Brian Brown, both of the Department of Geology, The University of Glasgow. This thesis reports on my own contribution to the group project. Any assistance by these other investigators is clearly and gratefully indicated in the acknowledgements and the text of this thesis. Publications, of which I am a co-author, concerning this group project are annexed as appendices.

Maurice A. Cucci.

Date 30 May 1979

ABSTRACT

Deposits of temperate water biogenic carbonate sediments occur on the inner western continental shelf of Scotland. A general survey of their extent and composition has been made and facies maps prepared for the area. One small portion of the area, the Sound of Iona, was studied in detail to ascertain the origin of the carbonates and their bed-forms and to attempt an estimate of local carbonate productivity.

In Iona Sound, barnacles and molluscs are the most important bioclastic constituents with locally dominant coralline algae (maerl). Barnacles predominate over most of the Sound because they grow prolifically on the coast, are readily broken down to sand size and easily transported.

Four facies are recognized in Iona Sound: 1) rippled sand, 2) sand waves and sand ribbons, 3) in situ maerl, and 4) relict glacial drift deposits. Seismic studies indicate that 1) bioclastic sediment is thickest at the sand wave facies diminishing in thickness laterally; 2) the sand waves are draped over a bathymetric high formed from glacial drift; 3) in the northern Sound glacial drift formed deltaic deposits. Facies are controlled as follows: the rippled sands are deposited under the influence of wind-generated waves and low-velocity tidal currents which winnow fines and create low bedforms; the sand waves are formed by the drag of tidal currents crossing the bathymetric high, sculpting a hierarchy of bedforms; an associated sand ribbon is formed by tidal current acceleration following deflection by an island; maerl forms because of 3-sided wave shelter, current deceleration, erosion resistant morphology and a greater growth rate of the algae over the ambient sedimentation rate. Glacial deposits were exhumed by scouring or lie exposed in areas of very slow sedimentation, or both.

Recent carbonate sedimentation is related to Pleistocene glacial

activity which created a complex coastal and seabed form trapping terrigenous sediment (termed "basinal terrigenes") in bathymetric deeps, lochs and convolute coastlines. Shallow-water, terrigene depleted, indurated rock localities of the inner shelf are exploited by carbonate producing organisms with high productivities shedding abundant bioclastic material to form "island margin carbonates".

This thesis is dedicated to

Dr. John Miller

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CHAPTER 1

PERSPECTIVES OF RESEARCH

1.1 Definition.

Temperate carbonate sediments: sediments which occur within the temperate zones and contain greater than 50% carbonate by weight.

1.2 Importance of temperate carbonates.

One aim of carbonate sedimentology is the generation of paradigms to aid in the interpretation of limestones in the geological record. A plethora of models based on Quaternary tropical and subtropical carbonates has found widespread application to ancient deposits. There are, however, occurrences of limestones which are not easily explained in terms of these tropical analogues; for example, in the Tertiary of New Zealand (Nelson, 1978), the Permian of Tasmania (Brill, 1956; Carey and Ahmad, 1961; David, 1950), the late Precambrian of northern Norway (Reading and Walker, 1966; Schermerhorn, 1974), the Precambrian of Islay (Spencer, 1971a, 1971b),the late Precambrian of South Australia (Harland, 1964) and the late Precambrian succession in the southern Urals (Harland *op. cit.*). These carbonates have a dearth of features diagnostic of tropical environments (*e.g.* oolites, or hermatypic corals for the Paleozoic localities); the nature of their flora and fauna and their being often interbedded with glacial deposits suggests they were deposited in cool or cold waters. Apart from their value in interpreting ancient carbonates, studies of Recent temperate carbonates may also have some economic significance since such deposits are becoming important sources of lime.

The parameters of temperate carbonate environments have not hitherto been studied in detail; so those temporal and spatial variations of physical, chemical and biological factors involved in their formation are not well understood. However, work of a reconnaissance nature has begun on temporate carbonate shelf deposits on N. America, Europe, Australia and Asia (see Table 1). A primary characteristic of these deposits is that they are biogenic and contain faunal associations composed of all or some of the following: molluscs, foraminifera, echinoderms, bryozoans, barnacles, ostracods, sponge spicules, worm tubes and ahermatypic corals as well as a flora dominated by calcareous red algae. Lees and Buller (1972) have proposed the term "foramol" for this temperate water association because foraminiferans and molluscs are usually present, often dominating the assemblages. The foramol group differs from the warm-water assemblages termed "chlorozoan" by Lees and Buller (op. cit.) where chlorophytes and zooantharians are significant contributors to the sediment. It is noteworthy that barnacles and bryozoans, which can be dominant components in temperate-water deposits, are usually minor components of tropical water deposits. A secondary characteristic observed at several sites (Table 1) is the close association of foramol faunas with glacial sediments. The inner shelf area adjacent to west coast of Scotland has long been known as an area of both temperate carbonate deposition and glacial sedimentation. Until the present study the interrelationship of these two aspects has not been thoroughly studied.

1.3 The N.E.R.C. Scottish West Coast Carbonate Project.

In July, 1975, a group of investigators formed under the sponsorship of the Natural Environment Research Council to study temperate carbonates of the Hebridean Sea area. Dr. T. P. Scoffin (University of Edinburgh) and Dr. G. E. Farrow (University of Glasgow) initiated a survey of sediment distribution over an area of some 7200 km^2 in the Hebridean Sea. I participated in this survey as an assistant on the

Table 1 Shelf deposits in temperate latitudes.

Carbonate composition : CO = coral, M = mollusc, C = cirriped (barnacle), CALG = calcareous alga, F = foraminifera, E = echinoderm, BR = bryozoa, BRAC = brachiopod.
* = carbonate occurs with or above glacial material.

	Latitude	water depth m	% $CaCO_3$	Components	Reference
<u>Northwest Europe</u>					
N. Scotland	59°N	beach	up to 97%	*M	Raymond and Hutchins, 1932.
N. Ireland S.W. Scotland	55°N	10-200	16-78	*M, C, CALG, F, E, Serpulids	Pendlebury and Dobson, 1976.
W. Ireland	53°N	0-40	40-100	*M, C, CALG, F, E, BR, Ostracods	Lees et al., 1969.
English Channel	49°N	40-140	80 ave.	M, C, F, E, BR, Serpulids	Channon and Hamilton, 1976.
N.W. France	47°N	5-30	5-75	M, C, CALG, BR, Serpulids	Vanney, 1965.
Barents Sea	75°N	50-300	0->90%	*M, C, F	Bjørlykke, et al. 1978.
<u>Mediterranean</u>					
Antibes, France	44°N	0-100	>50	M, F, C, CALG	Nesteroff, 1965.
Tunisia and Sicily	37°N	0-200	>50	M, F, BR	Blanc, 1958.
Algeria	36-37°N	70-80	24-66	CO, M, CALG, F, (E), BR, BRAC	Caulet, 1972.
Alboran Sea W. Med.	36°N	18-300	92-99	CO, M, CALG, F, BR	Milliman et al., 1972.
Straits of Gibraltar	36°N	46-889	12-64	CO, M, CALG, E, BR, BRAC	Kelling and Stanley, 1972.
<u>North America</u>					
Gulf of Maine	44°N	beach and nearshore	26-67	*M, C	Raymond and Stetson, 1932.
N. Carolina	36°N	40-200	50	M, CALG, BR	Tyler, 1934.
Anacapa Island, California	34°N	0-100	10-90	M, CALG, BR	Scholl, 1960.
Rosa Cortes Ridge, California	33°N	0-500	52-64	M, F, BR	Uchupi, 1961.
Cortes and Tanner Bank, California	32°N	33-550	25-96	M, F, BR	Holzman, 1952.
Coronado Bank, California	32°N	10-170	5-100	M, CALG, BR	Emery et al., 1952.
Sitka Sound, Alexander Archipelago, Alaska	57°N	beach and inner bay	37-94	*CO, M, C, CALG, E, BR, BRAC	Hoskin and Nelson, 1969.
Newfoundland, Canada	43-51°N	100-300	<10-86	*M, C, F, E, BR	Slatt, 1974, 1977.
<u>Australia</u>					
Warnbro Sd. W. Australia	32°S	0-27	82-97	M, F, E, BR	Carrigy, 1956
Eucla Shelf, S.W. Australia	33-34°S	0-130	up to 95	M, F, BR	Carrigy and Fairbridge, 1954.
S. Australia Coast	37°S	beach	65-95	not specified	Sprigg, 1952.
Victoria Coast	39°S	raised beach	>50	M	Gill, 1948 (relict, 3-5x10^3yr B.P. shells).
Coast of N.S. Wales	36°S	130-180	26-82	M	Shirley, 1964.
Bass Strait	40°S	31-220	40-80	M, CALG, F, BR	Wass et al., 1970.
<u>New Zealand</u>					
Cape Reinga - Three Kings Is.	34°S	10-200	25-100	M, F, E, BR, Serpulids	Summerhayes, 1969.
<u>Asia</u>					
Yellow Sea Korea	32°S	80-200	20-60	F, M, E, BR	Niino and Emery, 1961.

cruises (see Fig. 1 and appendix 1) and in subsequent laboratory analyses of samples collected on the expeditions. My particular task was to study in detail a small area of known high carbonate productivity, the Sound of Iona.

The aims of the overall project were four-fold:

1. To map the distribution of surface sediments within the designated area of the Hebridean shelf by ship-based sampling.
2. To determine the amount and composition of carbonate within the sediments (these analyses were performed by me).
3. To identify the dominant organisms contributing to and influencing carbonate sedimentation and to map the distribution of live benthic communities.
4. To identify sedimentological, biological and geochemical trends so as to assess the rates of production of carbonate materials in their source areas, and the means and effects of their dispersion.

1.3.1 The Sound of Iona Study.

Within the context of the large-scale study outlined above, I have investigated the sediments in the environs of the Sound of Iona (Fig. 2), in an attempt to determine in more detail the factors involved in the production of the temperate carbonate deposits. My specific aims were as follows:

1. Determination of location and nature of beaches and sublittoral areas where carbonate sediments predominate.
2. Assessment of possible transportation mechanisms by which locally produced carbonate might be dispersed from the site of origin.
3. Estimation of present carbonate productivity within the Sound.

A number of different lines of approach were used to collect data for fulfilment of these aims:

Fig. 1. Shelf sampling sites in the Columba-Colonsay Seas exclusive of Iona.

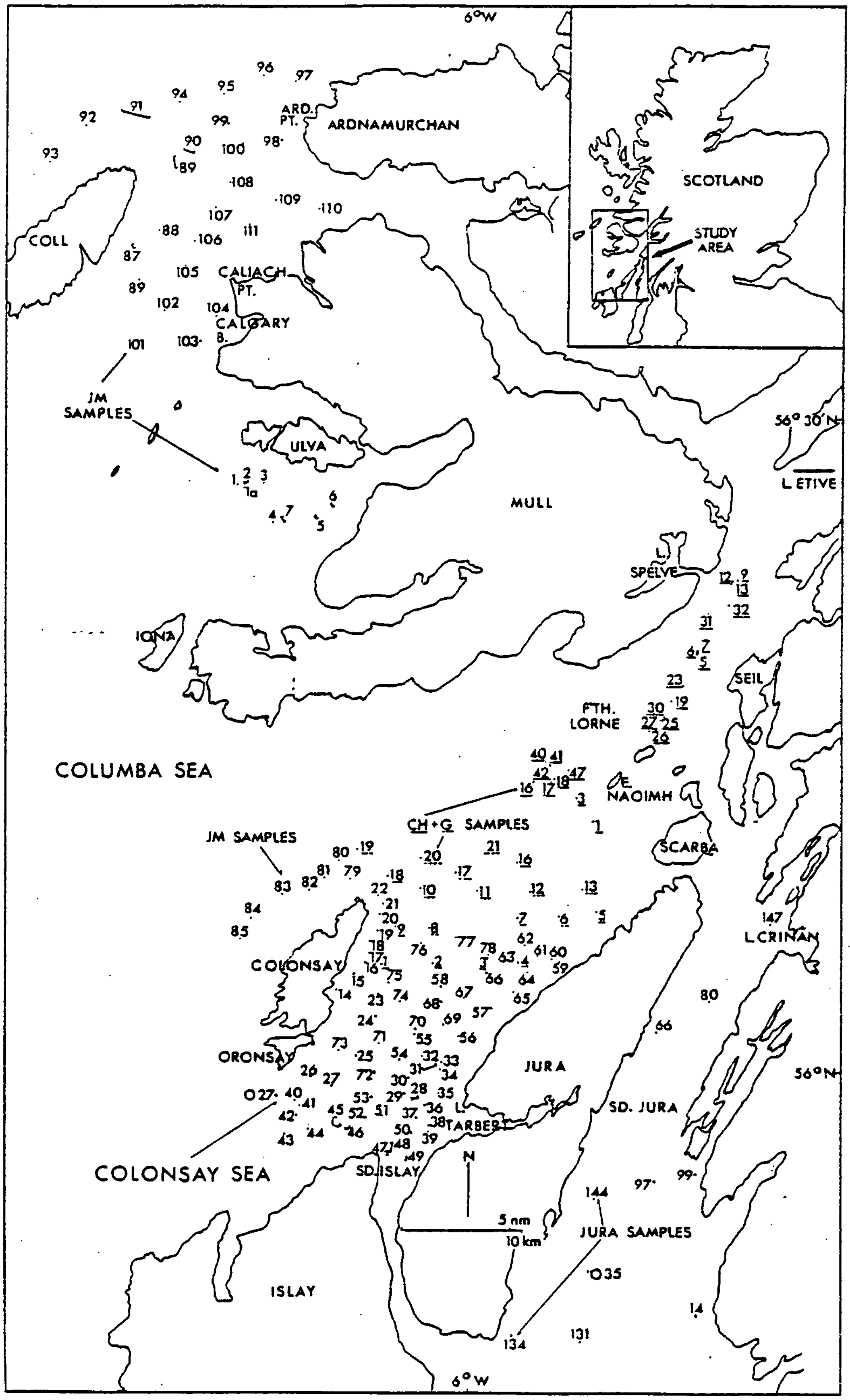

6°W
ARD. PT.
ARDNAMURCHAN
SCOTLAND
STUDY AREA
COLL
CALIACH PT.
CALGARY B.
JM SAMPLES
ULVA
MULL
56° 30'N
L. ETIVE
L. SPELVE
IONA
SEIL
FTH. LORNE
COLUMBA SEA
E. NAOIMH
CH + G SAMPLES
SCARBA
JM SAMPLES
COLONSAY
L. CRINAN
ORONSAY
JURA
56°N
SD. JURA
TARBERT
COLONSAY SEA
SD. ISLAY
N
5 nm
10 km
JURA SAMPLES
ISLAY
6° W

Fig. 2 A. Drift dive sampling sites in the Sound of Iona.

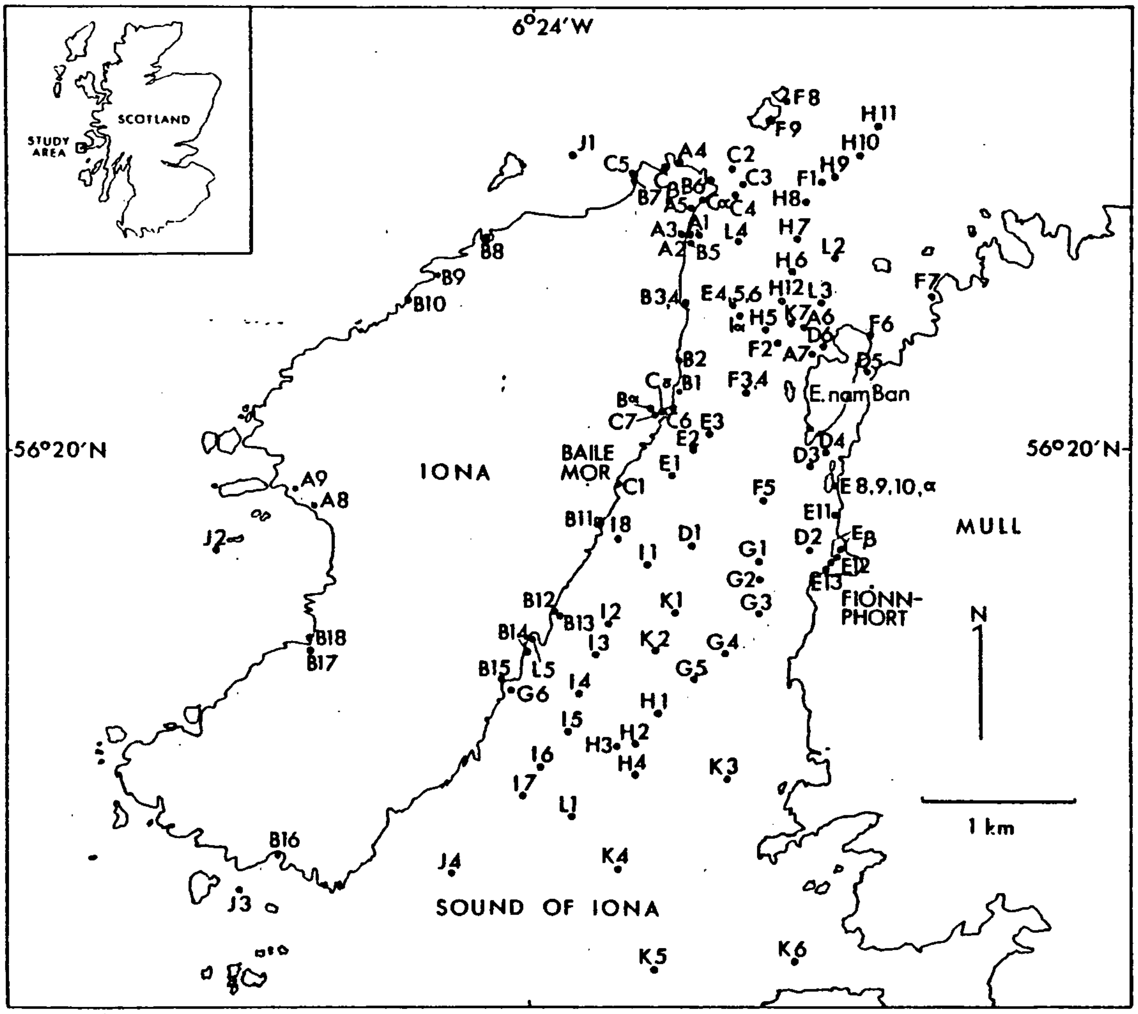
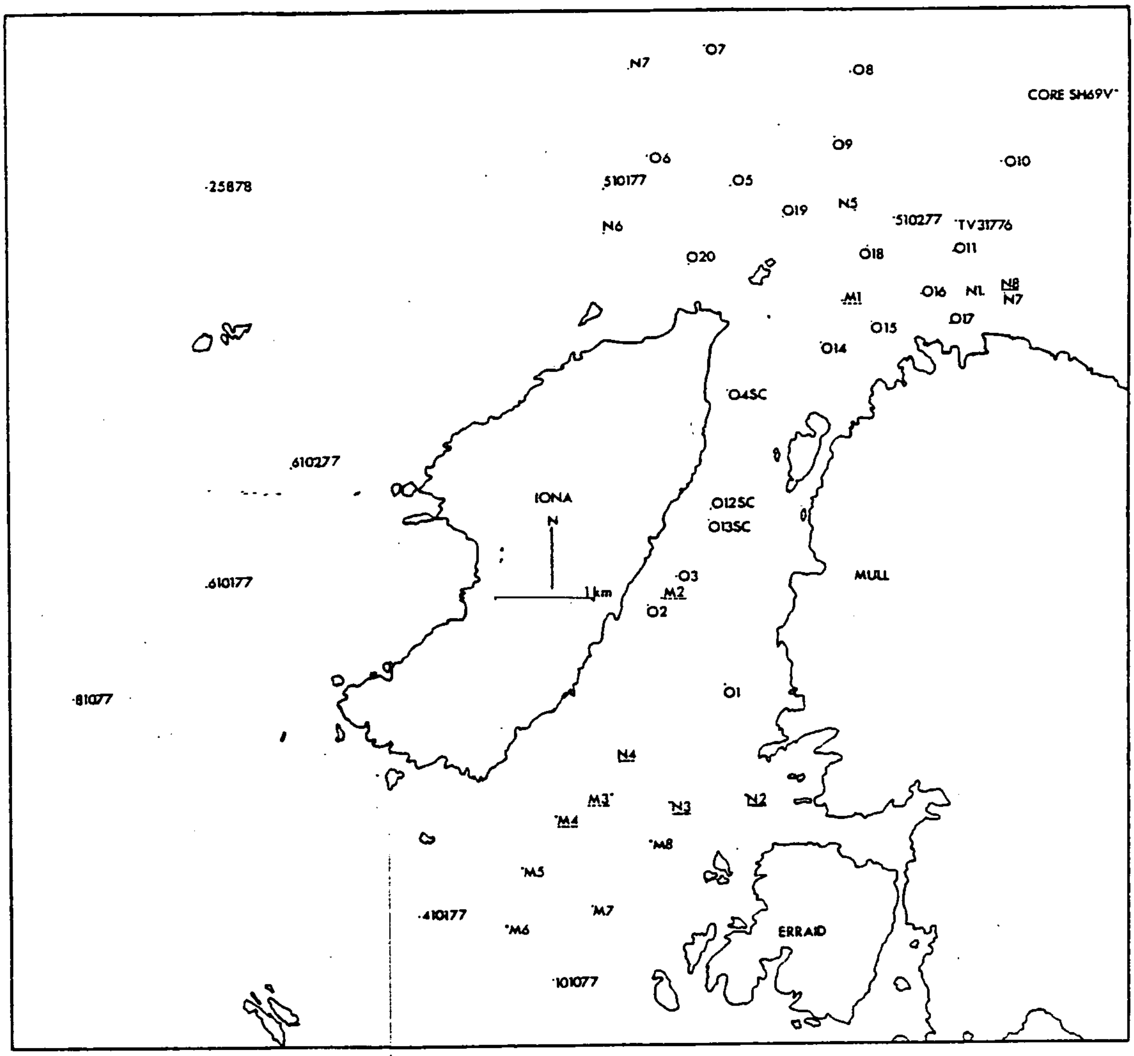

6°24'W
SCOTLAND
STUDY AREA
56°20'N
56°20'N
IONA
BAILE MOR
MULL
FIONNPHORT
E. nam Ban
SOUND OF IONA
N
1 km

Fig. 2 B. Anchor dredge (no line), Barnett Hardy suction bin (broken line) additional drift dive (solid line) and suction core (SC) sample sites.


N7
O7
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CORE SH69V
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O20
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O4SC
610277
IONA
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O13SC
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101077

1. Determination of physical parameters of the environment around the Sound by collating hydrographical and meteorological observations from relevant records and publications, supplemented by my own in situ measurements and observations. This included spot, tidal cycle, and long-term recording current measurements.

2. Assessment of the time stability of sedimentation conditions in the Sound by comparing charts and aerial photographs covering a period of 206 (1756-1962) years and 26 (1946-1972) years respectively.

3. Ship-borne and SCUBA (Self-Contained-Underwater-Breathing-Apparatus) assisted collection of seabed surface samples and their detailed analysis by a variety of techniques (see Appendix 2).

4. Examination of littoral and sub-littoral carbonate-producing organisms, estimates of biomass and rates of production.

5. Experimental studies of carbonate grain fragmentation, determination of entrainment velocities for carbonate sediments and artificial submarine substrates to study settlement and growth of sublittoral carbonate producing organisms.

6. Geophysical studies of bed-form distribution, rock-head configuration and glacial sediment fill of the Sound.

CHAPTER 2

REGIONAL SETTING : ENVIRONMENTAL PARAMETERS

2.1 Geographical location and limits of the study area.

The region selected for the overall N.E.R.C. project encompasses that part of the Sea of the Hebrides extending from the Ardnamurchan peninsula (56°45'N) southeastwards to the north tip of Colonsay (56° 08'N) and from the west coast of mainland Scotland (5°40'W) westward to approximately 7°W. For the convenience of description this area has been separated into two seas. The major part of the study area is here named the Columba Sea after the 6th century Irish saint who figured so prominently in its history. Brown (1979) has named the sea area bounded by the archipelago of Colonsay, Islay and Jura, the Colonsay Sea (Fig. 1).

2.2 Introduction.

Consideration of regional environmental factors provides a key to the interpretation of the sedimentological complexity of the shelf carbonates in the Columba Sea. Several meteorological factors are considered significantly important to influence sedimentary processes: wind direction (duration and magnitude), temperature and rainfall-runoff.

Linked with the meteorological factors are the mass physical properties of the waters which overlie the Hebridean shelf, such as speeds and directions of tidal currents, heights and propagative velocities of waves, and salinity.

2.3 Meteorology.

Meteorological data was obtained from Tiree airport; Kiloran, Colonsay; Rhuvaal (Rhuba A' Mhail), Islay; and Cnoc Mor, Iona. Tiree collects full meteorological data including temperature, rainfall and wind data. Colonsay and Islay collect temperature and rainfall data. Iona only collects rainfall data.

2.3.1. Air temperature.

At Tiree the range of mean daily values of air temperature over a period of 30 years from 1941 to 1970 varied between a minimum of 6.9°C to a maximum of 11.4°C. Kiloran, Colonsay had mean daily minimum and maximum temperature ranges of 6.0°C to 12.0°C for a 15 year period. Rhuvaal, Islay recorded a minimum value of 7.2°C and a maximum value of 10.7°C for a yearly average 1941-1970. These values are typical of cool temperate zones.

2.3.2 Rainfall.

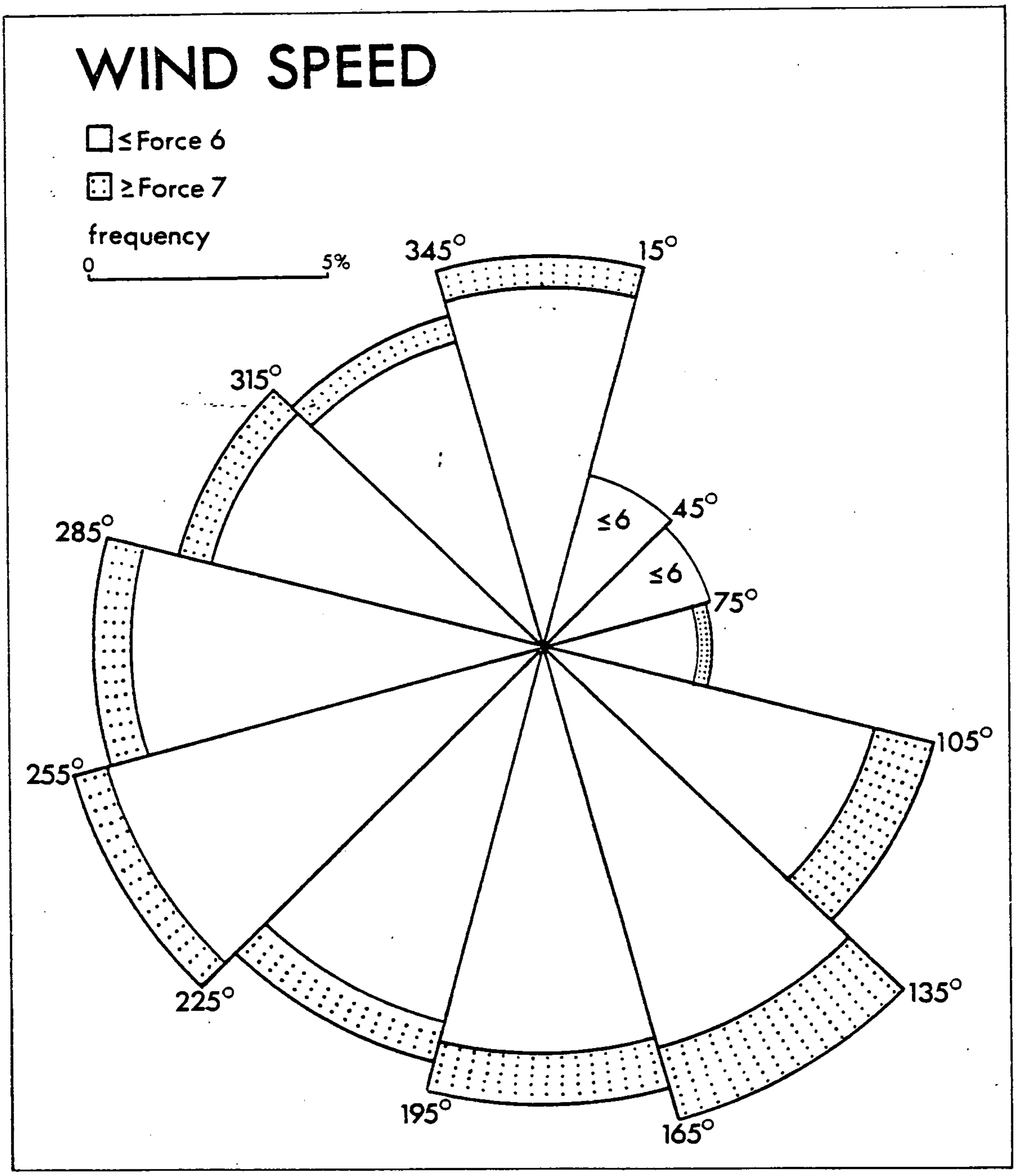
The mean yearly rainfall for the study area, averaged over a 30 year interval (1941-1970) is approximately evenly distributed over the Columba Sea with Tiree receiving 1129mm of rain, Colonsay 1265mm, Islay 1322mm and Iona 1168mm. This high rainfall accounts for the large discharge from the Clyde ($3km^3/yr$) and mainland Scotland ($18km^3/$ year: Mull of Kintyre to Skye (Craig, 1959)).

2.3.3 Wind.

An analysis of the wind data from Tiree collected over a 15 year period, 1962-1976, reveals that when all velocities are considered, the dominant wind directions are from an arc of 110°-250°. Data for average wind speed intervals are shown in Fig. 3. Lower velocity winds, $<$22knots show a similar frequency from all directions except the northeast and east where frequencies are small. Higher velocity winds show an increasing frequency of winds from the south-east.

Tiree lies 34 km north-west of Baile Mor, Iona and 62 km north-west of Kiloran, Colonsay. Despite the distances the wind velocities are probably representative of the winds on the seaward side of the

Fig. 3. Wind speed data in knots from Tiree weather station, 1962-1976. Note Force 6 = 22-27 knots, Force 7 = 28-33 knots.


WIND SPEED
≤ Force 6
≥ Force 7
frequency
0
5%
345°
15°
315°
45°
≤6
≤6
75°
285°
105°
255°
135°
225°
195°
165°

islands. However, it should be expected that in the sheltered regions of the study area, e.g. the northern end of the Sound of Iona and the inner reaches of the Colonsay Sea, there would be a diminution of wind velocity leeward of land. In the case of Iona, the northern area of the Sound is sheltered from easterly and westerly winds; the Colonsay Sea is sheltered from all sectors except the north.

2.4 Hydrological data.

2.4.1 Sea temperature.

Craig (1959) reports Columba Sea surface temperatures varying between 5°-14°C yearly while sea bottom (at depths >200m) temperatures vary between 4°-12°C annually.

In the Sound of Iona surface water temperatures for littoral and sub-littoral areas were 13°C in July 1975 and August 1976. These sea temperatures result from the warm water input by the North Atlantic Drift; the temperature makes possible greater species diversity and productivity than would otherwise be possible for this high latitude.

2.4.2 Salinity.

Surface salinities in the study area vary from 34.94‰ for localities in the Sound of Jura to 34.50°/oo for areas located just west of Islay, Iona and near Coll (Craig op. cit.). Bottom water salinities vary from 33.5°/oo for the Sound of Jura to 34.88°/oo in the area from the north-east tip of Coll to west of Islay. The surface waters in the Sound of Iona had a salinity of 34.4°/oo in July, 1975. Salinities over the Columba Sea region may be considered normal marine with only very local disturbances by coastal stream drainage; there are no large rivers draining into the Columba Sea.

2.4.3 Tides and Tidal currents.

Studies by the United Kingdom Hydrographic Department (Chart 5058,

1974) show that the tidal range for the study area is 0-4m; it is therefore classified as a macrotidal area[1] (Komar, 1976). Co-tidal lines indicate a counterclockwise motion of the tidal wave around an amphidromic point (i.e. a centre of rotation) located on Islay.

The Admiralty Tidal Stream Atlas (1973) maps a north-easterly directed flood tide with a maximum surface mean spring rate of 0.1 to 1.0 m/sec (0.2-1.8 knots). This is countered by a south-westerly directed ebb tide with a maximum surface mean spring tidal rate of 0.2-0.9 m/sec (0.3-1.7 knots).

Craig (op. cit.) notes that the usual net tidal water movements near the surface are to the north at an approximate drift velocity of 2-4 km/day. Net tidal water movements near the sea floor are to the north-east with a very approximate drift speed of 2 km/day.

The Sound of Iona has a mean spring tidal range of 3.5 m and a mean neap tidal range of 1.4 m. Tides are semidiurnal comprising a rectilinear north-east (020°) flowing flood tide and an opposing south-west (210°) flowing ebb tide. Surface current velocity studies by the Hydrographic Department (chart 2617, 1977) showed equal maximum spring flood and ebb velocities of 0.5 m/sec (0.9 knots). Maximum neap flood velocity was 0.2 m/sec (0.4 knots) while the maximum ebb velocity was 0.2 m/sec (0.3 knots). The Sound is thus dominated by swift reversing tidal currents.

2.4.4 Wave data.

Draper and Herbert (1976) have assembled wave data for the west coast of Scotland. At a station located 24 km north of Tiree in a water depth of about 160 m, the most frequently observed wave height

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[1] macrotidal area is a locality where the general tide range is greater than 4 m.

0.6 m with a period of 3 seconds. The range of wave heights was 0 - ≥3.4 m; periods ranged from 0 - 11 seconds. The most commonly observed swell height was 1.2 m with a period of 5 seconds. The range of swell height was 0 - ≥3.4 m; the range of swell periods was 0 - 15 seconds. During south-westerly gales, wave heights are much greater; gales (Force 7 or greater) occur with an annual frequency of 9%, particularly between the months of October and March (Meteorological Office, Edinburgh, personal communication, 1977). They may be expected to have considerable influence on sedimentation patterns.

2.5 Physiography.

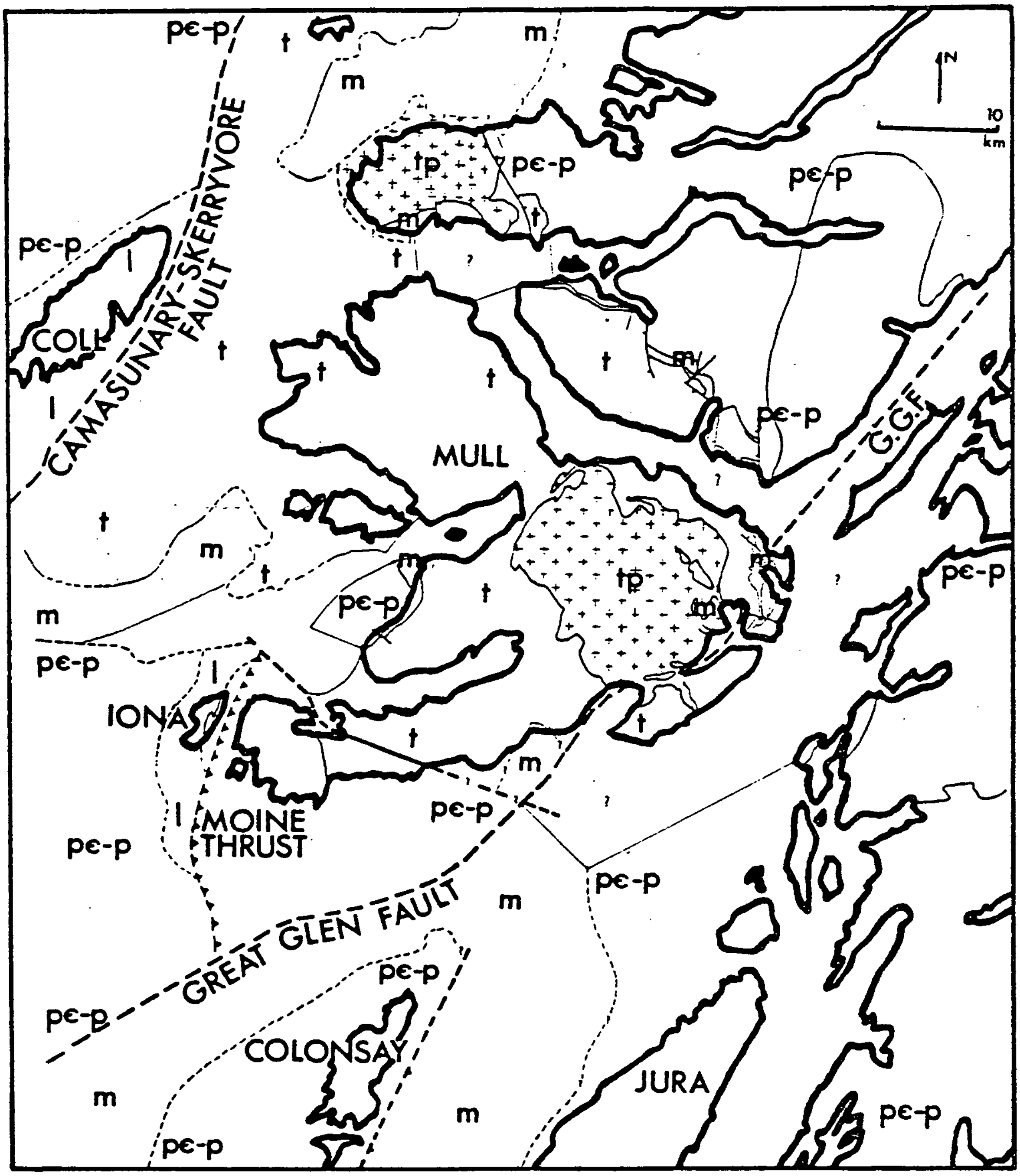
2.5.1 Bedrock and glaciation.

The bedrock of the Columba Sea is composed of a complex series of lithologies which can now be traced only because of deep erosion in late Tertiary and Pleistocene times (Binns et al., 1974). There are five dominant rock groups recognized: 1) Tertiary lavas, sills and minor intrusives; 2) Tertiary plutonic centres; 3) Mesozoic sediments; 4) late Pre-Cambrian and Paleozoic rocks; and 5) Lewisian gneisses (Fig. 4). The study area is structurally controlled by two main faults with a parallel north-east, south-west trend. The most westerly of these is the pre-Upper Cretaceous Camasunary - Skerryvore Fault; landwards of it is the late Jurassic to early Cretaceous Great Glen Fault (Binns et al., 1975). In the Colonsay Sea area the Loch Gruinart Fault transects the western sector of this archipelago, on a NE-SW trend line (Dobson, et al., 1975). The Moine Thrust fault is reputed to be located in the Sound of Iona (Kennedy, 1946).

Glacial processes were responsible for profound alterations in the geomorphology of the study. As ice sheets spread radially from the Highlands, some glaciers followed the pre-Pleistocene east-west

Fig. 4. Geology of the Columba Sea, after Binns _et al_. 1974a;

t = Tertiary lavas, sills and minor intrusives; tp = Tertiary plutonic centres; m = Mesozoic sedimentary rock; p = Paleozoic rocks; p€ = Pre-Cambrian rocks.



N
10 km
pє-p
t
m
tp
COLL
CAMASUNARY-SKERRYVORE FAULT
l
MULL
G.G.F.
IONA
MOINE THRUST
GREAT GLEN FAULT
COLONSAY
JURA

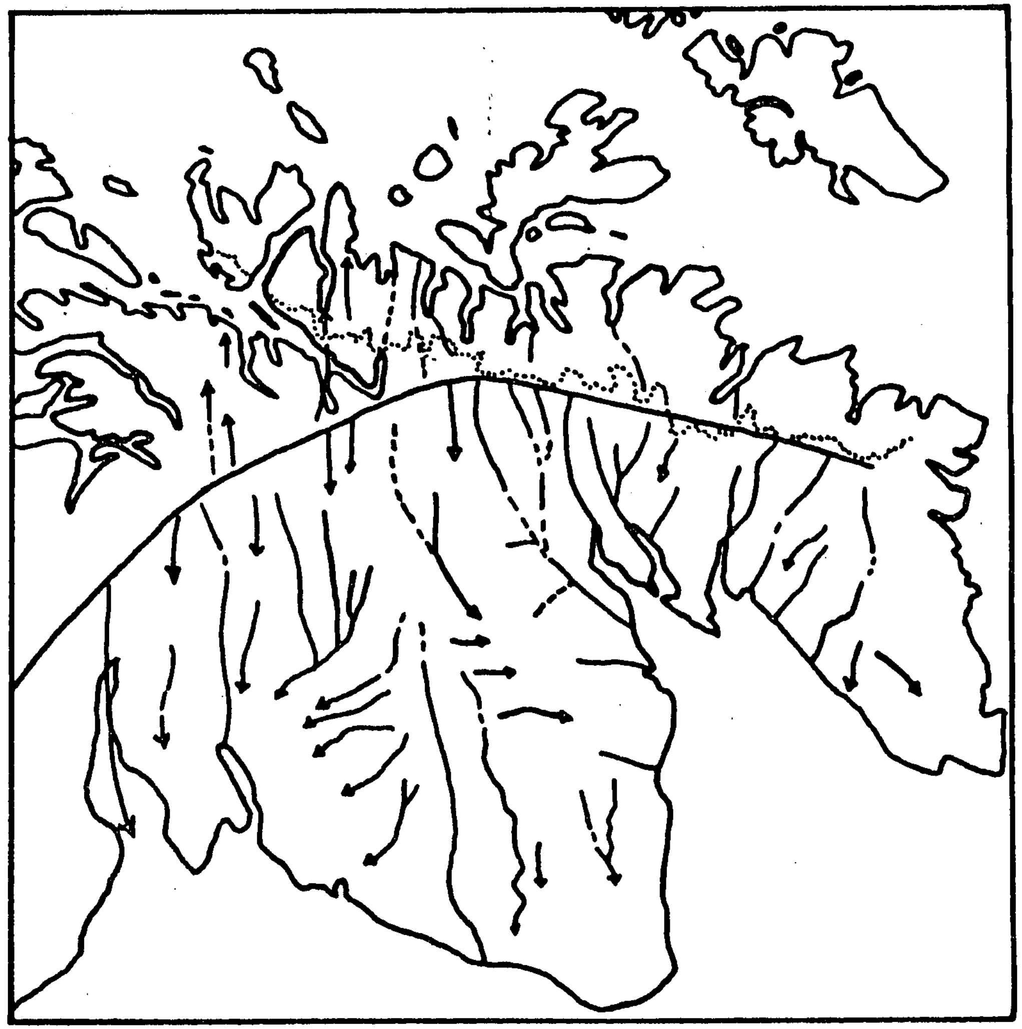
drainage (Fig. 5); other glaciers excavated new flow routes in a NE-SW direction along lines of rock weakness in fault zones of the west Scottish shelf; still other glaciers were deflected in north-west directions by pre-existing topographic highs e.g. Ben More, Mull (Binns et al., 1974; Sissons, 1976). Ben More generated a separate ice cap, itself (Bailey, et al., 1924). The net effect was a marked modification of drainage patterns by the creation of valleys, lochs and straits, an excavation of sediment and weak rock, an exhumation of older resistant rock surfaces and a seaward transport of excavated material in vast volumes and size ranges. Following the Holocene transgression coastal basins became sea lochs, shelf basins became bathymetric deeps.

The effects of the glaciation were to have far-reaching consequences, carrying forward to the present day; glaciation was the major influence on the distribution of Recent carbonate sediments on the inner shelf.

2.5.2 Physical geography of the study area.

Much of the islands' coastal land surface is less than 100-200 m in elevation. There are interior mountainous regions on Mull, Islay and Jura where elevations reach 500-1000 m. The islands are covered with moorland, bogs, small freshwater lochs and ponds. Glacial drift deposits are widespread on Jura and Islay but less extensive on Mull. Raised beach and marine deposits are found in coastal areas of these islands. Tiree has extensive deposits of raised beach and marine material and also a widespread covering of blown sand. Coll has similar deposits but of reduced lateral extent. Coastal areas alternate between bare rock outcrops, grass-stabilized dunes and pasture lands called machairs; these areas are highly indented with bays and headlands. No major drainage systems debouch from the islands due to the

Fig. 5. Pre-Pleistocene (solid line) and present-day (dotted line) drainage in Scotland, after Sissons (1967).



small island surface areas and the retention of runoff in the porous soils, bogs and freshwater lochs. Sea lochs are incised on the western sides of the islands *e.g.* Mull and Jura. The lochs characteristically have glacial drift deposits at their mouths which, wholly or partially, enclose the loch basin.

The geography of the mainland adjacent to the study area needs consideration as a possible source of terrigenous sediment. Relief of the western mainland is low only along a narrow coastal strip where there are occasional raised beaches and wave-cut platforms such as the classical localities near Oban. Mainland relief then changes abruptly inland to hills and mountainous areas of over 1000 m, the perimeter of the western Highlands. Drainage is into a profusion of glacial fresh and sea water lochs, many of which, *e.g.* Loch Linnhe, Loch Etive, Loch Creran, have their mouths partially blocked by either fluvio-glacial deposits or islands, or both (Sissons, 1976). Malcolm (1979) has shown that large quantities of terrigenous sediment are indeed moved into the lochs from the surrounding watershed (Table 2). Further, instead of suspended load passing from the lochs onto adjacent shelf areas, Price and Calvert (1973) have demonstrated predominant transport of suspended load into the lochs from the sea.

The Clyde is the only major river system on the west coast. Its discharge is primarily directed southwards, *i.e.* away from the study area, due to the long southward extent of the Kintyre peninsula. Northerly longshore transport of Clyde material is restricted not only by the Kintyre peninsula but also by the intervening complex coastline between the Mull of Kintyre and the Columba Sea (Guilcher and King, 1961).

The major drainage divide (Fig. 5) lies close to the western mainland coast (Sissons, 1967). The westward flowing drainage area is

Table 2. The amount of material deposited yearly in Loch Etive.

This material is trapped within the loch's two basins because of the barred seaward loch mouth. Data shown here is believed to be representative for similar lochs on the Scottish west coast. This information is from Malcolm (1979) and is used with permission.

Total basin area : 26 km^2; 2.6×10^{11} cm^2

% terrigenous material in sediment	: 86%
% calcium carbonate in sediment	: 10%
% organic matter in sediment	: 4%
Bulk density of the sediment	: 2.2 gm/cm^3
Average rate of sedimentation	: 0.42 cm/yr

This figure is an average of 6 values using 3 different techniques; [1]cv = 19%

Derived values : component rates of sedimentation and weights. Note the formula for weights = Y x density x total basin area where Y = % terrigenous material etc.

Terrigenous material	: 0.36 cm/yr; 4.9×10^{11} gm
$CaCO_3$	: 0.04 cm/yr; 5.7×10^{10} gm
Organic matter	: 0.02 cm/yr; 2.3×10^{10} gm

[1]cv = coefficient of variation $= \frac{\text{standard deviation}}{\text{mean}} \times 100\%$

small; most runoff is directed predominantly eastwards and southwards away from the study area.

Thus, although much terrigenous sediment is shed seawards as expected after a glaciation, very little of this material actually reaches the continental shelf; this is a vital factor in the development of the Recent carbonate deposit.

2.5.3 Submarine topography.

Bathymetric charts have been constructed by the Hydrographic Department and the Institute of Geological Sciences (Fig. 6). The bathymetry is very irregular and bathymetric highs are related to island masses, termed "rock platforms" by Sissons (1976). These alternate with inter-island basins. Seafloor basins with depths of 100 m or more are found to the south-east of Coll and Tiree, to the north-west of Jura and in the Sound of Jura. These basins lie adjacent to shallow water areas where water depths are commonly 40-60 m deep. It is likely that the NE-SW elongation of many basins is related to glacial erosion of fault-weakened rocks (Binns, et al., 1974); east-west alignment may be related to Tertiary drainage patterns. The basins are important to the present-day sediment regime: Bishop (1977) found that glacial basins in the Minches are the principal repositories for palimpsest (relict, reworked), terrigenous mud.

Bathymetry in the Sound of Iona can be conveniently divided into six tracts (Fig. 7): 1) a near-shore shallow-water area adjacent to the mainland and islands in the Sound termed the littoral-nearshore shoals; depths 0-4 m below O.D. 2) a shallow water area between Baile Mor, Iona and Fionnphort, Mull termed the central shoals; depths 0.1-4 m. 3) a slightly deeper water area located to the north of the central shoals, with an irregular bottom and termed the northern platform; depths 4-20 m. 4) a similar type of area lying to the south of the

Fig. 6. Bathymetry of the inner western Scottish shelf after Binns _et_ _al_. (1974a) and Brown (1979).

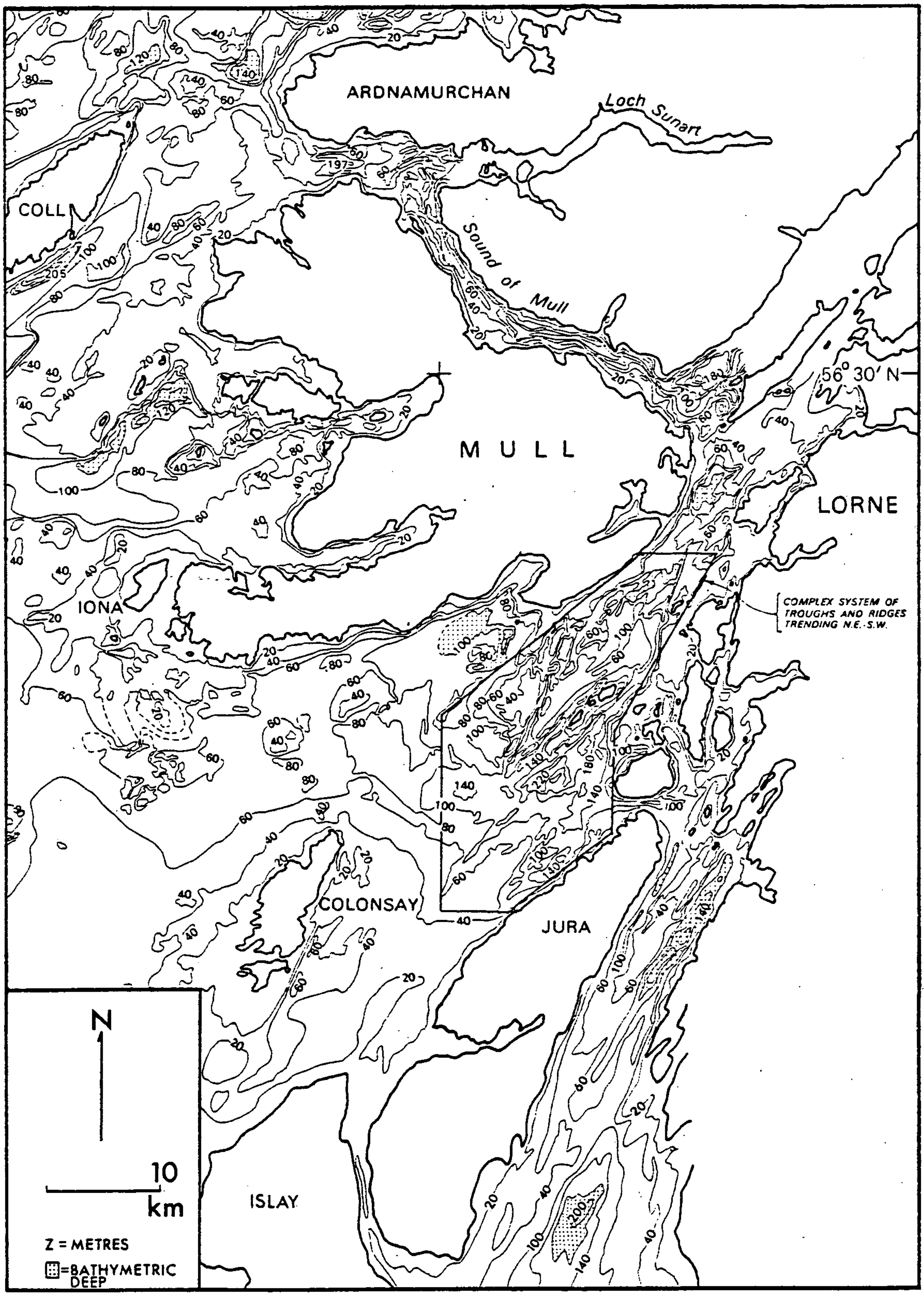

ARDNAMURCHAN
Loch Sunart
COLL
Sound of Mull
MULL
56° 30′ N
LORNE
COMPLEX SYSTEM OF TROUGHS AND RIDGES TRENDING N.E.-S.W.
IONA
COLONSAY
JURA
ISLAY
N
10
km
Z = METRES
=BATHYMETRIC DEEP

Fig. 7 A. Bathymetry of the Sound of Iona, from Admiralty Chart 2617, 1962.

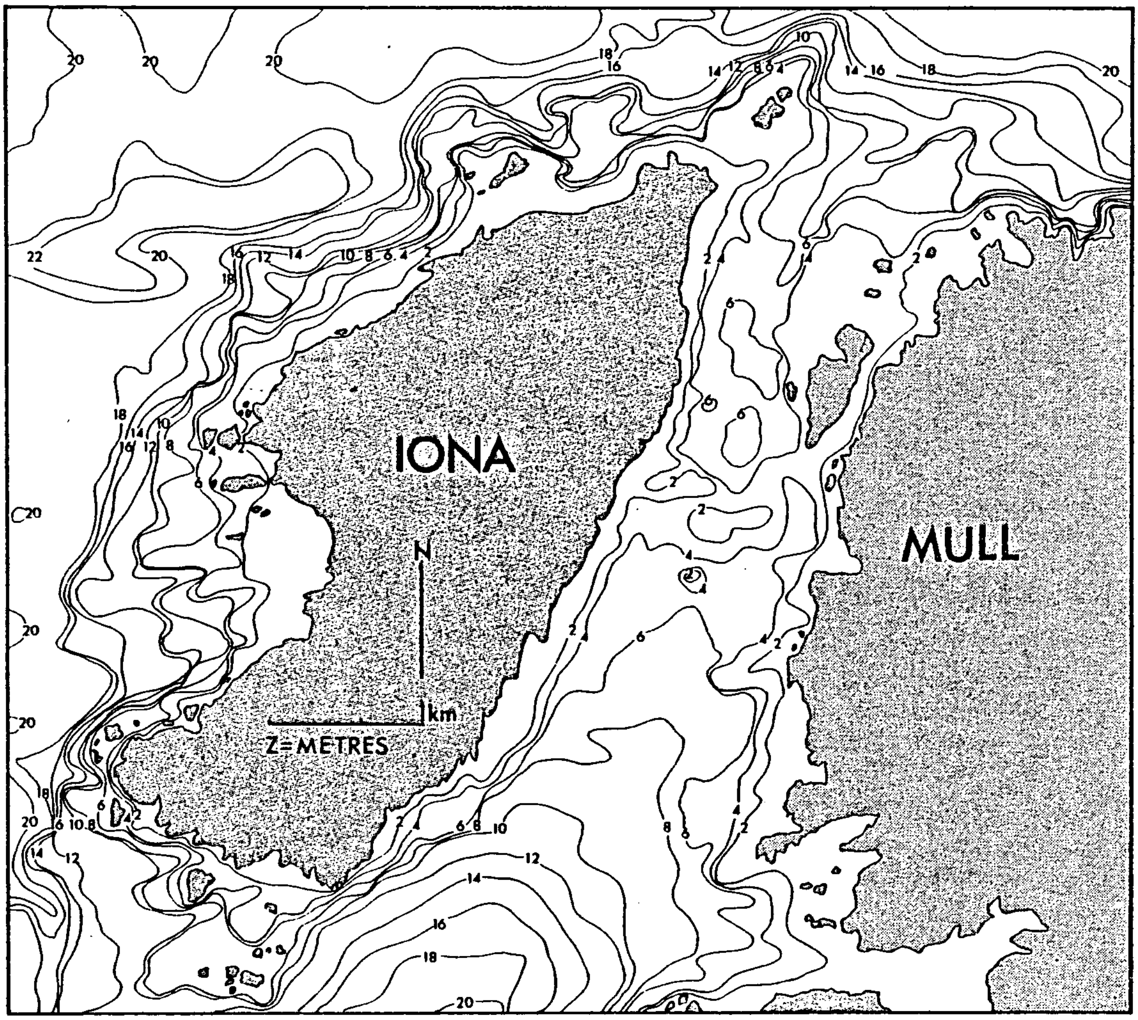
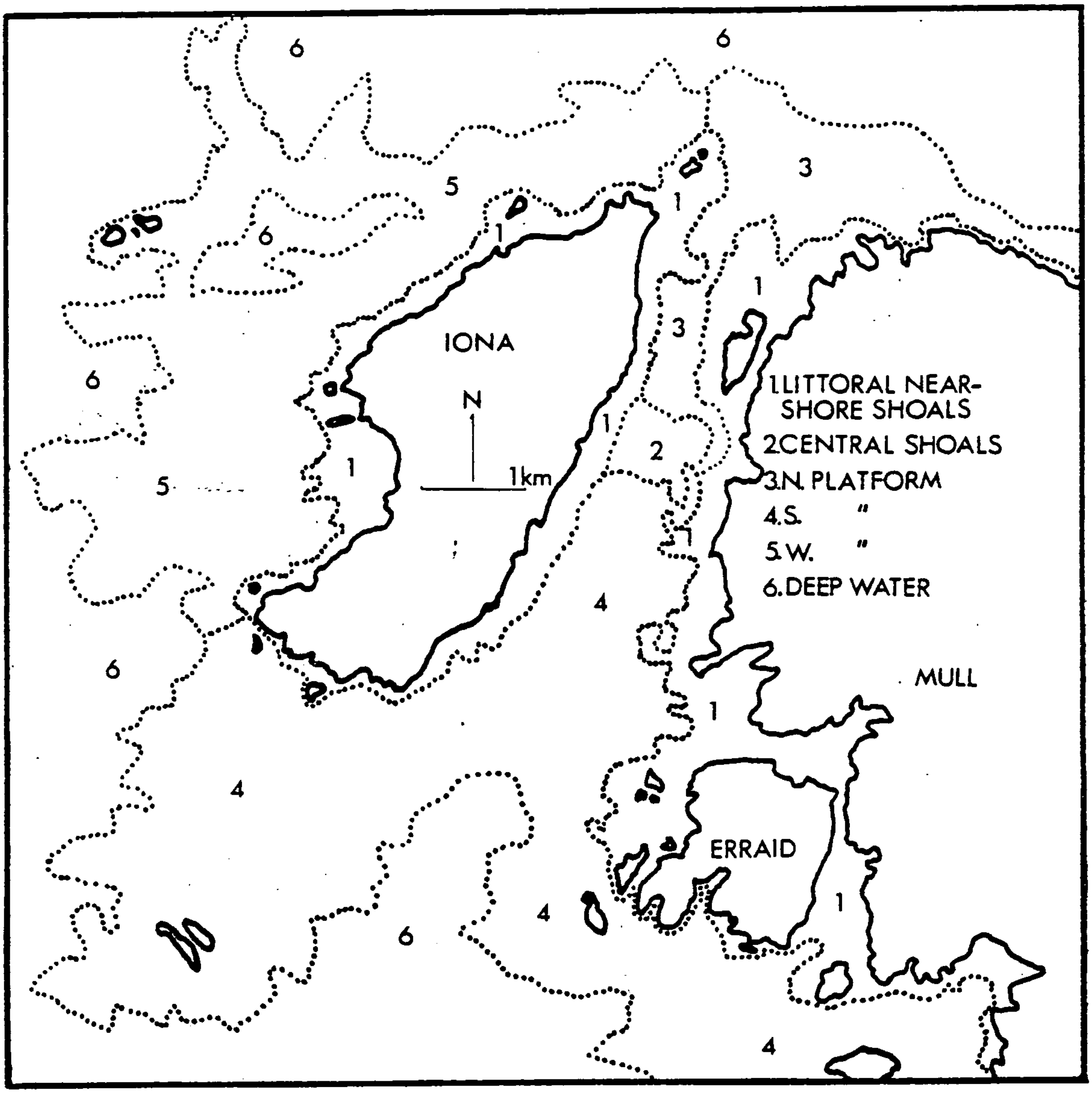

IONA
MULL
N
km
Z=METRES

Fig. 7 B. Bathymetric tracts in the Sound of Iona.



6
6
3
5
1
6
1
1
IONA
3
6
N
1.LITTORAL NEAR-SHORE SHOALS
2.CENTRAL SHOALS
3.N. PLATFORM
4.S. "
5.W. "
6.DEEP WATER
1
2
1km
5
4
6
MULL
1
4
ERRAID
4
1
6
4

central shoals with a regularly sloping bottom termed the southern platform; depths 4-20 m. 5) an area off the west coast of Iona; depths 4-20 m, called the western platform. 6) deep water areas in the extreme northern and southern perimeters of the Sound and offshore west of the island of Iona where depths are greater than 20 m. There is a gradual transition from one bathymetric tract to the next adjacent tract with two exceptions: 1) an abrupt change in depth from the northern platform to deeper waters adjacent to it; 2) a similar abrupt change from the western platform to deeper waters area peripheral to it.

2.6 Previous work.

2.6.1 Sublittoral studies of Quaternary sediment on the west coast of Scotland.

The first systematic sampling of the West coast sublittoral sediment was begun by M. Mackenzie (1776). His west Scotland work, undertaken in the years 1748 to 1757 (see Robinson, 1962) was concerned with brief descriptions of the quality of the bottom as well as the first reliable charting of bathymetry, hydrography and coastal configuration. Mackenzie's work was the predecessor to the British Admiralty hydrographic surveys (see Robinson, 1958) which made more extensive surveys of the bottom quality and improved on the accuracy of his charts (yet retaining Mackenzie's system of symbols of qualifying bottom sediments). Similar studies by the Admiralty have been issued periodically to the present day.

A cursory study of the biology and geology of the sublittoral area was undertaken by Herdman (1895). After a long hiatus an elaborate series of studies began under the sponsorship of the Institute of Geological Sciences (I.G.S.) in the late 1960's.

The I.G.S. combined observations from scuba (see Eden and Binns, 1973), a manned submersible (Eden et al., 1971; Eden, et al., 1973) and ship-borne methods (Binns et al., 1974)to obtain biological sedimentological, geological and geophysical data for the Scottish west coast offshore areas. Other investigators began generalized geophysical studies of large-scale sedimentary structures, most importantly a series of ribbons, patches and waves of sand now known to extend widely on the Scottish west coast platform and around the whole United Kingdom (Belderson, 1964; Belderson and Kenyon, 1969; Belderson et al., 1971; Belderson et al., 1972; Castor, 1976; Channon, 1971; Channon and Hamilton, 1976; Kenyon, 1970a; Kenyon, 1970b; Kenyon and Stride, 1970; Stride, 1972). Other studies have concentrated on glaciology (Jardine, 1977; Sissons, 1976), sedimentology (Bowes and Smith, 1969; Ferentinos, 1976), flora (Adey and Adey, 1973) and fauna (Pendlebury, 1974). Composite studies encompassing hydrography, sedimentology and biology include those on the south-west shelf by Pendlebury op. cit. and Pendlebury and Dobson (1976); Bishop (1977) studied hydrography, sedimentology and geophysics on the north-western sector of the inner shelf. Lovell (1979) studied the petrography of sediments on the western Scottish shelf and noted the offshore increase of biogenic carbonate from mainland Mull.

2.6.2 Sublittoral studies in the Sound of Iona.

Within the Sound of Iona, the earliest sedimentological work was undertaken by Mackenzie (1776) with subsequent studies provided by the British Admiralty. References to the sand banks which occur on the central shoals, were made by MacKenzie op. cit. and Pennant (1776). More detailed sublittoral studies were made later by the British Hydrographic Office. Bowes and Smith (1969) collected a number of sediment samples and compiled a series of echograms for the Sound; most of this material was unpublished. Little detailed work has been done on the marine biology of the Sound, beyond identification of sublittoral algae, including rhodophyta (Price and Titley, 1978).

2.6.3 Previous work on the littoral zone of the Sound of Iona.

For the Sound of Iona casual observations of beach composition have been made by Sacheverell (1688), Pennant (1776), Macculloch (1824); shore morphology was investigated by Mather and Crofts (1971); economic sedimentology has been reviewed by Bailey and Anderson (1924) and several studies of the glaciology were made by Craig et. al. (1911), Gray and Brooks (1972), Synge and Stephens (1966) and Sissons (1976). Lovell (1979) examined the terrigenous content of three shore sands on the Sound. A study of the littoral fauna of Iona and several other west coast islands was conducted by Kitching (1935) and Price and Titley (op. cit.). Gilham (1957) reported on coastal vegetation of the shoreline carbonate dunes of Iona.

2.7 Summary and concluding remarks.

The Columba Sea is a cool temperate sea having normal shelf salinity; it is characterized by strong wave action and swift tidal currents. Indurated, erosion-resistant bedrock outcrops are ubiquitous among the island archipelagos and mainland areas. Quaternary glaciers excavated the rock along Tertiary east-west drainage channels and along fracture-weakened NE-SW trending fault zones. The rock areas have been sculpted into irregular surfaces of topographic highs, juxtaposed deep basins and complex coastline. These basins presently appear as lochs along the coastline and bathymetric deeps on the inner shelf. Later glacial deposits and Recent carbonate sediment occur separately or mixed at various sites in the Columba Sea.

Present-day terrigenous input is strongly controlled by glacially moulded features: sea lochs trap much of the mainland terrigenous material at the coast; the intricate coastline prevents the longshore drift of any material which might have missed, or escaped from, the lochs. Submarine basins provide settling areas for palimpsest fine-grained glacial material. The effects of this terrigenous control on selected areas of the Columba Sea will be investigated in later chapters.

Despite the variety and volume of research done on the west coast sediments, no one has hitherto attempted to integrate hydrography, ecology, sedimentology and geophysics into a holistic view towards forming a model for Quaternary temperate carbonate sedimentation in the area. It was with this in mind that the N.E.R.C.-sponsored project described above was initiated.

CHAPTER 3

CARBONATE SEDIMENTATION ON THE INNER SCOTTISH SHELF

3.1 Introduction.

This chapter has a two-fold purpose: 1) it provides an overview of the sea bed studies in the Columban and Colonsay Seas; 2) it focuses on, and provides an elucidation of sediment processes in these areas through detailed studies in the Sound of Iona. Portions of this chapter appear in Farrow et al.(1978, 1979). Detailed studies of the fauna of this area appear in Brown (1979). Further work on sediment composition, size and mineralogy is currently in progress by Dr. T. P. Scoffin.

PART 1: General Carbonate Variation.

3.2 Variation in carbonate content in the Columba and Colonsay Seas.

The carbonate percentage has been determined in 118 samples from the Columba and Colonsay Seas (see Fig. 8 and appendix 3). The range is from 7% (CH5) to 100% (JM 106) with a mean of 38% (s.d. = 19). Samples with high (≥50% by weight) carbonate contents are shown in Table 3, these samples are characterized by their shallow depth of occurrence, nearness to land and swift tidal currents; grain sizes of these samples were extremely variable between a muddy bioclastic cobble size sediment and a silty fine sand.

Generally barnacles and molluscs are the dominant contributors to the sand-size or larger fractions. However, at two stations, JM 38 and 39 near the northern mouth of the Sound of Islay, a living rhodophyte *Phymatolithon calcareum*[1] is the dominant contributor. At JM 49, located in the mouth of the Sound of Islay, the living rhodophytes *Lithothamnum glaciale* (Fig. 9) and *Phymatolithon calcareum*

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[1] Calcareous rhodophyte identifications were made or verified by Mr. Julian Cloakie, The University(of Glasgow)Marine Station, Millport.

Table 3 Samples from the Columba-Colonsay Seas with high carbonate weight %

C = cirriped (barnacle), M = mollusc, BR = bryozoa, CR = calcareous rhodophyte (alga), F = foraminifera.

Sample	Location	Depth (m)	Distance from nearest land (km)	[1]surface current m/sec	% $CaCO_3$ and components	Estimated grain size	Roundness	Comment
JM 22	NE of Colonsay	16	1.3	0.5	95 C>M	med-crs sand	subrounded	sea bed = current ripples
JM 26	SE of Oronsay	36	1.1	weak	48 M>BR	silty sand	subangular	Turritella trails
JM 38	N. mouth, Sd. Islay	23	2.2	0.8	84 CR	muddy gravel	subrounded	megaripples
JM 39	N. mouth, Sd. Islay	23	1.7	0.8	67 CR	muddy gravel	angular to subrounded	megaripples
JM 41	NW of Islay	20	2.2	1.0	49 M>C>F	med-fine sand	subangular	
JM 42	NW of Islay	20	2.8	1.0	57 C>M	crs sand-gravel	subangular to subrounded	
JM 43	NW of Islay	20	4.3	1.0	87 C	gravel	subrounded	C=v. rounded
JM 53	between L. Tarbet of Oronsay	22	5.1	1.4	49 M	silty fine sand	angular	
JM 95	NW of Ardnamurchan Pt.	66	6.9	0.5-0.8	83 M	muddy pebble-size shell fragments	angular to subangular	M = whole & large broken fragments
JM 97	Nearshore of Ardnamurchan Pt.	85	2.3	0.5-0.8	61 M>C	muddy gravel	angular to subangular	
JM 102	NW of Calgary Bay, Mull	60-55	5.9	0.8	83 M>C	med sand	angular to subangular	
JM 106	NW of Calinch Pt. Mull	58	4.3	0.8	100 M	cobble-sized shells	angular to subangular	whole M shells
Jura 66	off E. coast of Jura	77	0.9	2-2.3	83 M	pebble-sized shells	subangular	whole M shells
Jura 147	L. crinan, N. Sd. of Jura	135-117	0.9	0.1	84 M	gravel-sized shells	angular to subangular	
CH 1	W. of Scarba	26	2.6	0.3-0.5	59 M>BR	crs sandy mud	v. angular to angular	
CH 6	Firth of Lorne, W of Seil	43-40	1.4	0.3-0.5	54 M>C	muddy pebble	angular to subangular	
CH 9	Firth of Lorne, E. of L. Spelve	38-40	1.7	0.8	59 -	sandy mud	angular	v.v. small spl.
CH 28	N. tip of Eilean Naoimh	100-85	1.2	0.3-0.5	71 M	muddy gravel with pebble-sized shell fragments	terrigene = angular shells = v. angular to angular	
CH 31	SE of L. Spelve	40	2.2	0.8	53 M	shelly mud	subangular	broken shells
CH 44	near E. Naoimh	30	4.4	0.3-0.5	59 M>F>BR	pebbly crs sand	terrigene= angular	shells = angular to subrounded
CH 47	W. of En. Naoimh	85	3.5	0.3-0.5	76 C>M	silty crs sand	subangular to subrounded	

[1]Surface current velocities are derived from the West coast of Scotland Pilot (1974); the surface current velocity data for JM 38 and JM 39 taken from Close's Fisherman's Charts, Scotland:West Coast (1908).

Fig. 8. Carbonate percentages in the Columba-Colonsay Seas as determined by HCl acid digestion, from Farrow *et al*. (1978) Fig. 1.

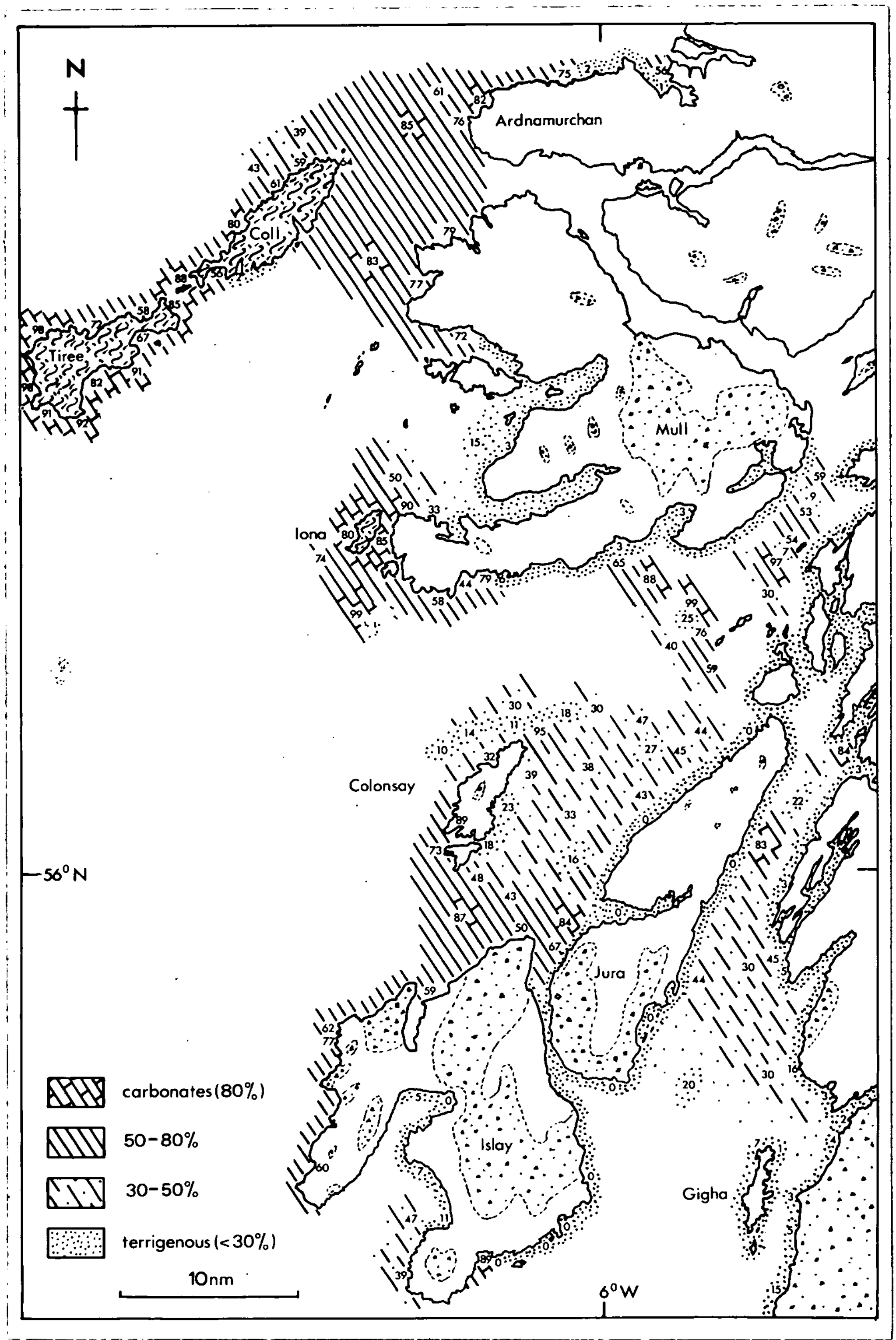
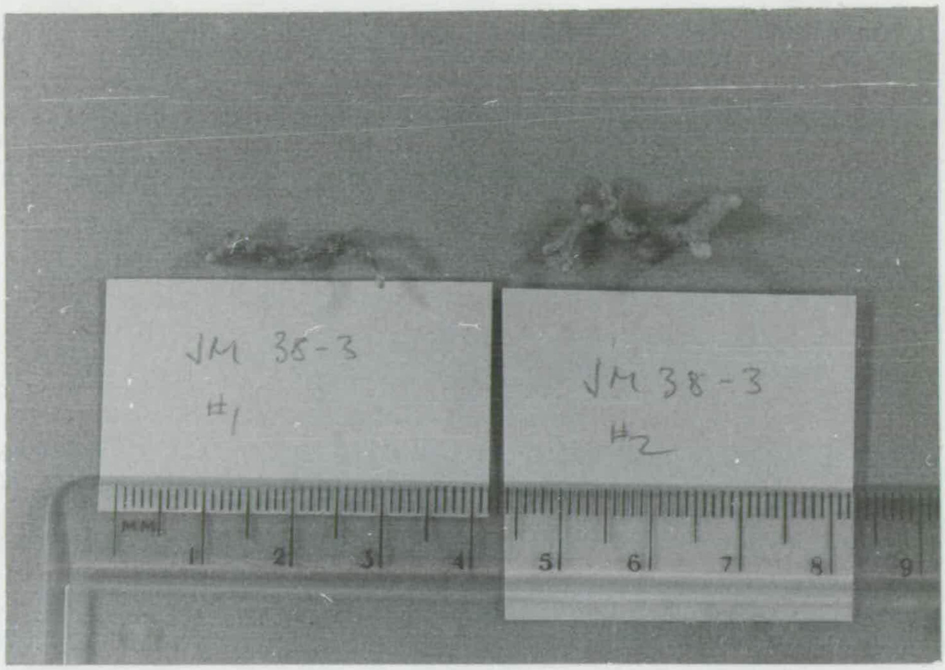

N
Ardnamurchan
Coll
Tiree
Mull
Iona
Colonsay
Jura
Islay
Gigha
56° N
6° W
carbonates (80%)
50-80%
30-50%
terrigenous (<30%)
10nm

Fig. 9 A. Specimens of *Phymatolithon calcareum* (P.) and *Lithothamnium glaciale* from the Colonsay Sea.


JM 38-3
#1
JM 38-3
#2
MM
1
2
3
4
5
6
7
8
9

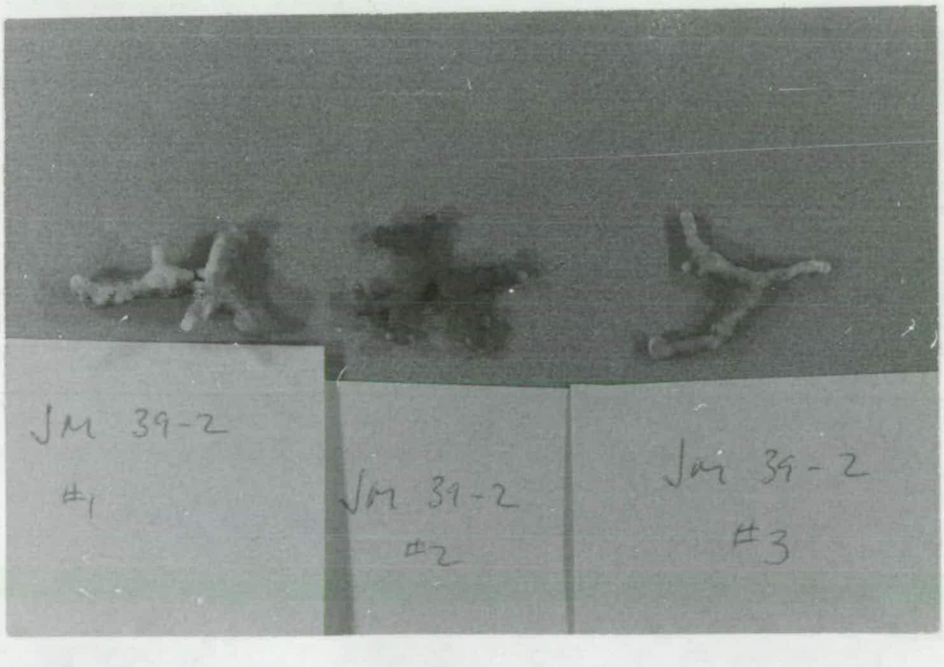
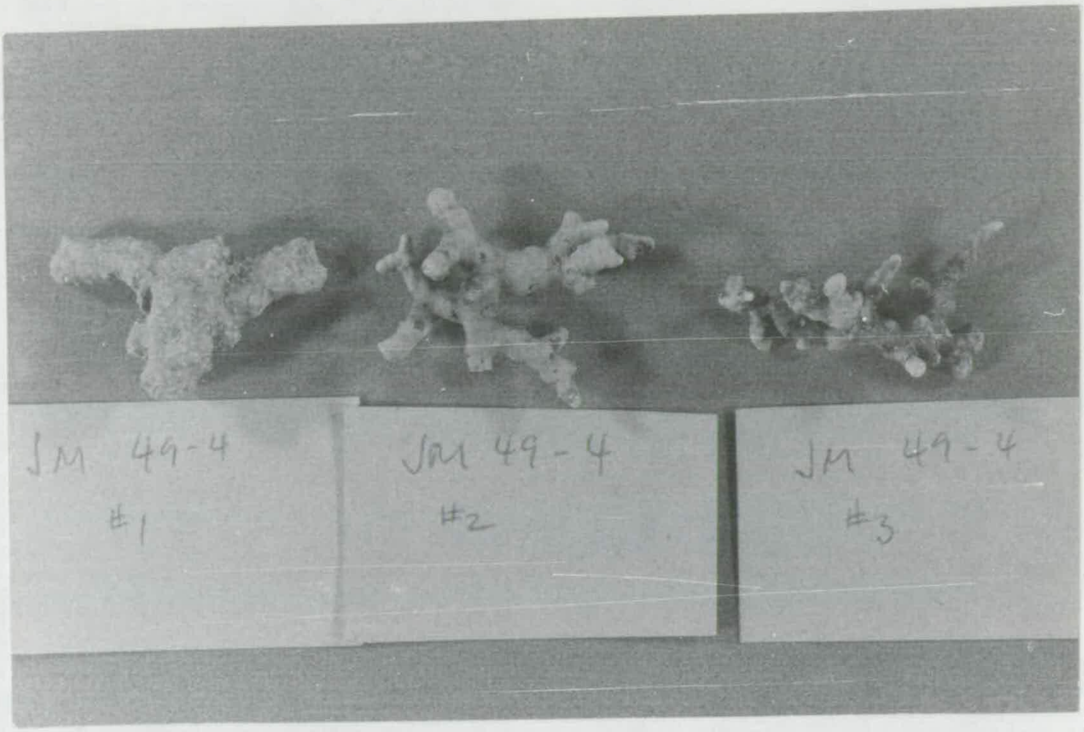
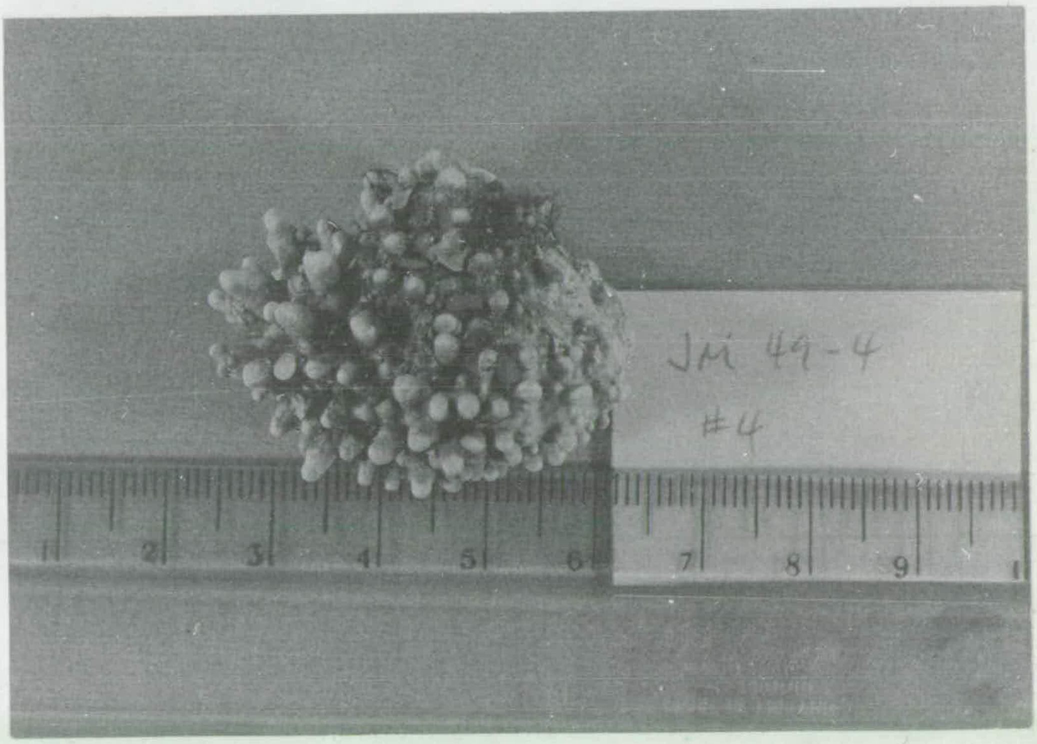

JM 39-2
#1
JM 39-2
#2
JM 39-2
#3

Fig. 9 B. Specimens of Phymatolithon calcareum (P.) and Lithothamnium glaciale from the Colonsay Sea.


JM 49-4
#1
JM 49-4
#2
JM 49-4
#3


JM 49-4
#4
1 2 3 4 5 6 7 8 9

are the major sediment contributors.

Fine-grain sediment mixtures of carbonate and terrigenous is ubiquitous in the Colonsay Sea (Fig. 8). X-ray diffraction studies (Table 4) of seven <63 um sieved samples showed that the dominant carbonate phase was low-Mg calcite; the mole % $MgCO_3$ varied from <1 - 8%. This material is most likely derived from the abrasion of barnacles (see section 3.8.3). Aragonite was observed in only one less than 63 μm sample, JM25; it was represented by a very small peak compared to low Mg calcite. The low amount or absence of aragonite from these samples, underscores the dominance of barnacle-derived sediment over other organisms.

Carbon-14 dates of superficial shell material (Table 5) indicates that the shells are of very recent origin, ranging in age from approximately 160-430 years old.

3.3 A note on terminology.

Terms used in the succeeding sections are defined according to Allen (1970) and Wright (1978):

ripples have a wavelength (λ) from 0.4 cm to 60 cm and heights up to a few tens of millimetres; their crests are perpendicular to current flow;

megaripples λ = 0.6-30 m; height = 0.4-1.5 m; crests are perpendicular to flow;

sand waves λ = 30-500 m; height = 1.5-25 m. Allen (1968) referred to these features as dunes; Dalrymple *et al.*, (1978) have shown that sandwaves form in a lower velocity field than dunes. The term sandwave is used here to indicate a very long wavelength bedform;

sand ribbons are linear features which form parallel to flow. They have a height of about 1 m, a width of tens of metres and a highly variable length.

Table 4. X-ray diffraction data for <63um fraction of sediments from the Colonsay Sea.

Sample	Depth (m)	% of sample <63 um	% $CaCO_3$ in <63um fraction	Carbonate mineralogy	Mole % $MgCO_3$	Other minerals
JM 17	21	25	34	calcite	<1	quartz, chlorite
JM 25	36	23	33	calcite	2	quartz, chlorite
JM 47	11-10	45	30	calcite	5	quartz, chlorite
JM 62	22	31	31	calcite	<1, <7	quartz
JM 65	30	9	36	calcite	8	quartz, chlorite
JM 74	32	25	32	calcite	5	quartz, chlorite
JM 77	26	20	32	calcite	<1	quartz, chlorite

Table 5. Carbon-14 dates for selected samples from the Columba-Colonsay Seas, samples analyzed by D. D. Harkness, Scottish Universities Research and Reactor Centre, E. Kilbride.

Sample	Location	Depth (m)	Collection device	$\delta^{13}C$ ‰	Age 1yr B.P.-SSWC[1]	±	$\sqrt{\text{Sample Standard Deviation}^2 + \text{SSWC Standard Deviation}^2}$	Resultant age 2 sig.fig.
JM 109 <u>Glycymeris glycymeris</u> burrowing bivalve	56°40'N, 6°16'W shell gravel bed between the islands of Mull, Coll and the Ardnamurchan peninusula	30	Rock dredge	+2.8	389	±	86	390 ± 86
JM 36 <u>Artica islandica</u> burrowing bivalve	55°59'N, 6°3'W shell gravel-sand bed between the islands of Colonsay, Islay and Jura	23	Rock dredge	+3.4	428	±	90	430 ± 90
O 27 barnacle plates	55°59'N, 6°15'W Misc. barnacle plates in shell gravel bed between the islands of Oronsay and Islay	20	Forster Anchor Dredge	+1.7	158	±	86	160 ± 86
O 35 <u>Pecten maximus</u> epifaunal bivalve	55°51'N, 5°50'W Muddy sand bed in the Sound of Jura	42	Forster Anchor Dredge	+2.6	232	±	86	230 ± 86

[1]SSWC = Scottish Seawater Correction = 400 ± 50 yr., hence the figure shown, <u>e.g.</u> 389 yr for JM 109 is the result of 789 the C-14 age, minus 400 yr.

3.4 Sedimentary facies.

Underwater television, dredge and grab sample (for a description of these techniques see appendix 2) data have been combined into a facies map for the Columba-Colonsay Seas (Fig. 10). The northern extent of the Columba Sea between Coll, the Ardnamurchan peninsula and north-west Mull, is dominated by a shelly sand facies. This belt-like deposit increases in lateral extent northwards. Adjacent to this deposit are rock and boulder areas which lie off-shore from Coll and Mull. The roundness, large size and distance from shore of these boulders suggests that they are of glacial origin. Shelly sands and gravels occur at the western periphery. Burrowed mud, including dolomitized crustacean concretions, are found at the eastern periphery between Ardnamurchan and northern Mull (Brown and Farrow, 1978). Further south, high carbonate sands and gravels are found from Iona eastwards through the Firth of Lorne to mainland Scotland.

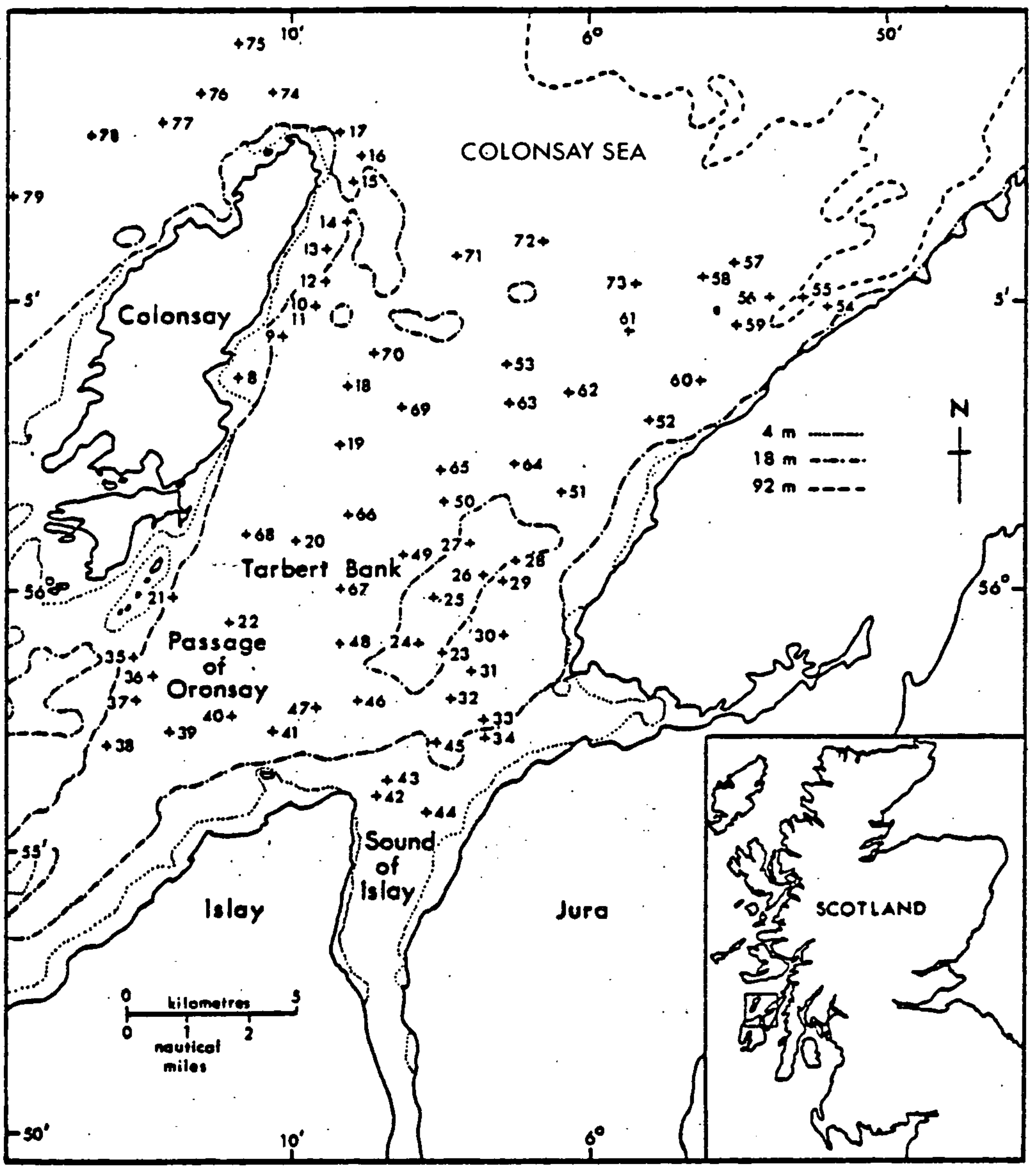
Farrow _et al_. (1978) found eleven facies in the Colonsay Sea area. They are considered in detail because of their similarity with the Sound of Iona's deposits.

1. _bare rock with echinoderms_ characterized by dense ophiuroid cover, a barnacle, serpulid and bryozoa epifauna on _Laminaria_ sp. and predatory gastropods and starfish. This facies is not widespread, it is found in water depths of 26-100 m and is confined to the Colonsay Sea margin.

2. _Lithothamnium - Phymatolithon facies_ is composed of two living coralline algae _Lithothamnium glaciale_ which commonly encrusts pebbles and may grow with the free-living alga _Phymatolithon calcareum_ (Fig 9). _Laminaria_ weed, _Ensis_ shells and _Macropipus_ crabs are frequently found associated with this deposit.

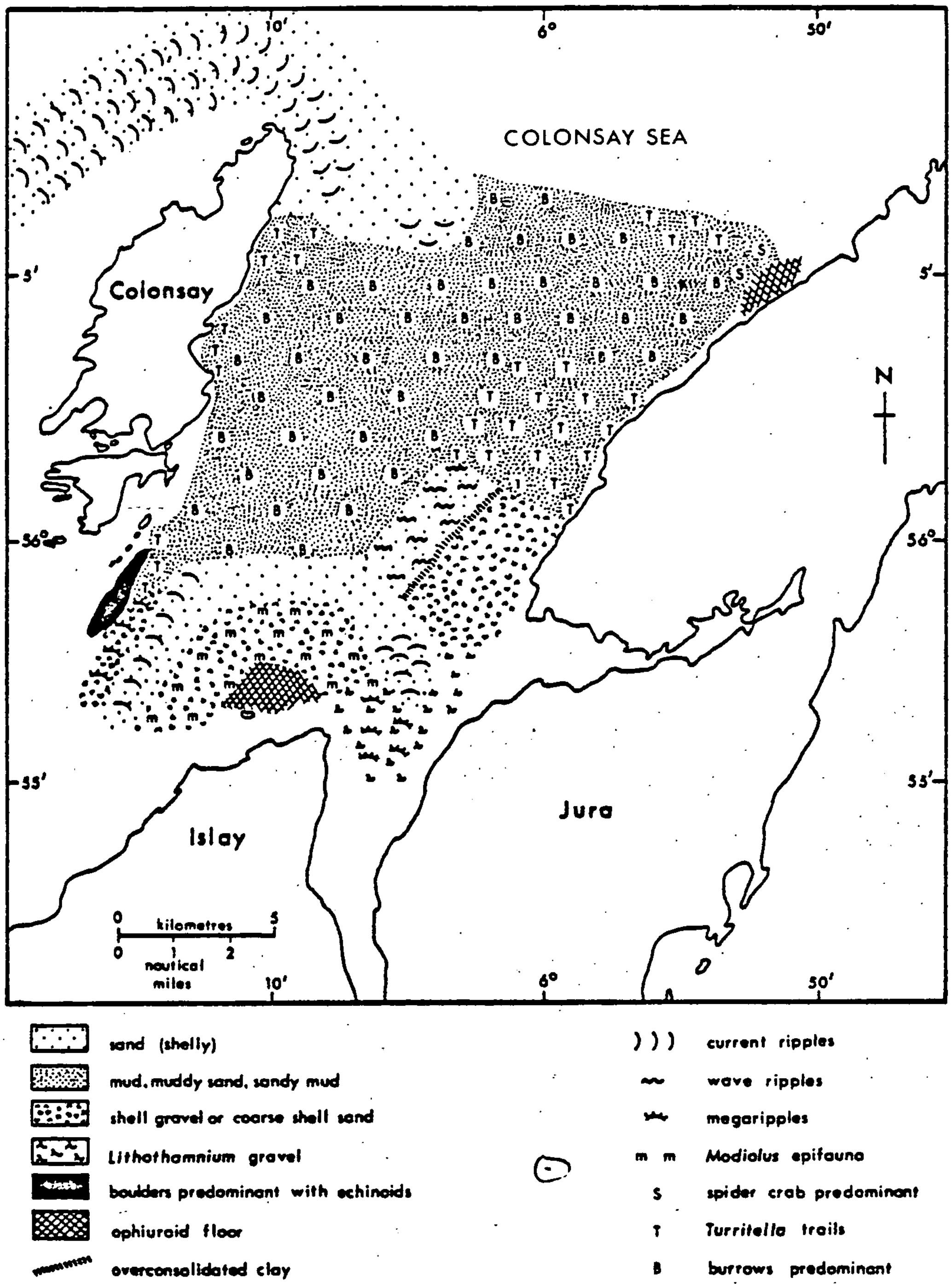
3. _megarippled sand_ was found in the Passage of Oronsay and near the northern mouth of the Sound of Islay. These structures were comprised

Fig. 10 A. Underwater television stations in the Colonsay Sea from Farrow _et al_. (1979) fig. 1.



COLONSAY SEA
Colonsay
Tarbert Bank
Passage of Oronsay
Sound of Islay
Islay
Jura
SCOTLAND
4 m
18 m
92 m
N
kilometres
nautical miles
10'
6°
50'
5'
56°
55'

Fig. 10 B. Facies maps for the Colonsay Sea from Farrow _et al_. (1979) fig. 2.



10'
6°
50'
COLONSAY SEA
5'
Colonsay
N
56°
55'
Islay
Jura
0 kilometres 5
0 1 2
nautical miles
sand (shelly)
mud, muddy sand, sandy mud
shell gravel or coarse shell sand
Lithothamnium gravel
boulders predominant with echinoids
ophiuroid floor
overconsolidated clay
))) current ripples
wave ripples
megaripples
m m Modiolus epifauna
S spider crab predominant
T Turritella trails
B burrows predominant

Fig. 10 C. Artist's reconstruction of gravelly Phymatolithon calcareum megaripples near the Sound of Islay; they are partly stabilized by the kelp Laminaria saccharina; from Farrow et al. (1979) fig. 4.

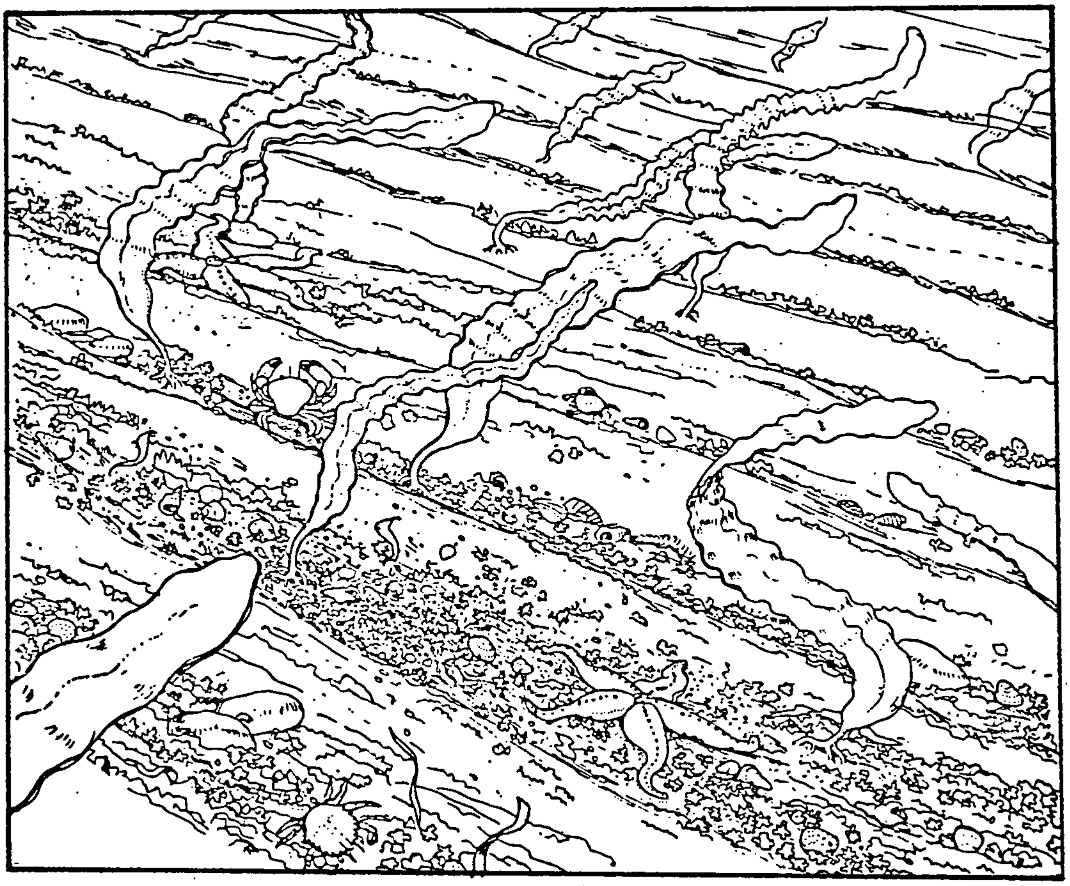
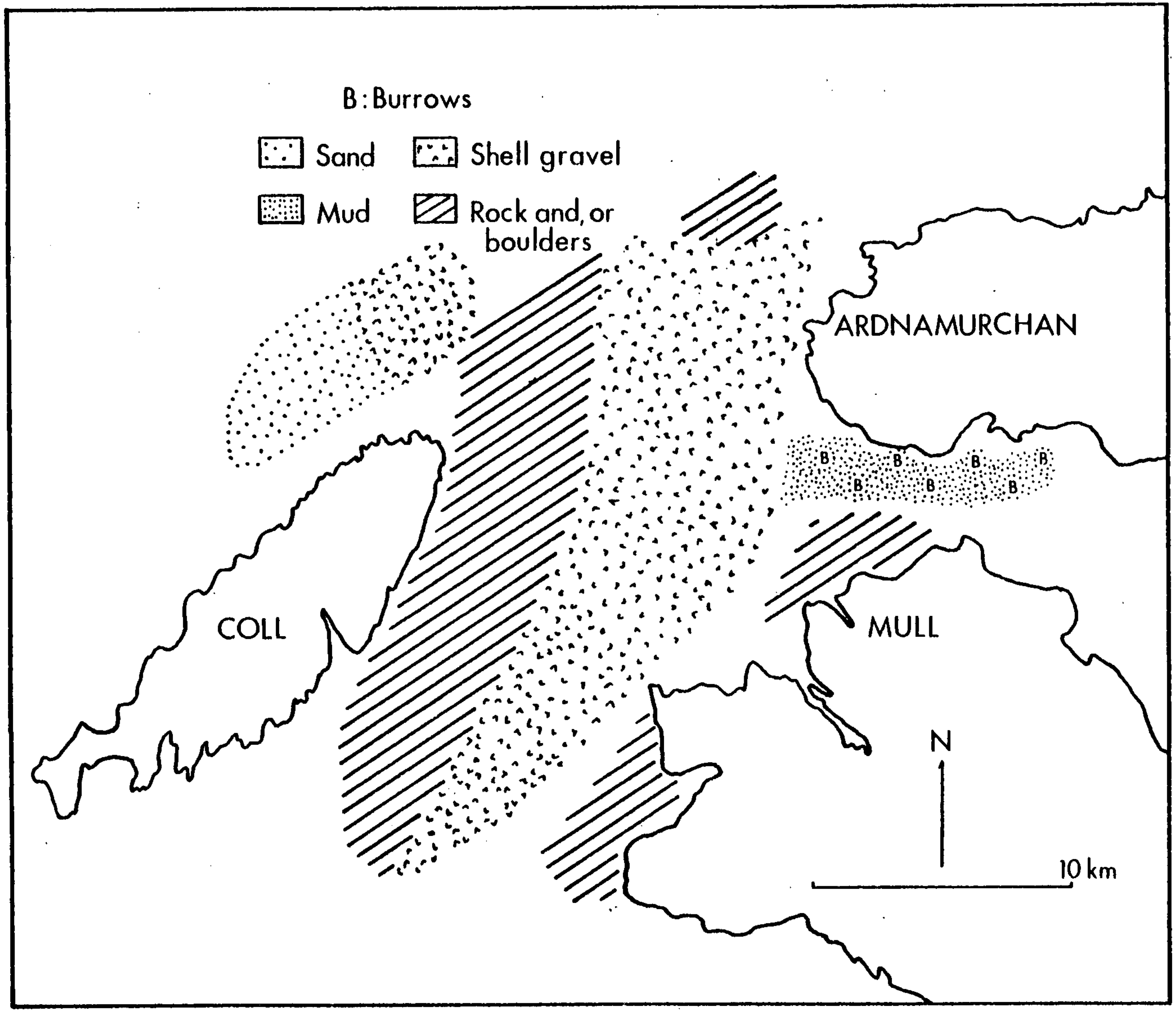


Fig. 10 D. Facies map for the northern sector of the Columba Sea
(from Brown, personal communication, 1977).


B : Burrows
Sand
Shell gravel
Mud
Rock and, or boulders
ARDNAMURCHAN
COLL
MULL
N
10 km
B

of living and dead thalli of Phymatolithon calcareum at the Islay locality and coarse shell sand debris at the Oronsay site. Wavelengths of approximately 1 m and heights of 10-20 cm were common. No fine-size sediment was observed when the sea-bed was disturbed by the camera frame or a lead weight attached to it. Whole, joined shells of Ensis sp. and Pecten maximus and live specimens of Chlamys and Asterias were observed. Laminaria saccharina locally stabilizes the megaripples, and provide cover for Macropipus crabs. This facies occurs over a depth range of 11-67 m, and is found at the margins of the Colonsay Sea (Fig.10 B,C).

4. current - rippled sand and 5. wave - rippled sand have been traditionally separated as different ripple forms (Pettijohn, 1975). However, as Wright (1978) shows, they can be identical and they are considered together here. The rippled areas are found near the northern tip of Colonsay. The Passage of Oronsay and Tarbert Bank. Depth of occurrence varied from 11-31 m. Wavelengths vary from 6-26 cm and amplitudes are 2-4 cm. Joined shells of Ensis and Artica were observed with the valves concave-up; Emery (1968) found this shell orientation to be the result of predatory scavengers or bioturbation.

6. Modiolus gravel is found between 23 m and 28 m to the north of Post Rocks. The Modiolus occurs in byssally joined clumps of live shells intermixed with convex up single shells of barnacle and serpulid encrusted dead Modiolus. Buccinum undatum, a voracious predator of bivalve molluscs, was abundant in this facies. Brittle stars and starfish were also observed.

7. Turritella fine sand, 8. filamentous-tube burrowed 'mud', 9. crustacean-burrowed mud, and 10. spider-crab mud have been placed together into a "burrowed mud" super-category. These facies are found inside the Colonsay archipelago where the percentage of terrigenous sediment is high, due to the high degree of shelter afforded to the basin's

interior by surrounding island masses.

11. overconsolidated clay is found at a depth of 23 to 28 m on the eastern margin of Tarbert Bank. Scoured and undercut grooves, clay balls, transported Chaetopterus worm tubes indicates that this tough, plastic mud is a relict and in places reworked deposit.

3.5 Conclusions.

High carbonate areas in the Columba-Colonsay Sea are characterized by: 1) a dominant contribution by barnacles and molluscs with local domination by rhodophytes; 2) shallow depth of occurrence; 3) a close proximity to bedrock outcrop; and 4) strong tidal currents.

3.6 Discussion of areas of high carbonate in the Columba-Colonsay Seas.

At the present very little terrigenous material is being transported onto the Scottish inner western shelf. This lack of input is a result of a glacially formed topography. Glaciers had the following effects:

With the diminution of mainland terrigenous input and the lack of terrigenous influx from indurated shelf islands the present-day sediment distribution readily separates into sites where shell material dominates, glacial material dominates or there is a combination of both sediment types. As was noted above and in Table 3, high percentage $CaCO_3$ sediment forms predominantly in shallow, wave and current-washed near-island localities. These sites are favoured because the high energy of their environments have assured that glacial material has been removed downslope to depositional basins. The small land area of the islands ensures that terrigenous influxes are minimal. The carbonates therefore occupy a marginal area between points lying above the inter-tidal zone, an island and adjacent basinal areas which lie near to the bathymetric point of deepest wave and tidal current influence.

The deposit are thus named island-margin carbonates. The terrigenous-rich deposits are found at sites which are sheltered from wave and current attack; relict glacial material remains within the shelter of an island archipelago or is transported into glacially sculpted basins. Such deposits may have little later carbonate input as on Tarbert Bank or, as is the usual case, become mixed with island margin carbonates to form a composite deposit. Terrigenous-rich sediments which occur largely because of the shelter provided by adjacent island or sea bed topography are termed basinal terrigenes.

3.7 Summary for Part 1.

Little terrigenous material is being moved from mainland Scotland onto the inner Scottish shelf, because of a glacially-sculpted barrier topography. Sites near islands have strong tidal currents and vigorous wave activity which winnow fines leaving indurated basement rocks or boulders. These sites contribute little terrigenous material and are exploited by carbonate organisms particularly barnacles in shallow waters, mixtures of barnacles and molluscs in slightly deeper waters. These sites are characterized by being close to bathymetric highs peripheral to bathymetric depressions and are termed island-margin carbonates. Sheltered basins lying within an island archipelago or on the open sea bed act as reservoirs for relict glacial material deposited during the Pleistocene or derived from wave and current reworked up slope glacial deposits; they are termed basinal terrigenes.

PART 2 : Sedimentation in the Sound of Iona.

3.8 Surface sediments.

3.8.1 Sampling.

The sampling area around Iona is shown in Fig. 2. Grab samples were obtained at shore and sublittoral stations. There were two types of shore samples: 1) beach material, defined as sediment found between average low and high water; 2) dune material defined as sediment found above mean high water. Sublittoral samples were collected by hand on scuba drift dives (see appendix 2). Deep water and rough-sea area sampling was conducted by mechanical grab and dredge samplers from research vessels (appendix 2). Diver-obtained hand grab samples were taken from the upper 5-6 cm, mechanical samples from the upper 10 cm and dredge samples from the upper 20-50 cm of the sediment accumulation.

3.8.2 Sediment composition.

There are three different types of sediment found in the Sound and its environs: 1) biogenic carbonate sand and gravels; 2) terrigenous sand to boulder-size sediment; 3) silt-size carbonate and terrigenous mud mixtures. The carbonate-rich sediments are restricted to shore and sublittoral areas of the Sound and western margin of Iona Island. Terrigenous clastic grains are pervasive throughout the Iona littoral and sublittoral sediment, although the richest areas of terrigenes are distal to the Sound. The fine-grained carbonate-terrigene mixture is confined to an area in the northern Sound.

Sand-sized samples were mounted in Araldite, ground to a standard thickness of 40 μm and modally analyzed by petrographic microscope (Chayes, 1956 and appendix 2). The following grain classes were found: cirripeds (barnacles), molluscs, rhodophytes (coralline algae), echinoderms, foraminifera, bryozoa, terrigenes and a composite category for minor sediment constituents such as serpulid worms and unidentifiable grains. Criteria for identification are listed in Table 6; see also Fig. 12. Roundness, an indication of the amount of grain transport, was studied by examining the degree of abrasion of natural fracture surfaces. As a further indication of grain provenance and relative age, grains were examined for signs of boring and diagenesis.

Bulk composition of sand-size fractions are shown in Table 7. To get a clearer indication of possible trends, data were recalculated and plotted on a terrigene-free basis for the principal contributors: barnacles, molluscs, rhodophytes and echinoderms (Fig. 11). Maerl, beach and dune samples can be readily separated from the other samples on the basis of the percent of sublittoral rhodophytes (Table 7 B).

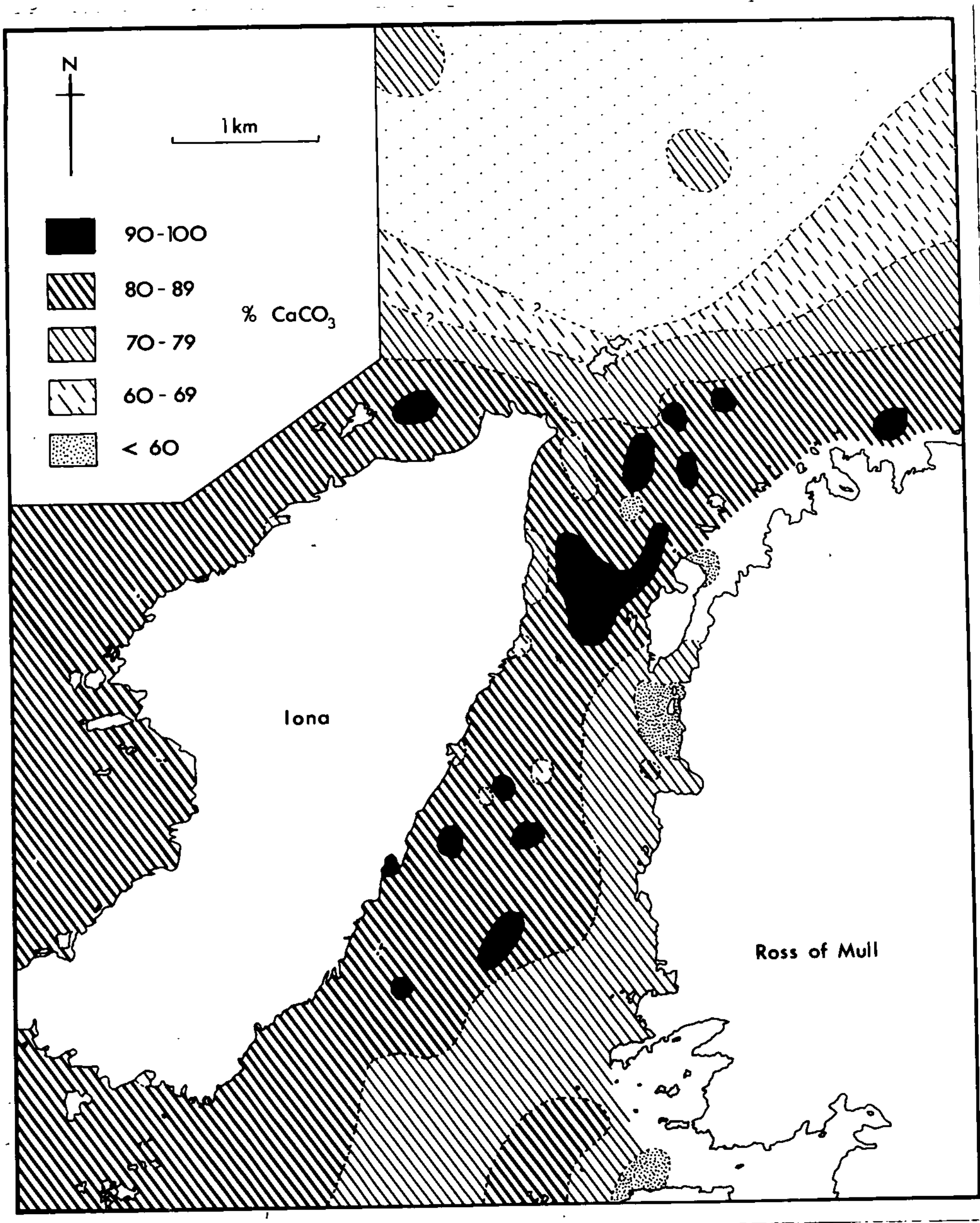
This material on the seabed is not transported transversely and upslope; grain transport is longitudinal rather than lateral within the Sound (see Section 3.9.4). Beach samples are enriched with respect to barnacles, when compared with sublittoral samples. Hence eulittoral zone barnacles are a significant source of carbonate sediment. This is verified independently by eulittoral barnacle population studies (see 3.23). Sublittoral mollusc proportions are slightly higher than beach samples. However, this difference is not judged to be significant because of the high coefficient of variation (97%) of the beach molluscs. Furthermore, the similarity of the sublittoral and the dune mollusc percentages suggests that the shore and sublittoral areas are identical in mollusc content. Mollusc material originates from both shore and seabed areas (see Section 3.14-17). The low values of foraminifera and bryozoa are problematic The paucity of foraminifera is believed to be related to the swift currents and shallow depth of the Sound. Guilcher and King (1961) and Lees _et al_. (1969) found foraminifera collected in bays in south-west Eire where a combination

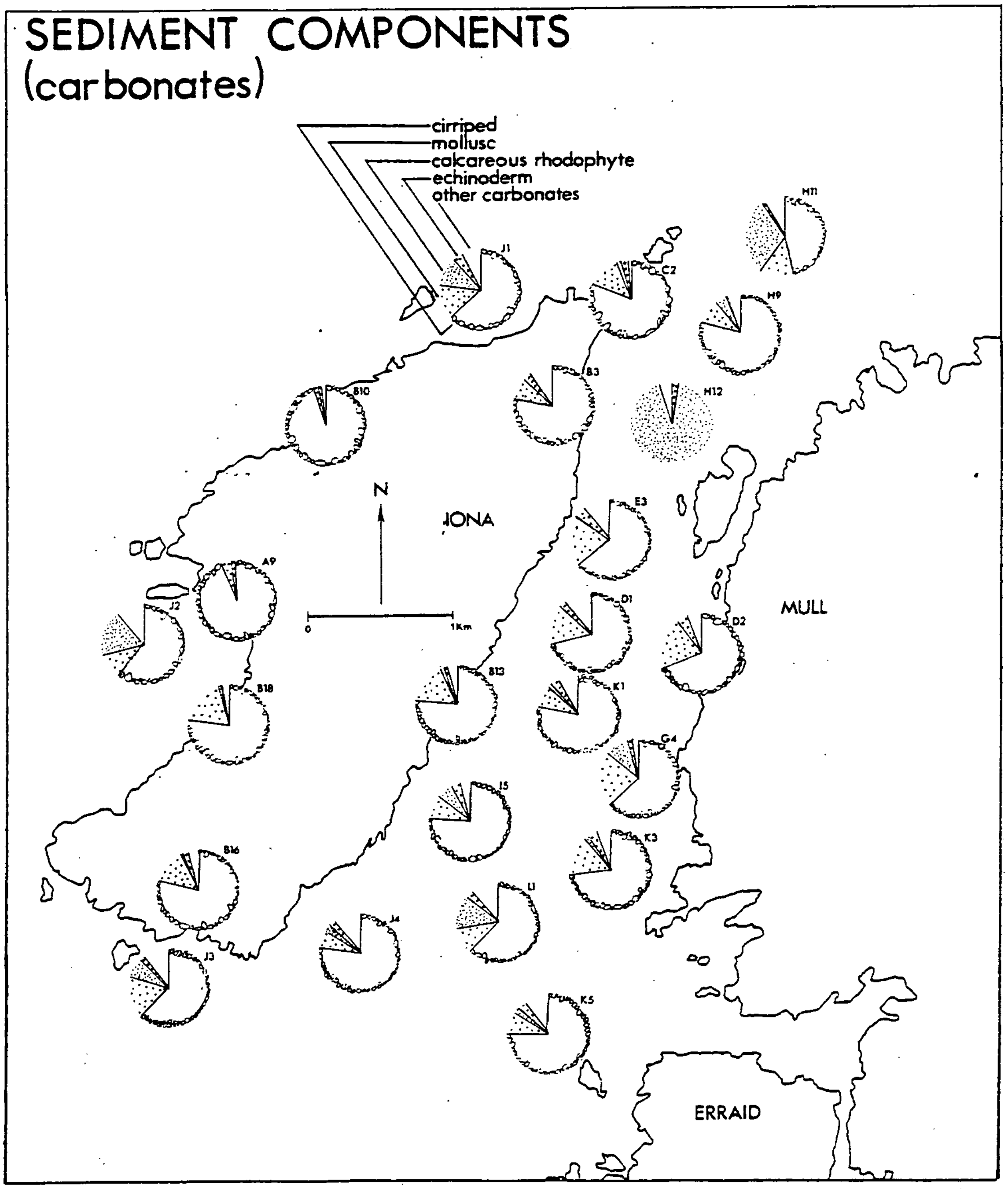
Table 6. Diagnostic criteria for identification of Recent sediments from the Sound of Iona.

Refs. B = Bathurst (1975); BY = Barrett and Yonge (1958); HP = Horowitz and Potter (1971); K = Kerr (1959); Ma = Majewske (1969); Mi = Milliman (1974); W = Wray (1977).

Grain + Ref.	Whole grain Binocular Microscope	Thin section Plane-polarized light	Crossed polaroides	Mineralogy
cirriped (barnacle) Mi	crenulate, triangular fragments, tubular "canals" in interior, white or green-grey shell colour: worn plates easily confused with molluscs.	brownish-colour grain microcrystalline internal structure; sinuous canals of grain diagnostic.	brown-translucent grain microcrystalline structure obscurs birefringence.	low Mg calcite
mollusc B, Ma	ornamental colour e.g. purple mytilids or structure e.g. ribbing observed.	Bøggild structures: homogenous, prismatic foliated, nacreous, grained single crystal, crossed-lamellar, complex crossed-lamellar.	extinction highly variable; unidirectional; unit; moving line; mosaic extinction in prisms; parallel, random irregular extinctions, also observed.	low Mg calcite or aragonite or both.
calcareous rhodophyte (alga) W	thallus is digitate or arborescent in shape if whole; bent "stick" appearance if fragmented; porous, cellular structure seen at high mag. large pores called conceptacles occasionally seen	thallus differentiated into hypothallus which consists of cells growing parallel to internal axis of thallus of substrate and perithallus which grows perpendicular to the axis or substrate; large pores or conceptacles occasionally seen, rarely containing spores.	microcrystalline calcite in cells walls, no birefringence observed; thallus brown coloured.	high Mg calcite
echinoderm Ma	large grains may show virtually intact ambulacral and interambulacral plates. Pores, tubercles and detached spines visible at high mag.	orthogonal network of plates and spines when observed in section spines in cross section circular with a lace-like internal structure.	unit extinction of grains characteristic.	high Mg calcite
foraminifera B, HP, Mi	coiled, globulose, spherical whole grains of small size <1mm.	small-size <1mm internal chambers often planispiral with external pores.	variable extinction: Textulariina (Agglutinating). opaque to semi-opaque: Miliolina (Porcellanea) extinction lines normal to edge of grain: Rotaliina (Hyalina)	any derived grains: Textulariina. high Mg calcite: Miliolina. high Mg calcite: low Mg calcite: aragonite: Rotaliina.
bryozoa B, Mi	zoarium (skeleton) has fenestrate structure composed of cells (zooecia); commonly encrusts other shells within the Sound.	colonial plexus granular calcite surrounded by a thin inner layer and a thick outer layer of lammated calcite (sclerenchyma). Skeletal rods radiate into the sclerenchyma.	granular calcite birefringence	high Mg calcite low Mg calcite aragonite.
Annelid (worm tubes) BY, Ma	1) white, tightly-coiled planospiral about 5mm diam.; 2) white irregularly bending tube triangular shape; 3) pale green and pink round tube.	laminated tubes	no birefringence observed in some specimens; moving line extinction observed in other specimens.	high Mg calcite and aragonite
Terrigene K	grains identified by the presence of quartz, feldspar, mica and mafic minerals.			

Fig. 11 A. Carbonate distribution map for the Sound of Iona from Farrow et al. (1978) fig. 2.


N
1 km
90-100
80-89
70-79
60-69
< 60
% $CaCO_3$
Iona
Ross of Mull



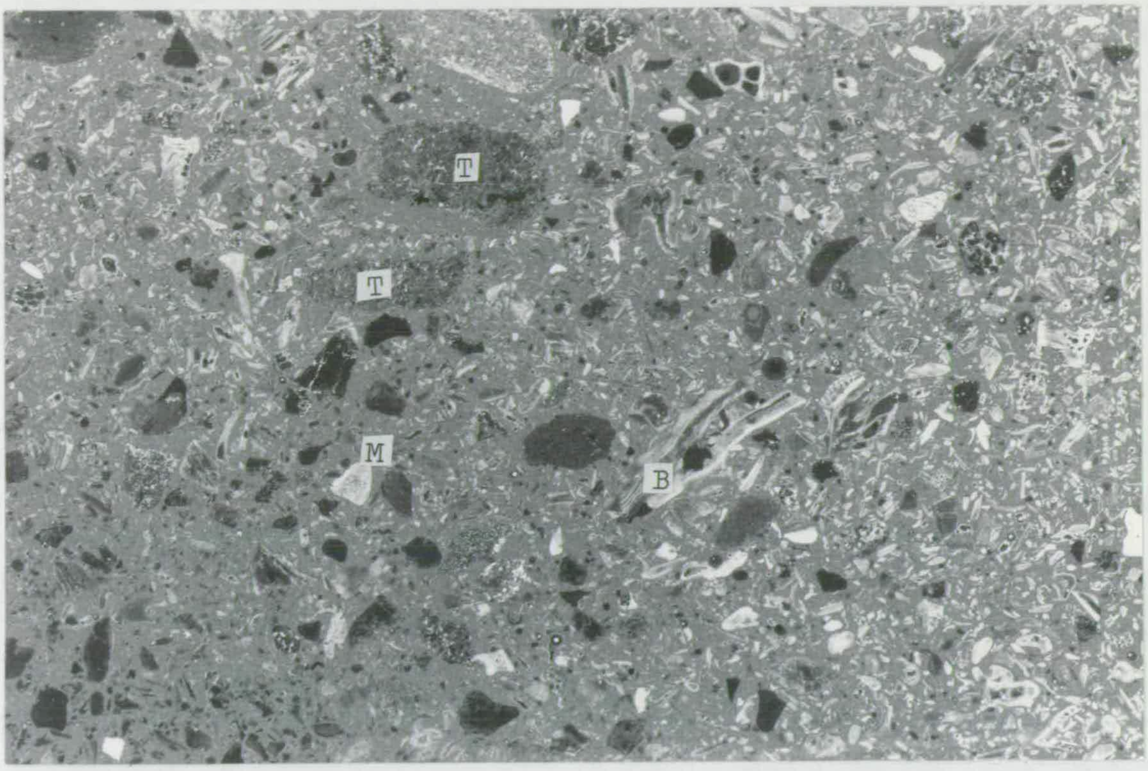
SEDIMENT COMPONENTS (carbonates)

Fig. 12 A-I Component grains in the Sound of Iona sediment negative print, ordinary light:

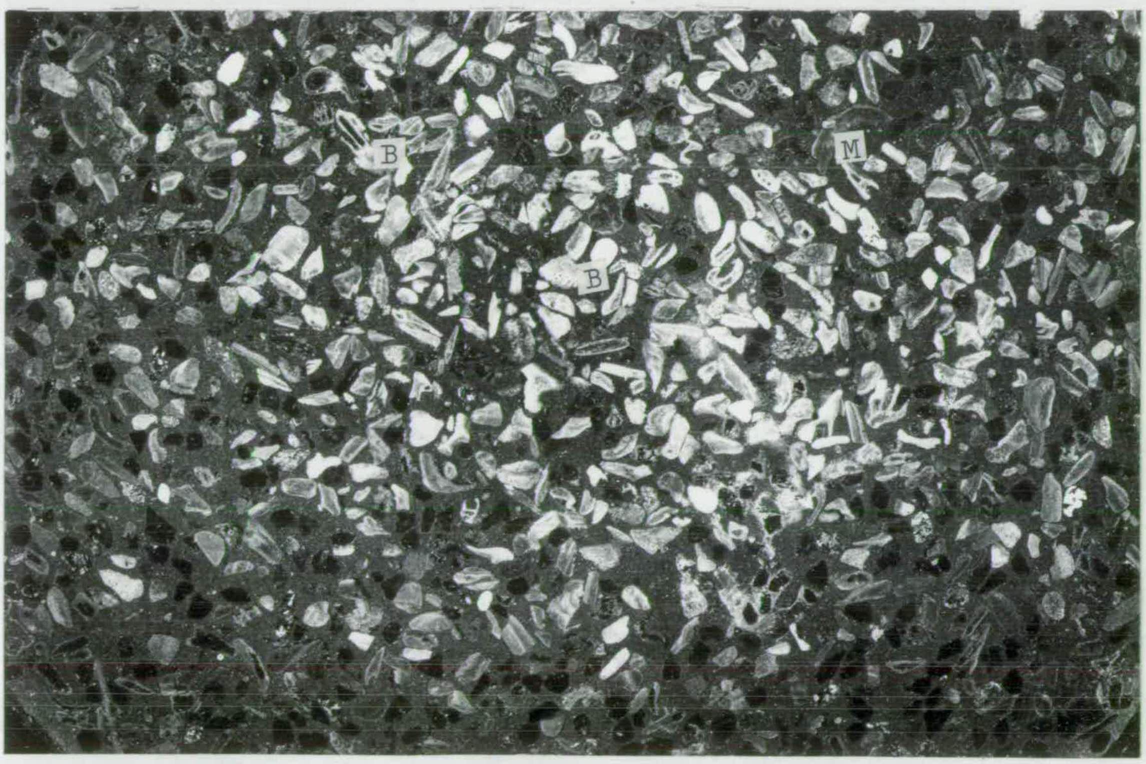
B = barnacle
M = mollusc
CR = calcareous rhodophyte
E = echinoderm
F = foraminifera
BR = bryozoa
S = serpulid
O = ostracod
T = terrigene.

Fig. 12 A Sample B3 (beach)

Fig. 12 B Sample D1 (central shoals)
Note small grain size.



5mm



5mm

Fig. 12 C. Sample H6 (N. platform 1)


CR
B
M
CR
T
T
5mm

Fig. 12 D. Sample H7 (N. platform 1).

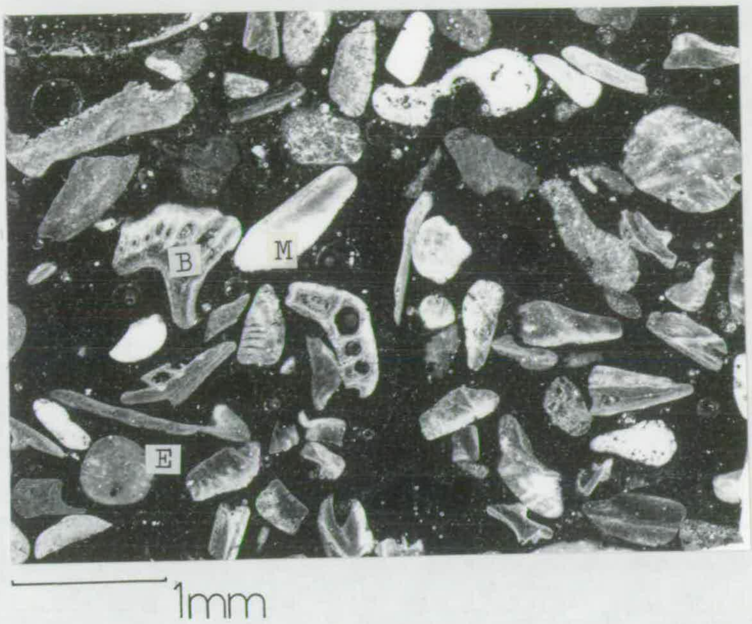
5mm

Fig. 12 E. Sample H11 (N. platform 1).


CR
CR
B
5mm

Fig. 12 F. Sample I3 (S. platform).

Fig. 12 G. Sample I4 (S. platform).


B
M
E
1mm

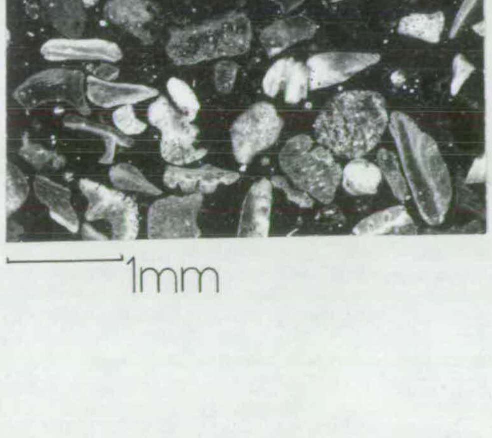

M
1mm

Fig. 12 H. Sample L3 (N. platform 1).


CR
CR
CR
F
5mm

Fig. 12 I. Sample L5 (beach).

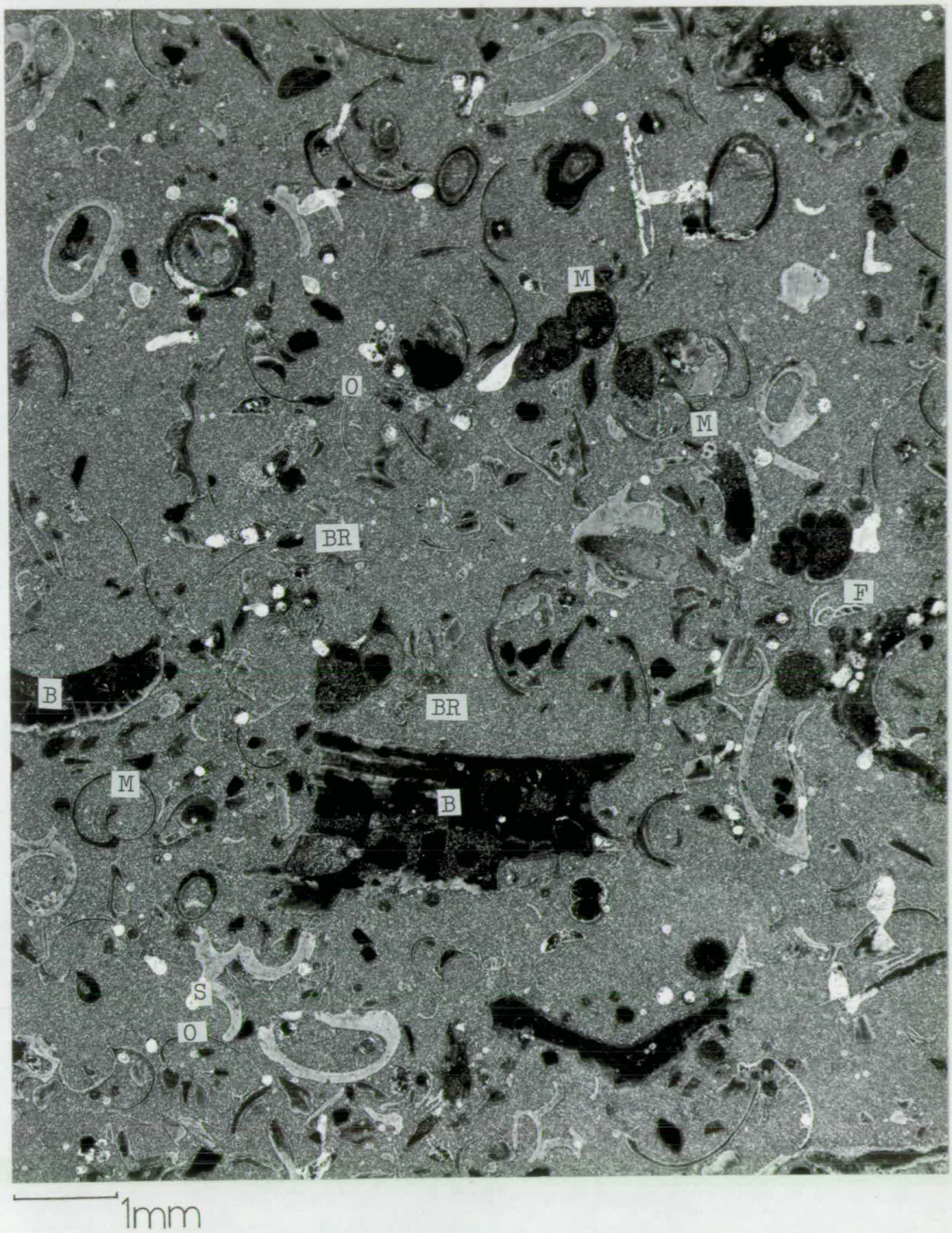

M
O
M
BR
F
B
BR
M
B
S
O
1mm

Table 7A Thin section analyses of 6 dune, 27 beach and 57 sublittoral samples from Iona gave the following average percentage analyses.

Note: sd = standard deviation; cv = coefficient of variation: sd/mean x 100%; tr = trace; TF = terrigenous free; data recalculated only for the first four classes using carbonate percentages including the "other" category; nc = not calculated.

	Dune samples n = 6				Beach samples n = 27			
	mean %	sd	cv%	TF%	mean%	sd	cv%	TF%
cirriped	62	12	19	79	56	24	43	77
mollusc	12	8	65	15	7.8	7.6	97	12
calcareous rhodophyte	tr(0.42)	0.8	188	tr(0.55)	tr(0.52)	1.1	212	tr(0.68)
echinoderm	tr(0.96)	1.5	157	1.2	1.6	1.6	100	2.5
foraminifera	tr(0.08)	0.2	245		tr(0.64)	1.7	266	
bryozoa	0	nc	nc		0	nc	nc	
other	4	2.7	69		4.1	4.2	102	
terrigene	22	4.7	21		29	24	83	

	Littoral-nearshore shoals n = 4				Western platform n = 2			
	mean %	sd	cv%	TF%	mean %	sd	cv%	TF%
cirriped	55	9	16	68	53	5	9	62
mollusc	18	4	22	22	10	4	40	12
calcareous rhodophyte	1	1	100	1	12	2	19	15
echinoderm	4	2	50	5	2	2	100	2
foraminifera	tr(0.42)	0.84	200		tr(0.13)	0.18	140	
bryozoa	0	0	0		0	0	0	
other	4	1	25		8.5	1.8	21	
terrigene	19	10	53		15	7.4	49	

	Southern platform n = 21				Central shoals n = 6			
	mean %	sd	cv%	TF%	mean %	sd	cv%	TF%
cirriped	54	14	26	71	57	5	9	72
mollusc	11	4	36	14	11	3	27	14
calcareous rhodophyte	4	3	75	5	3	3	100	4
echinoderm	2	1	50	3	3	2	66	4
foraminifera	tr(0.01)	0.05	550		tr(0.07)	0.18	260	
bryozoa	tr(0.04)	0.09	220		0	0	0	
other	5	4	80		7	7	100	
terrigene	24	15	63		21	9	38	

	Northern platform 1 n = 19				Northern platform 2 : maerl area n = 5			
	mean %	sd	cv%	TF%	mean %	sd	cv%	TF%
					analyzed by weight, see Appendix 4.4			
cirriped	52	15	29	60	tr(0.19)	0.29	150	=mean%
mollusc	11	4	36	13	5.8	10	172	"
calcareous rhodophyte	14	14	100	16	83	21	125	"
echinoderm	2	1	50	2	tr(0.30)	0.68	230	"
foraminifera	tr(0.05)	0.13	270		nc : comprise sand and gravel			
bryozoa	tr(0.09)	0.28	310		nc : comprise sand and gravel			
other	7	4	57		tr(0.01)	0.01	100	
terrigene	14	12	86		tr(0.38)	0.85	220	
sand & gravel					10	11	100	

Dune spls. as noted in appendix 4; Beach spls. as noted in appendix 4; Littoral-nearshore shoals: A1, D2, G6, I8; Western platform spls.: J1, J2; Southern platform spls.: G4, G5, H1, H2, H3, H4, I2, I3, I4, I5, I6, I7, J3, J4, K1, K2, K3, K4, K5, K6, L1; Central shoals spls.: D1, E1, F5, G1, G2, I1; Northern platform 1: A6, A7, C2, C3, C4, D3, E2, E3, F1, F3, H7, H8, H9, H10, H11, K7, L2, L3, L4; Northern platform 2: E4, F2, H5, H6, H12.

Table 7B Sample statistics: These techniques are from Siegel, S. (1956) Nonparametric statistics. McGraw-Hill, Kogakusha Ltd. Tokyo 312 p.
Results of the Mann-Whitney U-Test p = probability of occurrence under H_o and must be greater than 0.05 for the two groups to be drawn from the same population.
Data: original calcareous rhodophyte percentage, appendix 4.1 and 4.4.
dp = different population; sp = same population; v.s. = very small.

	N. platform 2 (maerl)	N. platform 1	Central shoals	S. platform	W. platform	Littoral nearshore shoals	Beach	Dune
N. platform 2 (maerl) n = 5	-	dp p 0.05	dp p=0.002	dp p = v.s.	sp p=0.094	dp $p < 0.008$	dp p =v.s.	dp p=0.004
N. platform 1, n = 19		-	sp $p > 0.05$	dp $p < 0.05$	sp $p > 0.05$	sp $p > 0.05$	dp p =v.s.	dp $p < 0.05$
Central shoals, n = 6			-	sp p=0.1362	sp p=0.072	dp p=0.01	dp p=0.18	dp $p < 0.008$
S. platform n = 21				-	sp p=0.292	dp p=0.0118	dp p =v.s.	dp p = v.s.
W. platform n = 2					-	sp p=0.134	dp p=0.0204	sp p=0.072
Littoral near-shore shoals, n = 4						-	sp p=0.134	sp p=0.476
Beach, n = 27							-	sp p=0.92
Dune, n = 6								-

Summary: 1) On the basis of the calcareous rhodophytes, dune, beach and littoral-nearshore shoal samples are from similar populations;
2) Sublittoral areas are for the most part from similar populations;
3) the maerl area (northern platform 2) is a distinct population.

Note: Data did not meet the requirements of parametric statistics, hence these were not used. Rhodophytes were selected for analysis because they are ubiquitous, present in large percentages and are environmentally sensitive.

Table 7.C Spearman rank correlation coefficients, from Siegel (see Table 7A). Data original thin-section mean percentages Table 7A; significance level $\alpha = 0.05$, one-tailed; for n = 8 bathymetric tracts = 0.643.

Note: s = significant; ns = not significant.

	Cirripede	Mollusc	Calcareous rhodophyte	Echinoderm	Terrigenes
Cirripede	-	0.4524 ns	- 0.9286 s	0.1905 ns	0.7381 s
Mollusc		-	- 0.4524 ns	0.5714 ns	0.0714 ns
Calcareous rhodophyte			-	-0.1190 ns	-0.7857 s
Echinoderm				-	0.1429 ns
Terrigenes					-

Summary: The strong negative correlation between the rhodophytes and the cirriped and terrigenes suggests that alga will not be found where there is an abundance of these grains i.e. in areas of high sedimentation.

The strong positive correlation between the cirripeds and the terrigenes is easily explained because barnacles grow on rock surfaces which would be the source areas for terrigenous grains and 2) barnacle shells would be expected to accumulate in areas where there is a supply of terrigenous grains to dislodge encrusting dead shells by abrasion and impact.

of weak tidal currents and a semi-enclosed coast captured these organisms and incorporated them as sediment. The low mean terrigene content reflects the erosion resistance of the indurated metamorphic rocks of Iona and the granites of the Ross of Mull. However, high terrigene values for the Ross of Mull beaches reflect local stream input.

The similarity of sediment constituents of beach and dune samples suggests a similar faunal origin for these deposits. The dune sands are generally finer and better sorted than the beach sands. Mather and Crofts (1972) state that the dune areas are raised beach material. Furthermore the dunes are slowly being wave-eroded (Mather and Crofts op. cit.) so they are remanie deposits stranded by post-glacial uplift; not as once thought (Cunningham, 1851) wave-derived deposits formed in the present-day.

Examination of Table 7 shows that within the sublittoral area of the Sound, only one area is significantly different in composition from the rest, this is the maerl area on the Northern platform. The reason is that source sediment for most groups originates throughout the littoral and sublittoral areas of the Sound. Once the organism dies the shell is quickly shattered by wave action and dispersed by tidal currents. The lack of any discernible trend in the components attests to the power and efficiency of this process.

The rhodophyte sediment is localized to two areas north and south of the central shoals in the Sound; the larger deposit of algal sediment is found in the three-sided shelter of the northern platform. The southern platform is fully exposed to south-western wave attack. This disrupts algal growth by breaking the thallus and burying it by the surrounding sediment, this is statistically noted in Table 7 C.

Grains were examined for signs of boring and diagenesis. Bored grains were commonly observed in all types of organisms (Fig. 13).

Fig. 13 Scanning electron microscope (SEM) photographs of sublittoral sediment from the Sound of Iona (from Farrow _et al_. (1978) Pl. 3).

A. Well-rounded lightly bored bivalve grain (spl. J3).

B. Close-up of A. showing unaltered nacreous microstructure.

C. Borings, probably of algal origin in a bivalve (spl. H11).

D. Borings, probably of algal origin in a barnacle plate (spl. D4).

E. Borings of unknown origin in an echinoid spine (spl. D4).

F. Very pitted surface of a barnacle grain, showing corroded grain of _Campylodiscus_-like diatom (spl. D4).

G. Benthic diatoms inside a barnacle plate chamber.

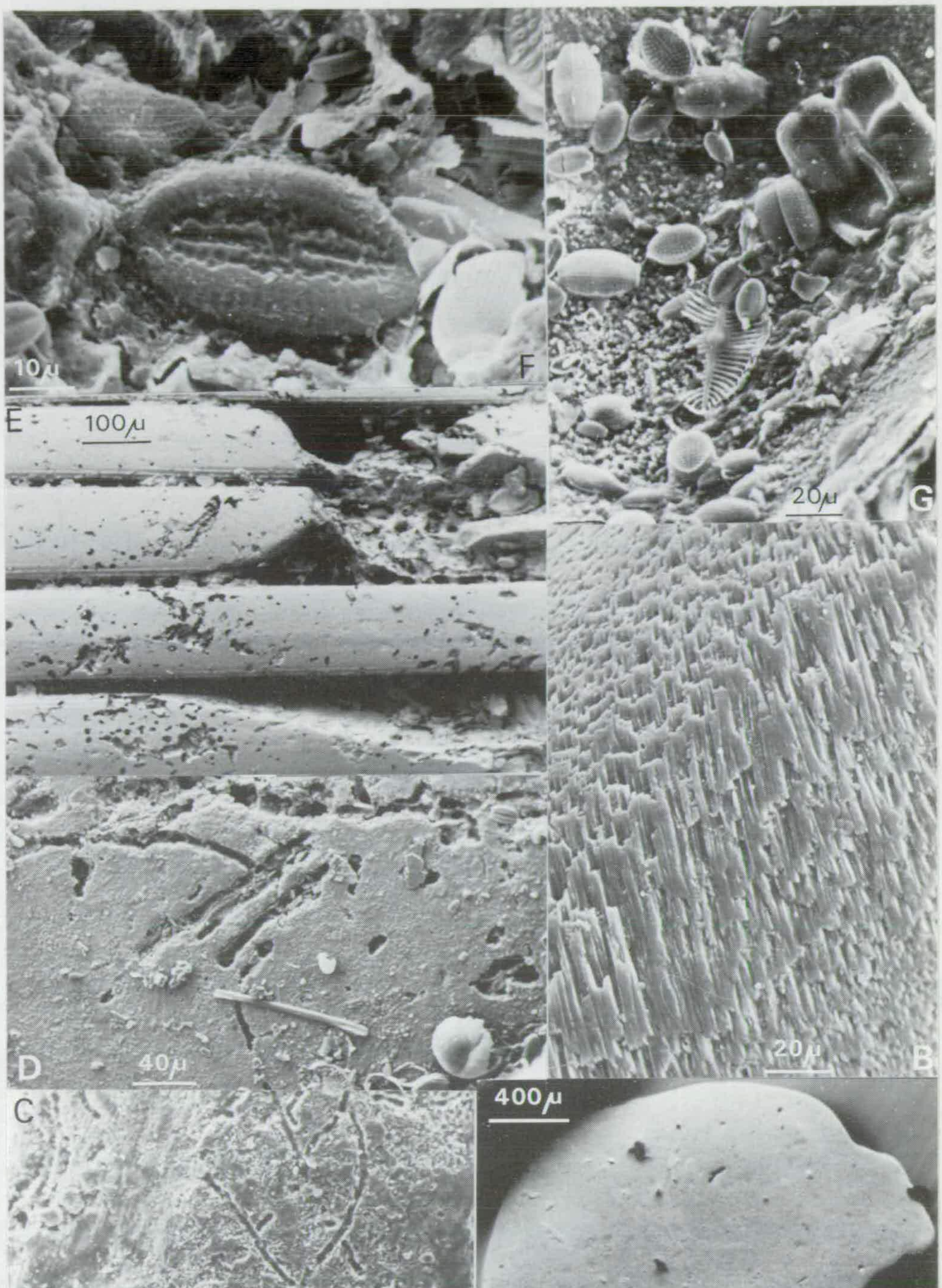
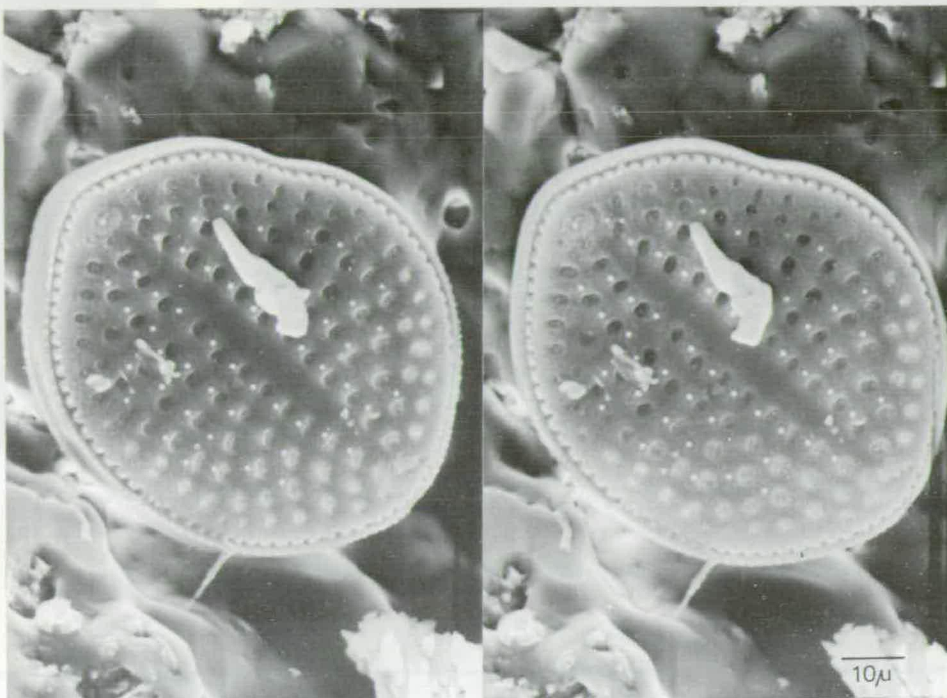

10μ
F
E
100μ
20μ
G
D
40μ
20μ
B
C
400μ
40μ
A

Fig. 14. SEM stereopairs of benthic diatoms in corroded pits of relict *Phymatolithon* thalli (from Farrow *et al.* (1978) Pl. 5).

A. *Cocconeis*-like diatom on a floor of a small thallus pit.

B. *Diploneis*-like diatom within a thallus cavity

The association of these organisms with the pit-like structures suggests that the pits may be related to metabolic activities of the diatoms.


10μ


40μ

Algae appear to be the main agent for the boring (Fig.13C,D). Carbonate grain dissolution is associated only with two types of diatom metabolic activity (Fig. 14). No other type of carbonate dissolution is observed, not even the physico-chemical type commonly ascribed to temperate deposits (Alexanderson, 1972). Saturometry determinations (Weyl, 1961) conducted here show that the waters of Iona are supersaturated with respect to $CaCO_3$. No evidence of cementation is observed in any samples. Siliceous Campylodiscus-like diatoms appear to be corroded (Fig. 13F). This suggests that this sediment was effected by silica undersaturated waters. The fact that this is not observed in other diatoms indicates that the process is very slow acting and the grain is very old, or that the grain was in contact with silica-undersaturated waters at some time in its past, or both.

Included in the carbonate sediment were grains that were highly bored, had a brownish or greyish-coloured tint to them (compared to fresh material which was white), very rounded edges and sometimes were abundantly encrusted with serpulids (Fig.12,13). Grains having these are thought to be relict. They were a small constituent of the samples averaging about 5-10% of the total grain bulk. Most commonly they consisted of barnacle and mollusc fragments but relict rhodophyte (Phymatolithon calcareum) fragments were observed. A C-14 date of this type of rhodophyte gave an age of 3800 yr B.P. at station 03 located on the central shallows (see appendix 2 for a description of the technique).

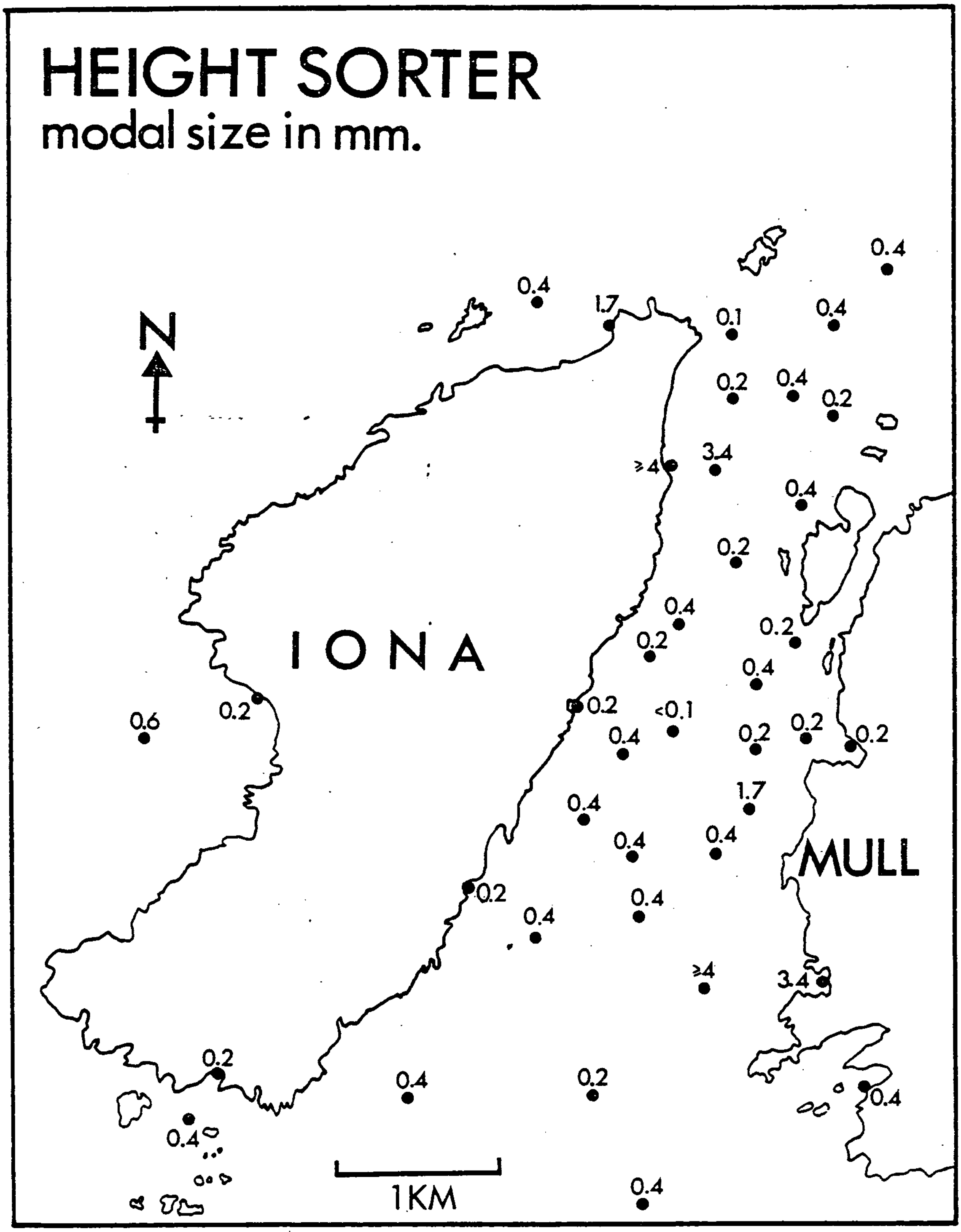
The low amount of relict material means that there is a high input of fresh material.

3.8.3 Textural parameters : grain size and roundness.

Grain size was studied to understand transport processes, direction and grain maturity. The height sorter technique of Lees et al., (1969) was used for an approximate size analysis for 39 samples of Iona sediment. This method measures the minimal thickness of a grain which passes through a slit of known width (see appendix 2). This method was considered the most appropriate for the Iona sediment because it consistently measured the same dimension of all grains. Sieving is less consistent; it measures cross-sectional area of spherical grains; the intermediate axial dimension of platy grains and the minimal axial measurement of columnar grains. The disadvantages of the height sorter are that: 1) it is not a commonly used technique there it is difficult to compare values to other published size studies; 2) the technique, like sieving and fall columns can misclassify grains, e.g. a mollusc fragment 1 cm^2 in area and 1 mm thick could be sorted into the same fraction as a foraminifera 1 mm in diameter (Lees, op. cit.); 3) as with the other carbonate size techniques the data is only semi-qualitative because shells and hence grain size can be generated in situ. Hence it is not susceptible to statistical analysis.

Sand-size sediment predominates throughout the Sound (Fig. 15) save for the algal deposits on the northern and southern platforms. These deposits are generated by in situ growth and are termed maerl. This accounts for the size transitions. On the northern platform detrital coralline algae form a crescentic deposit around a "core" of whole, predominantly living calcareous algae (Fig. 15). The maerl is attacked at periphery by oscillatory currents and waves (see Section 3.18) creating the bioclastic fringe. The large algal size of the core of the maerl is due to shelter from the most severe southerly wave attack by three-sided land, central shoals and the maerl's situation in a slight depression on the seabed. This latter situation would also create a diminution of current strength; lessening the prospects of transport and abrasion which would kill the algae. There is an apparently paradoxical situation whereby the finest sizes are found in central shoals

Fig. 15. Sediment size in the Sound of Iona as determined by the height sorter. Dominant modal size classes are shown.


HEIGHT SORTER
modal size in mm.
N
IONA
MULL
1KM
0.4
1.7
0.1
0.4
0.4
0.2
0.4
0.2
≥4
3.4
0.4
0.2
0.4
0.2
0.2
0.4
0.6
0.2
0.2
<0.1
0.4
0.2
0.2
0.2
1.7
0.4
0.4
0.4
0.2
0.4
0.4
≥4
3.4
0.2
0.4
0.2
0.4
0.4
0.4

where currents are swift and depths less than 2 m. It was expected that the larger grain types would be found here. The contradiction was resolved by flume studies, Table 8 (and see appendix 2) whereby fine sand size sediment was transported at lower velocity than the larger sediment sizes. The large-size sediment remains behind or beneath (Fig. 16). A similar situation occurs in the Sound: the northward-flowing flood tide would create a lag on the southern flank of the central shoals; a southward flowing ebb tide would create a lag on the northern flank. The fine sand being most easily transportable and most frequently in motion would accumulate in the central shallows, the strand point for this transported sediment. The significance of this is that in an area of oscillatory tidal currents, reverse size grading can take place, where the finest sizes are found in shallow water and coarser sizes in deeper water. Finest grain sizes are found on exposed beaches of the southern half of Iona and Fionnphort Bay. Wave action would quickly break down shell material on Iona accounting for the small size there; the fine sediment sizes of Fionnphort Bay reflect lateral derivation of this sediment from the central shoals.

Sorting is a statistical parameter which measures size class dispersion in a sieved sediment population (Folk, 1974). It has limited applicability to the carbonate studies because grains originate in situ as well as being transported from adjacent areas. However, a very crude approximation of sorting can be discerned in the number of height sorter size classes at a station. The small number of size classes for samples on the central shoals would indicate "good sorting"; the somewhat larger number of size classes on the southern platform would indicate "fair sorting"; the large number of size classes for stations on the northern platform would indicate "poor sorting". The "sorting" (Fig 17) is interpreted as follows: the powerful oscillatory tidal currents of

Table 8. Flume erosional velocity studies for sediment from the Sound of Iona

C = cirriped (barnacle), M = mollusc, CR = calcareous rhodophyte (alga)
E = echinoderm, F = foraminifera, BR = bryozoa, oth = other.

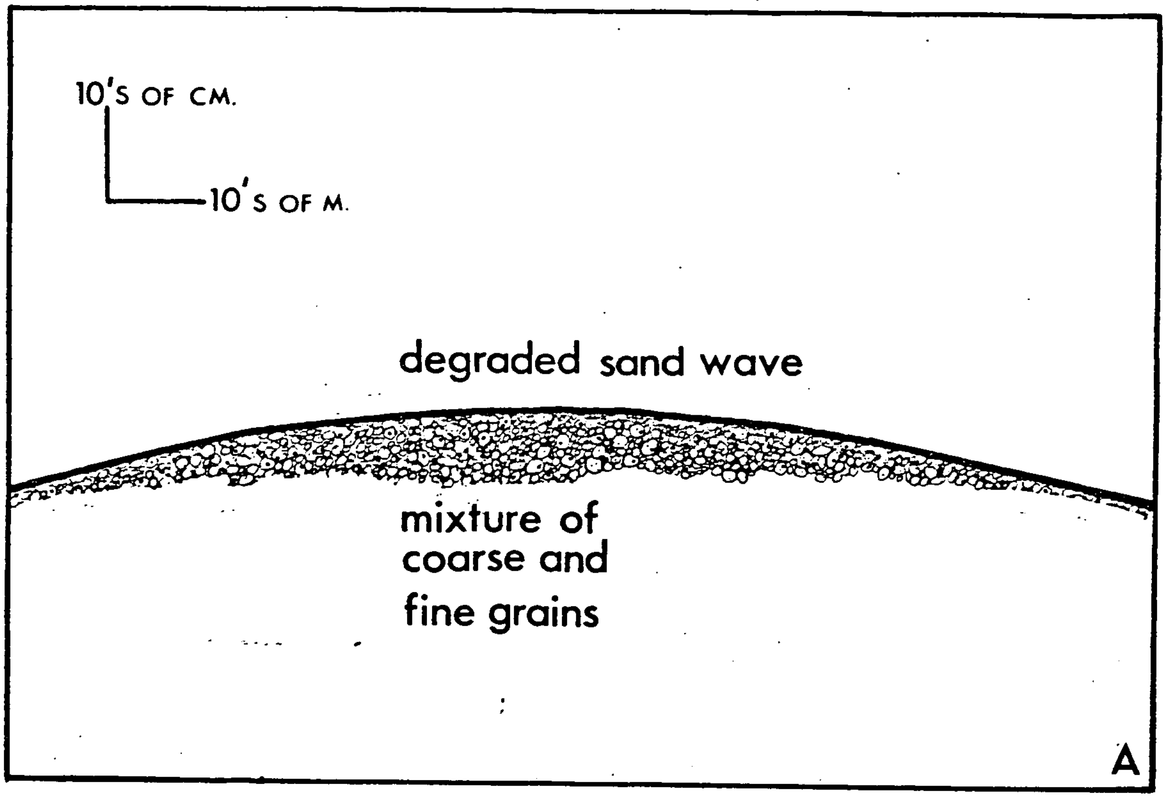
Sample	Composition	Dominant height sorter size class	Transport Velocity whereby 10% of sample volume moved (fine sand size)	Transport Velocity whereby 50% of sample volume moved (≥med. sand size)
H11 (northern platform)	6% terrigene; 94% carbonate; 43%C; 13%M, 29%CR; 1%E; 0%F; 0% BR; 8% oth.	36% (by weight = w) 0.3, 0.5cm	16.1cm/sec, 5 runs average	22.0cm/sec, 5 runs average
D1 (central shoals)	31% terrigene; 69% carbonate; 49% C; 11% M; 0% CR; 2% E; 0% F; 0% BR; 7% oth.	85% (w) 0.1cm	12.2cm/sec, 5 runs average	20.2cm/sec, 5 runs average
K5 (southern platform)	11% terrigene; 89% carbonate; 67% C; 8% M; 2% CR; 3% E; 0% F; 0% BR; 9% other	54% (w) 0.3, 0.5cm	12.4cm/sec, 5 runs average	22.6cm/sec, 5 runs average

Note: Lees et. al., 1969 found that the flume velocity required to initiate movement of Phymatolithon calcareum from Dunvegan, Skye, was between 38 and 50cm/sec. It is believed that velocities of similar order of magnitude would be required to transport P. calcareum in Iona.

Fig. 16. A hypothetieal process whereby fine-sized sediment accumulates on the central shoals.

A. Degraded sand wave profile after a severe storm.

B. The accumulation of fine-sized sediment into sand waves during calm weather periods when tidal currents are the principal formative agents.
(See also Fig. 27)


10's OF CM.
10's OF M.
degraded sand wave
mixture of
coarse and
fine grains
A

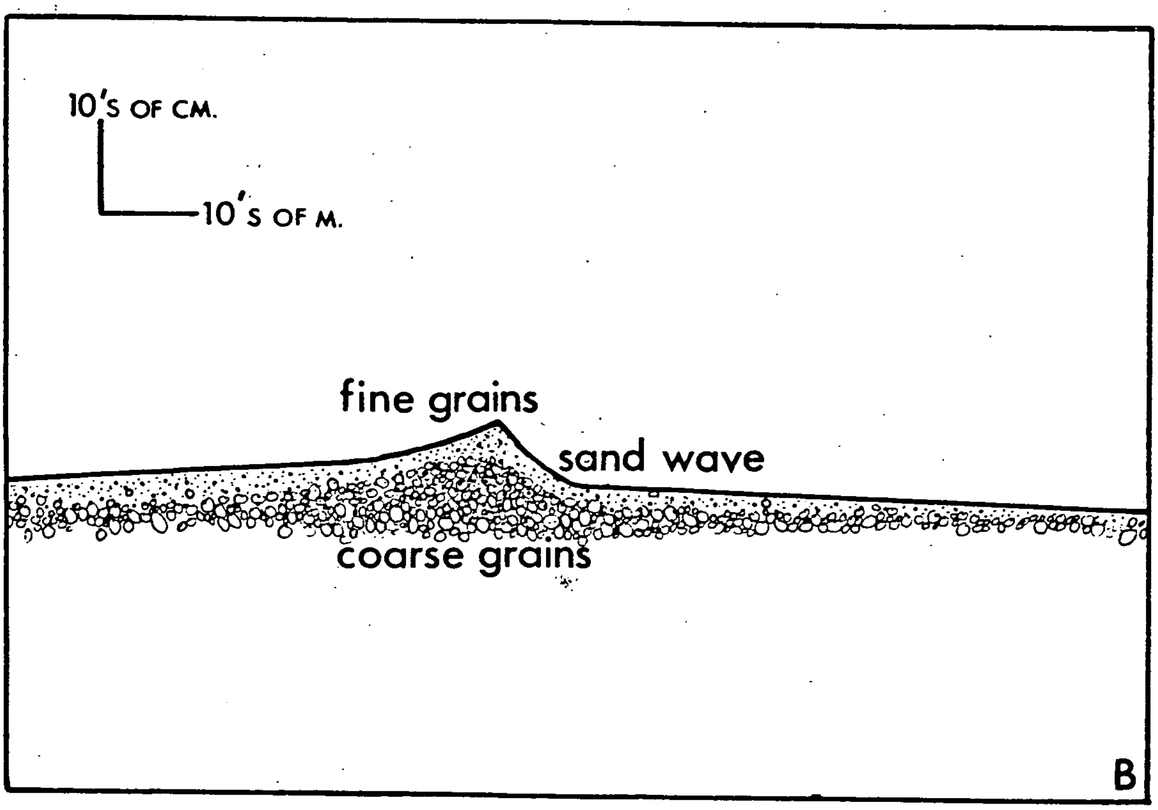
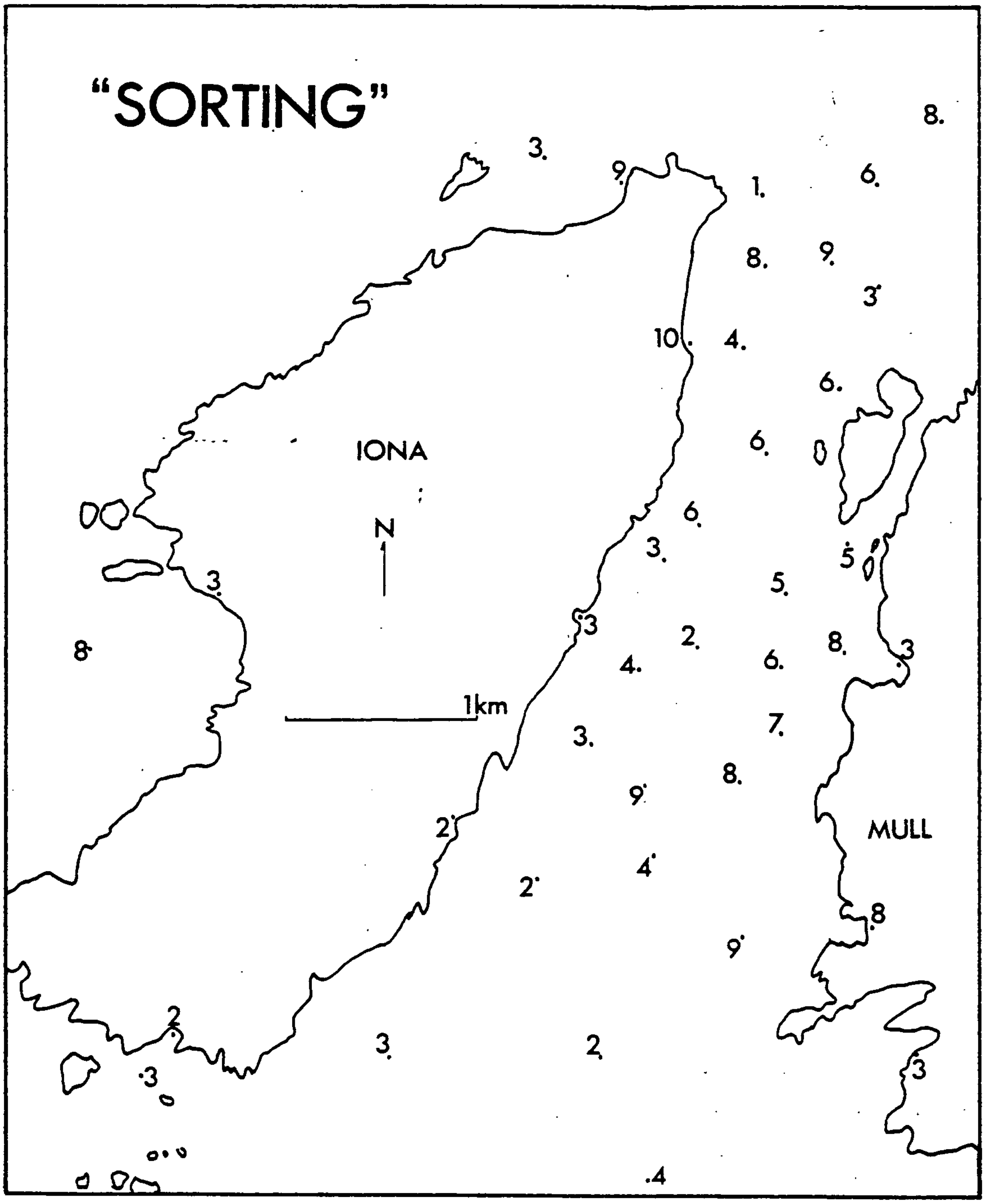

10's OF CM.
10's OF M.
fine grains
sand wave
coarse grains
B

Fig. 17. Sediment "sorting" figures shows the number of size classes for a particular sample as determined by the height sorter. The larger the number the more poorly sorted the sample.


"SORTING"
IONA
N
1km
MULL

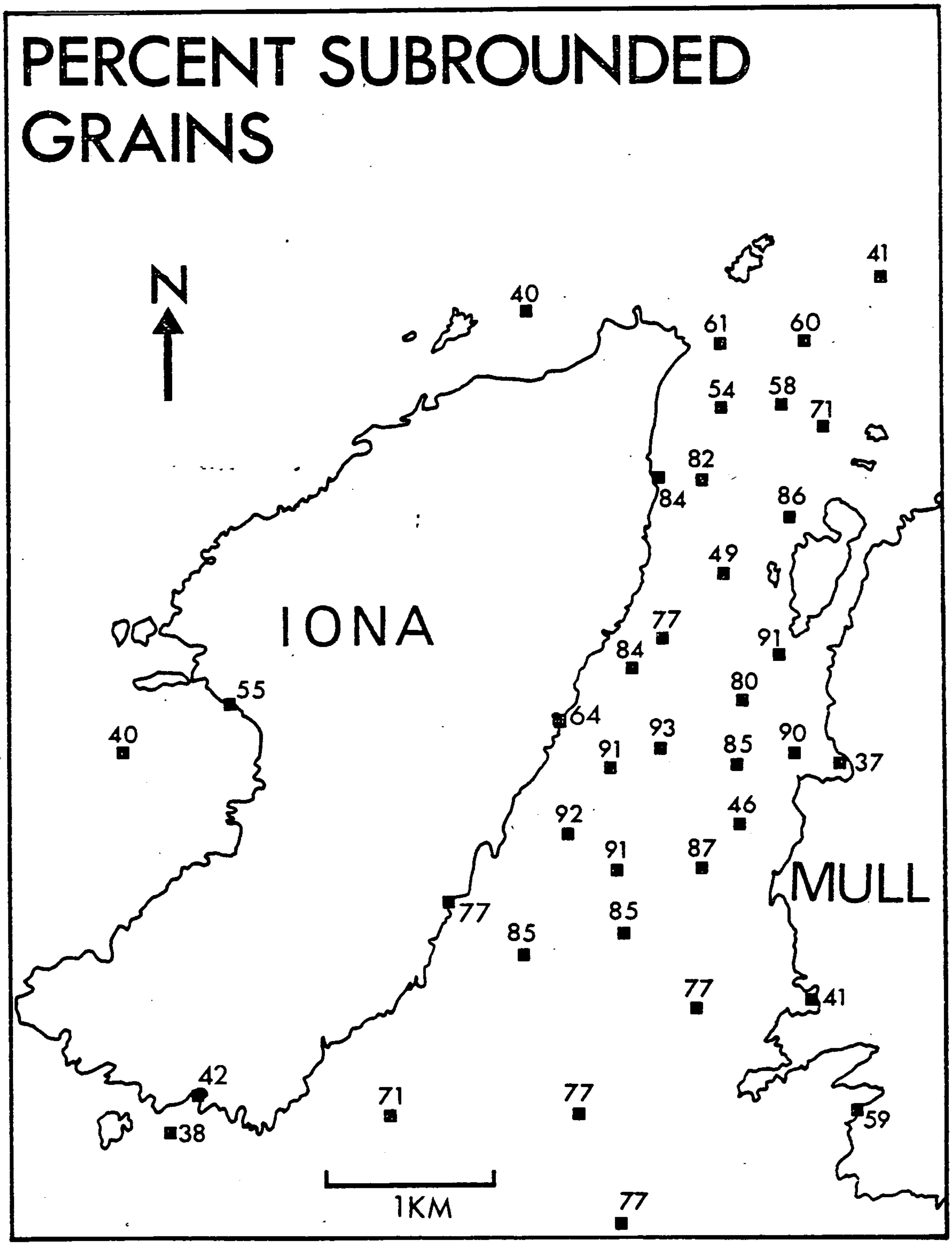
the central shoals would create a preferential selection of the fine sediment sizes, the constantly moving sand would inhibit the colonization by shelled organisms; hence in situ sediment production is minimized. Sediment is derived from the action of powerful tidal currents and sorting is good. The sediment on the southern platform is affected by slower moving tidal currents which could be more conducive to colonization by organisms (Fig. 44), storm wave attack is from the south and shell breakdown would be swift, but constant shell production would prevent it from being complete. Sorting would worsen as compared to the central shallows. There is an abundant shell production associated with the algal bank on the northern platform (Fig. 44). The shelter from wave attack afforded by land and the central shoals (Figs. 30, 44) inhibits skeletal carbonate breakdown, except for shell material lying at the periphery of the maerl and bioclastics derived from the littoral nearshore shoals. This admixture creates a diverse number of size classes and apparent poor sorting. Shore samples have "good sorting" due to the open wave exposure of beaches on the southern part of Iona; the Fionnphort beach sample has its good sorting derived from the sources on the central shoals.

Fine-grained sediment is virtually absent from the Sound save for the interstices of the maerl deposit, here material is washed into the algal network and works its way down among the dead, buried thalli. Elswhere in the Sound the swiftness of the currents prevents the fines from being deposited. It is only in the extreme northern end of the Sound in the deep water areas where a terrigenous mud is found. X-ray analyses (see appendix 2) show the terrigenous fraction is dominated by quartz, feldspars and clays; it also contains 27% by weight low Mg calcite.

Roundness, another parameter indicative of textural maturity was studied in thin-section for 39 stations in the Sound, using the chart comparison technique of Folk (1974). One hundred carbonate and terrigene grains per section were sequentially examined. There was a precaution taken with carbonate grains that only fracture surfaces were studied because of the innate roundness of some grains, e.g. foraminifera. Roundness classes ranged the entire spectrum from the very angular to the very rounded (terms from Folk op. cit.); most of the sediment consisted of sub-rounded grains (Fig. 18). The highest proportions of sub-rounded grains are found on the central shoals due to the strong oscillatory tidal currents. The grains become slightly less rounded on the southern platform; there is a fall-off in the proportion of sub-rounded grains and an increase of sub-angular grains especially near the deep water areas. This drop in rounding values is related to the concomitant drop in tidal current velocity (Fig. 29). The least rounded grains are found on the northern platform to deep water area where currents are weak and hence grains are less frequently moved. Shore stations on the straight eastern coast of Iona have high percentages of sub-rounded grains, this data agrees with the findings of Lovell (1979); this coastline would provide little impedance to the strong nearshore tidal currents. Shore stations on the indented coasts of Iona and the Ross of Mull have low rounding values. The coastal configuration would retard current strength which would thereby inhibit grain rounding.

The size, "sorting" and rounding data are used together to provide an index of grain maturity. The maturity hierarchy based on these parameters is as follows: central shoals > southern platform > shore areas > northern platform. The fine grain size, the small number of height sorter size classes ("good sorting") and the highest proportion of sub-rounded grains indicate that the central shoals have the most intensely worked sediment, i.e. the most mature sediment. The successively

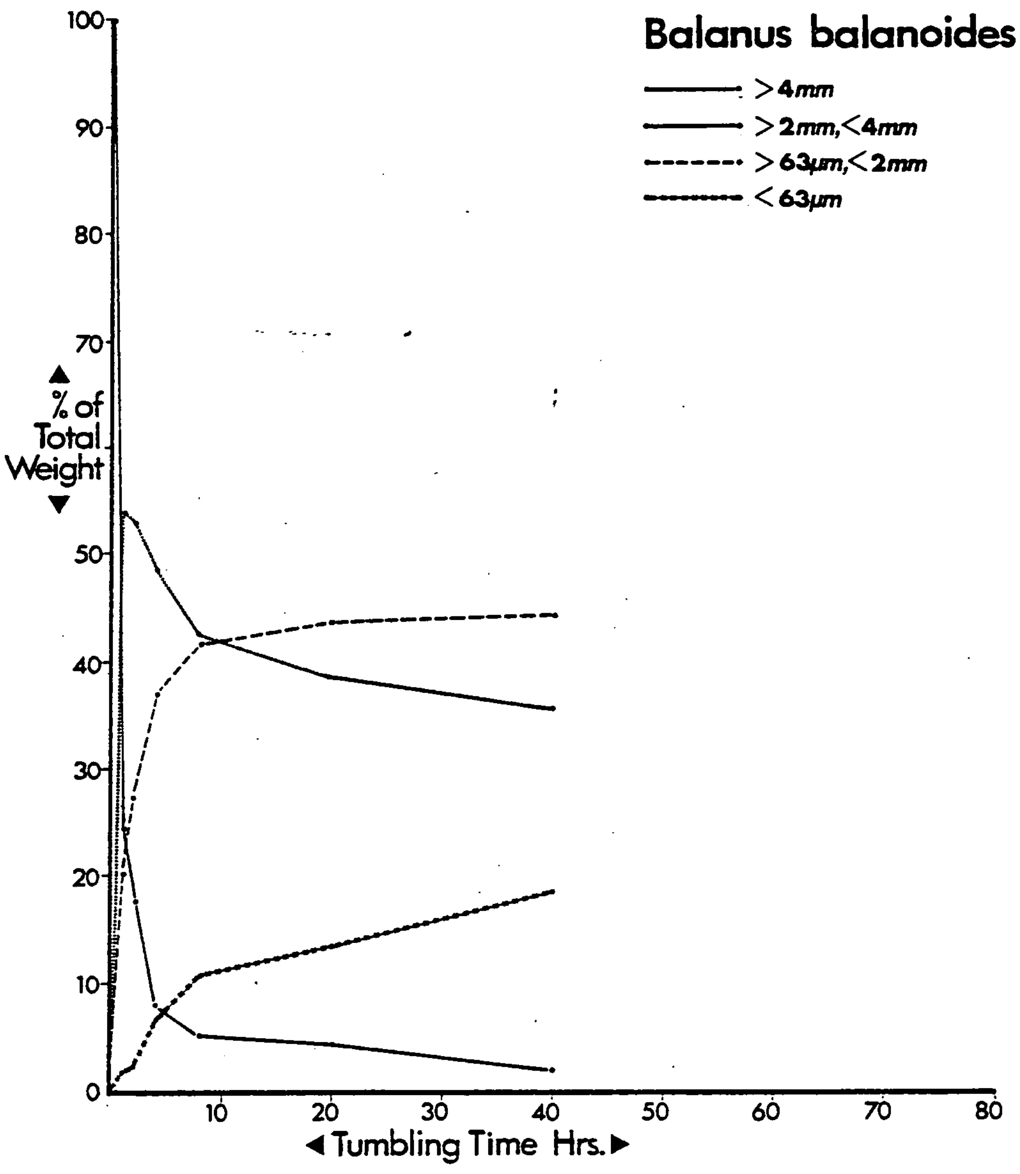
Fig. 18. Roundness values for grains data is shown for the percentage of subrounded grains.


PERCENT SUBROUNDED GRAINS
N
IONA
MULL
1KM
40
41
61
60
54
58
71
82
84
86
49
77
84
91
80
55
40
64
93
91
85
90
37
92
46
91
87
77
85
85
77
41
42
38
71
77
59
77

descending members of the maturity hierarchy reflect a diminution of wave and tidal current energy. Thus the large, whole shells and algal thalli, the "poor sorting" and the general angularity of the grains in the northern platform make this a texturally immature deposit.

A series of experimental shell breakdown studies similar to those described by Chave (1960, 1964) were conducted on whole shell material collected from the Sound. The purpose of the study was to examine rates of shell breakdown and roundness to understand these processes within the Sound. Specimens of the sublittoral alga Phymatolithon calcareum, the eulittoral barnacle Balanus balanoides and the eulittoral gastropods Littorina littoralis and Patella sp. were chosen because they represent a cross-section of dominant organisms and shell types in the Sound. The shells were tumbled wet using a 1:1 mixture of chert pebbles and shells (see appendix 2). The rate of shell breakdown from whole shells to sand-sized sediment is as follows: Balanus (fastest breakdown rate) > Phymatolithon > Patella > Littorina (Figs. 19 A-D). The sequence reflects an increase of skeletal strength from the porous barnacle grains to the massive and compact gastropod shells. The initial small size of the barnacles and the lines of shell weakness caused by the inter-plate sutures would ensure a quick breakdown of the organisms. The high abundance, rapid rate of production (Peterson, 1966) and the tendency to breakdown rapidly to sand-size (but not be pulverised to unidentifiably finer sizes) account for the dominance of barnacles in the Sound sediment. The barnacle shell breakdown sequence is: 1) the sloughing off of tergal and scutal plates; 2) the fracturing of inter-plate sutures; 3) longitudinal and traverse intra-plate fracturing (Fig. 20). An algal thallus fractures first at branch junctions creating a moderately rapid reduction in size from pebble to sand dimensions. Further size reduction occurs by fracturing of branches

Fig. 19 A. Breakdown rate for the barnacle <u>Balanus balanoides</u> by tumble mill experiments.



Balanus balanoides
>4mm
>2mm,<4mm
>63μm,<2mm
<63μm
% of Total Weight
100
90
80
70
50
40
30
20
10
0
10
20
30
40
50
60
70
80
Tumbling Time Hrs.

Fig. 19 B. Breakdown rate for the periwinkle gastropod *Littorina littoralis* by tumble mill experiments.

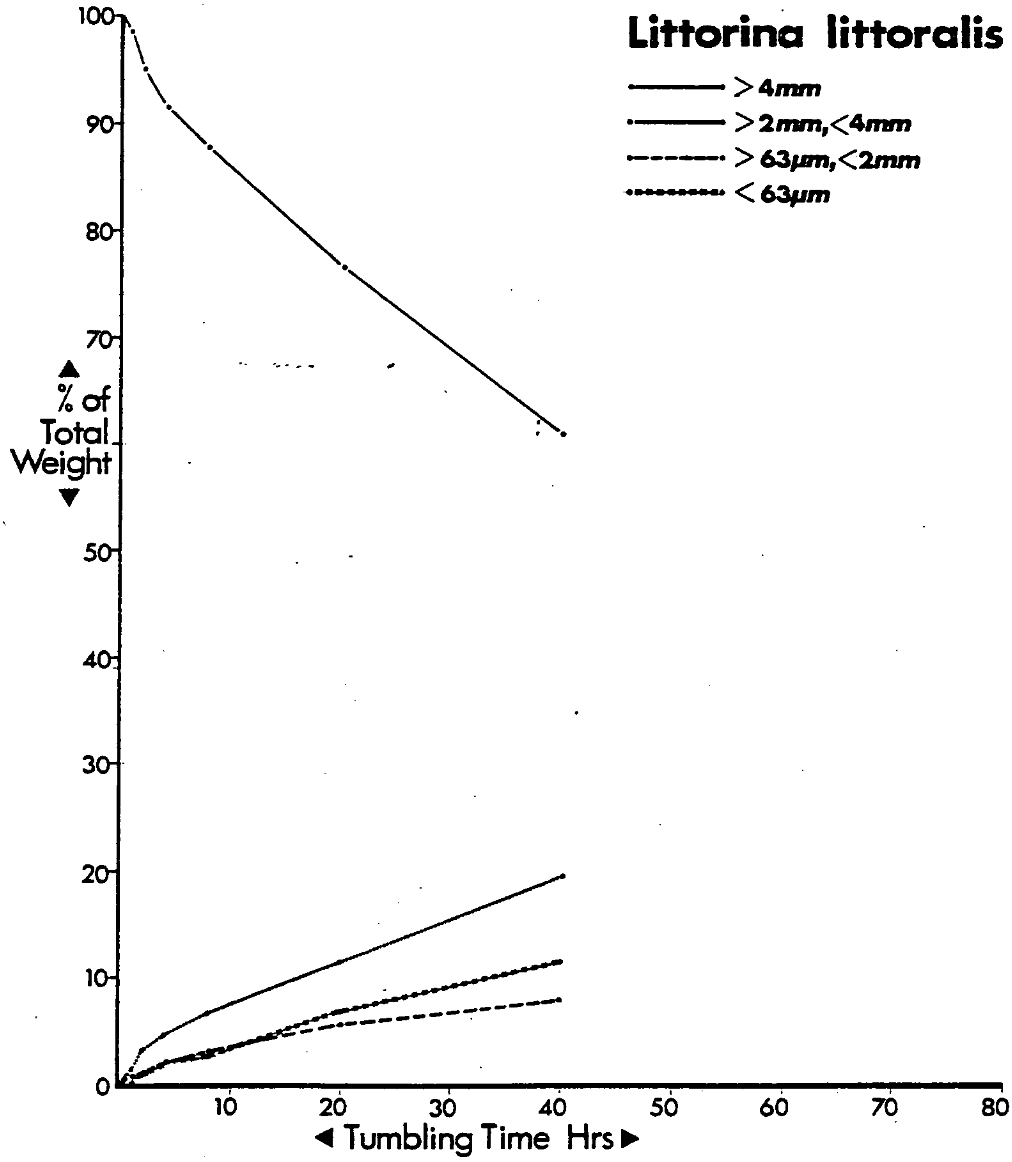
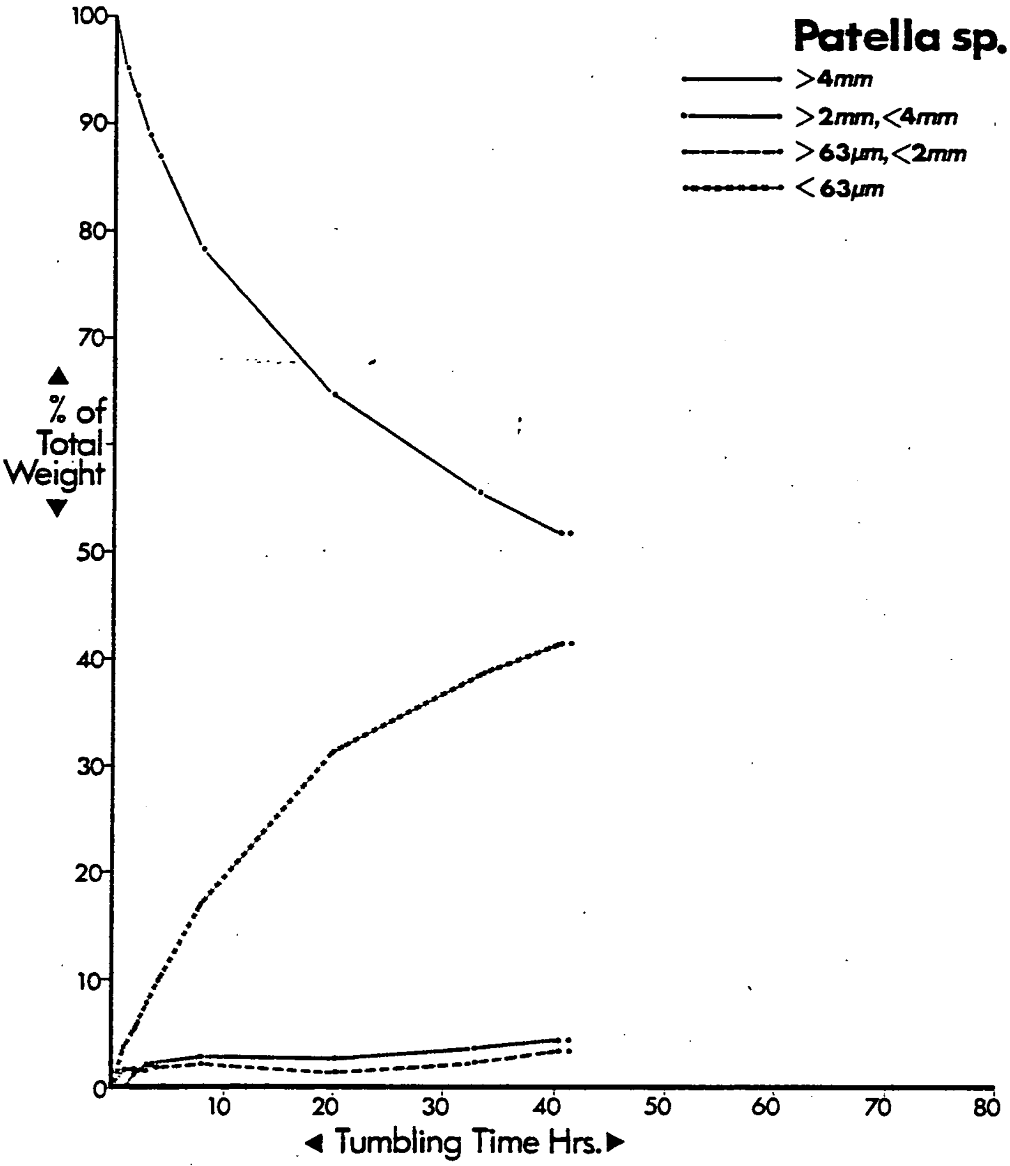

Littorina littoralis
> 4mm
> 2mm, < 4mm
> 63μm, < 2mm
< 63μm
% of Total Weight
Tumbling Time Hrs
0
10
20
30
40
50
60
70
80
90
100

Fig. 19 C. Breakdown rate for the limpet gastropod _Patella_ sp. by tumble mill experiments.



Patella sp.
>4mm
>2mm,<4mm
>63μm,<2mm
<63μm
100
90
80
70
% of Total Weight
50
40
30
20
10
0
10
20
30
40
50
60
70
80
Tumbling Time Hrs.

Fig. 19 D. Breakdown rate for the calcareous alga *Phymatolithon calcareum* by tumble mill experiments.

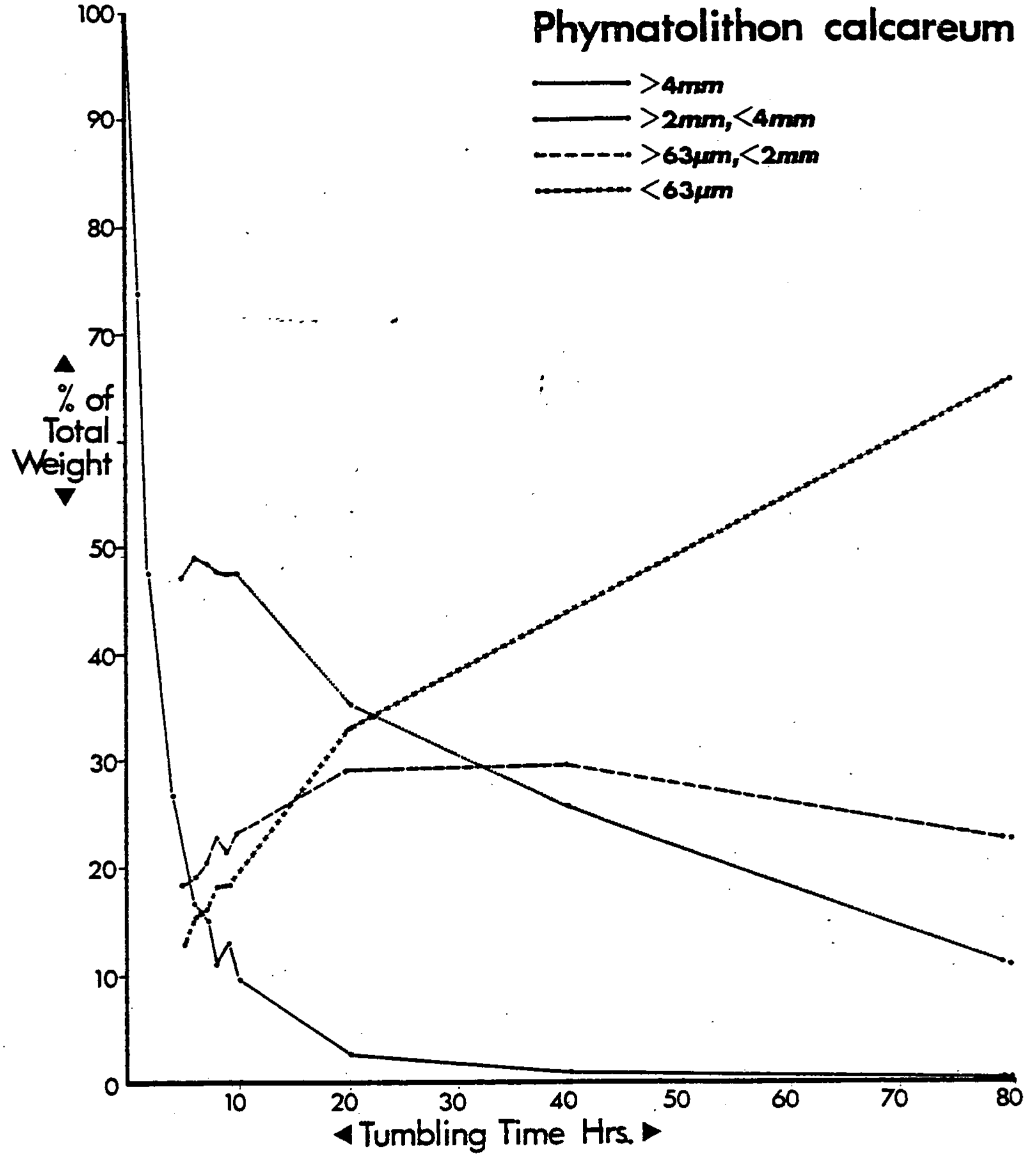
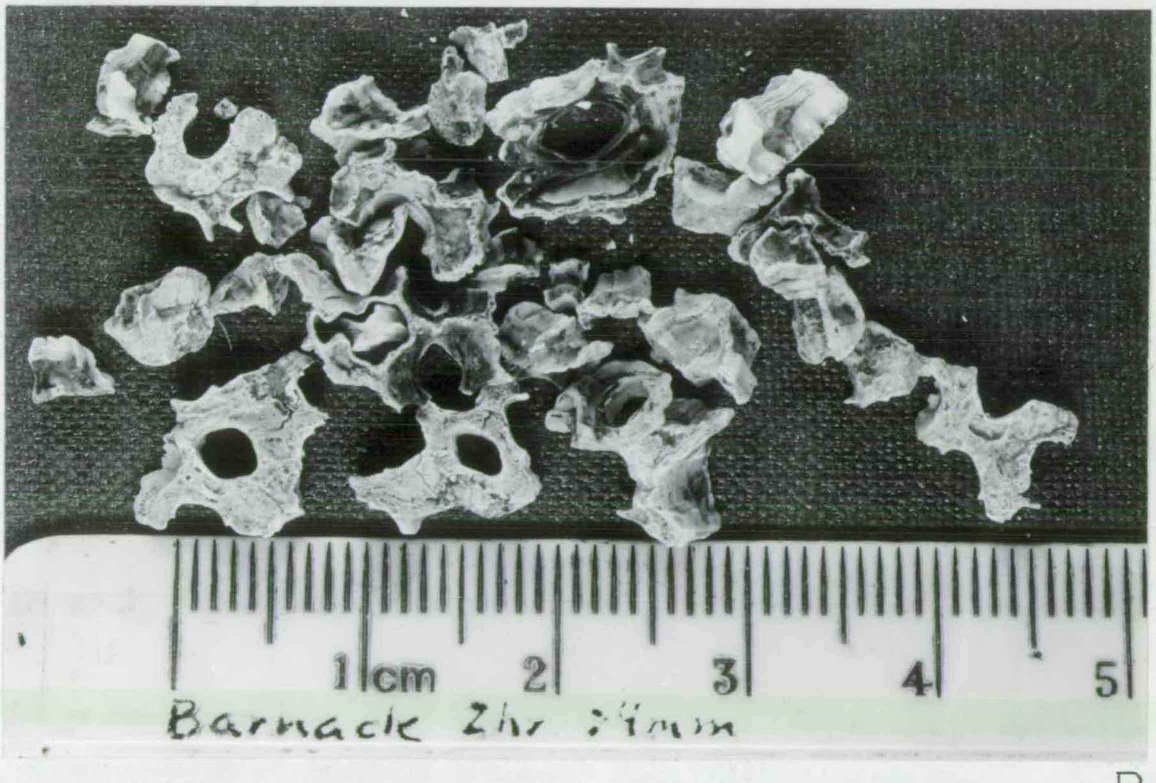

Phymatolithon calcareum
>4mm
>2mm,<4mm
>63µm,<2mm
<63µm
% of Total Weight
100
90
80
70
50
40
30
20
10
0
10
20
30
40
50
60
70
80
Tumbling Time Hrs.

Fig. 20. *Balanus balanoides* breakdown sequence in tumbling experiments.

A. Whole shells > 4 mm at the start of the run, note tergal and scutal plates are absent.

B. Shells >4 mm after 2 hours of tumbling, note that the breakage has occurred between shell plates.

A



B

Fig. 20 C. B. balanoides shell material between 2 mm and 4 mm size, note shell material has examples of breakage within a shell plate.

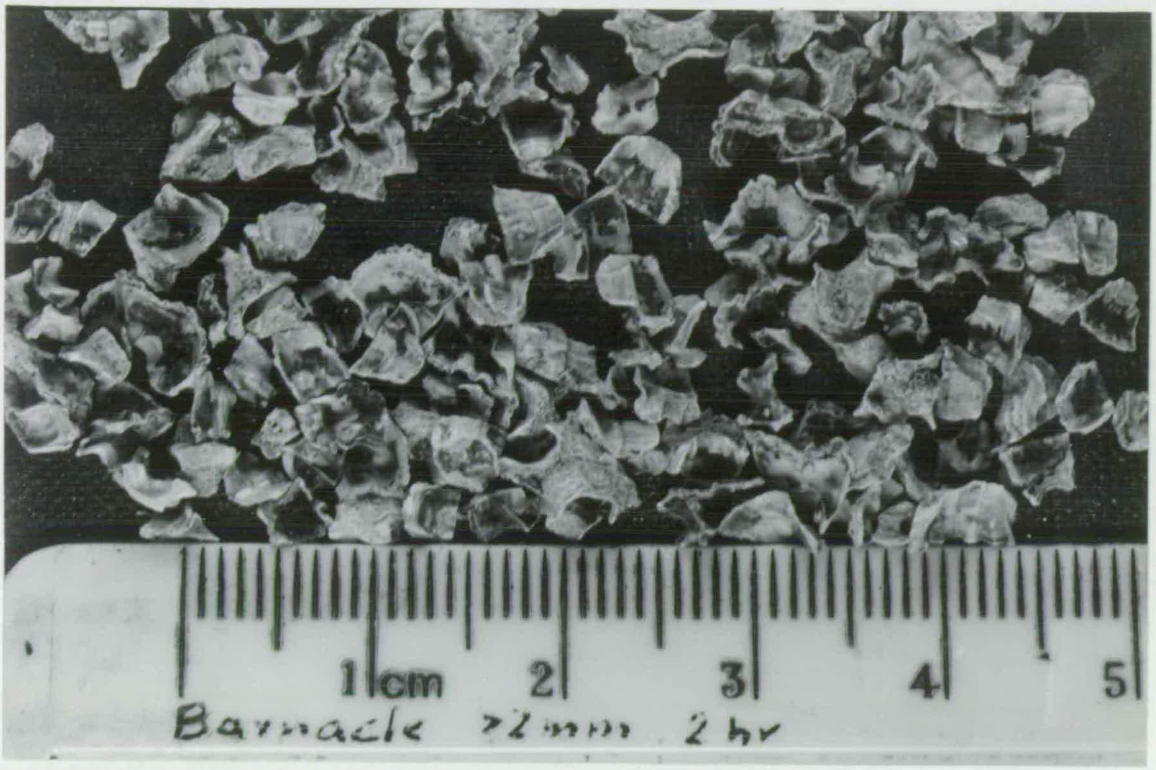
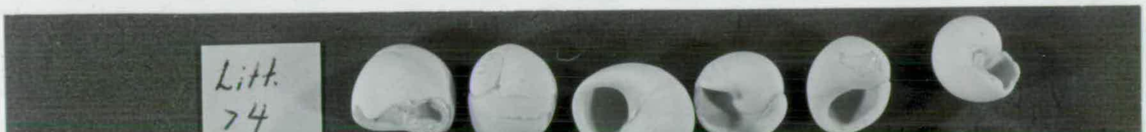

1 cm 2 3 4 5
Barnacle >2mm 2 hr

Fig. 21 A. *Littorina littoralis* after 1 hr of tumbling time, the massive shells will resist breakage for much of the run.

B. Even after 40 hours of tumbling some *L. littoralis* shells are still whole.


1 cm 2 3 4 5 6

A


Litt.
74
40 hr.
0 90 100 110 120 130 140 150 160 170 180 190 200 210

B

Fig. 22. *Patella* sp. after 8 hours of tumbling; these massive shells will also be resistant to abrasion during the entire run; points of weakness are the shell apex and places where boring has occurred.

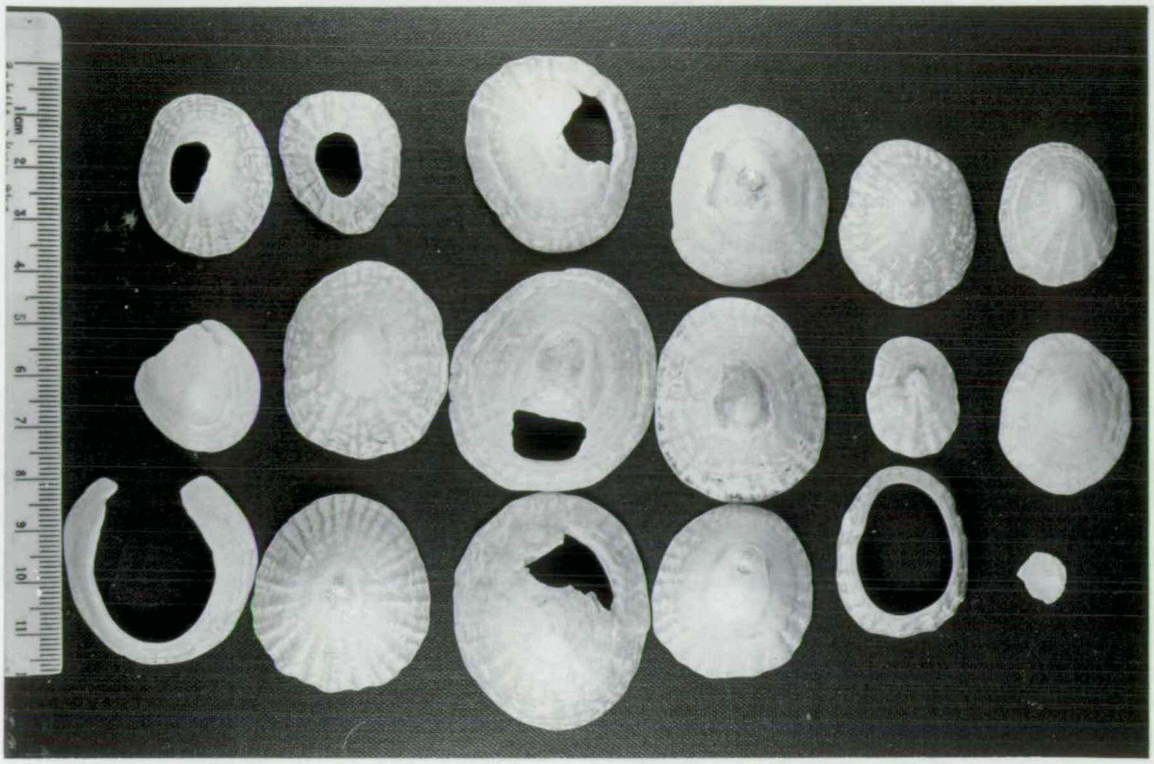
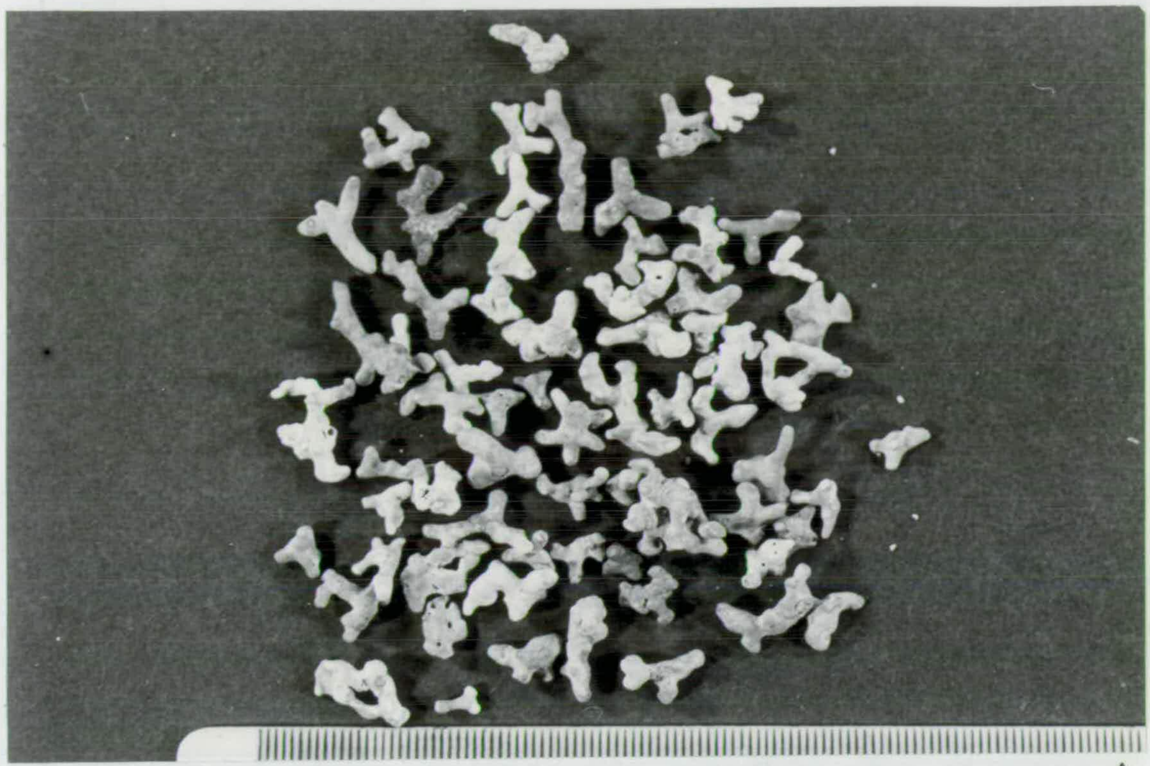
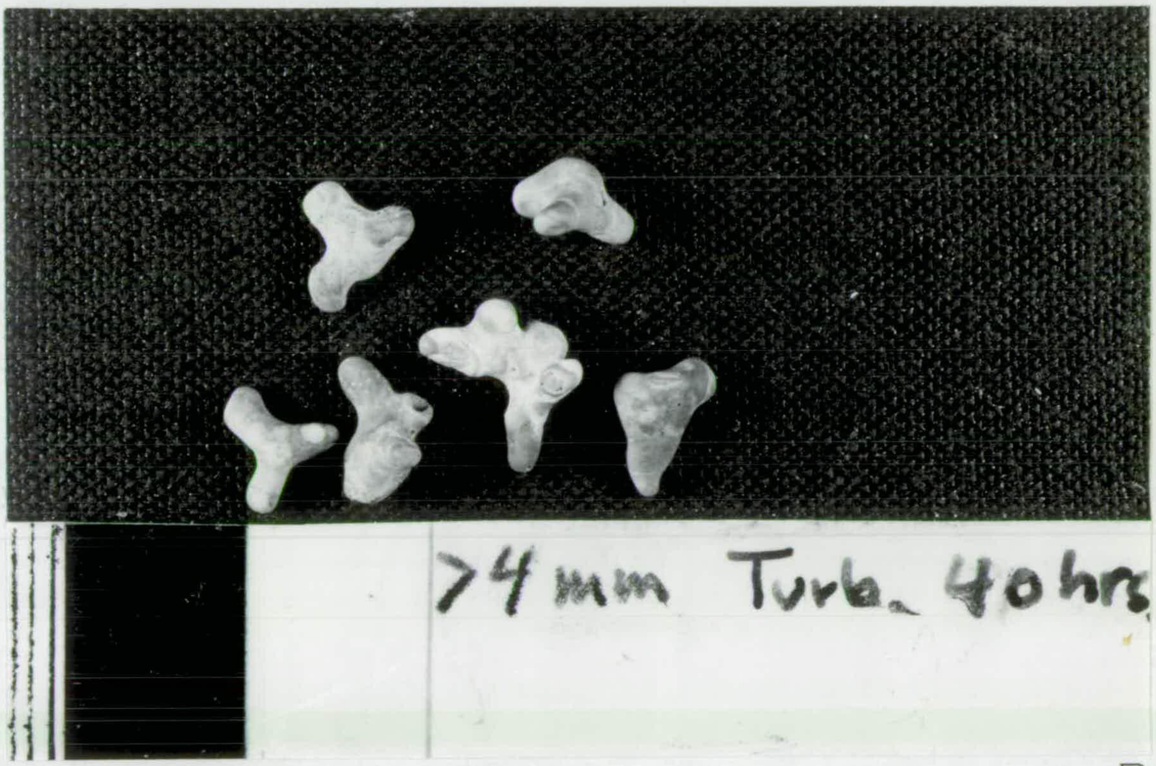

1cm 2 3 4 5 6 7 8 9 10 11

Fig. 23 A. Phymatolithon calcareum after several hours grinding, note central ring in several thalli is preserved and is resistant to attack.

B. P. calcareum after 40 hours of tumbling, grains are very rounded and growth bands are observed. Their appearance is very similar to coralline P. calcareum observed in a suction core (Fig. 33).

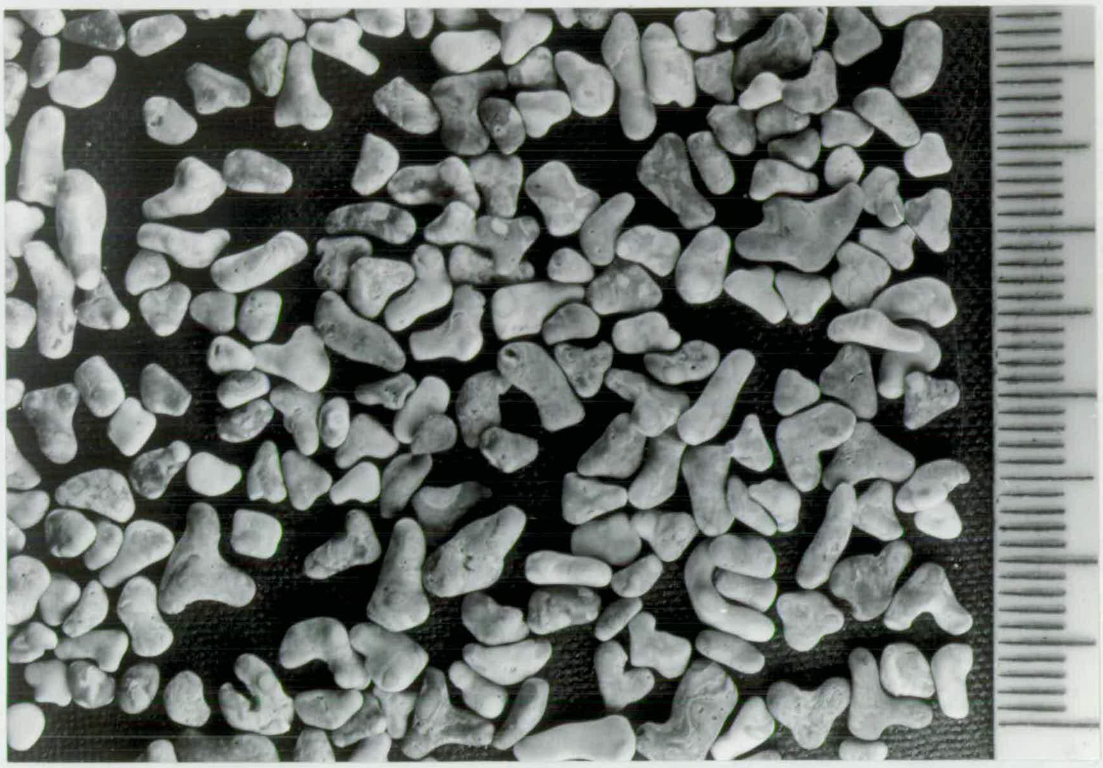


A



B

Fig. 23 C. P. calcareum grains after 80 hours of tumbling. Size between 2 and 4 mm and their roundness is very similar to grains in Iona's sediment (c.f. thin sections Fig. 12).



perpendicular to the branch axis and parallel to growth layers (Fig. 23). Gastropod breakdown occurs at shell margins and apices (Figs. 21, 22) borings in the shell also afford points of weakness for subsequent abrasional attack. The thickness of the mollusc shells and the lack of sutures compared to the barnacles and algae ensures the slow break-up of this material. The retarded rate of mollusc breakdown combined with the low rate of production of the organisms (e.g. 3-15 yrs for Patella (Fretter and Graham, 1962)) explains the subordination of this group to barnacle material. The molluscs on the other hand show a breakdown process that results rapidly in production of $<63 \mu m$ material (Fig.19B,C) which is not recognized in the Sound sediment samples. This in combination with their slow rate of production and relatively low living abundance, account for the subordinate position in the component analyses of the Sound's sediment.

Roundness of these shells occurs in a different sequence than breakdown: Phymatolithon (most rounded) > Patella > Littorina > Balanus. The sequence reflects the shell susceptibility to abrasion. The alga and gastropods abrade easily, in the process creating much fine grain sediment, $< 63 \mu m$. The algae are especially vulnerable to rounding because of the particulate nature of the thallus whereby abrasional sediment could occur along lines of intercellular sutures (c.f.Wray,1977). This finding is similar to that of Folk and Robles (1964) for hermatypic corals. The massive structure of the mollusc is resistant to fracture so the energy of grain to grain contact is converted to abrasion and concomitent rounding of grains and the production of carbonate mud. Barnacles do not round quickly because the relatively fragile shell responds to grain contact by fracturing rather than abrading. Barnacle sediment dominates in the Sound but carbonate mud would only be produced slowly from shell abrasion. This may explain why so little carbonate mud found near the Sound, e.g. 27% by weight, is contained in the analysis of an I.G.S. core SH69V from deep water areas north of the Sound (the low Mg calcite content of the core, identical to the barnacle mineralogy, suggests that barnacles are the source).

3.8.4 Bedforms.

Bedforms were studied with a view to: 1) obtain information on sediment transport, and 2) to combine grain-size and bedform data so as to delineate facies in the Sound. Bedforms were studied using multiple techniques because of the extreme ranges of sizes of bedforms: historical maps, Ordnance Survey aerial photographs, scuba observations, underwater television, side-scan and vertical sonar (for a description of the electronic devices see appendix 2). Bedform data was compiled into Table 9. Ripples dominate in the southern platform and littoral-nearshore shoals; these bedforms are due to tidal currents and the degree of asymmetry reflects the strength and duration of the tide at the time of observation. Laminarian algal cover found in the littoral and nearshore areas would trap and bind sediment and prevent bedform formation (Fig.24). Strong wave action in both these areas destroys or prevents the building of larger bedforms. A smaller wave force from the south is expended on the southern margin of the central shoals. The shoaling of the seabed from the southern platform to the central shoals cause the acceleration of northward flowing flood tidal currents sculpting a hierarchy of bedforms from ripples to sandwaves. A deflection to the north caused by the partial blockage of stream lines by the small island Eilean nam Ban, cause an acceleration of the current on the flood tide (Fig. 29); sediment is derived from central shoals and is transported northwards into deeper water via a sand ribbon (Fig.24). A widening and deepening of the Sound on the northern platform causes a drop of flood tidal velocity (Fig. 29). Wave shelter provided by

Table 9. Summary of bedforms in the Sound of Iona.

λ = wavelength; H = height; as = asymmetrical + compass facing direction of steep side if known; sy = symmetrical.

Bathymetric tract	Figs.	Type of bedform and shape data	Type of observation	Comment
southern platform		ripples: λ = few cm to > 30cm; H ≤ 8cm; as; sy.	Diver's	ripples predominate over most of the southern platform. P. calcareum found in troughs of ripples, fine sed. in crests.
		megaripples: from 90cm; H ≤ 15cm as(S) to λ = < 30m H ≤ 90cm as (S)	Diver's	sandwaves and megaripples are found near central shoals.
		sandwave: λ = 150m-270m; H1m; as(S); sy.	Diver's; aerial photographs, echo sounders.	
central shoals		ripples: λ = 8cm to megaripples H : 5cm or more	Diver's	sandwaves and megaripples on N. side of the central shoals have a steep N. face; these structures on the S. side of the central shoals have a steep S. face. Sandwave crests bifurcate to the east and are truncated at channels. Folk (1976) describes bifurcations to lateral deterioration of hydraulic rollers.
		megaripples: λ = 1.5-13m H : 23cm or more as (N.and S.)	Diver's; aerial photographs, echo sounders.	
		sandwave: λ = 40-300m H : 2m or more as (N.and S.)	Aerial photographs, echo sounders.	
northern platform		Non-maerl sediment:		
		megaripples: λ = 0.9-21m; H = 0.2- > 1m, sy, as(N.and S.)	Diver's; aerial photographs, echo sounders.	
		sandwaves: λ = 34-150m; H = 1-3m; as (N. and S.)	Diver's; aerial photographs; echo sounders.	the largest sandwaves and the sand ribbon are located adjacent to the central shoals.
		sandribbon: width 380m (central shoals); H = 3-4m (central shoals); width narrows to 85m on N. platform where relief merges with local bed roughness	aerial photographs; bathymetric maps.	
		Maerl sediment:		
		megaripples: λ = 0.9-4m; H = 30-50cm; sy; as (N. and S.)	Diver's	Bedforms made of living and dead Phymatolithon calcareum
nearshore and littoral shoals		small ripples (several cm λ and H)	Diver's	extensive cover of laminarian kelps retard bed transport and ripple formation
		megaripples: occasionally observed e.g. adjacent to central shoals. λ = 1.5 H = 23cm.	Diver's	
Other Areas: western platform		Abundant rock and boulder cover indicates lack of sediment for large bedform development. Aerial photographs show extensive dense algal cover occasionally broken by large (≥ 280cm wide) patches barren except for sediment cover.	Divers; aerial photographs; echo sounder.	

Fig. 24 A. Aerial photograph by the U.K. Ordnance survey, 1946.

B = bifurcations
C = channels
GS = glacial striae
L = laminarians
MR = megaripples
SW = sand waves
SR = sand ribbon.

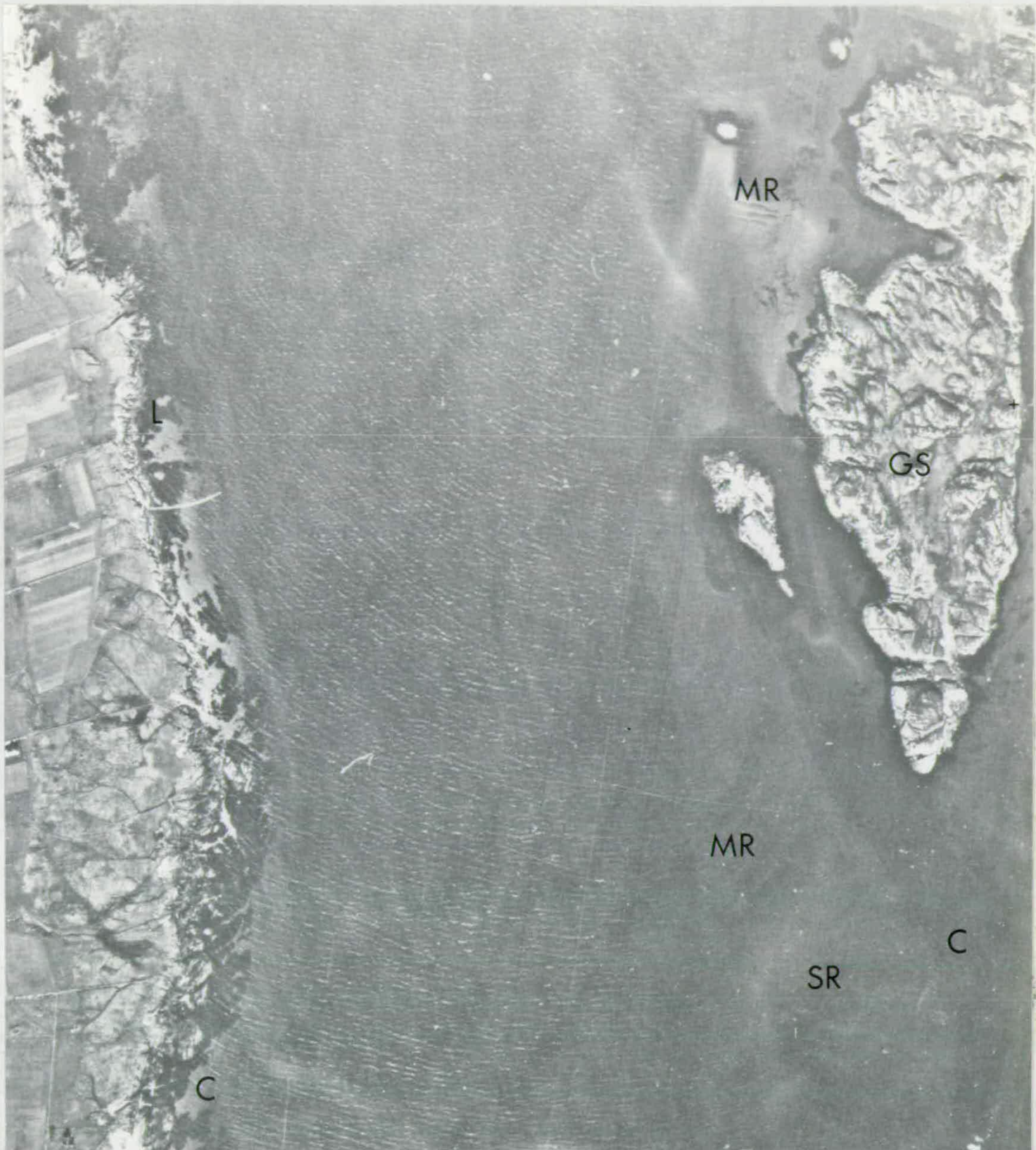

MR
L
GS
MR
C
SR
C
B
B
SW
L

Fig. 24 B. The Sound of Iona 1972, symbols as 24A.

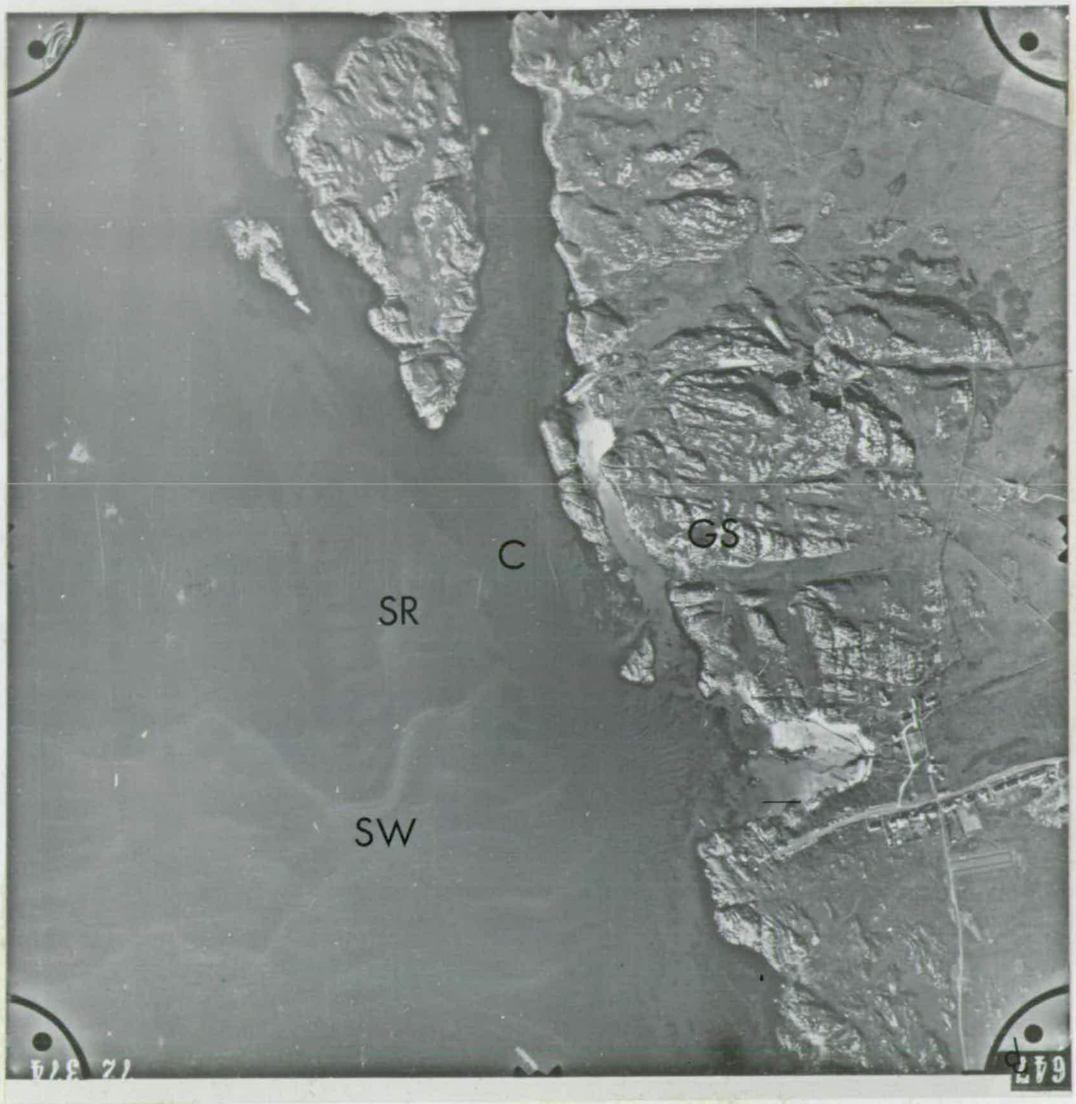
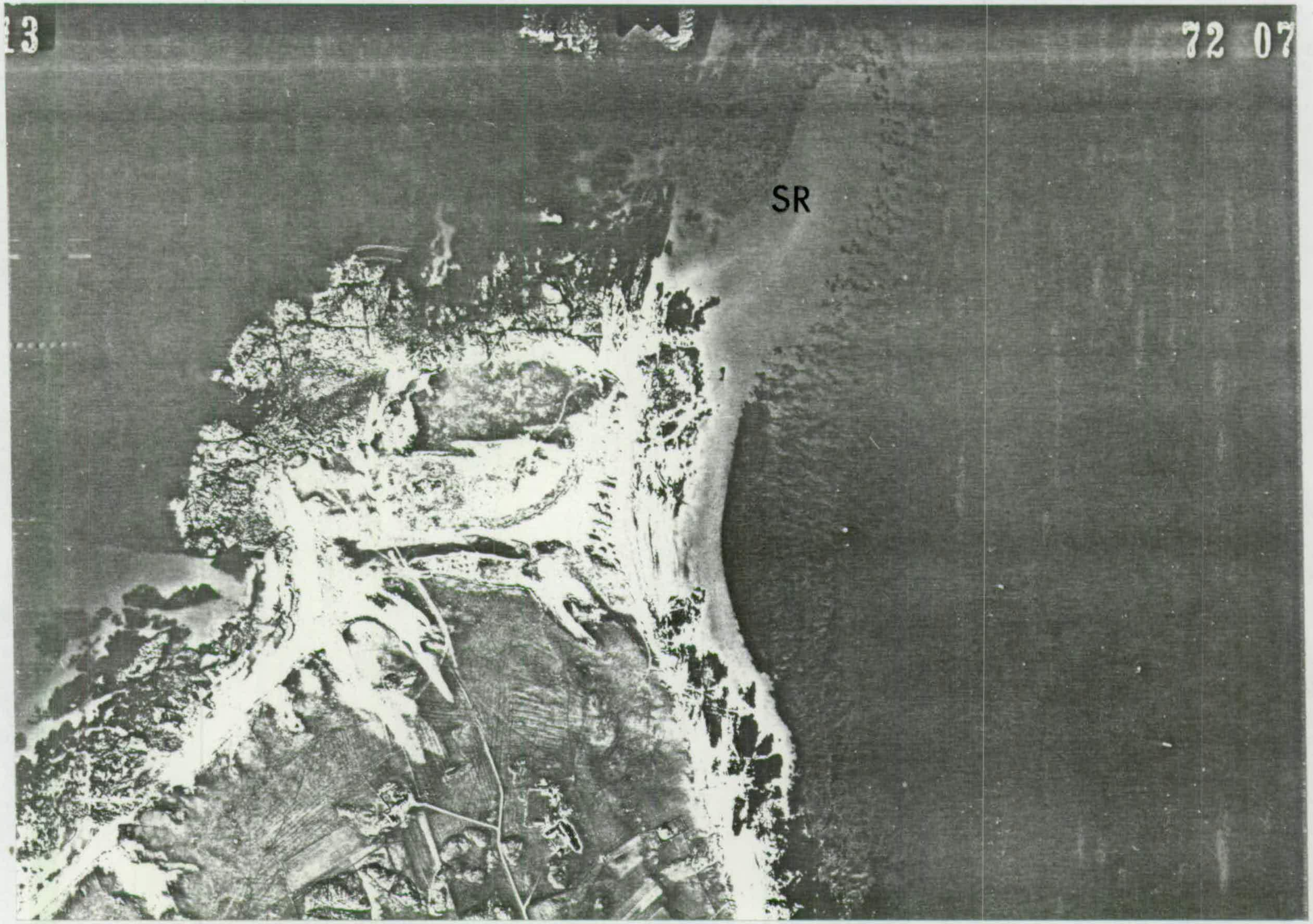

C
SR
SW
GS

Fig. 24 C. The N. Sound of Iona, 1972.

Note sand ribbon (SR) formed by current acceleration following its deflection by small islands just visible at the top edge of the photograph.


13
72 07
SR

Iona island, the central shoals, and the Ross of Mull, leaves this area responsive only to the short-fetch waves from the north. Bedforms present are ripples and megaripples. Ripples are formed by tidal currents and small waves. Megaripples are found in the Phymatolithon deposits (Fig. 25) and further east near Eilean nam Ban. Repeated diving observations on the pure Phymatolithon megaripples show that they are not in motion on tidal currents; velocity profile measurements (Fig. 34) show that the seabed velocities are not competent to move the sediment; the maerl megaripples are destroyed during storms of Force 7 winds. It is likely that the Phymatolithon megaripples are formed by wind-generated waves of less than Force 7 magnitude, as suggested by Lees et al. (1969). This may especially be true when the wind direction coincides with the tidal direction.

Bedforms of the western platform consist of ripples interspersed between extensive beds of cobbles and boulders, and extensive laminarian seaweed cover. The weed cover would have a similar function to that found in the Sound and would diminish wave and tidal current effects as well as trapping and binding sediment. Bedforms in the deep water areas are largely unknown. Side-scan and vertical sonar traces show extensive rock cover broken by occasional sediment patches especially in the western and southern areas. This is the result of the exposure of these areas to the storm waves which derives from the south and west, which would inhibit colonization by sediment producing organisms. Sediment cover is more pervasive in the deep water areas north of the Sound; fine-grained terrigenous sediment was observed on underwater television with small crater-like depressions possibly the result of burrowing. The presence of the material attests to the low energy environment.

In summary, bedforms are best developed in wave sheltered shallow

Fig. 25. Megaripples composed of P. calcareum formed in the maerl area at station H12. Knife is approximately 25 cm long (c.f. Fig. 10 C.).

water high velocity current areas where there is abundant sediment available; thus the central shoals and the juxtaposed northern and southern platform areas have a hierarchy of transverse bedforms. Where currents become very swift, as on the central shoals, longitudinal bedforms, sand ribbons, are formed. High energy wave activity on the southern platform near deep water areas, on the western platform and the adjacent deep water areas would disrupt bedforms.

3.8.5 Time stability of bedforms.

Historical maps dating back to 1756 show that the sand wave field (i.e. the seabed area encompassing the sandwaves) located on the central shoals has remained apparently stationary throughout this period (Fig. 26). Aerial photographs taken in April and May, 1946, and again in 1972 reveal that general features of the sand waves and sand ribbon pattern remain unchanged although with some variation, there is an enhanced curvature of the northern sand wave face adjacent to the sand ribbon, from the 1946 to 1972 photographs. Megaripples superimposed on the sand waves and sand ribbons have, however, altered position in the 1972 photographs (Fig.24).

While no change in megaripples symmetry or position was actually observed by divers, it is likely that they slowly shift position of central shoals by gradual tidal sediment transport (Reineck and Singh, 1975) and they alter position during periods when wind-generated waves are coincident in direction with the tidal flow, especially a strong spring tide (J.O. Malcolm, IOS(T), pers.comm.,1979). Ripples and small megaripples on the central shoals were observed to change by tidal and wave action (Fig.27). Seabed geometry and bedform information is summarized in Table 10.

Fig. 26. Mackenzie's 1756 bathymetric survey of the Sound.

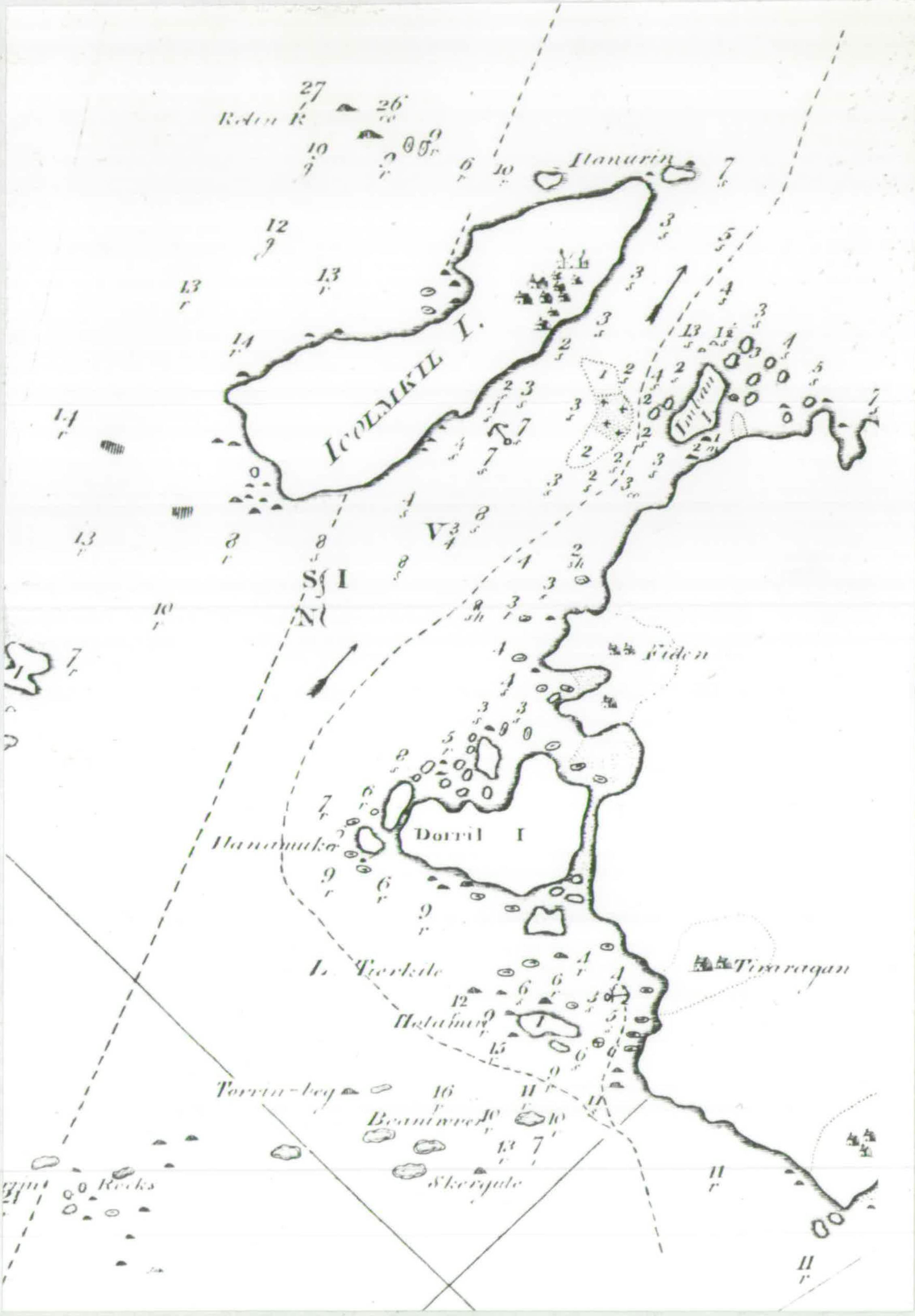

ICOLMKIL I.
Fiden
Dorril I
Rocks

Fig. 27. Suction core showing cross-bedding resulting from oscillatory flood and ebb tides (central shoals). Fine sand occurs at the top of the core, coarser sand towards the bottom.

Top

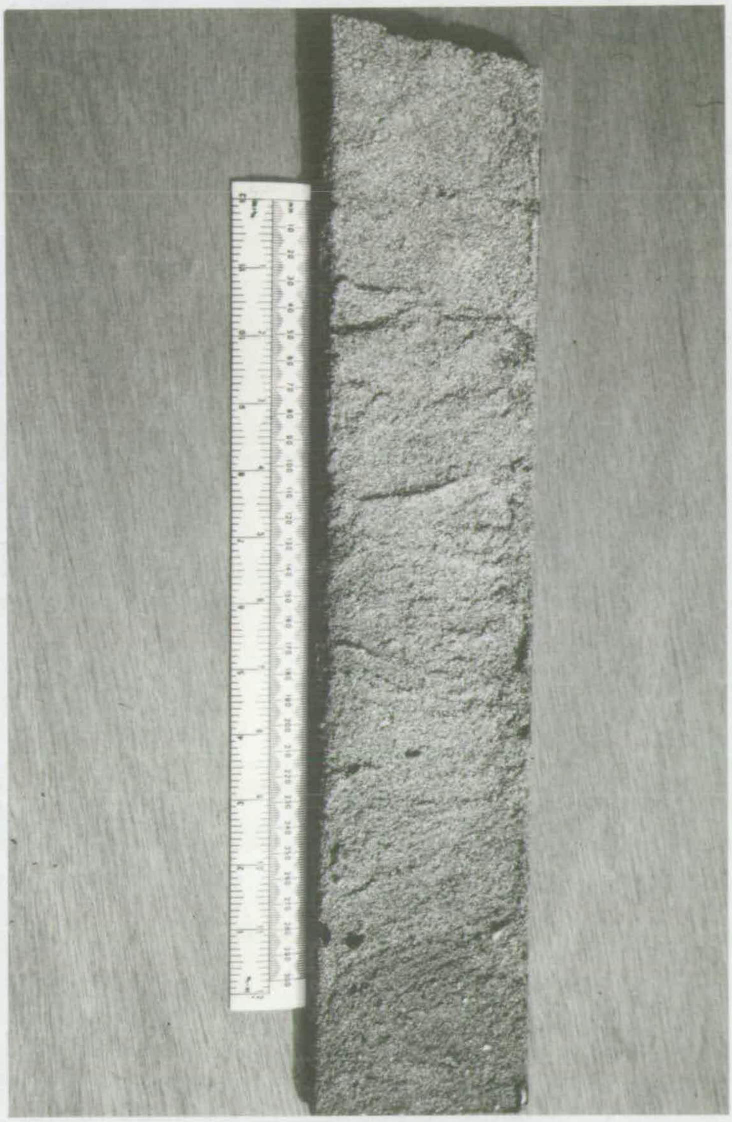


Table 10. Summary of bedform stability times and formative agents.

Type	Period of stability	Evidence	Formative agents
Sand wave field	centuries	historical maps	not known, possibly related to the shallow bathymetry created by relict glacial drift.
Sand waves	decades to centuries	historical maps and aerial photographs	tidal currents working in conjunction with wind-generated waves (Channon and Hamilton, 1976; J. Malcolm, personal communication, 1979).
Sand ribbons	decades to centuries	aerial photographs	high velocity tidal currents (Kenyon and Stride, 1970).
Large megaripples	years (≤decade?)	aerial photographs	tidal currents (Houbolt, 1968), wind-generated waves of less than storm strength (inferred from Malcolm, op. cit.).
Small megaripples (Phymatolithon gravel)	months (seasonal)	diving observations	waves generated by winds < storm strength.
Small megaripples (cirripede-rich sand)	months to days	diving observations	tidal current or small waves or both.
Ripples	minutes to days	diving observations	tidal current or small waves or both.

3.8.6 Facies.[1]

Facies in the Sound are characterized by consistent associations of sediment composition, bedforms and biota (Fig. 28).

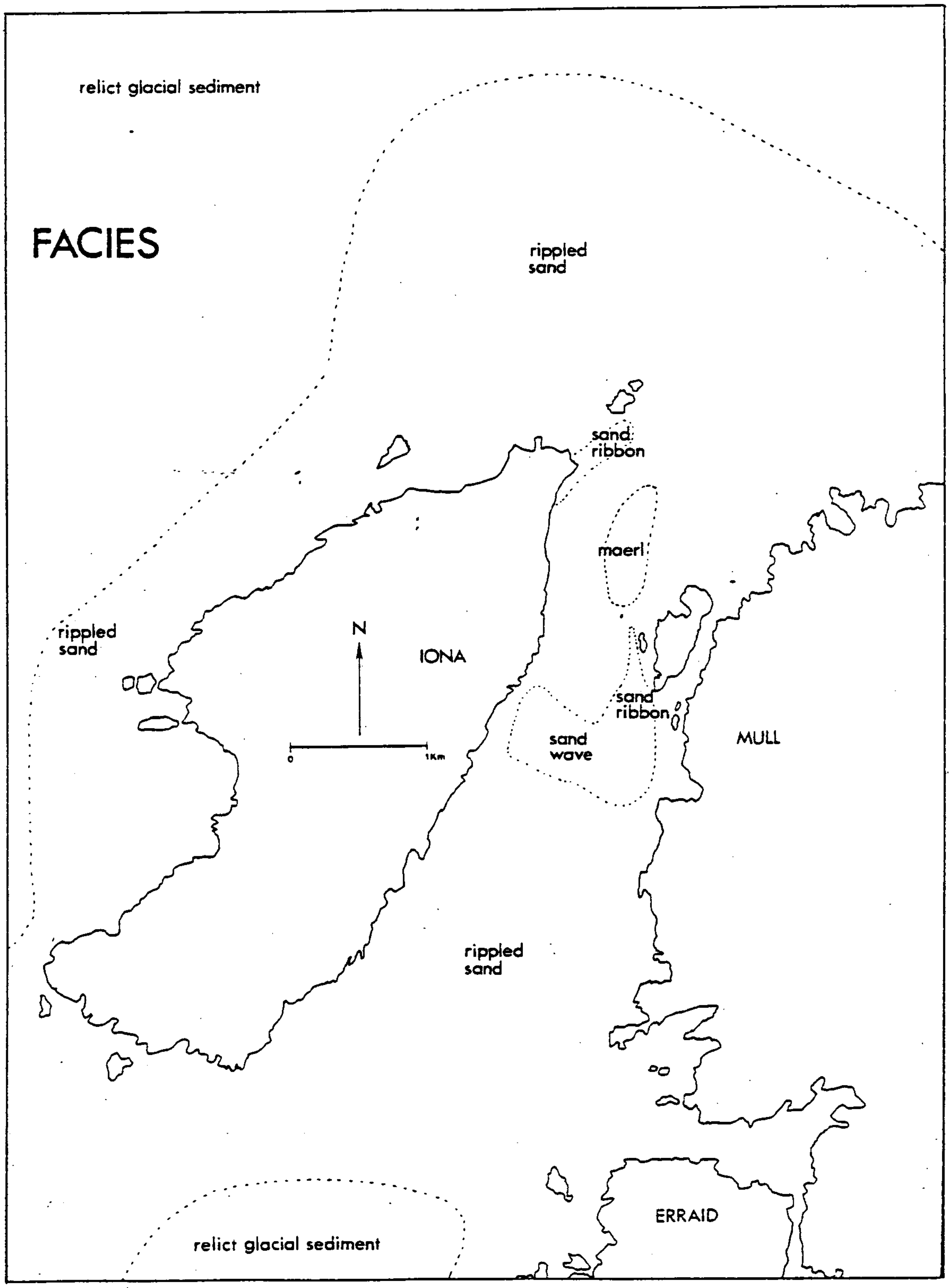
1. Boulder and cobble facies. This is a relict sediment from past glacial activity in the Sound; it represents a glacial drift deposit from which muddy material has been removed. The large-sized material has been left behind as a coarse sediment lag. Boulder areas are found in the deeper water areas extending in a belt-like tract around the periphery of Iona. Dredge samples show that the dominant organisms are encrusting barnacles, algae, serpulid worms and bryzoa. Brittle stars Ophiothrix and Ophiocomina may be locally abundant on boulder surfaces.

2. Rippled sand facies covering the southern platform, the nearshore shoals around the islands, the inshore area of the western platform, and the extreme northern portion of the northern platform. This is the most extensive facies in the Sound. The facies consists of rippled medium sized biogenic carbonate sand. The sand is well washed and lacks mud. Living shelled organisms are sparse on the southern platform but include the burrowing molluscs Glycymeris glycymeris and Spisula sp. Living organisms are much more abundant on the wave sheltered, low velocity current area of the northern platform, where common molluscs include Aporrhais pespelecani, Arctica islandica, Cochlodesma praetenne, Cultellus pellucidus, Dosinia exoleta, Lucinoma borealis and Venus sp. Laminarian weed and seagrasses grow at the margin of this facia, near the shore, forming an important wave-baffle and sediment binding agent.

3. Sandwave and sand ribbon facies occupies the central shoals area of the Sound. The sediment is a medium to fine sized biogenic sand which has been sculpted by waves and currents into a hierarchy of bedforms

[1] Fauna of this and succeeding sections were identified by B.J. Brown

Fig. 28. Sedimentary facies in the Sound of Iona.


relict glacial sediment
FACIES
rippled
sand
sand
ribbon
maerl
rippled
sand
N
IONA
0
1Km
sand
ribbon
sand
wave
MULL
rippled
sand
ERRAID
relict glacial sediment

varying from ripples to megaripples and sand waves. These bedforms are symmetrical or asymetrical in profile. The sediment, which lacks mud, supports a very sparce fauna in this current-swept area where substrate is mobile.

4. Maerl (algal) facies is dominated by living, or dead, or both living and dead thalli of Phymatolithon calcareum. There is an abundant associated benthic shell fauna, principally of the burrowing bivalves Dosinia, Glycymeris and Venus. These shells may be incorporated as a living infauna in the megaripples formed of the alga. The algal thalli are closely-spaced with their branches interlocked to form a compact skeletal network. The sediment is gravel-sized or larger due to the elongate algal thalli; but fine sand and mud is found a few centimetres into the thalli network, beneath the well-washed surface of the mearl.

A final terrigene mud facies may be of limited extent as it has been observed only from an I.G.S. borehole SH69V and a nearby underwater television station. It consists of terrigene rich mud. There is some evidence of burrowing from the crater-like seabed depressions observed in the video pictures. Phytoplankton analyses of the core showed an abundant Spiniferites and Peridinium flora identical to that found in the present-day, indicating the flora in the core sediment was deposited in Recent times (R. Harlan, I.G.S., personal communication).

3.9 Hydraulics of sediment transport.

Factors controlling facies, waves and tidal currents, have been alluded to in the previous sections. Currents and waves are investigated in more detail here. This section and the following section on subsurface deposits will lead to an elucidation of facies formation.

3.9.1 General features of tides in the Sound.

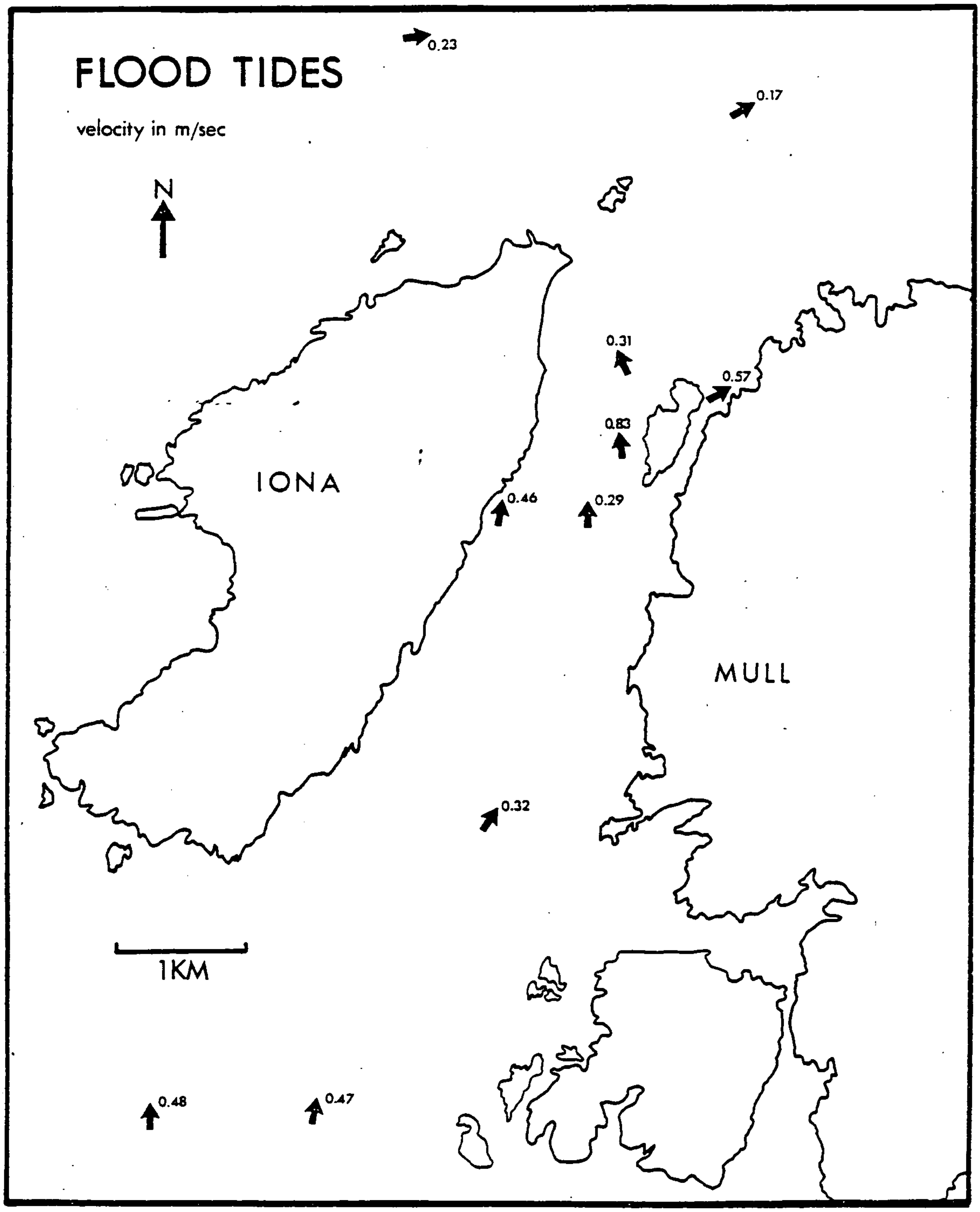
Shore stations on both sides of the Sound show that high water occurs virtually simultaneously throughout the Sound; low water is also simultaneous. Observed tidal times show good agreement with predicted tidal times. The tide changes direction in the centre of the Sound one hour before high water occurs on the shore.

Surface currents were studied by Plessey direct reading current meter (see appendix 2). Current velocities for the northward flowing flood tide are shown 1hr. and 3hr. after low water (Fig.29B). The flood water locally slows around sand waves but generally accelerates as it passes over the central shoals. This velocity increase is compensated by an increase in drag sculpting a hierarchy of bedforms from ripples to sand waves. Further acceleration occurs near the south end of Eilean nam Ban where the island deflects the tidal stream towards true north.

The deflection, a partial blocking of stream flow would cause a higher rate of discharge in this sector, and is manifest as an increase in tidal velocity. This acceleration forms a sand ribbon. On an ebb tide (Fig. 29) there is a deceleration as currents flow from the northern platform up the sand ribbon. However, the prominent sand wave morphology creates a current deflection and acceleration. As the Sound widens and deepens to the south currents are slowed at the southern flanks of the central shoals. Ebb currents are very slow in the deeper water open areas of the southern platform.

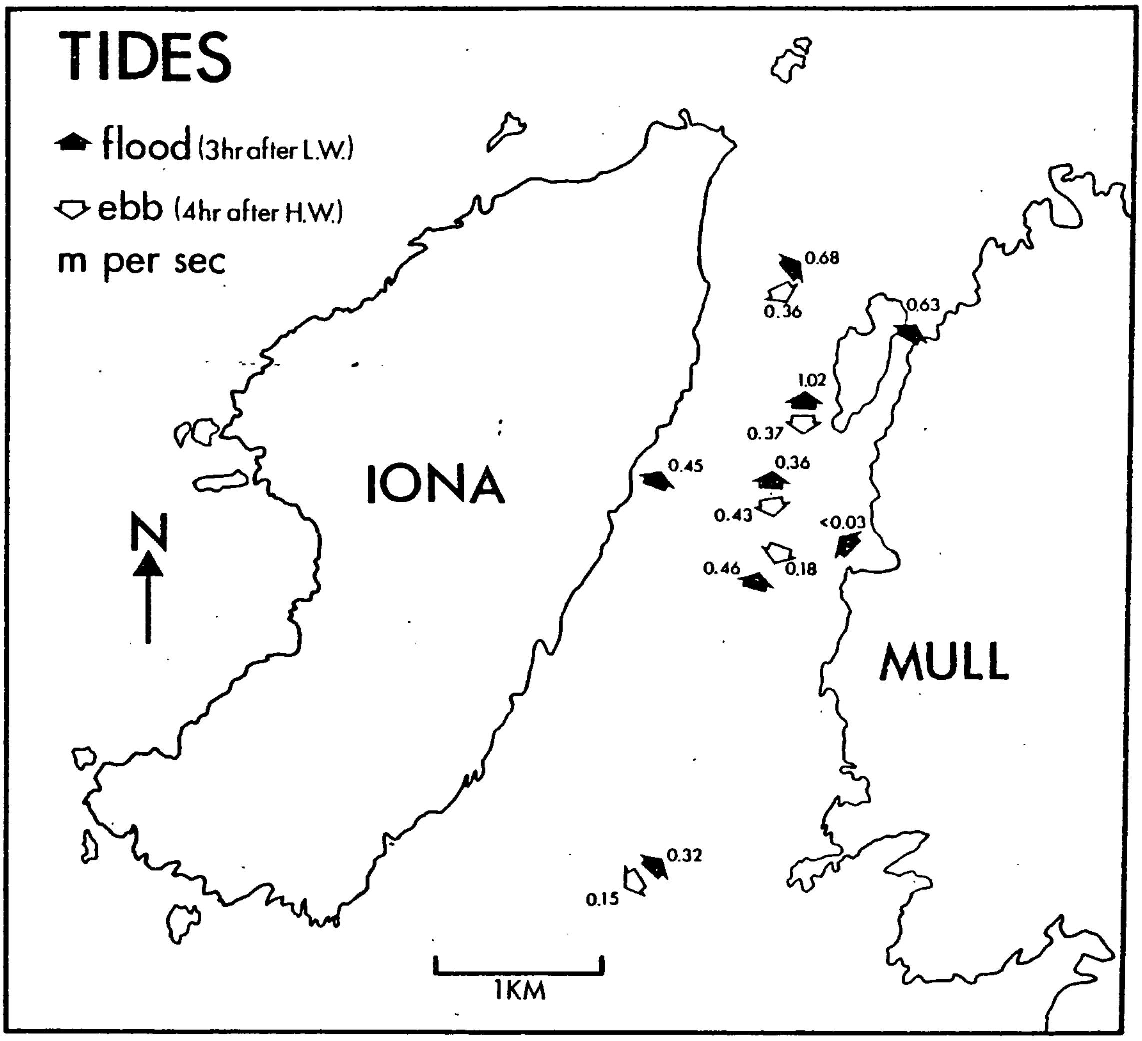
Subsurface currents were measured for 10 days 1 m above the sea bed simultaneously on the northern and southern platforms (see Fig. 30 and appendix 2). Some general patterns which can be recognized are:

Fig. 29 A. Flood tide velocities 1 hr. after low water.



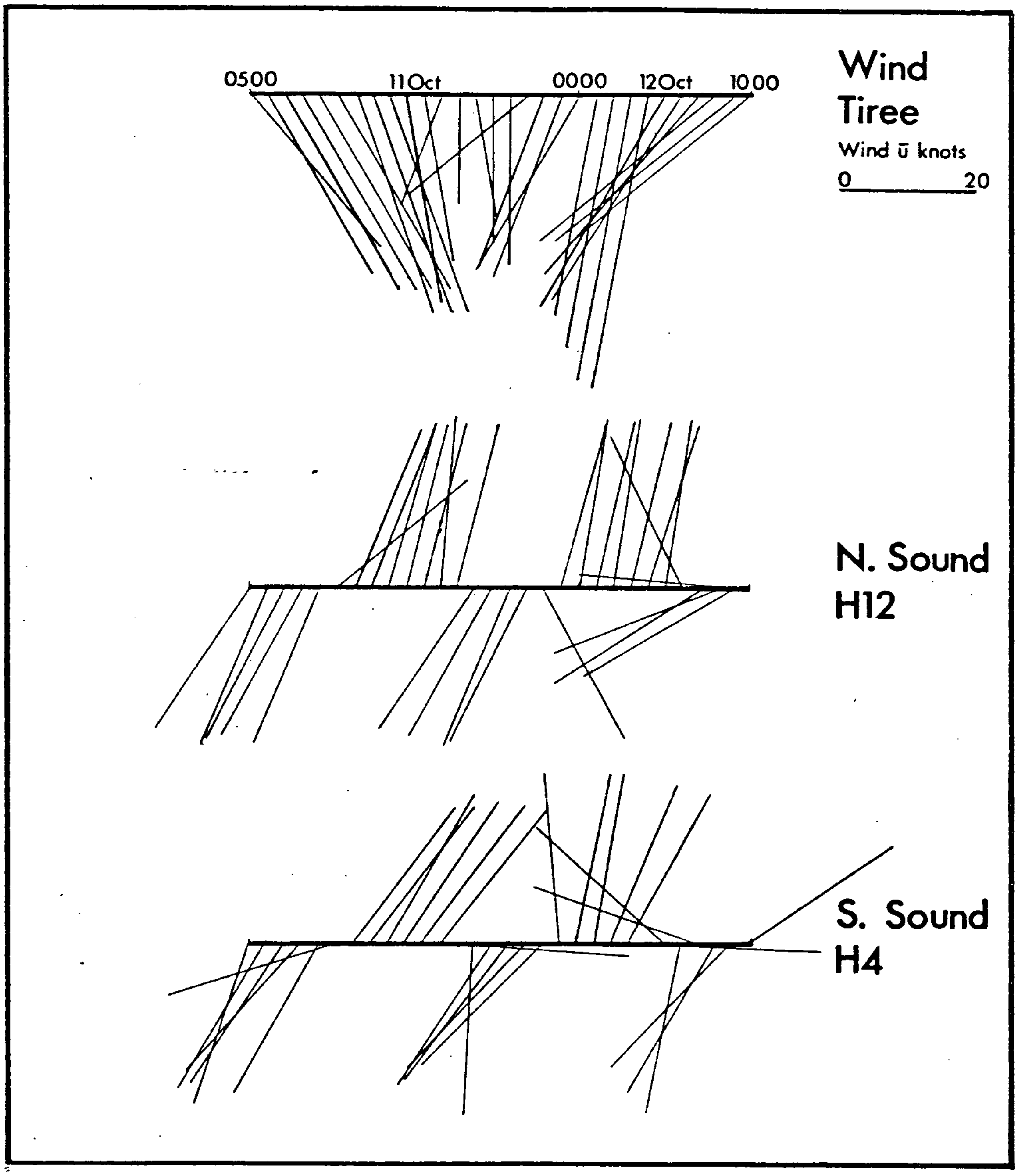
FLOOD TIDES
velocity in m/sec
N
0.23
0.17
0.31
0.57
0.83
0.46
0.29
IONA
MULL
0.32
1KM
0.48
0.47

Fig. 29 B. Flood and ebb tide velocities.



TIDES
flood (3hr after L.W.)
ebb (4hr after H.W.)
m per sec
N
IONA
MULL
0.68
0.36
0.63
1.02
0.37
0.45
0.36
0.43
<0.03
0.46
0.18
0.32
0.15
1KM

Fig. 30. Subsurface current meter measurements during a Force 7-8 storm. Note the more orderly pattern of currents in the N. Sound versus the less ordered pattern in the S. Sound.



0500
11Oct
0000
12Oct
1000
Wind
Tiree
Wind ū knots
0
20
N. Sound
H12
S. Sound
H4

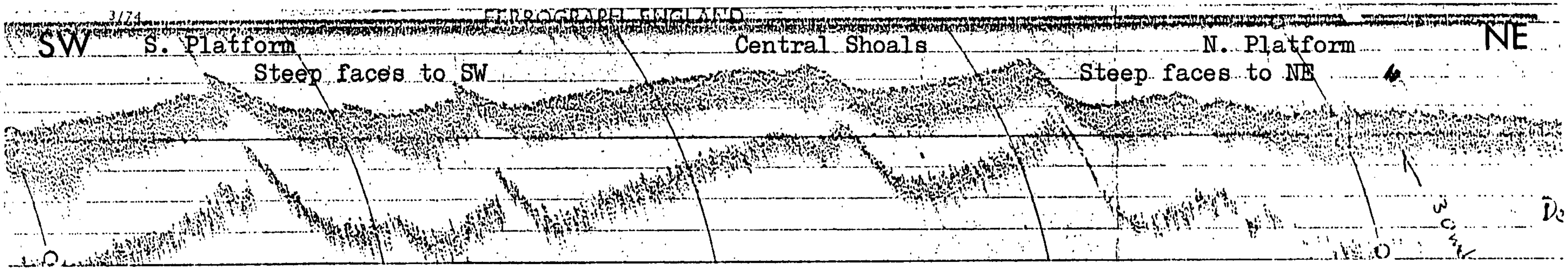
1) the flood tidal flow is to 020°, the ebb flow is to 200°;
2) the northern platform floods about 1hr before the southern platform; the southern platform ebbs 1hr before the northern platform.
3) because of the differences in tidal onsets, the flood tide lasts longest in the northern platform, approximately 7hr versus 5hr in the south; the ebb tide has the longest duration in the southern platform, 7hr, versus 5hr in the north;
4) at the turn of tide the platforms in the Sound break into two temporary "cells" characterized by rotary tidal flow in either a clockwise or anticlockwise direction. The water flow in the northern platform cell is independent of that in the southern cell.

Time dominance of the two tides is due to the strong influence exerted by the central shoals. This has a marked effect on sediment transport. On the northern platform the northward-flowing flood tide transports sediment for a total of 4hr longer than the ebb current. Conversely on the southern platform, the southward flowing ebb current transports sediment for 4hr longer than the flood currents. This feature explains the difference in bedform asymmetry observed in these two sectors of the Sound (Fig. 31).

3.9.2 Tidal currents.

Diving observations show that tidal currents are the main agent of sediment transport in the central shoals area. Transport occurs either to the north (flood tide) or to the south (ebb tide). Historical maps (Fig. 32) have shown sediment is eroded from one part of the shoals, transported and deposited. Sediment is later re-eroded and transported in the opposite direction. This has created a series of onlapping beds (Fig. 27). This condition of equilibrium ends at the sand ribbon located on the north-east side of the central shoals. Divers have observed sediment in motion along the central axis of the ribbon. The ribbon

Fig. 31 A. Vertical sonar trace of asymmetrical bedforms on the northern and southern platforms and the central shoals. Each horizontal line = 5 feet.



SW
S. Platform
Steep faces to SW
Central Shoals
N. Platform
Steep faces to NE
NE

Fig. 31 B. Location diagram for the vertical sonar trace.

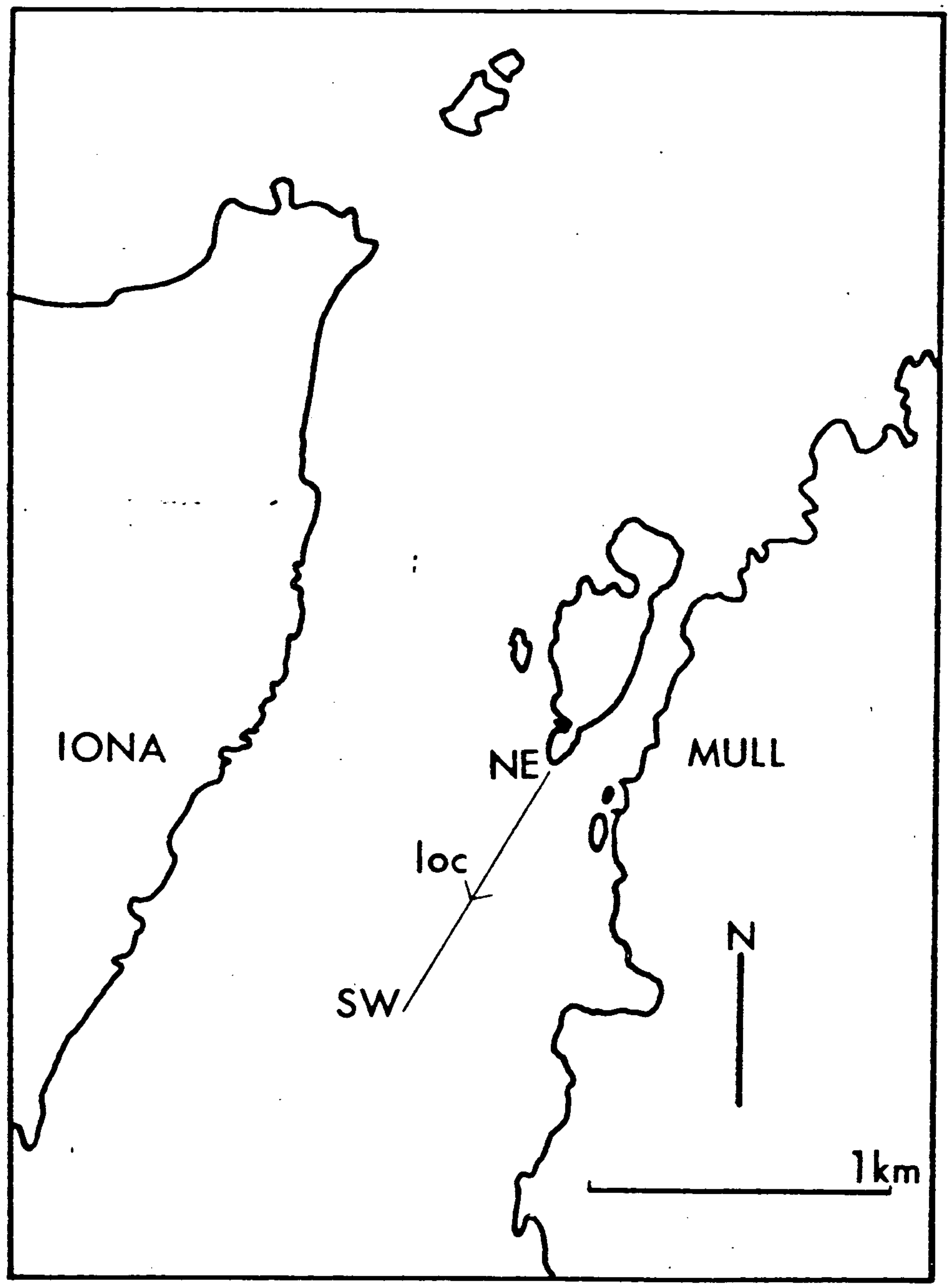
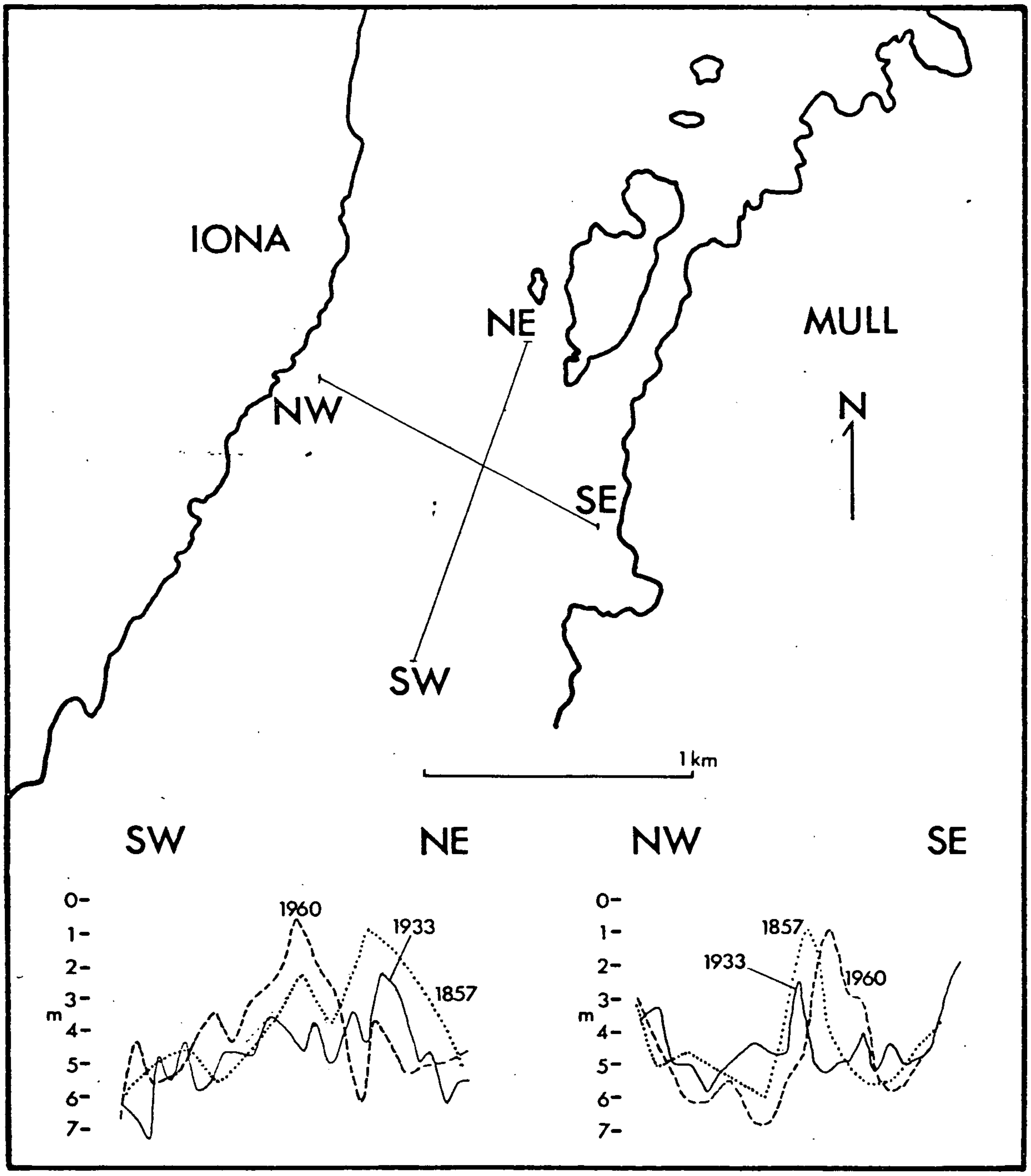

IONA
NE
loc
SW
MULL
N
1km

Fig. 32. Historical bathymetric surveys of the central area of the Sound showing the oscillatory sediment movement.

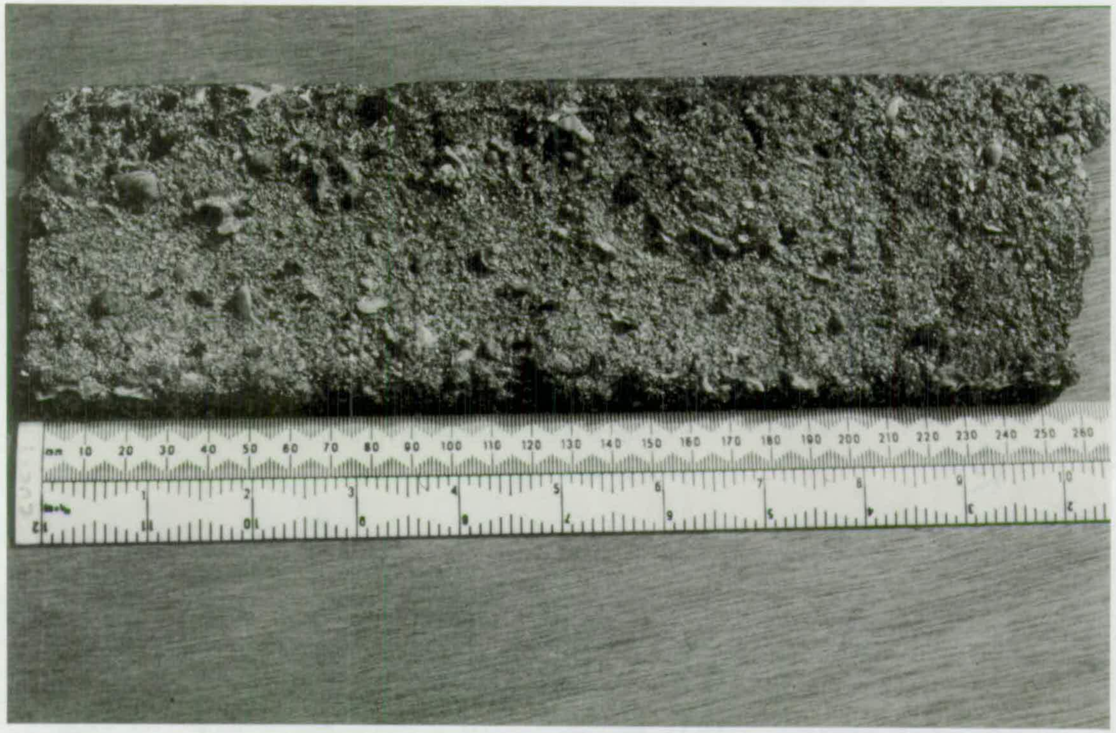

IONA
MULL
NE
NW
SE
SW
N
1 km
SW
NE
NW
SE
0-
1-
2-
3-
4-
5-
6-
7-
m
1960
1933
1857
1857
1933
1960

acts as a control "valve" for the east-central periphery of the sand wave field; tidal channels denoted by sharp terminations in bifurcating sand wave crests and the undulation in the wave field margins (Fig. 24) regulate sediment build-up in peripheral areas of the field. This condition of diverging sediment transport directions has been termed bedload parting (Kenyon and Stride, 1970). Thus, the sand wave field acts as a sublittoral reservoir for sediment but sediment volume is controlled by flood and ebb structures at the periphery of the field.

On the north Iona littoral shoals of the Sound, flood tide sediment transport has created a conspicuous plumose sand ribbon (Fig. 24 C). Sediment on the opposite side of the Sound near a group of very small islands named the Breughs, has been observed in motion to the south. Thus there exists a differential in sediment transport across the Sound. This is related to current deflection and compensating acceleration caused by island blockage between the Isle of Storms on the north sector of the Sound and the Breughs and Eilean nam Ban on the eastern side of the Sound. A point of bedload convergence (Fig.36)(Kenyon and Stride op. cit.) occurs on the eastern side of the northern platform where the northwardly moving sediment of the central shoals sand ribbon meets the southward moving Breugh sediment. Here a small sand wave field is created. This convergence is sequential relating to states of tidal flow rather than a simultaneous confluence.

The peculiarities of sediment transport in the northern part of the Sound help explain the existence of the Phymatolithon maerl deposit there. Sediment is only in motion at the periphery of the deposit (Fig.33) i.e. the shallower water because fluid drag is greatest there. In the areas where transport occurs it is always away from the maerl. Thus one reason the maerl exists is because it grows in an area of slow sediment deposition.

Fig. 33. Suction core at the periphery of the maerl deposit showing sand-sized sediment mixed with dead algal thalli (station 04).


mm 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260
1 2 3 4 5 6 7 8 9 10

The flow regime on the sea bed at the maerl deposit was investigated in more detail. A velocity profile was taken during a north flowing flood tide backed by Force 7 (34 knots gusting to 45 knots) winds blowing to the north (see appendix 2). This meteorological situation created current velocity 24%-170% above calm weather flood velocities (c.f. Fig. 29) hence the derivative sea bed velocity would be well above the norm. A plot of velocities were made using the Karman - Prandtl equation for turbulent flow (Channon and Hamilton, 1976):

$$\frac{\bar{U}_z}{U_*} = 5.75 \log_{10} \frac{(z + Z_o)}{Z_o}$$

where $\bar{U}_z$ = average current speed at height z above the seabed,

U_* is the velocity at the seabed,

z = height above the seabed,

Z_o is the height of the roughness of the bed which can be translated to mean theoretical ripple height, grain size and grain shape.

The quantities $\bar{U}_z$ and Z are known from in situ measurements. In practice U_* and Z_o can be sought empirically from a graphical plot. The roughness length Z_o can be calculated as the y axis intercept of a three point line plot of $\bar{U}_z$ versus log z; $U_* \frac{m}{5.75}$ where m = slope and is determined from the graph (Fig. 34). Linear plot of velocities was produced showing that turbulent flow extended from the air-sea surface to the seabed. A maximum seabed velocity of 4cm/sec was recorded with a roughness height of 3 cm. This velocity is capable of moving quartz grains (density : 2.65gm/cc) of 0.2 mm (Inman, 1949). *Phymatolithon* grains have a density less than that of quartz (Table 11) but the maximum axial thallus length is much larger than 0.2 mm, averaging 2 cm or more. The combination of large thallus size and the interlocking network formed by the thalli makes the maerl resistant to erosion. There

Fig. 34. Velocity profile for the maerl tract at station H12.

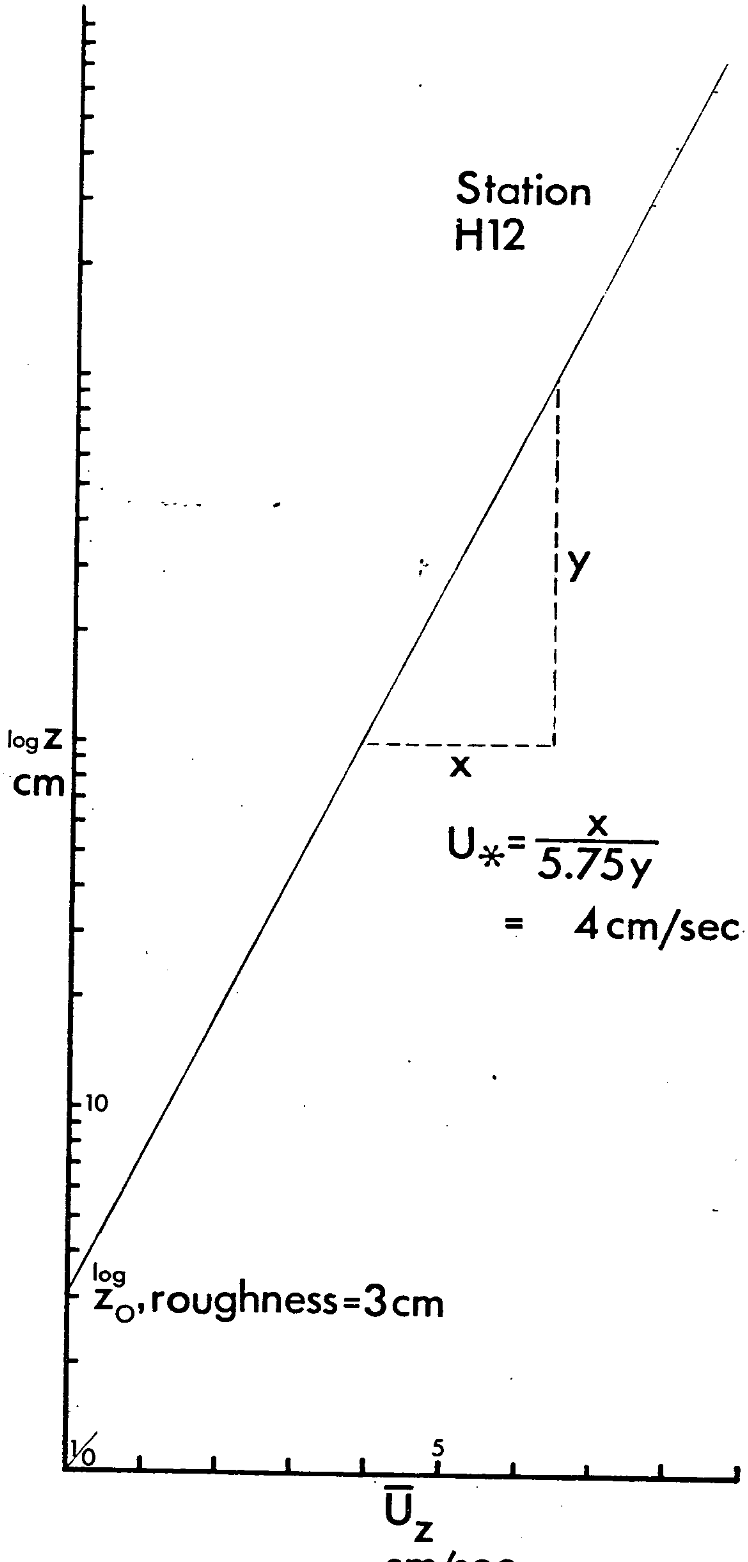

Station
H12
y
x
log z
cm
$U_* = \frac{x}{5.75y}$
= 4 cm/sec
10
log
z_o, roughness = 3 cm
1/0
5
$\overline{U}_z$
cm/sec

Table 11. Density of a selection of shell grains in the Sound of Iona.

Type	Density gm/cc	Measuring Technique and Comment
Balanus balanoides (eulittoral barnacle)	2.07	Water volume displacement of bulk sample.
Dosinia exoleta (burrowing sublittoral bivalve)	2.65	Archimedes principle : volume = (dry weight - wet, suspended weight) 2 shells sampled.
Littorina littoralis (eulittoral gastropod)	2.68	Archimedes principle. 8, air-free, shells sampled.
Patella sp. (eulittoral gastropod)	2.65	Archimedes principle. 17 shells sampled.
Phymatolithon calcareum (sublittoral rhodophyte alga)	2.14	Water volume displacement of bulk sample.
	2.04	Archimedes method. 20 thalli sampled.

is also a marked deceleration of the dominant current, the flood tide (Fig.29B) as it moves from the central shoals into this deeper and wider area of the northern platform. This deceleration is beneficial for the maerl because it lessens the possibility of: 1) thallus transport and 2) transport of other sand grains into the maerl, thus minimizing the likelihood of burying the deposit. The roughness element shows poor agreement with an observed megaripple height of 50 cm or more. However, this discrepancy is resolved because the megaripples are not formed by currents. Diving observations indicate the megaripples in maerl are not moving by tidal current actions, it is concluded that the megaripples here are formed by large waves; Lees et. al. (1969) have shown that waves are the agent forming megaripples in the maerl in western Scotland.

3.9.3 Interaction of tides and waves.

Low velocity winds produce small waves. Diving observations in the Sound show that small amplitude waves lift the sediment off the seabed; when the wind and wave direction are similar or coincident a constructive bedform is produced. If these directions are opposing, the wave action tends to reverse and destroy the action of currents; small bedforms are modified or destroyed.

The axis of the Sound is oriented at 020°-200°; it is especially vulnerable to storm-wind generated waves from these sectors. Greatest fetch distance lies to the south, it is 124 km SW from Iona to the coast of Ireland. During the storms which were observed in the Sound, the largest waves came from this direction because of the great open sea area. Much smaller waves entered the Sound when storm winds were from the NNE; this is related to the smaller maximum fetch distance, 24 km from Iona to the Mull coast. When storm-waves entered the southern platform they cause a large number of quick and erratic changes in water flow direction; this effect is most pronounced when the storm wind opposes the ebb tide. When the winds and tide coincide large waves are produced which break on the southern flanks of the central shoals. It is suspected that the coincidence of tide and wave is responsible for the small amount of shell material in the extreme southern end of the Sound; any material produced being pushed northwards by flood tides and southerly storm winds. This form of hydraulic activity would also inhibit the construction of large scale bedforms in this area.

The land masses of Iona and Mull and the central shoals jointly shelter the northern platform; note (Fig. 30) the uniformity of tidal direction on the northern platform compared to the erratic tidal direction on the southern platform, during a storm. Thus, southwest waves on the northern platform are locally produced. They account for an acceleration of coincident flood tides as noted in the previous section, causing accelerated transport in non-maerl areas. Side-scan sonar (Fig.35) showed that a storm transported sediment laterally on the northern platform. Lateral sediment transport by waves could account for the apron-like dispersion of sediment on the northern platform-deep water areas.

The ubiquitous occurrence of the barnacle fragments is explained by their high productivity, ease of breakdown to sand and ease of transport due to the low skeletal density (Table 11). With a density of 2.07 gm/cc and small grain size, the barnacles would be very vulnerable to wave and tidal current transport. This ease of transport would account for the uniformity in values throughout the Sound. Molluscs have a larger initial skeletal size and also a much higher shell density, very similar to that of quartz. The localized high mollusc values (Fig. 11) reflect these shell properties.

Fig. 35 a. Side-scan sonar traces before and after a storm of Force 7-8, location near the central portion of the Sound.

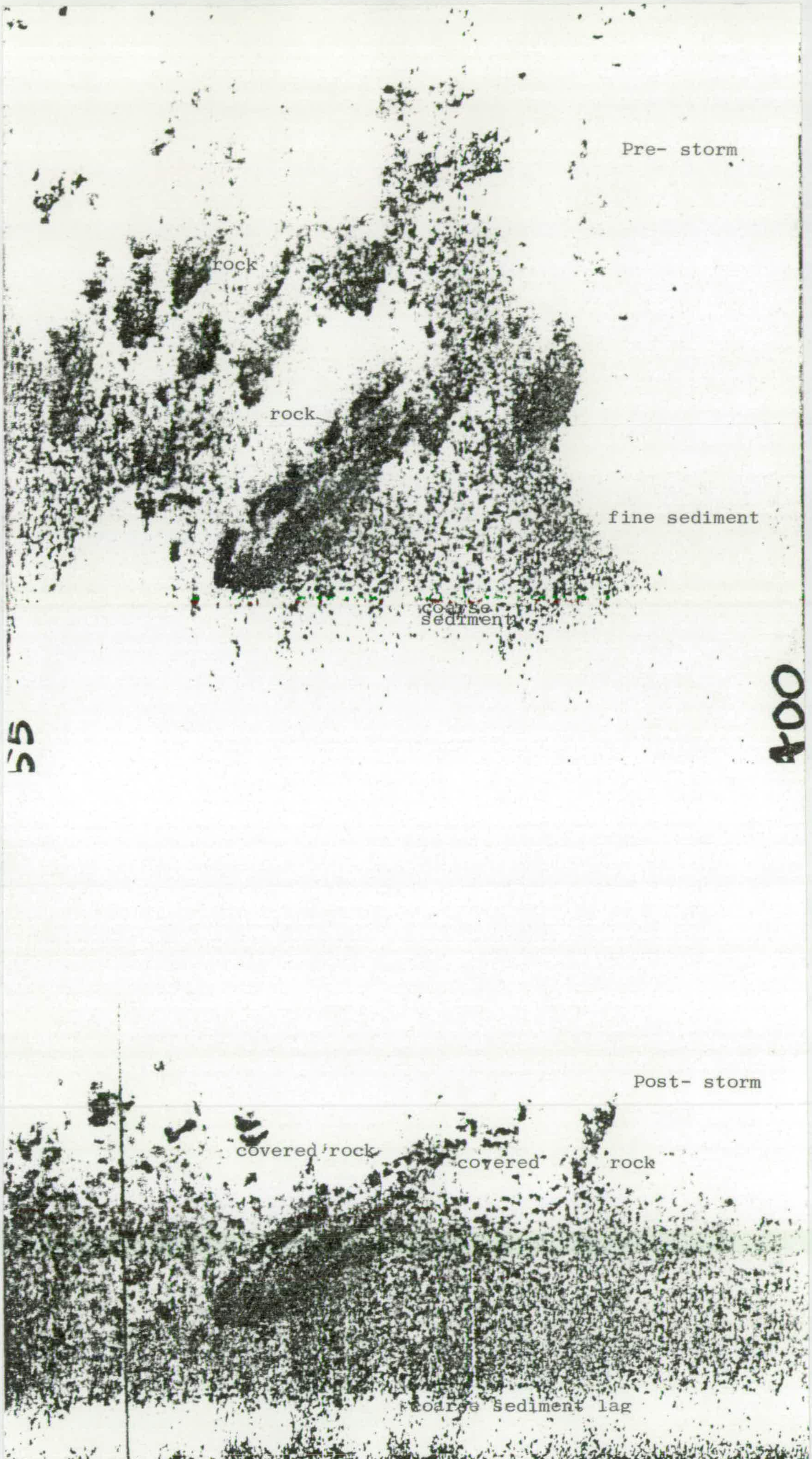
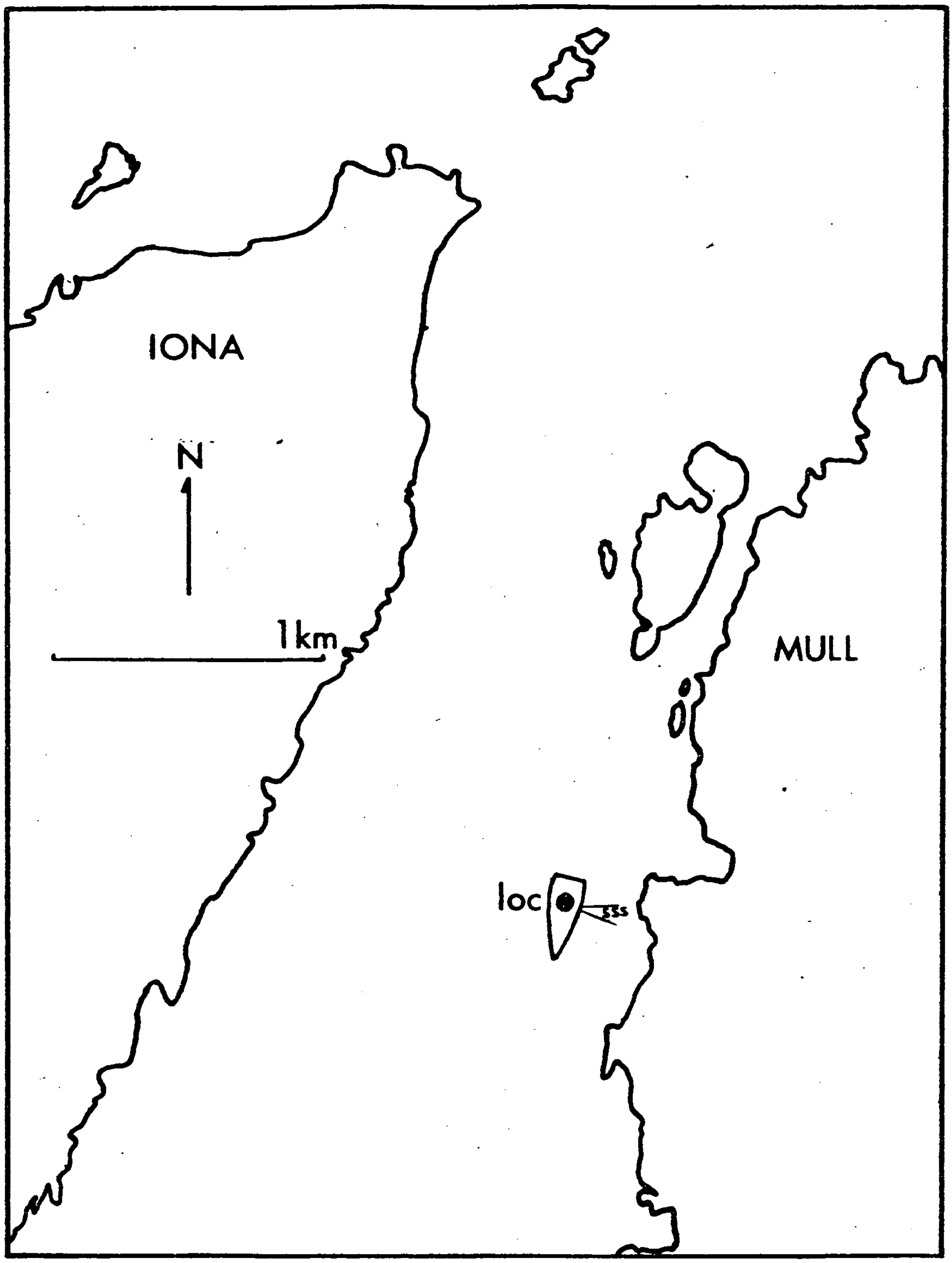

Pre- storm
rock
rock
fine sediment
coarse sediment
Post- storm
covered rock
covered
rock
coarse sediment lag

Fig. 35 B. Location diagram for the side-scan sonar trace.


IONA
N
1km
MULL
loc
sss

3.9.4 Summary of sediment transport.

Sediment transport paths in the Sound are diagrammed in Fig. 36. The sediment transport paths can be summarized as follows:

Southern platform. Subsurface current meters and bedform asymmetry shows that dominant transport direction is to the south. However, this area is vulnerable to counter transport by northerly flowing storm-wind waves which could prevent sediment from escaping in the southern deep waters, by moving it north to the central shoals.

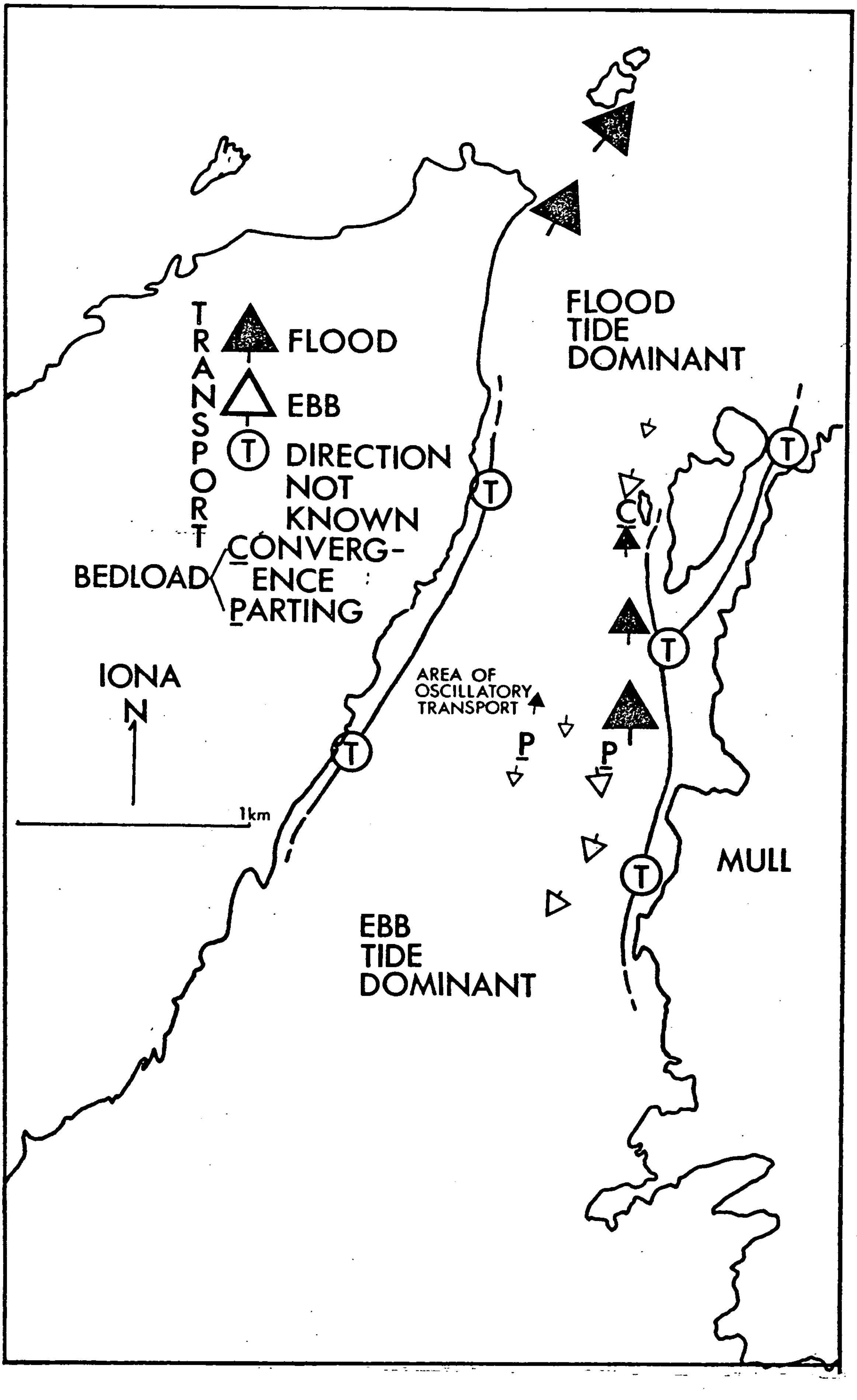
Central shoals have oscillatory transport as shown by diving and surface current meters. There is no equilibrium because there is the flood-dominated sand ribbon on the eastern sector of the shoals the flood moving sediment northwards. Local ebb and flood dominated sectors create asymmetrical bedforms.

Northern platform, studied by diving, surface current meters velocity profiles has a maerl "core" where no apparent transport takes place, a prominant sand ribbon extending from the central shoals transports sediment to the north.

Littoral-nearshore shoals, studied by diving and aerial photographs are dominated by fucoid and laminarian algae which help build sediment and reduce transport. In the areas peripheral to the central shoals and northern platform linear patches of sediment are noted. These are small scale sand ribbons; transport is to the north for one such ribbon at the north tip of Iona; transport direction of the other sand ribbons is not known. There would also be transport in a vertical sense as shore sediment is moved downslope during storm activity (Mather and Crofts, 1972).

Western areas of Iona (includes all areas from the littoral near-shore shoals to the western deeper water bathymetric provinces) has been little studied. Brown algae dominate the seabed except for occasional

Fig. 36. Sediment transport directions in the Sound.


TRANSPORT
FLOOD
EBB
DIRECTION NOT KNOWN
BEDLOAD
CONVERGENCE
PARTING
FLOOD TIDE DOMINANT
IONA
N
1km
AREA OF OSCILLATORY TRANSPORT
T
C
P
MULL
EBB TIDE DOMINANT

bare patches observed in aerial photographs. It would inhibit transport. Wave action is dominant, shown by diving and shore observations of this area. Tidal currents, studied by current meters, are weak. Coastal studies by Mather and Crofts (1972) have shown that there is seaward transport of raised beach sediment.

Overall transport in the Sound is to the north: this is due to flood tide dominance in the northern platform creating northward sand ribbon transport of sediment and wind generated waves from the southern sectors which push sediment northwards from the southern platform onto the central shoals.

3.10 Subsurface sediments.

Two seismic devices were used to study sediment structure below the sea bed: 1) a Huntec boomer which used high frequency sound, and 2) an E.G.G. sparker which utilizes low frequency sound. The two techniques are complementary. A boomer has high resolution but shallow sound penetration being used to examine the upper portions of the subsurface sediments. The sparker has lower resolution than that of a boomer but much deeper acoustic penetration; it was used to study deeper sediment layers. Technical details of these two devices are described in appendix 2.

3.10.1 Boomer studies.

Boomer traces reveal that the thickest sediment accumulation (approximately 2 m, assuming a seismic velocity of 1.8 m/msec) is in the eastern side of the central shoals (Fig. 37) These thicknesses are supported by industrial excavations of the nearshore shell sediment which shows it is 1 m deep near Iona and 2 m deep near Mull. Sediment gradually thins until it is approximately 1 m thick on the northern platform. Sediment thickness is difficult to estimate on the southern

Fig. 37 A. A boomer profile of the central shoals - S. platform area of the Sound.

Each horizontal mark = 10 milliseconds.

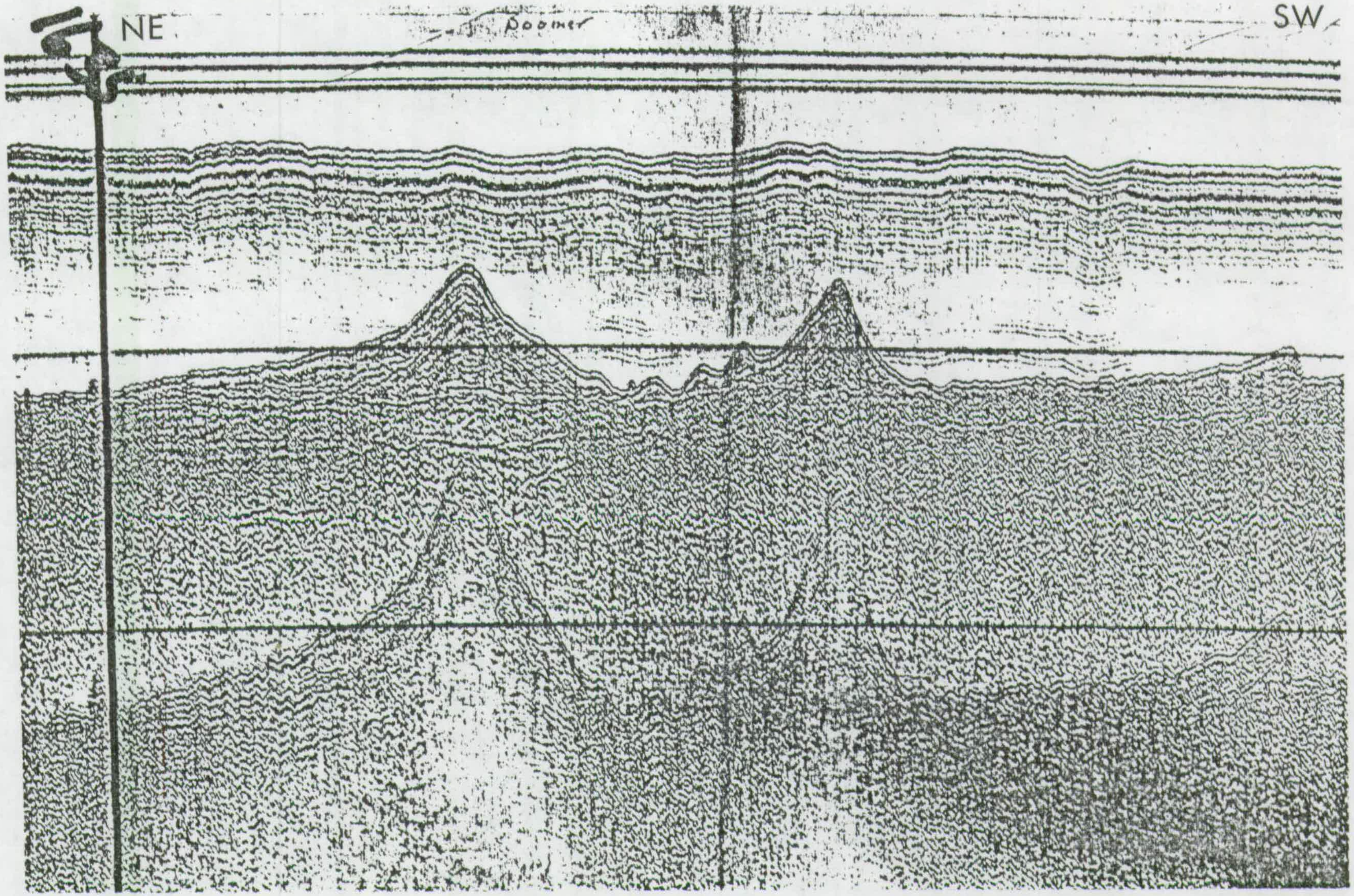
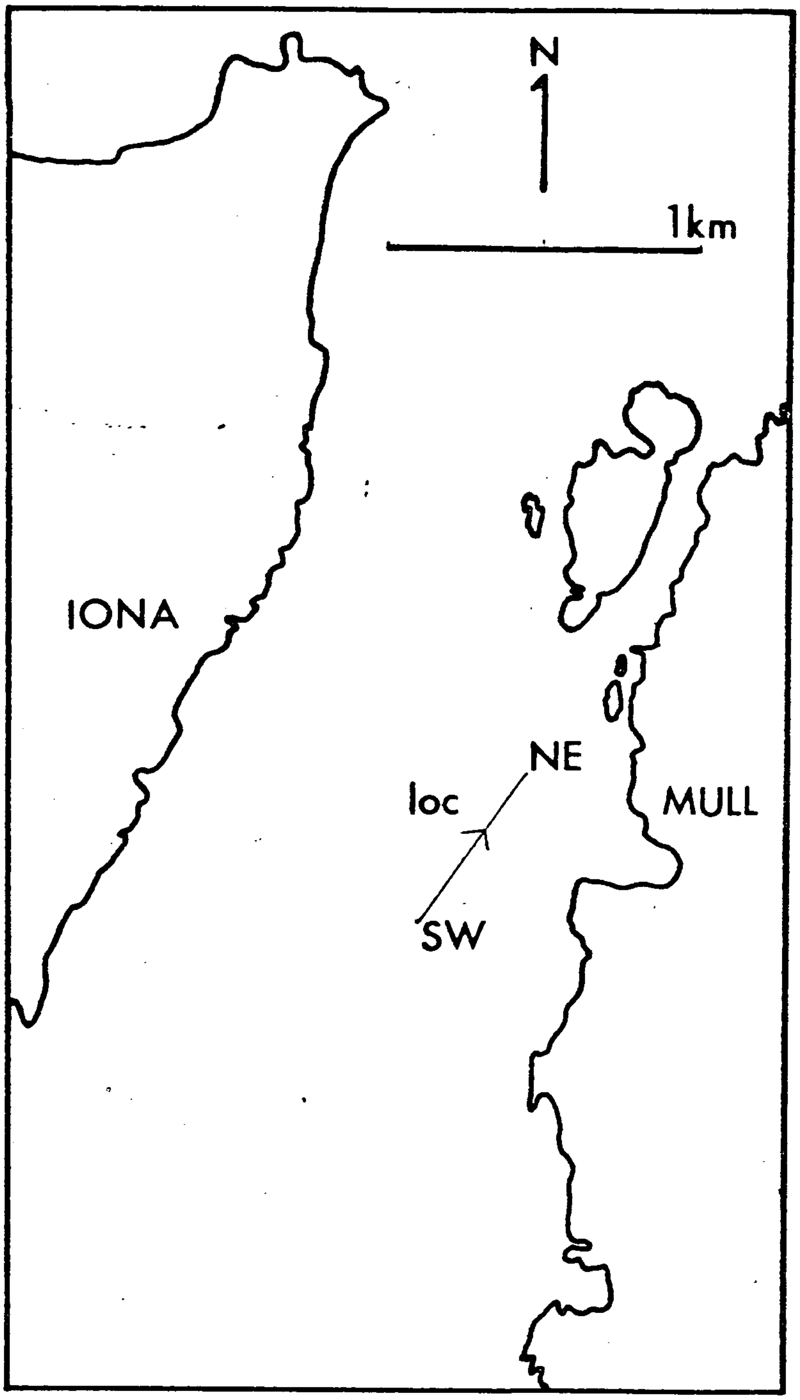

NE
Boomer
SW

Fig. 37 B. Location diagram for boomer trace.


N
1km
IONA
NE
loc
SW
MULL

platform because it is obscured by the pulse width (sound interference at the sediment-water interface). However, it is judged to be under 1 m in thickness.

3.10.2 Sparker studies.

Sparker seismic traces indicate the presence of buried sedimentary beds. Most striking is an arcuate-lobate configuration of steeply dipping beds at the northern sector of the Sound (Fig.38A). Beds here have an apparent dip of 6°-8° to northeast through northwest directions. Total thickness of these beds is disconformable undulatory underlying strata,(using an assumed minimum sonic velocity of 1.8 m/msec) is 40 m for the sector northwest of Iona, 27 m for the northern sector and 23 m for the beds to the northeast sector. Barnacle and mollusc rich sediments were dredged from the seabed near the north and northeast sectors of these deposits. On the northwestern beds rounded boulders up to 0.5 m in maximum length were recovered. The thickness, lateral extent, bedding angles and known weakness of currents in the area suggests that the dipping beds are not of present-day origin. It is unlikely that they are of ancient origin because the metamorphosed beds found on Iona have north-south strikes and steep, nearly vertical dips. Binns et al. (1974) found no deposits of Mesozoic or Tertiary age, but did find Pleistocene and Recent sediments in the area. It is suggested here that these dipping beds are Pleistocene in origin. Sissons (personal communication, 1978) thought that beds of this type could have originated from periglacial frost shattering of shore rocks; the sediments were driven northwards by the very strong winds of late Pleistocene times. However, this idea would not adequately account for the large volume of sediment the great distance from the Sound and the presence of the rounded boulders at great distance from land. It is proposed here that these beds were formed as a glacio-deltaic deposit formed by the ablation of a

Fig. 38   A.   Sparker trace in the N. platform 1 - deep water area of the Sound.

Each horizontal mark = 40 milliseconds.

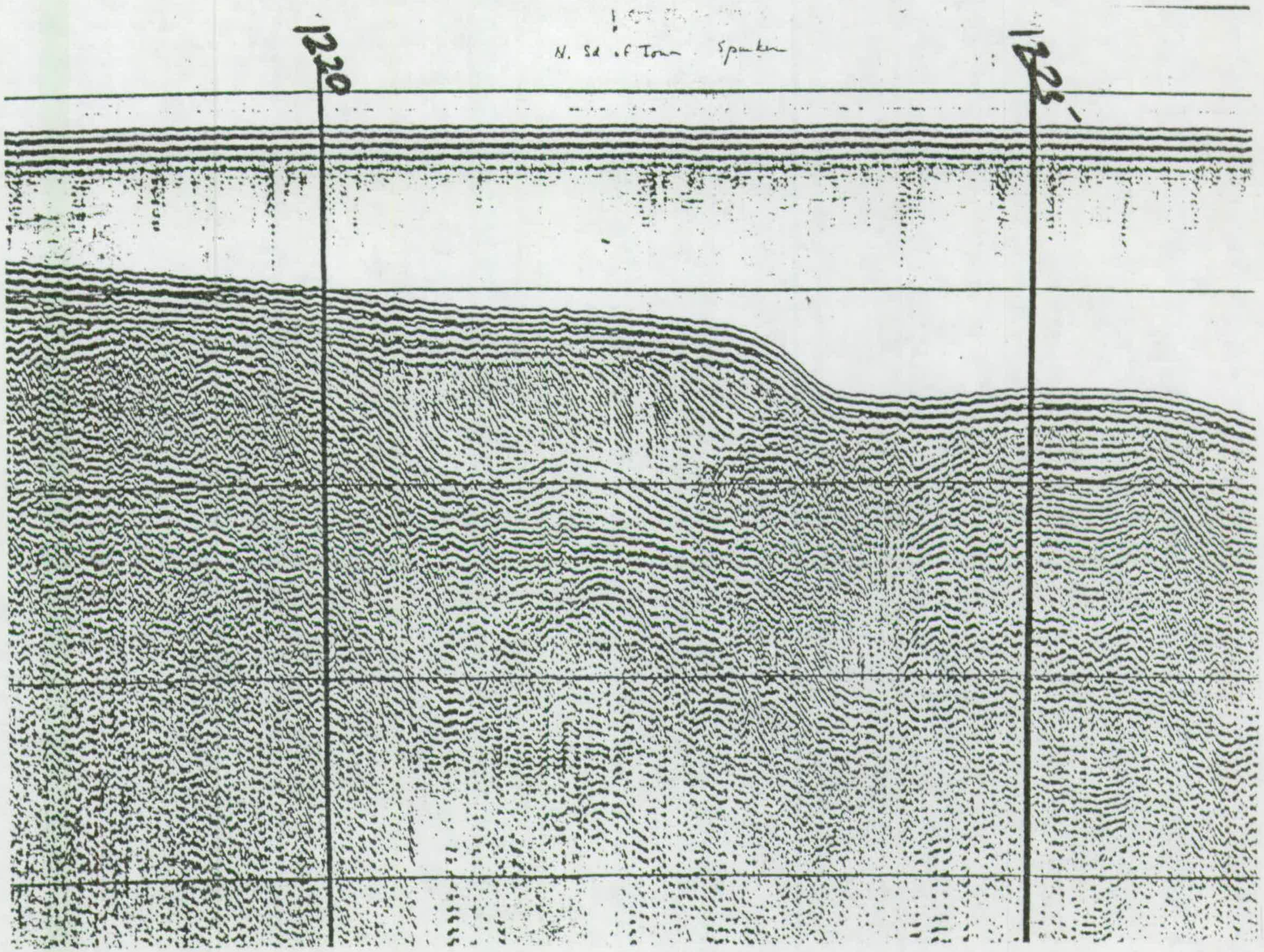

N. Sd of Town Sparker
1220
1225

Fig. 38 B. Sparker trace in the central shoals.

Each horizontal mark = 40 milliseconds;

p = parabolic reflector.

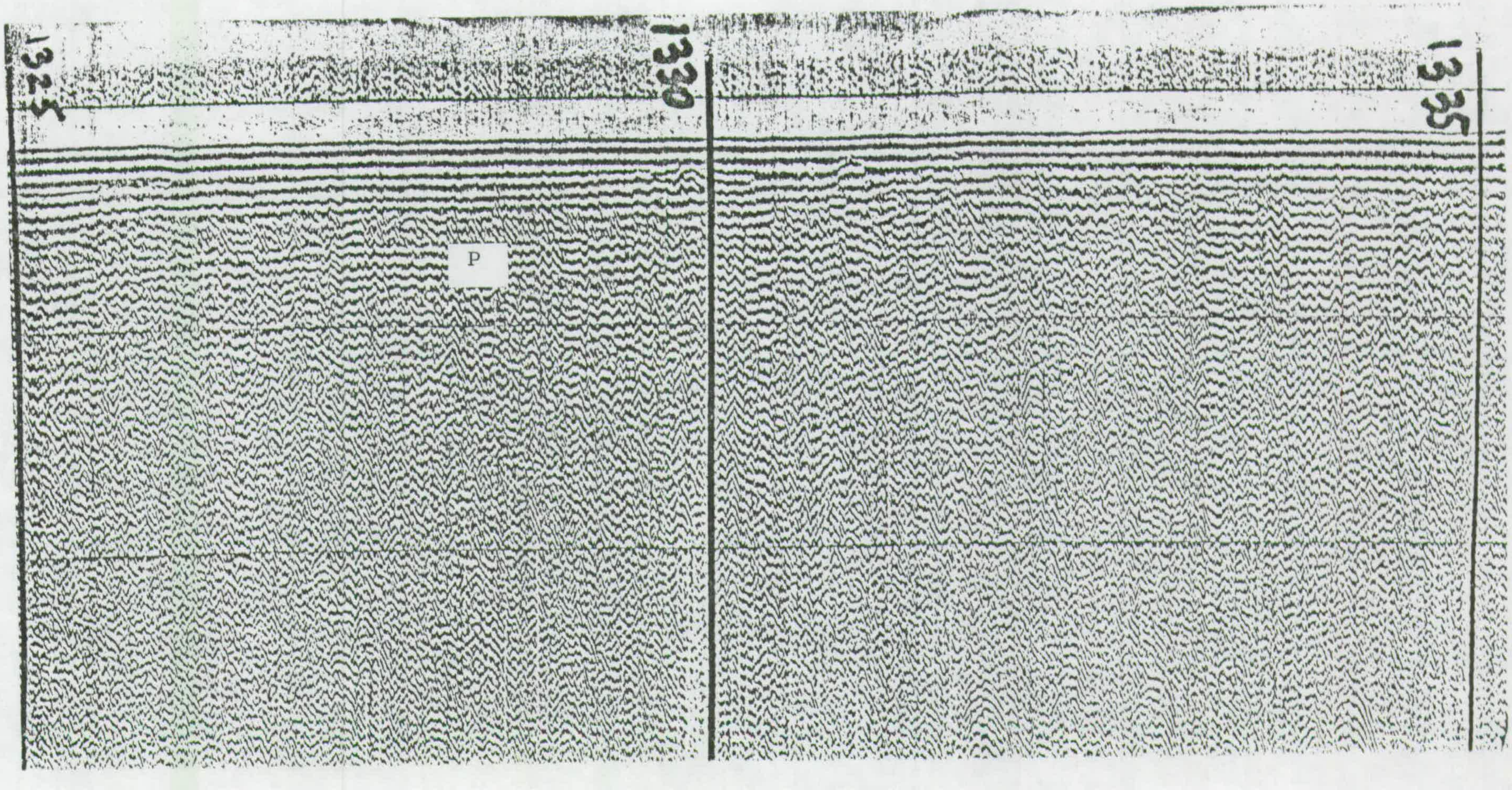

1325
1330
1335
P

Fig. 38 C. Sparker trace in the Southern platform.

Each horizontal mark = 40 milliseconds;

p = parabolic reflector.

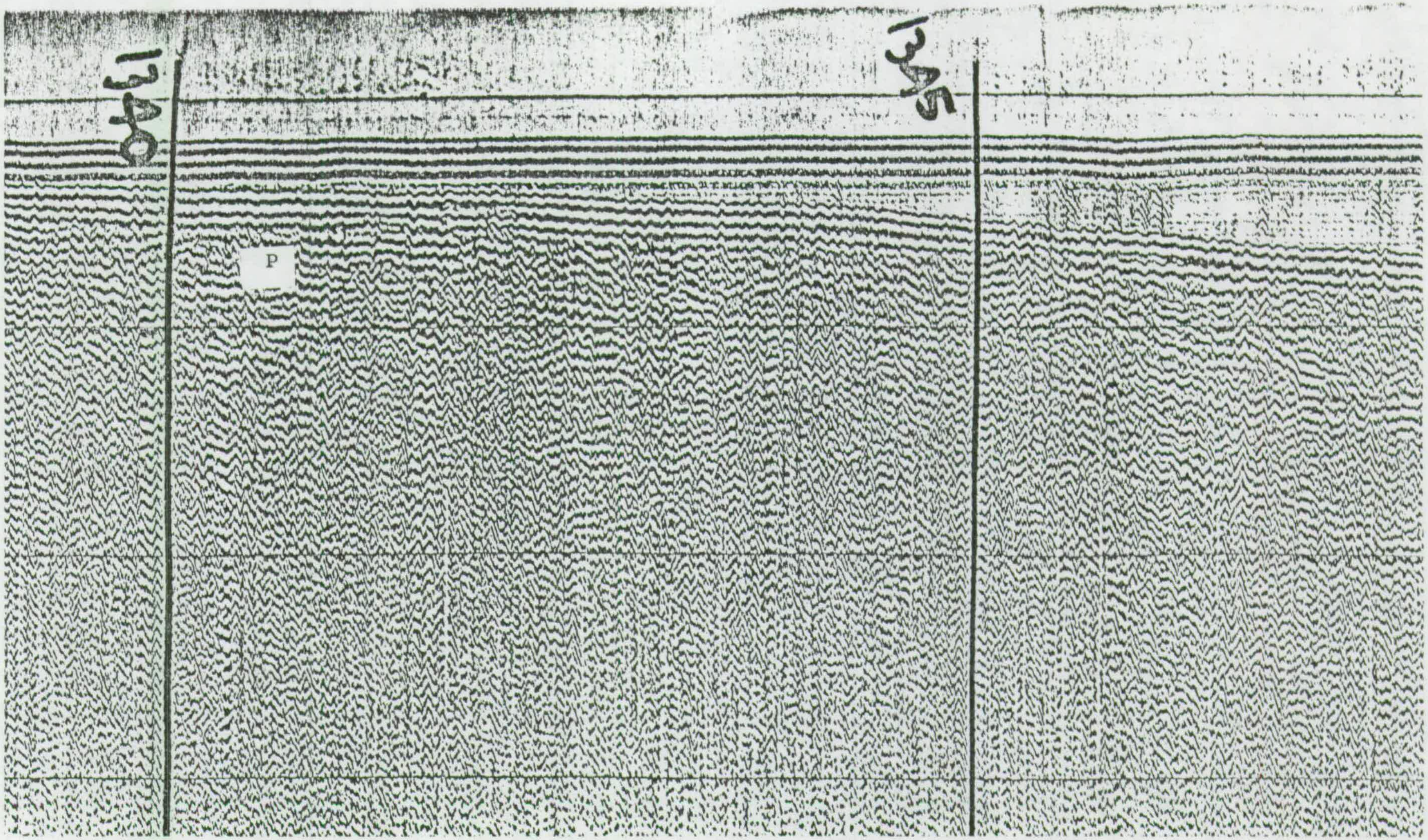
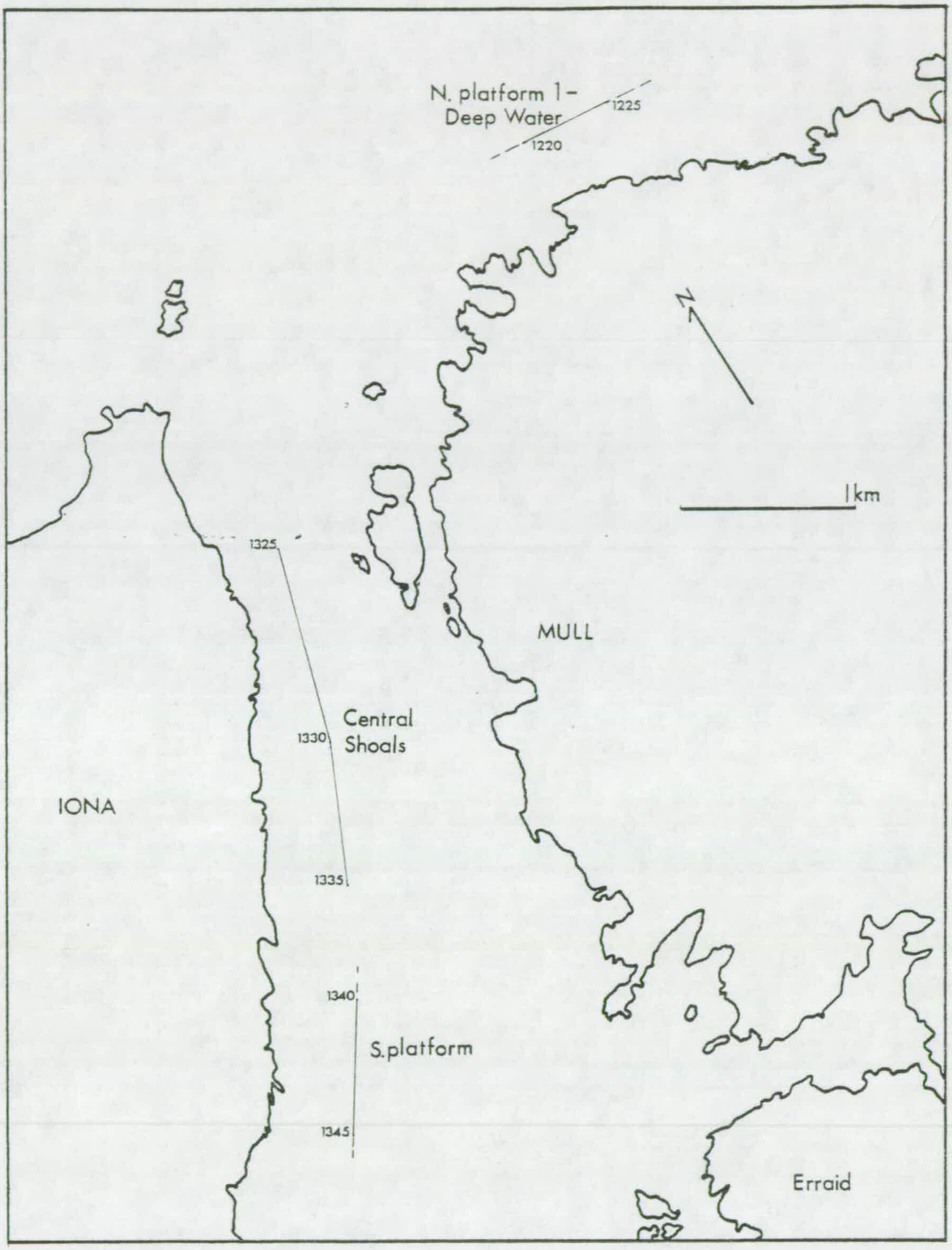

1340
1345
P

Fig. 38 D. Location diagram for sparker traces.


N. platform 1-
Deep Water
1225
1220
1km
MULL
1325
Central
Shoals
1330
IONA
1335
1340
S.platform
1345
Erraid

high-elevation glacial spur from a main ice mass moving at a lower level to the NW (Rayner, 1971); Craig et. al.,(1911) found glacial detritus and striae in the environs of Iona (c.f. Fig. 24). The boulders would be emplaced by dropping from ice bergs which calved off the glacier. The fine grain terrigenous sediment recovered from borehole SH69V would be the material winnowed during Recent times from these deposits. The carbonate deposits are of Recent origin related to post-glacial colonization of these animals in the Sound.

The glacio-deltaic beds can not be traced into the Sound. But there is a 10 m thick sequence of beds found underlying the Recent carbonate sediment of the central shoals. The presence of closely spaced parabolic reflectors in the beds (c.f. Telford et. al., 1976 p. 246) could represent glacial boulders and cobbles formed from glacial ablation as the ice mass retreated southward through the Sound (Fig. 38 B).

In the southern areas of the Sound sediment cover is slight (Fig. 38 C). Parabolic reflectors indicate the presence of pointed bedrock surfaces or diffraction around large boulders or clusters of small boulders. Anchor dredge hauls in this area recovered rounded boulders of 0.3-0.75 m diameter. This suggests that glacial spur material was locally derived from within the Sound and pushed northwards; if it had been derived from the main glacial mass there would be ablation deposits at the south end of the Sound.

3.10.3 Significance of glacial activity in the Sound of Iona.

1. The presence of locally derived glacial sediment in the Sound suggests that the Sound originated or more likely was significantly modified by glacial activity. Kennedy (1946) postulates the Moine thrust to pass along the Sound and Binns et. al. (1974) have shown that glaciers readily exploit fault weakened rocks. The glacial spur may

have eroded rock fractures caused by the Moine thrust.

2. The deltaic removal of large amounts of terrigenous material to downslope depositional sites lessens the likelihood of terrigene dilution of carbonate material.

3. The very coarse sized glacial drift deposits reported 1 m below shell sand (during excavation of piers, 1977) are the key to development of all the facies in the Sound; they create the bathymetric high which iniates current drag and the formation of the sand wave facies; they act as a buttress against the powerful southwest storm waves, thereby providing protection for the growth of the maerl deposit; the exhumation or non-burial of the glacial drift creates the relict glacial facies; the presence of the central shoals may retard the flushing action of tides and currents which would transport the sand into the deeper water areas; therefore the central shoals help preserve the rippled sand facies.

3.11 Summary for Part 2 : Sedimentation.

Carbonate rich biogenic carbonates are accumulating in the Sound of Iona. Barnacle and mollusc grains are the dominant components except in maerl areas found on the northern platform where Phymatolithon thalli dominate. Barnacles are ubiquitous, because they are highly productive, easily broken down and their low density favours transport. A small proportion of the grains are well-worn and bored (and are termed "relict"), but 90% of the grain appear fresh indicating very recent origins. The waters are supersaturated with respect to calcium carbonate, but no cementation is observed in either subaerial or submarine sample sites.

Medium to coarse sand dominates the biogenic sediment of the Sound although fine sand is found on the central shoals and maerl gravels are found on the northern platform. The fine sand forms on the shoals because it is the most easily transported size fraction moved by the oscillatory tidal currents; the maerl is localized because it has achieved dominance of a favourable growth site. Grain rounding and "sorting" are best perfected on the central shoals because of the strong tidal current control; roundness and sorting values fall on the southern and northern platforms and at shore stations where currents have less, or no influence.

Large scale bedforms occur on the central shoals and the platform areas just peripheral to the shoals; a hierarchy of bedforms from ripples to sand waves and sand ribbons are found here. Megaripples and ripples are found on the other platform and shoals areas. The large sand waves are formed by the drag of tidal currents coursing across the central shoals, the sand ribbon forms by the acceleration of northern flowing flood tide currents around a partial blockage in the channel in the vicinity of Mull. A smaller sand ribbon forms by a similar mechanism on the northeast tip of Iona.

Four facies are recognized within the Sound: 1) rippled sand; 2) sand wave and sand ribbon; 3) maerl; 4) relict glacial drift. The first three facies originate from carbonate secreting organisms and form a thin veneer of sediment over rockhead and glacial material. In the Sound the relict glacial material forms dipping deltaic deposit at the far northern mouth and more horizontal beds in the Sound. This latter deposit controls the biogenic facies in the Sound by blocking disruptive storm waves which would flush the rippled sand facies out of the Sound, cause drag on tidal currents thereby forming the sand wave and sand ribbon facies and providing wave shelter for the maerl deposit.

SUMMARY OF CHAPTER 3 : PARTS 1 and 2

A comparison of the Quaternary histories of the Sound of Iona to the Columba-Colonsay Sea.

Sedimentary processes and products in Iona, discussed in the previous sections have a wider context in this study. This is shown in terms of a comparison in Quaternary histories between Iona and the Columba-Colonsay Sea in Table 12.

Table 12. Sedimentation history of the study areas - comparisons between depositional sites in the Columba-Colonsay Seas and the Sound of Iona.

Columba-Colonsay Sea	Evidence	Sound of Iona	Evidence	Comment
Glacial sculpting of seabed and coastline along lines of EW Tertiary drainage or NE-SW faults, creating basins. Seaward (to W) shift of drainage divide.	Binns et al. (1974) Sissons (1967, 1976).	Glacial sculpting of the Sound along trend of Moine thrust.	Seismic studies aerial photographs	Accelerated transport of terrigenous material shelfwards.
Glacial deposition during ablation at the end of the last major glacial episode e.g. creation of the Tarbert Banks (?glacial moraine).	Farrow et al. (1978, 1979).	Ablating glacier creates deltaic sediments deposited on northern platform-deep water areas; layered glacial drift deposits form the central shoals.	Seismic studies	
Holocene sea level rise; flooding of the shelf; glacial basins on the coast become sea lochs, glacial basins on the shelf become bathymetric deeps	Gray and Lowe (1977) Binns et al. (op. cit.) Sissons (op. cit.)	Flooding of the Sound.	Deductive observation from W. Scottish ref. cited opposite.	
Resumption of non-glacial erosion; relict glacial material moved into bathymetric deeps and sea beds.	Bishop (1977); Malcolm (1979)	Resumption of non-glacial erosion; relict glacial material moved basinwards.	Core SH69V	Formation of 'basinal terrigenes'.
Iniation of carbonate sedimentation (≥ 8,000 yr. B.P.)	C-14 date for Firth of Clyde bivalves (B. Brown pers. comm. 1977).	Iniation of carbonate sedimentation (≥ 4,000 yr. B.P.)	C-14 date of maerl	Seabed areas of low terrigenous input near islands form "island margin carbonates".
Isostatic uplift of land following disappearance of glaciers; formation of raised beach deposits.	Sissons (op. cit.) Johnson (1919).	Isostatic recovery of Iona formation of raised beach deposits	Mather and Crofts (1972).	
With the creation of present-day meterological patterns Recent facies formed		Formation of present-day facies:	Data from this study	
1. bare rock with echinoderm facies	Farrow et al(1979) General reference for this and following facies	echinoderm noted in dense numbers at one sample station off W. Iona not extensive enough to call a facies	Data from this study	This echinoderm deposit associated with strong wave and current areas and is not likely to be preserved.
2. maerl facies - forms by the in situ growth of Phymatolithon calcareum and Lithothamnium glaciale and grows due to wave shelter and in response to swift currents.	hypothesis of facies creation drawn from analogous facies in the Sound of Iona	1.maerl facies forms by in situ growth of Phymatolithon calcareum	Data from this study	The encrusting alga Lithothamnium glaciale is not found in the Sound of Iona
3. megarippled sand formed maerl. Megaripples form wave activity.	"	(megarippled maerl sand incorporated into maerl facies in the Sound).		

Columba-Colonsay Sea	Evidence	Sound of Iona	Evidence	Comment
4.and 5. current wave rippled sand form in very exposed swift current areas.	hypothesis of facies creation drawn from analogous facies in the Sound of Iona.	2.rippled sand forms on the southern platform due to wave exposure and currents.	Data from this study	
6. Modiolus gravel		no direct analogue in Iona		Modiolus occurs in sublittoral samples from Iona but it does not form extensive deposits.
7. Turitella fine sand; and 8. filamentous tube burrowed mud; and 9. crustacean-burrowed mud; and 10. spider crab mud, are considered together as a burrowed mud facies here; they originate as the result of winnowing of relict glacial material; the low Mg calcite component probably derived from barnacle shell abrasion.	"	fine-sized terrigenous sediment deposited by the winnowing of glacial deltaic deposits in N. Sound.	"	
11. Overconsolidated clay, a relict glacial deposit.	Farrow et al. (1979)	No parallel facies in the Sound		relict glacial clay is not recognized in the Sound.
		3. sand wave and and sand ribbons facies form by tidal current drag and island deflection of water flow, respectively.	"	these facies may eventually be recognized in the larger study area by detailed studies of seabed structures.
		4. Relict glacial coarse grain sediment facies - formed by exhumation or lie exposed in areas of very slow deposition e.g. W. Iona and deeper water bathymetric tracts.	"	This facies is probably present in the larger study area also.
Overall transport direction is not known.		Dominant sediment transport direction, based on bedform structure, is to the north.		The most compelling evidence of transport direction comes from the structure of sand ribbons which occur in the Sound.

PART 3 : Provenance of carbonate sediments in the Sound of Iona

3.12 Reasons for studying provenance.

Thin section analyses showed the dominance of barnacles and molluscs in the sediment. Large numbers of living barnacles were observed on the littoral rock faces of the Sound. Within the Sound there is little sublittoral rock exposed, the sediment extends to the littoral zone. This suggested that eulittoral zone barnacles were dominant contributors to the sublittoral sediment. Littoral molluscs were ubiquitous in the Sound and this suggested they would contribute sediment as well; however, the large number of sublittoral molluscs noted in dives and from dredge hauls suggests that a substantial contribution from this area, also Coralline alga originating from *Phymatolithon calcareum* originate here also. Little quantitative data is available for sites of origin of carbonate components. Lees *et. al.* (1969) briefly try to answer the problem but not in any detail.

3.12.1 Organisms of the eulittoral zone.

In order to estimate the feasibility of local productivity accounting for the bulk biogenic carbonate in the Sound a sampling programme was instituted within the littoral zone. The lower part of the littoral zone (= eulittoral zone, (Lewis, 1964, p. 49)) was selected for quantitative study because the majority of intertidal carbonate contributors live there: the barnacles[1] *Balanus balanoides*, *Chthamalus stellatus*, *Chthamalus montagui* (Southward), the limpets *Patella* sp., the periwinkle *Littorina* spp., the dogwhelk *Thais* (*Nucella*, *Purpura*) *lapillus* and the mussel *Mytilus edulis* .

3.12.2 A note on other epilithic littoral organisms.

Additional epilithic organisms besides those mentioned above were found on the littoral shores of the Sound. These included the coralline alga *Corallina officinalis* and the encrusting red algae *Lithophyllum*

[1] Barnacle identifications were made or verified by Dr. A. J. Southward, The Laboratory, Marine Biological Association, Plymouth.

incrustans, Lithothamnium glaciale, Phymatolithon laevigatum, P. lenormandi, P. polymorphum and Tenarea corallini. These lime-secreting plants are ubiquitous, frequently found together in tidal pools and the encrusting algae can sometimes attain thicknesses of 2-3 cm. However, they were judged not to be significant sediment contributors for the following reasons: 1) encrusting algae are slow $CaCO_3$ producers because of their long life spans of 50 years or more (Adey, 1970); 2) both Corallina and encrusting algae are found most frequently in the confines of a rock pool; this sheltered environment would inhibit their distribution by waves and currents; 3) despite occasional thicknesses of 2-3 cm the encrusting algal layer is usually thin, about several mm in thickness.

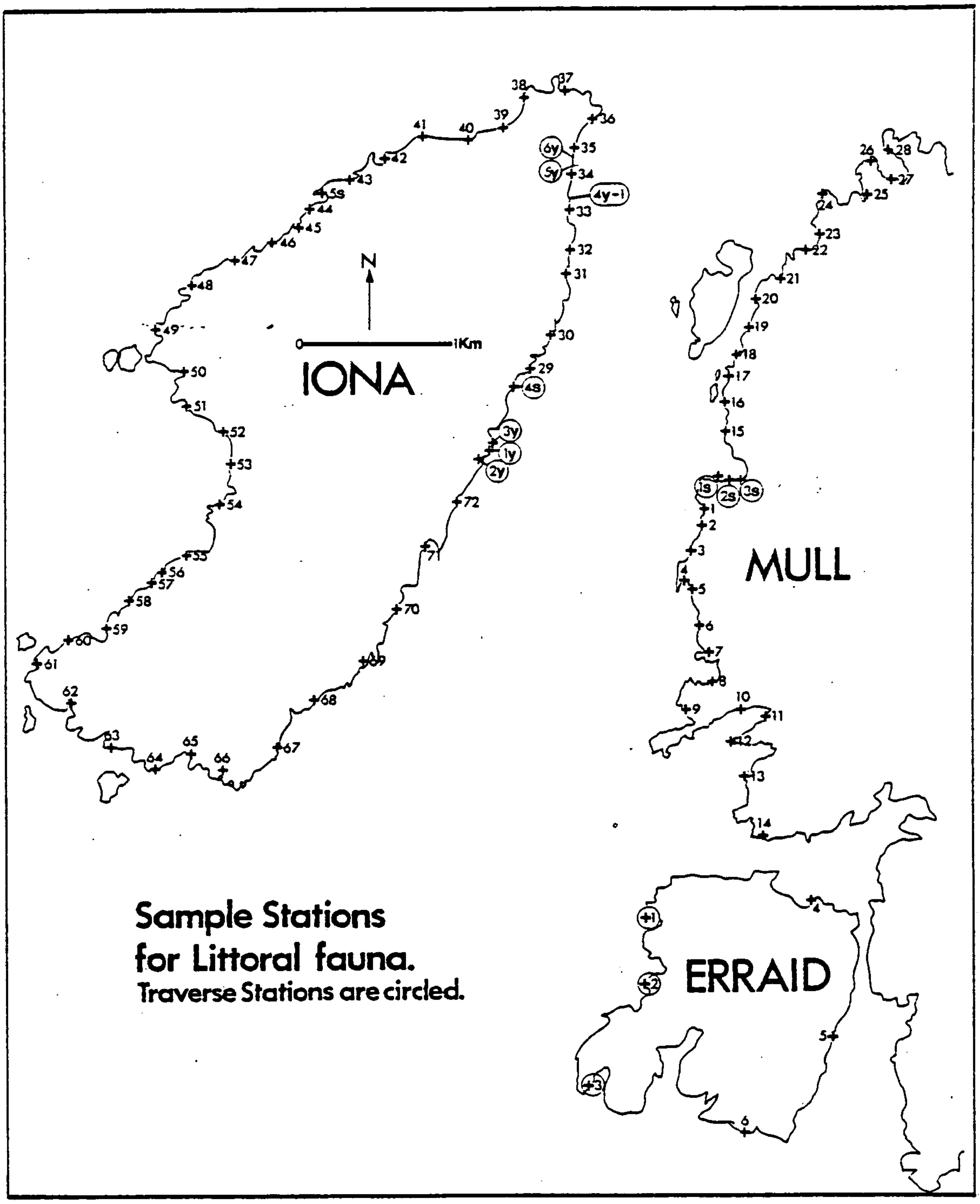
A more complex aspect of the eulittoral study involves the presence of soft-bodied algae attached to the rocks, including the fucoids and Pelvetia algae. They are locally abundant on the shore. In some transects the holdfasts occupy 90% of the shoreline. They would diminish the potential rock surface area for barnacle settlement. However, the fronds would provide a grazing surface for the gastropod Littorina spp. However, in this study mollusc population studies were confined solely to rock surfaces.

3.13 Sampling techniques and comment

3.13.1 Sampling techniques for population estimation.

Two techniques were used to measure eulittoral organism density: spot stations and lateral traverses. Spot stations were localities selected at regular intervals of 150-250 m along the shore of the Sound (Fig. 39) A 5 cm x 5 cm quadrat was placed upon a barnacle-encrusted rock face in the eulittoral zone, defined as the region above the laminarian algae zone (the average low water mark) and below the Pelvetia algae zone (the average high water mark). The small quadrat size was necessitated from the standpoint of practicality and

Fig. 39. Spot-and traverse stations on the shores of the Sound.



Sample Stations for Littoral fauna.
Traverse Stations are circled.

counting efficiency; this area could contain more than 100 barnacles. An attempt was made to obtain an unbiased sample by standing backwards to a eulittoral rock face and gently tossing the quadrat onto the rock face. A count of the number of living and dead, adult and fry barnacles within the quadrat was noted and recorded. The density of gastropods was measured over a larger area from 1 m^2 to >5 m^2 and would include the quadrat. The presence of coralline algae and the percentage weed cover was also noted. Traverse technique was derived from Stearn et. al. (1977). Traverses were conducted at selected areas of the Sound to record areal variations in organism density (Figs.39,40). Measurements were made by placing a nylon line on a eulittoral rock face, perpendicular to the shore line. Organisms lying under the line (barnacles, molluscs, weed etc.) were identified at 20 cm intervals from the laminarian zone to the Pelvetia zone. Upon completing a perpendicular traverse, a traverse was made parallel to the shoreline at the midpoint of the first traverse for an equal length and sampling interval.

3.13.2 Comments regarding estimates of organism density.

It is very difficult to make accurate large-scale quantitative estimates of standing crop for the eulittoral organisms because of the many variables involved. Distribution of intertidal animals is subject to local physical factors: exposure, angles of shore slope, nature of substrate, time of Extreme Low Water Spring tides, salinity, proximity to abrasive sand and many other parameters. Distribution is also affected by biological factors: time of year, spat settlement, biological competition, e.g. with fucoid algal settlement, predation, recruitment, seasonal or diurnal migration of vagile fauna etc. Therefore population number and distribution vary greatly both spatially and temporally within the framework of overall ecological equilibrium for the eulittoral zone.

Fig. 40. Schematic diagram of a traverse and quadrat sampling methods.

(after Lewis, 1964).

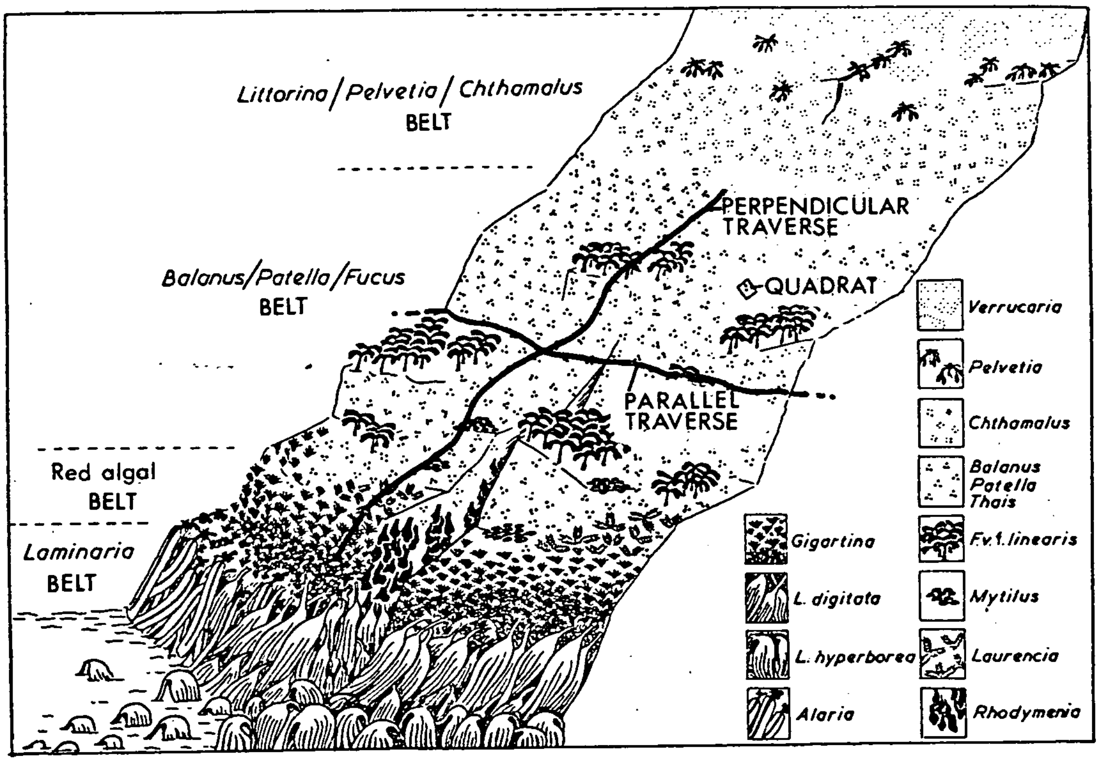
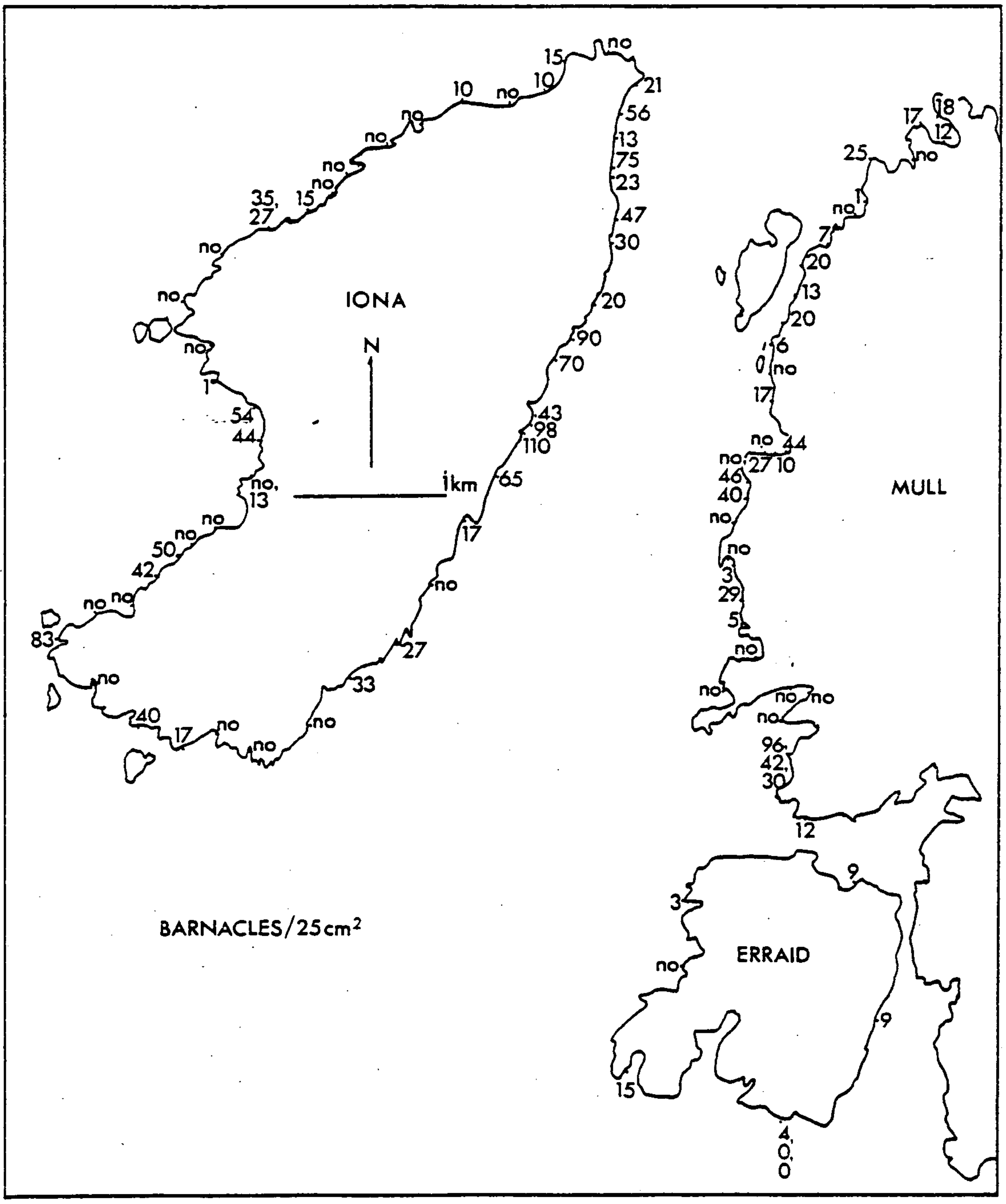

Littorina/Pelvetia/Chthamalus
BELT
Balanus/Patella/Fucus
BELT
Red algal
BELT
Laminaria
BELT
PERPENDICULAR
TRAVERSE
QUADRAT
PARALLEL
TRAVERSE
Verrucaria
Pelvetia
Chthamalus
Balanus
Patella
Thais
F.v.f. linearis
Mytilus
Laurencia
Rhodymenia
Gigartina
L. digitata
L. hyperborea
Alaria

Fig. 41. The numbers of large living _Balanus balanoides_ barnacles per 25 cm^2 as determined by quadrat counts at spot stations.


IONA
MULL
ERRAID
N
1km
BARNACLES/25cm²

Taking into account these secular variations as well as sampling errors, it is possible to do no more than reach an order of magnitude approximation as to the numbers of littoral carbonate shell producers with which to assess the importance of their contribution to carbonate sediments in the Sound of Iona.

3.14 Results of spot stations and traverse studies.

3.14.1 Results of the spot station studies.

Faunal data from spot stations are presented as organisms per cm^2 or per m^2. The results of the numbers of full-sized ("adult") living attached organisms are summarized from Fig. 41 and Table 13:

1. The Balanus[1] counts were highest on the wave sheltered east coast of Iona, particularly in the mid-point of the coastline. This suggests that the sand waves act to dispel destructive waves; it is also significant that the sandwaves have a local source of sediment supply.

2. Patella exhibited a distribution similar to that of barnacles with larger populations on the east coast of Iona; this close association is to be expected because barnacles settle in areas scraped clean of soft algae by browsing Patella (Lewis, 1964).

3. Littorinids have a very patchy distribution on Mull, Erraid and the west shore of Iona; they are virtually absent from the east coast of Iona. Subsequent to sampling it was learned that a commercial dealer of the periwinkle Littorina littorea is situated at Fionnphort on the shores of the Sound. Collection of this foodstuff on the easily accessible eastern shores of Iona may account for these low values.

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[1] Barnacles in the eulittoral zone are predominantly Balanus balanoides (Linnaeus). Chthamalus stellatus (Poli) and Chthamalus montagui (Southward) were noted at spot station 57 on the southwest coast of Iona. However, Balanus balanoides is the species found along the shores of the Sound and for this reason the barnacle population there may be regarded as monospecific.

Table 13A Average number of eulittoral specimens at spot stations for different sectors of the Sound.

n = number of observations; $\bar{x}$ = mean; sd = standard deviation; cv = coefficient of variation = $\frac{sd}{\bar{x}}$ x 100%.

Organism	W. Coast of Iona n = 30			E. Coast of Iona n = 22			Mull n = 35			Erraid n = 8		
	$\bar{x}$	sd	cv%	$\bar{x}$	sd	cv%	$\bar{x}$	sd	cv%	$\bar{x}$	sd	cv%
Balanus balanoides/25cm^2	15	22	150	39	33	80	15	20	130	5	6	120
Patella sp./m^2	43	95	220	75	136	180	11	35	320	2	6	300
Littorina sp./m^2	104	388	370	0	0	-	78	200	260	2	6	300
Thais lapillus/m^2	3	7	230	148	519	350	54	193	360	0	0	-
Mytilus edulis/m^2	4	9	230	3	11	370	0	0	-	0	0	-

Table 13 B Numbers of eulittoral molluscs/m^2 at spot stations for different sectors of the Sound.

Note: n.o. = not observed.

Station	*Patella* sp.	*Littorina* sp.	*Thais lapillus*	*Mytilus edulis*
E. Coast of Iona				observed at only one station, 69.
36	2	n.o.	n.o.	
35	28	n.o.	n.o.	
34	48	n.o.	16	
4Y	1	n.o.	n.o.	
33	8	1	n.o.	
32	13	n.o.	12	
31	48	n.o.	2	
30	96	n.o.	1	
29	40	n.o.	52	
4S	70	1	n.o.	
3Y	1	n.o.	n.o.	
1Y	2	n.o.	1	
2Y	n.o.	n.o.	n.o.	
72	89	1	4	
71	89	n.o.	65	
70	n.o.	n.o.	80	
69	n.o.	n.o.	2400	54
68	112	n.o.	24	
67	4	n.o.	600	
66	300	n.o.	n.o.	
65	600	n.o.	n.o.	
64	100	n.o.	n.o.	
W. Coast of Iona				observed only at stations shown
37	48	222	n.o.	
38	12	5	n.o.	
39	n.o.	n.o.	n.o.	
40	1	1	n.o.	
41	2	800	n.o.	
42	1	8	n.o.	
43	500	64	n.o.	
5S	5	2000	n.o.	
44	n.o.	n.o.	n.o.	
45	64	n.o.	16	
46	48	n.o.	1	
47	n.o.,150	n.o.	n.o.,16	
48	n.o.	n.o.	1	
49	2	n.o.	12	
50	64	n.o.	1	
51	2	n.o.	n.o.	
52	4	n.o.	n.o.	
53	n.o.	4	n.o.	
54	125, 32	24,n.o.	n.o.,16	
55	1	n.o.	n.o.	
56	32	n.o.	n.o.	18
57	20	n.o.	n.o.	8
58	20	n.o.	n.o.	14
59	90	n.o.	n.o.	
60	48	n.o.	n.o.	10
61	n.o.	n.o.	n.o.	37
62	20	n.o.	24	13
63	n.o.	n.o.	1	28

Table 13B(cont.)

Station	Patella sp.	Littorina sp.	Thais lapillus	Mytilus edulis
Coast of Mull				not observed at any Mull stations
28	n.o.	n.o.	n.o.	
27	4	800	n.o.	
26	n.o.	200	n.o.	
25	n.o.	48	n.o.	
24	1	1	n.o.	
23	1	16	n.o.	
22	n.o.	n.o.	800	
21	8	n.o.	8	
20	200	n.o.	n.o.	
19	n.o.	n.o.	n.o.	
18	n.o.	n.o.	n.o.	
17	1	2	n.o.	
16	3	n.o.	8	
15	2	n.o.	n.o.	
3S	n.o.	n.o.	n.o.	
2S	n.o.	n.o.	n.o.	
1S	1	n.o.	n.o.	
Pier	8	12	40	
1	n.o.,1	n.o.	n.o.	
2	4	8	n.o.	
3	n.o.	128	n.o.	
4	4	300	n.o.	
5	55	4	n.o.	
6	16	n.o.	16	
7	5	4	n.o.	
8	8	300	n.o.	
9	16	n.o.	800	
10	n.o.	n.o.	96	
11	n.o.	800	n.o.	
12	1	1,32	n.o.	
13	24,3	n.o.	n.o.	
14	n.o.	n.o.	4	
Erraid				not observed at any Erraid stations
1	n.o.	1	n.o.	
2	n.o.	n.o.	n.o.	
3	n.o.	n.o.	n.o.	
4	n.o.	n.o.	n.o.	
5	n.o.	n.o.	n.o.	
6	n.o.n.o.,18	2xn.o.,16	n.o.	

4. *Thais* have very patchy distributions on all shores but the largest populations are found on the eastern shore of Iona. They are predators of *Balanus* (Lewis, 1964) hence the largest number of the dogwhelksare found where there is the greatest barnacle population.

5. *Mytilus* is infrequently observed in the Sound's environs. It is confined to the wave exposed southern half of Iona and entirely absent on Mull and Erraid. It is an organism which favours very exposed shores (Lewis *op. cit.*).

3.14.2 Results of the transect studies.

The calculations for the percentage occurrence of nine eulittoral groups can be found in Table 14. The significant aspects are summarized here:

1. Bare rock, averaging 41% of all observations, dominates the eulittoral zone, but the variability is great, from a low value of 3% at station 2 on Erraid, to 96% at station 6Y on Iona.

2. Barnacles are the most areally dominant organisms. They are found over 24% of the eulittoral rock zone. Variability is large with values of 3% encrustation at station 2 on Erraid, but 62% of the rock area at station 4Y on Iona is covered with barnacles.

3. Soft algae, principally fucoids are the next most abundant organisms. They have an average coverage of 14% of the rock surface. Values range from 48% at station 2 on Erraid to complete absence from station 6Y on Iona.

4. Encrusting red algae can be locally very abundant, e.g. they occupy 25% of the rock surface at station 1 on Erraid. Their skeletal fragments are rarely encountered in sediment samples and this probably results from a low production rate and a crustose existence in sheltered rock pools.

Table 14. Percentage of occurrence of 9 groups of organisms in the eulittoral zone as determined by transect studies; n = number of transect counts, $\bar{x}$ = mean.

Station	Station	*Balanus*		*Littorina*		*Thais*		*Patella*		encrusting coralline algae		soft algae		lichen		bare rock		other		
	n	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	
Iona: 1Y	72	21	29	0	0	1	1	4	6	3	4	27	38	0	0	16	22	0	0	
2Y	91	25	27	1	1	0	0	0	0	0	0	20	22	0	0	44	48	1	1	(sand)
3Y	87	41	47	0	0	0	0	2	2	9	10	1	1	7	8	25	29	2	2	(*Corallina*)
4Y	81	50	62	0	0	0	0	1	1	3	4	10	12	0	0	16	20	1	1	(sand)
5Y	76	7	9	0	0	0	0	1	1	2	3	5	7	0	0	60	79	1	1	(sand)
6Y	81	3	4	0	0	0	0	0	0	0	0	0	0	0	0	78	96	0	0	
4S	93	48	52	1	1	0	0	1	1	5	5	2	2	0	0	34	37	2	2	(sand)
	$\bar{x}$ =		33		0.3		0.1		1.6		4		12		1.1		47		1	
Mull: 1S	76	15	20	0	0	0	0	1	1	0	0	4	5	1	1	34	45	9 9 3	12 12 4	(cobble) (pebble) (sand)
2S	72	6	8	1 (gastropod not specified)			1%	0	0	3	4	7	10	5	7	45	63	3 2	4 3	(boulder) (sand)
3S	80	8	10	0	0	0	0	0	0	0	0	4	5	2	3	21	26	21 18 2 4	26 23 3 5	(boulder) (cobble) (pebble) (sand)
	$\bar{x}$ =		13		0		0		0.5		1.3		7		4		25		31	
Erraid: 1	63	4	6	2	3	0	0	3	5	16	25	10	16	3	5	9	14	1 6 4 4 1	2 10 6 6 2	(*Corallina*) (spirorbis) (boulder) (cobble) (sand)
2	60	2	3	1 (gastropod not specified)			2%	0	0	5	8	29	48	0	0	2	3	7 5 1 4 4	12 8 2 7 7	(*Corallina*) (*Spirorbis*) (sponge) (sand) (water)
3	167	53	32	0	0	0	0	2	1	2	1	14	8	0	0	96	57	0	0	
	$\bar{x}$ =		14		1.5		0		2		11		24		2		25		21	
Total n	1099																			
Average of all values	$\bar{x}$ =		24		0.5		0.1		1.4		5		13		2		41		12	

5. Corallina, Spirorbis are occasionally found at some traverse stations; they have very minor overall importance.

6. The molluscs Mytilus, Littorina, Patella and Thais have a very localized distribution but can be present in large numbers in aggregates. This contrasts with the spot station measurements which show they can be quite abundant though over very small areas.

3.15 Experimental eulittoral encrustation studies.

Studies were conducted at three sites in the eulittoral zone of the Sound to observe the rates of barnacle shell production of a sheltered rock face versus an exposed rock face. Two sites were selected close to station 3Y on the land and sand-wave sheltered eastern coast of Iona. The third site was situated at the wave-exposed shores of station 13 on Mull. The encrusted rock faces were scraped clean of organisms at these three localities. The carbonate contents were identified and weighed (Table 15). The rock faces were re-examined at 1 yr and 2 yr intervals.

The Iona sites were re-colonized most quickly. Barnacles returned after 1 yr exploiting rock surface irregularities formed by fractures; the sites were completely re-encrusted after two years (Fig. 42). The Mull site, though only receiving 1 yr of study, showed markedly less re-colonization than the Iona sites for the same time interval. At this site the juvenile barnacles only appeared at the periphery of the scraped face, whereas at the Iona localities juveniles dot the entire face.

The significance of the study is that highest productivity occurs in the wave-sheltered sites of the Sound. Hence the densest barnacle encrustation areas are found on the central east coast of the Sound. Dense population implies large production of sediment hence a thick

Table 15. Eulittoral carbonate encrustation study of Balanus balanoides and Patella sp; note: nd = not determined

Station	Iona Barnacle 1	Iona Barnacle 2	Mull Barnacle
Location	30m S. of station 3Y	10m N of 3Y	at station 13
Total area cm^2	543	554	613
Original encrustation:			
B. balanoides density 4mm diam. living per $25cm^2$	approx 50	approx 75	30
Mollusc density per total area sampled	4 Patella, length 1-2.3cm approx 150 ?rissoidae gast./$543cm^2$	2 Patella length 1cm	none
Carbonate + organic wt. per total area (no salt correction)	61.2	88.9	61.2
Barnacle carbonate + org (6%/w) wt. gms	59.5	88.8	60
Mollusc wt. gms. Shell only	1.8	0.13	1.0
New encrustation after 1yr:			
B. balanoides density 2-3mm diam. living per $25m^2$	150	64	34 confined to perimetry of site
Mollusc density per total area	1 Patella length 1.8m 3 littorinids length 2mm	4 littorinids length 2mm	no new colonization
Balanus wt. gms per $25cm^2$	0.33	0.10	nd
Mollusc wt. gms. per total area	0.34 Patella, littorinids = nd	0.02 littorinids	nd
Calculated new encrustation weights per total area, gms.	7.2	2.2	trace (0.05)

Fig. 42 A. Iona barnacle station 1 after scraping the rock bare.

B. Iona barnacle station 2 after scraping the rock bare.

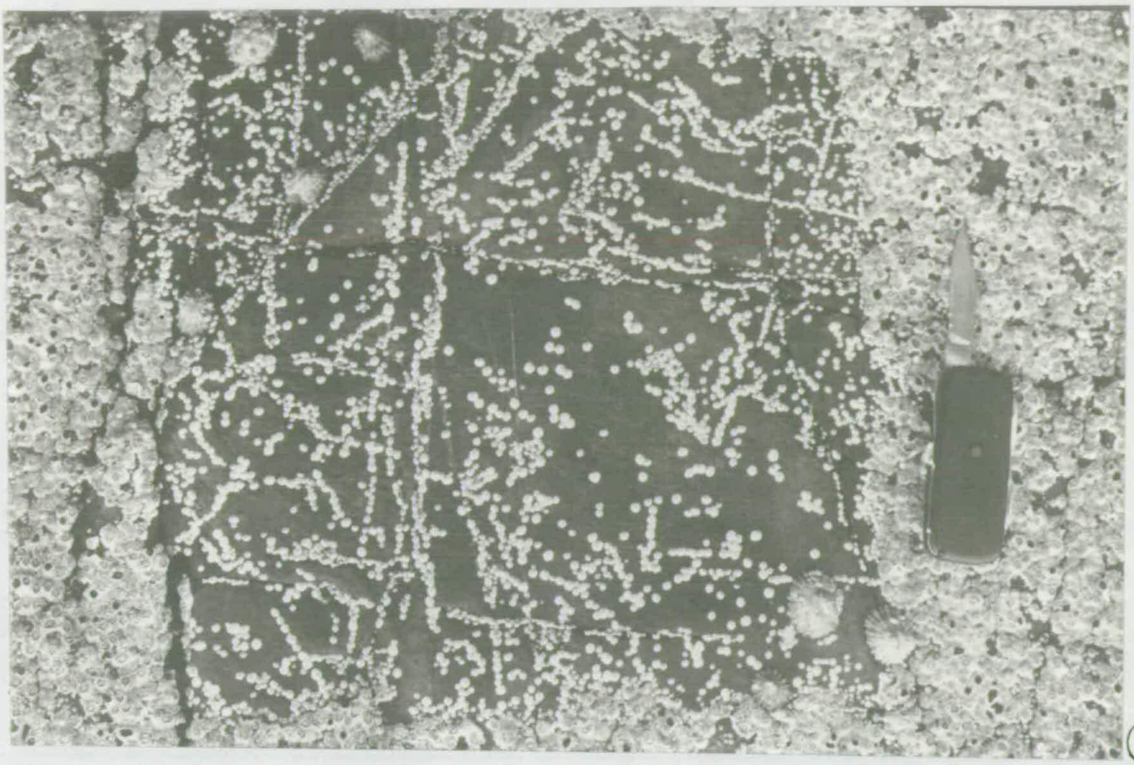

A


B

Fig. 42 C. Iona barnacle station 1 after 1 year re-encrustation.

D. Iona station 2 after 1 year re-encrustation.

Encrustation occurs along rock fracture at both stations.


C

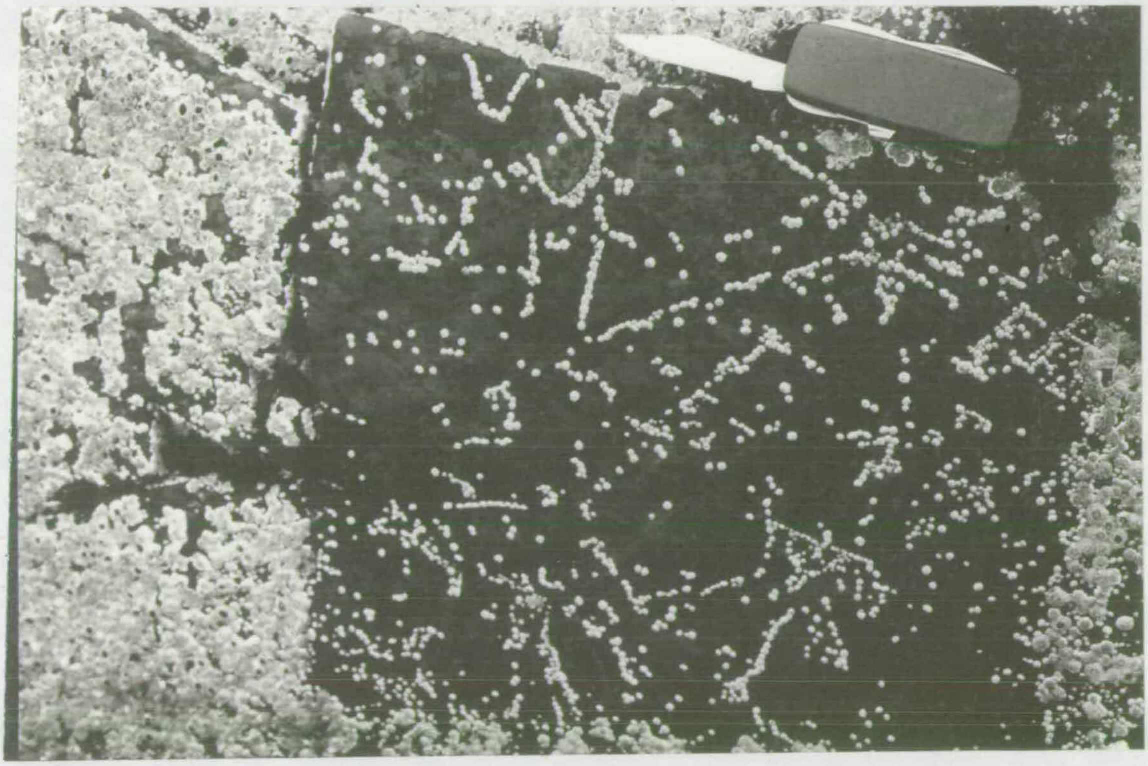
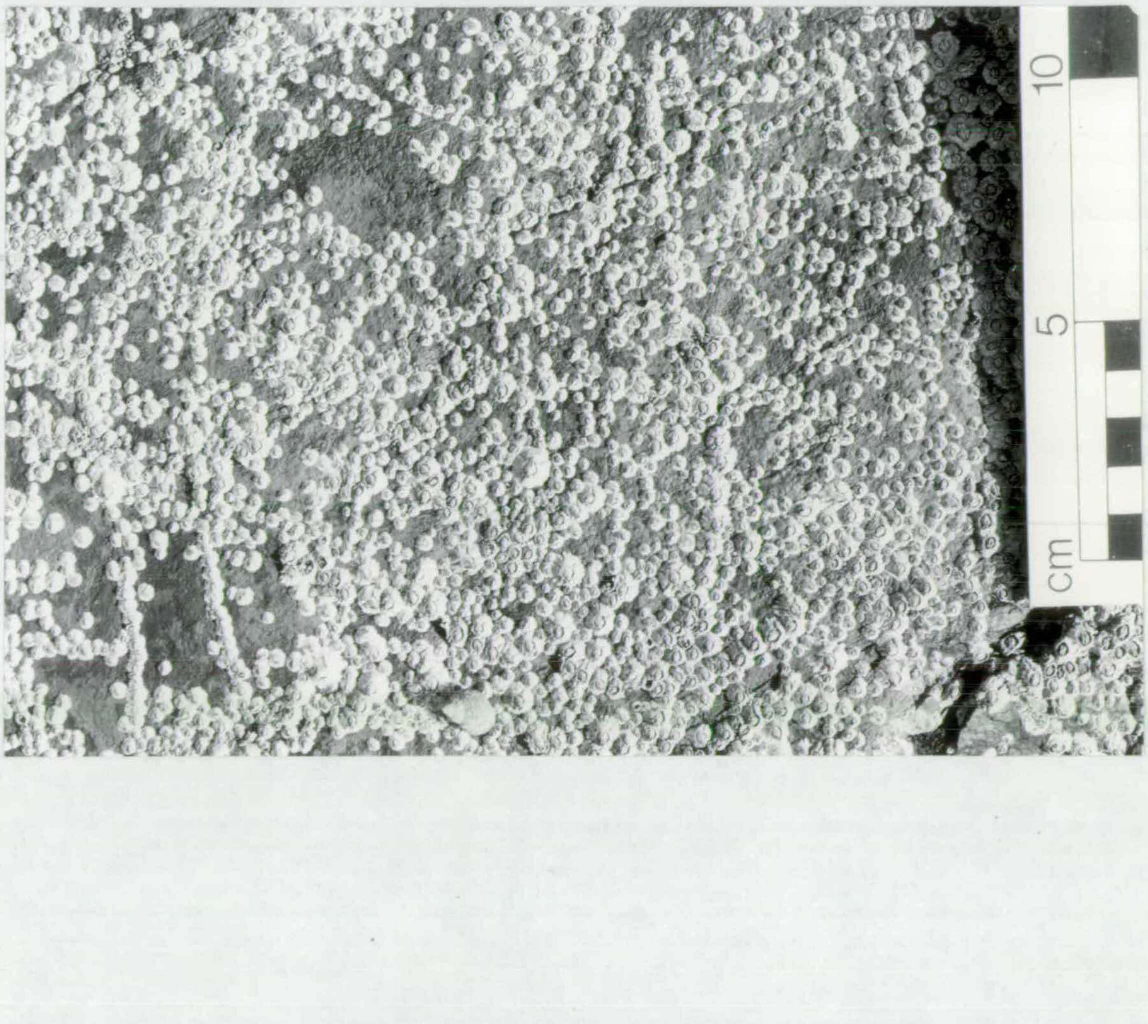

D

Fig. 42 E. Iona barnacle station 1 after 2 years of re-encrustation.

F. Iona barnacle station 2 after 2 years of re-encrustation.

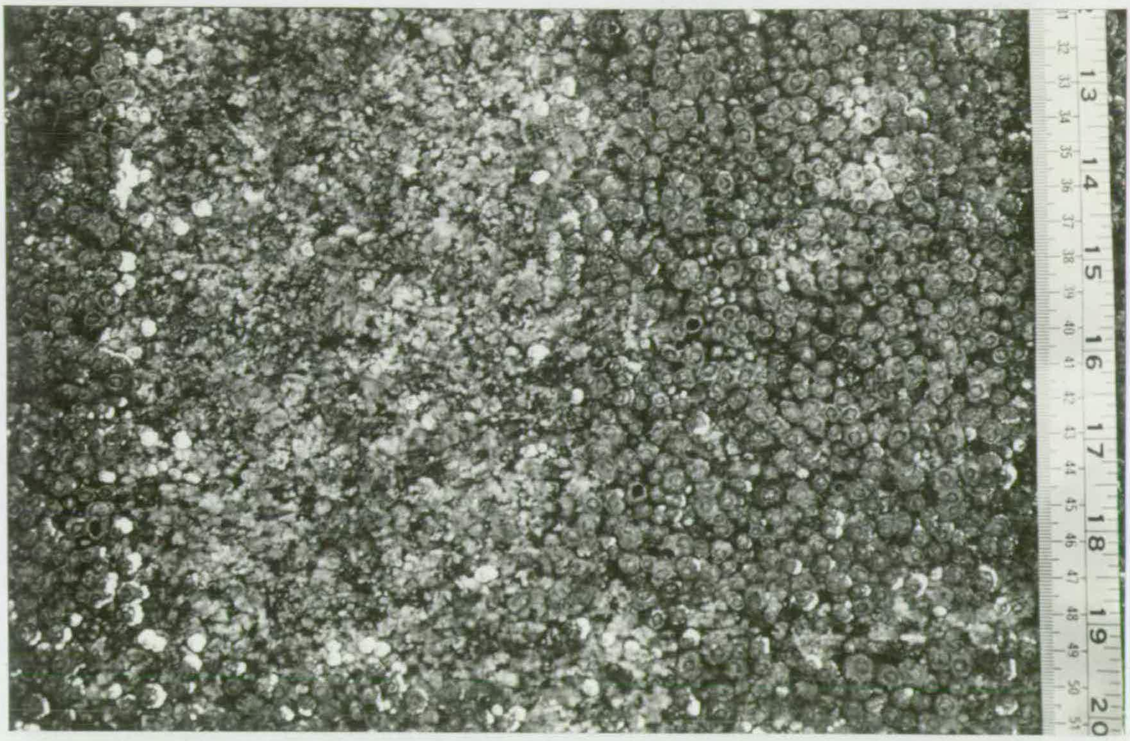
Encrustation is virtually complete.

E



F

Fig. 42 G. Mull barnacle station 13 after 1 year of re-encrustation (white spots = new organisms). Very little new encrustation occurred at this very exposed locality.



sediment bed was observed. The slower barnacle production on Mull demonstrates the detrimental effect of waves to barnacle propagation at exposed areas. This accounts for the low barnacle densities on exposed areas of Mull and western Iona. It also explains the thin sediment cover observed by seismic instruments in these areas.

3.16 Fauna of eulittoral zone sediment - evidence from shells.

The eulittoral rock faces contain abundant barnacle populations and much smaller mollusc populations. However, there are significant amounts of shell material originating from the sediment of the eulittoral zone. Organisms are known predominantly from shell material because of the difficulty in sampling living burrowing organisms. Shell material in the eulittoral zone principally consists of molluscs (Fig. 43). The mollusc material is commonly composed of:

1. a gastropod epifauna: *Gibbula cineraria*, *Littorina littoralis*, *L. littorea*, *L. saxatilis*, *Nassarius incrassatus*, *Patella* sp., *Patina pellucida* and *Thais lapillus*.

2. a eulittoral bivalve infauna: *Lucinoma borealis*, *Lutraria lutraria*, *Mya truncata*, *Venerupis pullastra* and *Venus striatula*.

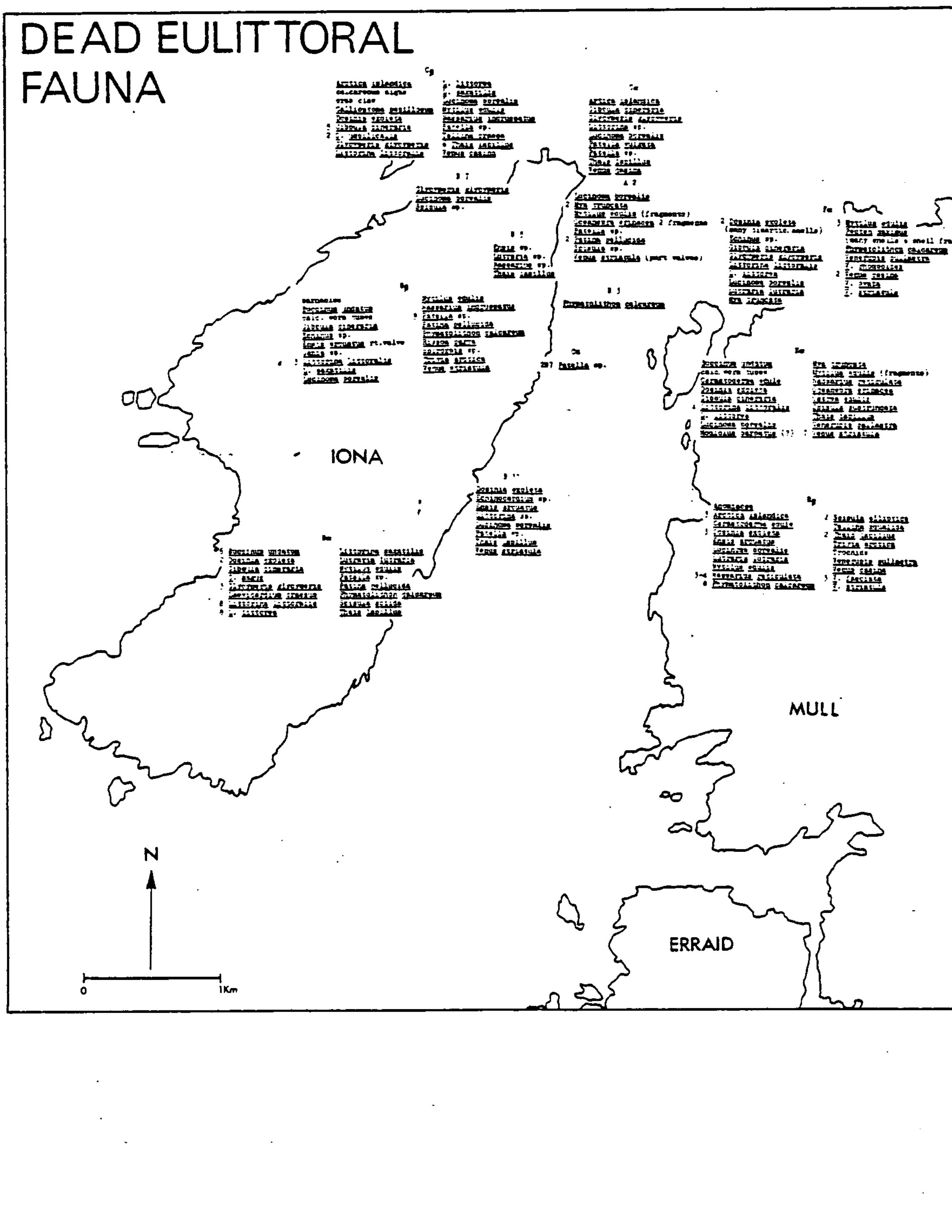
3. a bivalve epifauna: *Mytilus edulis*; this was found on the eulittoral rock faces but it can also live attached to cobbles, boulders etc.

4. material derived from adjacent sub-littoral areas: the bivalves *Glycymeris glycymeris* and *Venus casina*, the gastropod *Buccinum undatum* and the coralline alga *Phymatolithon calcareum*.

The ranges of many of the molluscs extend into the sublittoral zone (Campbell and Nicholls, 1976), *e.g.* *Gibbula*, *Nassarius*, *Patina* and all of the bivalves.

The significance of these observations is that there is a reservoir of mollusc material in the eulittoral zone where it can be readily

Fig. 43. Identities of dead eulittoral macrofaunal shell material.


DEAD EULITTORAL FAUNA
IONA
MULL
ERRAID
N
0
1Km

attacked by waves and transported by tidal and wave-generated currents.

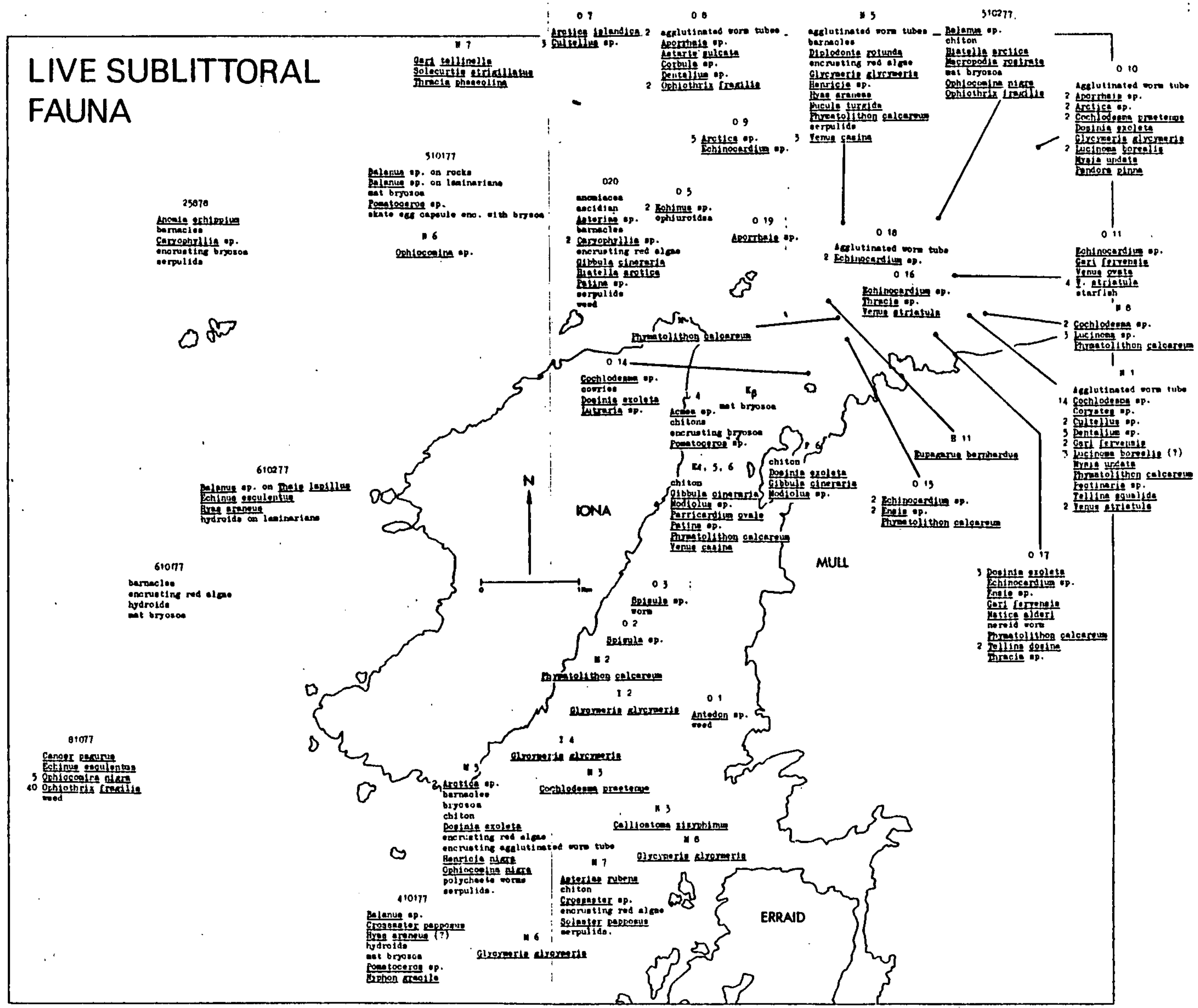
3.17 Living organisms of the sublittoral environment.

An encrusting fauna and flora dominate the boulder fields to the south and west of Iona (Fig.44A). Common organisms include balanoid barnacles, serpulid worms, mat-like bryzoa and encrusting red algae. Mobile epilithic echinoderms such as *Echinus* sp., *Ophiocomina nigra*, *Ophiothrix* sp. and *Crossaster papposus* are observed. Molluscs are not abundant.

Glycymeris glycymeris and *Spisula* sp. are observed in the sparsely populated southern platform and the central shoals of Iona. However, the diversity of species increase markedly in the northern platform beginning at the coralline algal banks. The banks themselves are locally important, as noted previously, as producers of *Phymatolithon calcareum* (Fig. 44A). Diversity is more marked in the shell sand areas beyond the maerl banks. Molluscs dominate, especially the burrowing bivalves *Arctica islandica*, *Cochlodesma praetenne*, *Cultellus pellucidus*, *Dosinia exoleta*, *Gari fervensis*, *Lucinoma borealis*, *Thracia phaseolina* and *Venus striatula*. Other common carbonate organisms include the burrowing gastropod *Aporrhais pespelicani*, the burrowing echinoid *Echinocardium* sp. and occasional specimens of *P. calcareum*.

In summary, the most prolific areas of skeletal carbonate production lie in the barnacle shell sands to the north of the Sound. This supports the contention of Lees *et.al.* (1969) that shelled epilithic organisms provide a substrate by gradual deposition of their shells.(Fig.44B). This sediment provides a substrate for burrowing organisms. Within the sublittoral area of the Sound the sole area of any appreciable numbers of living organisms is the maerl banks of the northern platform. This area would be favourable because of its wave shelter and the

Fig. 44 A. --Identities of living sublittoral macrofaunal shell material.



LIVE SUBLITTORAL FAUNA
N 7
Gari tellinella
Solecurtis strigillatus
Thracia phaseolina
O 7
Arctica islandica 2
5 Cultellus sp.
O 8
agglutinated worm tubes
Aporrhais sp.
Astarte sulcata
Corbula sp.
Dentalium sp.
2 Ophiothrix fragilis
N 5
agglutinated worm tubes
barnacles
Diplodonta rotunda
encrusting red algae
Glycymeris glycymeris
Henricia sp.
Hyas araneus
Nucula turgida
Phymatolithon calcareum
serpulids
5 Venus casina
510277
Balanus sp.
chiton
Hiatella arctica
Macropodia rostrata
mat bryozoa
Ophiocomina nigra
Ophiothrix fragilis
O 10
Agglutinated worm tube
2 Aporrhais sp.
2 Arctica sp.
2 Cochlodesma praetenue
Dosinia exoleta
Glycymeris glycymeris
2 Lucinoma borealis
Mysia undata
Pandora pinna
O 9
5 Arctica sp.
Echinocardium sp.
510177
Balanus sp. on rocks
Balanus sp. on laminarians
mat bryozoa
Pomatoceros sp.
skate egg capsule enc. with bryozoa
N 6
Ophiocomina sp.
25878
Anomia ephippium
barnacles
Caryophyllia sp.
encrusting bryozoa
serpulids
020
anomiacea
ascidian
Asterias sp.
barnacles
2 Caryophyllia sp.
encrusting red algae
Gibbula cineraria
Hiatella arctica
Patina sp.
serpulids
weed
O 5
2 Echinus sp.
ophiuroidea
O 19
Aporrhais sp.
O 18
Agglutinated worm tube
2 Echinocardium sp.
O 16
Echinocardium sp.
Thracia sp.
Venus striatula
O 11
Echinocardium sp.
Gari fervensis
Venus ovata
4 V. striatula
starfish
N 8
2 Cochlodesma sp.
3 Lucinoma sp.
Phymatolithon calcareum
Phymatolithon calcareum
O 14
Cochlodesma sp.
cowries
Dosinia exoleta
Lutraria sp.
I 4
Acmea sp.
chitons
encrusting bryozoa
Pomatoceros sp.
mat bryozoa
N 1
Agglutinated worm tube
14 Cochlodesma sp.
Corystes sp.
2 Cultellus sp.
5 Dentalium sp.
2 Gari fervensis
3 Lucinoma borealis (?)
Mysia undata
Phymatolithon calcareum
Pectinaria sp.
Tellina squalida
2 Venus striatula
B 11
Eupagurus bernhardus
610277
Balanus sp. on Thais lapillus
Echinus esculentus
Hyas araneus
hydroids on laminarians
N
IONA
K4, 5, 6
chiton
Gibbula cineraria
Modiolus sp.
Parricardium ovale
Patina sp.
Phymatolithon calcareum
Venus casina
chiton
Dosinia exoleta
Gibbula cineraria
Modiolus sp.
O 15
2 Echinocardium sp.
2 Ensis sp.
Phymatolithon calcareum
MULL
610177
barnacles
encrusting red algae
hydroids
mat bryozoa
O 17
3 Dosinia exoleta
Echinocardium sp.
Ensis sp.
Gari fervensis
Natica alderi
nereid worm
Phymatolithon calcareum
2 Tellina donax
Thracia sp.
O 3
Spisula sp.
worm
O 2
Spisula sp.
N 2
Phymatolithon calcareum
I 2
Glycymeris glycymeris
O 1
Antedon sp.
weed
61077
Cancer pagurus
Echinus esculentus
5 Ophiocomina nigra
40 Ophiothrix fragilis
weed
I 4
Glycymeris glycymeris
N 3
2 Arctica sp.
barnacles
bryozoa
chiton
Dosinia exoleta
encrusting red algae
encrusting agglutinated worm tube
Henricia nigra
Ophiocomina nigra
polychaete worms
serpulids.
N 3
Cochlodesma praetenue
N 3
Calliostoma zizyphinum
N 8
Glycymeris glycymeris
N 7
Asterias rubens
chiton
Crossaster sp.
encrusting red algae
Solaster papposus
serpulids.
ERRAID
410177
Balanus sp.
Crossaster papposus
Hyas araneus (?)
hydroids
mat bryozoa
Pomatoceros sp.
Xyphon gracile
N 6
Glycymeris glycymeris

Fig. 44 B. Resin impregnation of a Barnett-Hardy suction bin sample showing mollusc colonization of sediment produced by barnacles (station N8).

Top

transport resistance of Phymatolithon. There is sparce living fauna on either the central shoals where there are swift currents which constantly shift sediment, or on the southern platform which lies open to severe storm wave attack.

3.18 Special studies of sublittoral organisms.

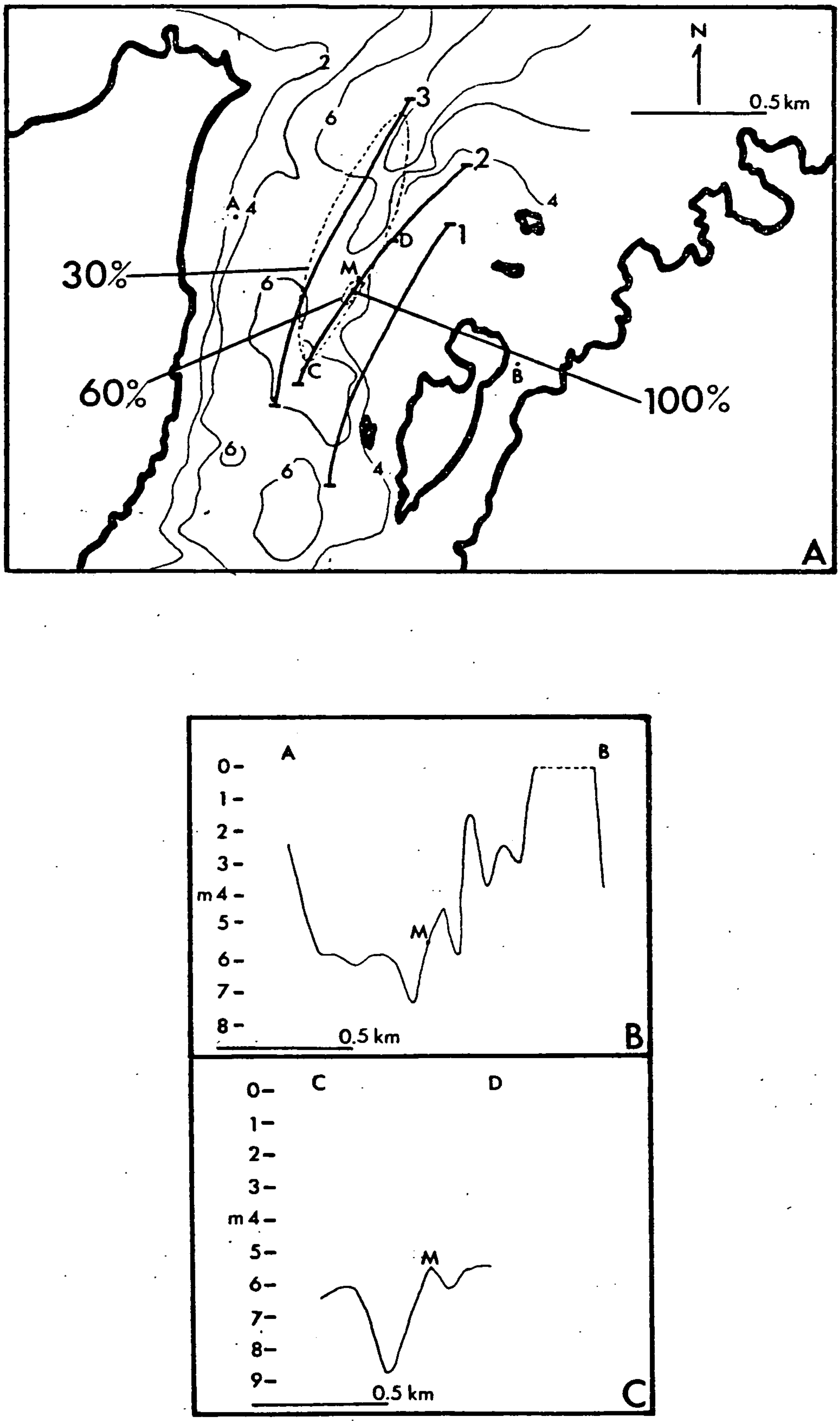
3.18.1 The maerl deposit : recap of previous concepts; form studies.

As noted in previous sections, the maerl deposit received detailed study because of the uniqueness of the deposit and the dearth of data regarding its formation. Diving observations showed that this free-living alga interlocks with adjacent thalli as a "living bedform" into a series of symmetrical and asymmetrical megaripples (Fig.25). A velocity study (Fig.34) shows that tidal currents at the sea bed are not sufficient to transport the thalli; Lees et. al. (1969) have shown that only wave activity can form ripples in the Scottish maerl. From towboard observations (see appendix 2 for details of this technique), the densest amount of living maerl cover borders a small sea bed depression approximately 2 m deep on the northern platform (Fig. 45). The percentage of living algae diminishes upslope in all directions away from this central core (Fig. 45). The percentage living algae is further reduced towards the northern deeper waters where, as noted before, some living specimens are recovered. No living corallines are found on the central shoals. On the wave-exposed southern platform live maerl is rare; living specimens were found on the area of this platform near the central shoals. The proportion of living cover bears direct relation to the degree of wave shelter and mobility of the sediment. The sheltered inner northern platform provides enough protection so that long-fetch slow waves do not effect the deposit. Locally generated waves do form on the platform, attack and destroy the periphery of the deposit (Fig.33) and

Fig. 45. Mapping of the maerl area by a submersible tow-board.

A. The three tracks of the tow-board, percentage living maerl cover (0-30%, 30-60%, 60-100%) and bathymetry shown in metres.

B and C. Cross section of the sea bed in the maerl area. M = maerl = station H12.


N
0.5 km
30%
60%
100%
A
B
C
D
M
1
2
3
4
6
0-
1-
2-
3-
m 4-
5-
6-
7-
8-
9-

create megaripples in the central core. On the central shoals the constantly shifting sands would smother maerl thalli hence these shoals are virtually devoid of the alga. The strong wave activity on the southern platform severely restricts the sites of viability to scattered sites south of the central shoals.

Bosence (1976) suggested that the form of an algal thallus and the branch density was related to wave exposure; platy and densely branched forms are found in exposed areas, spheroidal and open-branched forms in quiet areas. Thalli structure was studied using his techniques (see appendix 2). In the Sound open-branched forms are found on both the northern and southern platform areas (Fig. 46), however, an analysis of plots of growth forms (Fig . 47) show no shape preference at the sites investigated. Densely branched forms are confined to one station H4 on the southern platform where they are mixed with open-branched forms. However, all specimens were dead at this station, and forms may be relict of a different hydrodynamic environment. Bosence's hypothesis can not be denied nor can it be confirmed by my data, but there is a significant conclusion to be drawn from the form studies, relating to sediment provenance and production. Sparsely branched forms are resistant to tidal current transport (Bosence, op. cit.) but vulnerable to wave transport (Lees et. al., 1969). It is suggested that the maerl periphery deposit of broken thalli is due to this open branch structure; it is a structure suited to current resistance but vulnerable to wave attack.

3.18.2 Algal studies using an artificial substrate.

Alizarin-Red S stained thalli of Phymatolithon calcareum were wired down to a small seabed platform (substrate) placed near Eilean nam Ban at a depth of 6 m (see appendix 2). The staining technique was derived from a coral growth measuring method of Barnes (1972).

Fig. 46. Examples of different types of algal thalli in the Sound.

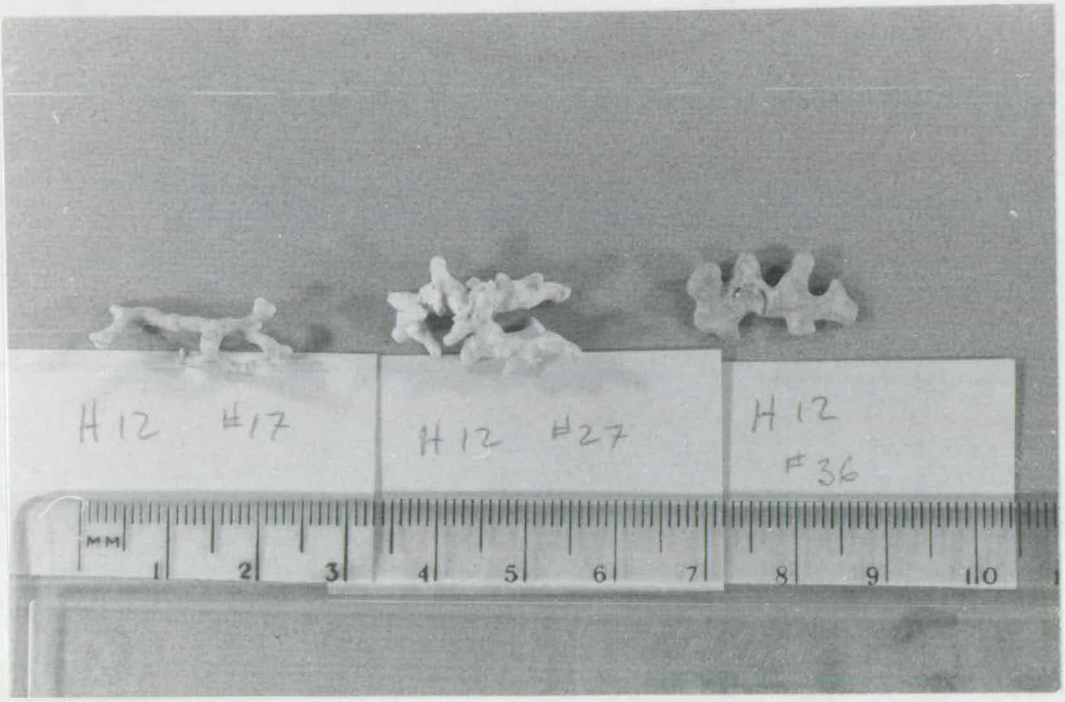
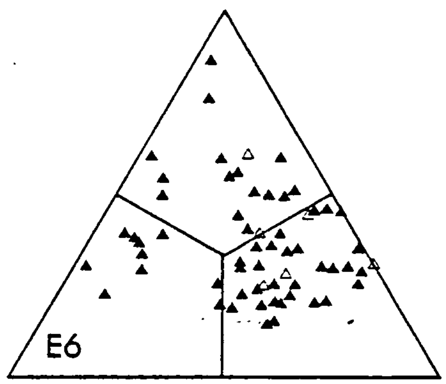
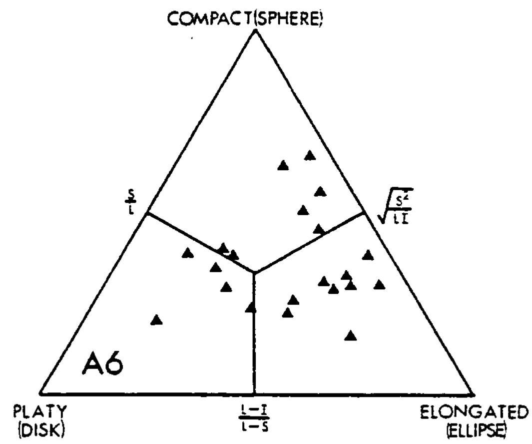
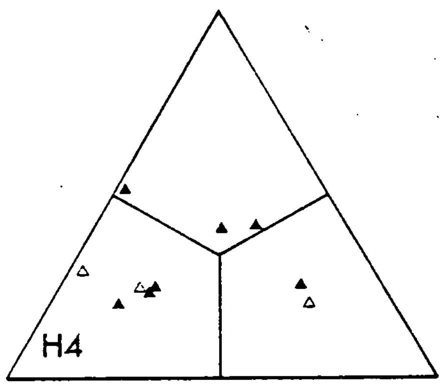
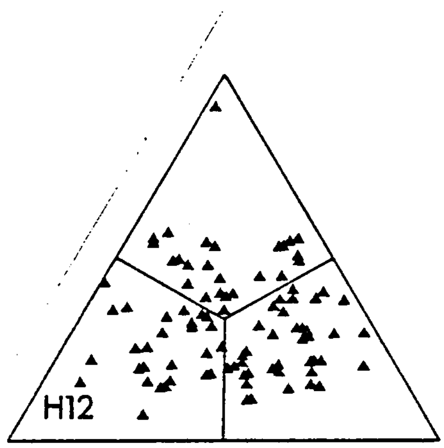

H12 #17
H12 #27
H12
#36
MM
1
2
3
4
5
6
7
8
9
10

Fig. 47. Classification of _Phymatolithon_ thalli according to the technique of Bosence (1976).


E6


COMPACT(SPHERE)
S/L
√(S²/LI)
A6
PLATY (DISK)
L−I/L−S
ELONGATED (ELLIPSE)


H4


H12

It was hoped that new carbonate growth would occur over the stained layer and provide an indication of the growth rate. Unfortunately the stain did not take to thallus; it is thought that stain times greater than 2 hr as tried here might be needed.

Despite the lack of staining success, the recovery revealed some interesting information; the thalli originally tied with wire twisted many times was now free from the wire, the thalli, carefully selected because of their large (≥ 2.5 cm) length and nearly 100% living thalli, were broken and some were completely dead. The substrate legs were buried by 10 cm of sediment.

The interpretation of these observations are as follows:

1. oscillatory tidal currents freed the thalli from their twisted retaining wire, abrading and killing all or parts of the thallus;
2. the rotary motion of (storm) waves raised and lowered the thalli off the substrate breaking them against the side and base of the apparatus.

The significance of the studies is it shows the detrimental effect to maerl of the combination of tidal currents and waves. This explains the dearth of live algae at the margins of the maerl deposit as well as explaining the small numbers of live algae near the central shoals.

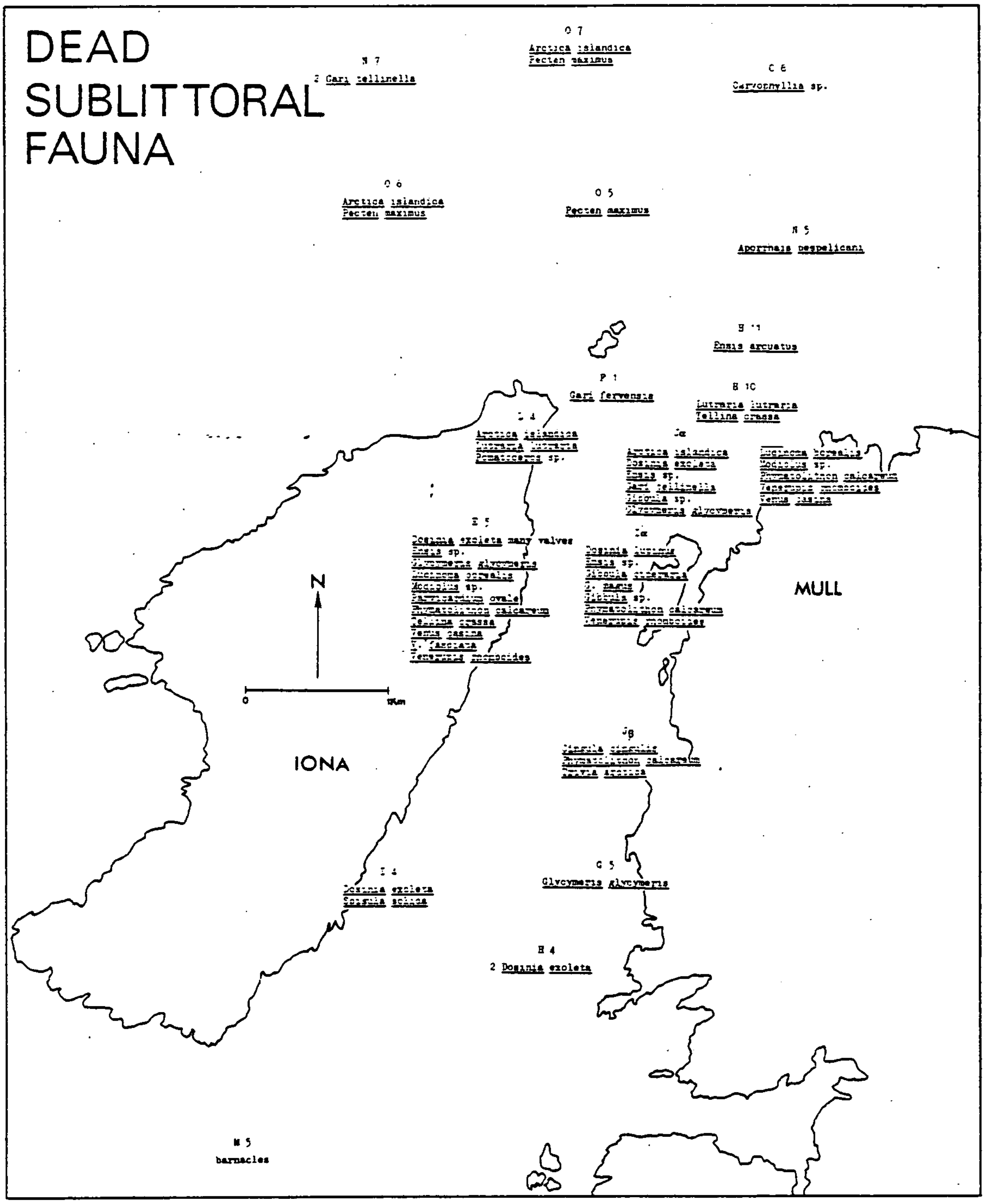
3.18.3 Barnacle encrustation of the artificial substrate.

Upon retrieval of the substrate it was noted that the shallow-sublittoral barnacle Balanus crenatus had almost entirely encrusted the originally barren metal portion of the apparatus. Barnacle densities reached as high as 76, 5 mm diameter individuals per 25 cm^2. Such values are very comparable to the highest encrustation densities observed on the eulittoral rocks of the Sound. Groups of barnacles covering a known area were weighed after oven-drying. The weight result (7.6 $gm/25cm^2$) showed that the 1.3 m^2 surface areas of the metal substrate frame had an encrustation weight of 4 kg. The importance of this data is that it shows that sublittoral rock faces can be important suppliers of barnacle shell sand.

3.19 Dead sublittoral fauna.

Shifts in the faunal and floral diversity are reflected in the dead shell assemblages around the Sound (Fig. 48). Dead shells are entirely lacking from the southern platform - deep water areas south of Erraid. This reflects the removal of shell material either to the interstices between the boulders or the breakdown and transport out of the area entirely. On the southern platform shells of the burrowing bivalves Glycymeris glycymeris, Dosinia exoleta and Spisula sp. are found because living examples of these species are found in the area. Predictably few dead organisms were recovered in the central shoals - for no living organisms were found here. The greatest abundance of dead shell material is found in the maerl area of the northern platform (Fig. 48). The diversity of bivalve and gastropod species exceeds that of the living fauna; Dosinia sp., Ensis sp., Venus sp., and Venerupis rhomboides are commonly found in this area. This suggests that the shelter provided in the area retards shell breakdown substantially. The northern platform to deep water areas show a sparse distribution of mollusc shells and is confined principally to Arctica islandica (which is found live, also) and Pecten maximus (which is not observed alive). The paucity of shell material indicates that the tests are either rapidly broken up or buried, by the short fetch waves observed in the area.

Fig. 48. Identities of dead sublittoral macrofaunal shell material.


DEAD
SUBLITTORAL
FAUNA
Arctica islandica
Pecten maximus
Gari tellinella
Caryophyllia sp.
Pecten maximus
Aporrhais pespelicani
Ensis arcuatus
P 1
Gari fervensis
B 10
Lutraria lutraria
Tellina crassa
Pomatoceros sp.
Dosinia exoleta many valves
Ensis sp.
Modiolus sp.
Parvicardium ovale
Phymatolithon calcareum
Tellina crassa
Venus casina
Ensis sp.
Gibbula sp.
Phymatolithon calcareum
N
0
IONA
MULL
Glycymeris glycymeris
H 4
2 Dosinia exoleta
barnacles

3.20 Mineralogy of the dominant organisms.

Gunatilaka (1972) determined the mineralogy of many marine organisms. His findings are shown in Table 16. These determinations can be compared to X-ray analyses of three samples of the Sound of Iona sediment: the northern platform (station H12) was predominantly high Mg calcite reflecting the strong contribution by Phymatolithon calcareum, the central shoals (station D1) and the southern platform (station K5) had X-ray showing a predominance of low Mg calcite from the substantial barnacle shell material, with much lesser amounts of aragonite and quartz due to molluscs and terrigenous material at these stations.

3.21 Summary of Part 3 : Provenance.

The spot stations and transects showed that barnacles are both locally abundant and areally extensive. Eulittoral molluscs form dense clusters on the shore, but they are not vertically and laterally abundant. Barnacles are most plentiful on the east coast of Iona where the shelter from storm wave attack is provided by the land and the central shoals. Barnacle density may be related to the grazing of Patella sp. which clear sites of algae. Thais, a predator on Balanus has highest concentrations on those coastal sites where the barnacles are dominant. It is difficult to comment on the distribution of Littorina because of probable commercial collection on the easily accessible eastern coast of Iona. Eulittoral encrustation studies show that barnacle and mollusc production is greatest in sheltered areas, where the protection from wave attack affords greater likelihood of larval settling and growth. Eulittoral and sublittoral shell samples show that an abundant burrowing mollusc fauna exists in areas of sediment substrate; sublittoral rock areas have a plentiful supply of encrusting organisms. Experimental substrate studies show that there are rich

Table 16. Mineralogy of some carbonate organisms found in the Sound of Iona.

A = aragonite; HMC = high Mg calcite; LMC = low Mg calcite (from Gunatilaka (1972), unless noted otherwise).

Taxa	Mineralogy % phase
Phylum Arthropoda	
Class Crustacea	
Order Cirripedia	
Balanus sp. (Milliman, 1974)	100 LMC
Chthamalus sp.	100 LMC
Phylum Mollusca	
Class Gastropoda	
Buccinum undatum	70 LMC, 30 A
Calliostoma zizyphinum	100 A
Gibbula cineraria	100 A
G. magus	100 A
G. umbilicalis	100 A
Littorina littoralis	95 LMC, 5 A
L. littorea	80 LMC, 20 A
L. saxatilis (rudis)	90 LMC, 10 A
*Nassarius tartonis	100 A
Thais (Nucella, Purpura) lapillus	98 LMC, 2 A
Patella vulgata	95 LMC, 5 A
*Trivia monacha	100 A
Turritella communis (core SH69V)	100 A
Class Bivalvia	
Cerastcderma edule	100 A
Dosinia exoleta	100 A
*Ensis ensis	100 A
Glycymeris sp.	100 A
Lutraria sp.	100 A
*Modiolus modiolus	75 LMC, 25 A
*Mya arenaria	100 A
Mytilus edulis	70 LMC, 30 A
Ostrea edulis	100 LMC
Pecten maximus	100 LMC
Venerupis decussata	100 A
Venus fasciata	100 A
Class Scaphopoda	100 A
Phylum Plantae	
Class Rhodophyceae	
Phymatolithon calcarean	HMC
Coralline officinalis	HMC
Phylum Echinodermata	
Class Asteroidea	
Asterias rubens	HMC
Henricia sp.	HMC
Class Echinoidea	
Echinus esculentus body	HMC
spines	LMC
Class Ophiuroidea	HMC
Phylum Protozoa	
Order Foraminiferida	
Family Globigerinidae	100 LMC
Family Miliolidae	HMC
Family Rotalidae	100 LMC
Family Textularidae	HMC + LMC
Phylum Bryozoa	
Class Gymnolaemata	
Order Cheilostomata	
Membranipora sp.	100 A
Phylum Annelida	
Class Polychaeta	
Family Serpulidae	HMC + A (trace amounts)

* Genus, but not species found in Sound of Iona.

supplies of sublittoral barnacles. The data supports the hypothesis of Lees *et. al.* (1969) that encrusting shelled organisms provide sediment which is exploited by burrowing organisms, as this sediment accumulates the area of these encrustation sites diminishes. Hence the importance of encrusting organisms may diminish with time, if all other external factors remain constant.

PART 4 : An estimate of carbonate production in the Sound for barnacles and red algae

3.22 Introduction.

Owing to the large number of variables and the difficulty of making reliable estimates of standing crop for all potential carbonate producers in the Sound, it is impossible to construct a full carbonate budget for the area. It has, however, proved possible to produce a potential budget for Balanus balanoides and Phymatolithon calcareum so reasonable biomass estimates could be made for these. Judging from the composition of the Sound sediments they appear to be amongst the major sediment contributors.

3.23 Balanus sediment production.

3.23.1 Introduction : morphogenesis and ecology.

Balanoid barnacles are hermaphroditic necessitating growth in tightly packed clusters to enable cross-fertilization to occur; single barnacles are infertile (Barnes, 1966). After fertilization and brooding the larva are released in a nauplius, i.e. swimming form. The animal moults and undergoes form changes culminating in the cyprid larva or settling form (Barnes op. cit.), and colonization takes place where current speeds are less than 1 knot (Yonge, 1949). Calcification of the mural and opercular plates begins soon after settling, though the basal plate remains membranous in Balanus balanoides. The six mural plates, characteristic of balanoids, never completely coalesce but remain mobile with respect to one another throughout life (Schäfer, 1972). Unlike other arthropods the calcareous shell is never moulted and shell growth is continuous but independent of body growth, (Schäfer op. cit., Barnes op. cit.). While the shell is not moulted, the skin of the animal within is shed through the opercular plates

(Schäfer, op. cit.).

B. balanoides inhabits the eulittoral zone from an area approximately mid-way between low water neaps and low water springs to near the high water spring mark, but spatial competition with the higher lying Chthamalus may restrict its upper limit (Connell, 1961). Balanoids may form extensive encrustations on any firm substrate but encrustations of their own shells is rare (Schäfer op. cit.). While conical shell growth is the norm, occasionally in areas of crowding, small, 10 cm diameter patches of tall cylindrically-shaped organisms occur.

Natural death is rare among B. balanoides, for the shell is likely to be attacked from the end of its first year by boring green and blue-green algae, giving the deposits a greenish-gray colour (Schäfer op. cit.). Although this does not cause complete destruction of the shell, an attack of the opercular margins destroys the seal and the animal is susceptible to dessication during periods of low water (Schäfer op. cit.). Predation by the gastropods Littorina and Thais and by starfish, will also kill the organism (Schäfer op. cit., Connell op. cit.). These factors make it rare for B. balanoides to live more than three or four years (Schäfer op. cit.); however, animals living highest on the shore may live for five to six years (Yonge, 1949; Petersen, 1966).

Once the animal dies and decays the opercular plates are released and a hollow shell remains. The lateral plates are only attached to the substrate at the bottom margins because the basal region of B. balanoides is uncalcified. Hence a small shear stress by breaking waves can dislodge the mural plates individually or en masse (Schäfer, op. cit.).

3.23.2 Calculation of the barnacle sediment contribution.

The barnacle contribution will be calculated from the adult barnacle $CaCO_3$ mass. With this method the total weight of the living barnacles on the shoreline is divided by the lifespan of the barnacle. An assumption is made that the population is at dynamic equilibrium, i.e. that the total population is not presently increasing or decreasing in size. Another assumption is that the barnacle shells are eroded immediately or soon after death.

The weight of the barnacle sediment contribution is determined from:

1. the topographic areas of the shore covered by barnacles (Table 17 row 4)

2. the number of encrusting barnacles per 25 cm^2 (Table 17 row 6)

3. the weight of an average adult $CaCO_3$ shell (0.077 gm, n = 20

and 4. the longevity of an adult barnacle (3 yrs. (Petersen, 1966)).[1]

The product of 1 x 2 x 3 gives the amount of barnacle material in the eulittoral zone. When this is divided by longevity it indicates the amount of barnacle $CaCO_3$ eroded per year (4.0×10^7 gm/yr for the Sound of Iona, 21 gm/m^2).

3.24 Phymatolithon calcareum sediment production.

The only species of maerl alga in the Sound of Iona collected in this study is P. calcareum (J. Cloakie, personal communication, 1978). Therefore the alga forms a monospecific deposit in the Sound.

3.24.1 Morphogenesis and ecology.

Bosence (1976) basing his concepts on the writings of Cabioch (1972) and Adey and McKibbin (1970), presents the following life for two species of corallines Phymatolithon calcareum and Lithothammium coralliöides:

1. Reproduction is by sexual or asexual mechanisms. Cabioch (1970) has found sexual spores in the special reproductive bodies of the coralline, called conceptacles. Conceptacles can also produce asexual

[1]This figure is obtained by averaging Peterson's data for a west coast U.K. eulittoral locality.

Table 17. Calculation of Balanus balanoides shell production for the Iona and Ross of Mull areas.

Rows	W. Coast of Iona	E. Coast of Iona	Ross of Mull	Erraid
1 Area of rocky intertidal coastline determined by planimetry	$2.1 \times 10^5 m^2$	$1.4 \times 10^5 m^2$	$1.8 \times 10^5 m^2$	$1.6 \times 10^5 m^2$
2 Relief factor: ratio of contour measurement/linear measurement of a rock surface (appendix 5)	not measured but a figure of 2.1 is used, i.e. the average of the other three values used here.	1.7	1.6	3.0
3 Topographic area: (planimetric area x relief factor) (row 1 x row 2)	$4.4 \times 10^5 m^2$	$2.4 \times 10^5 m^2$	$2.9 \times 10^5 m^2$	$4.8 \times 10^5 m^2$
4 Percentage of intertidal rock area covered by barnacles (Table 14)	not measured but the figure from Erraid, 14% will be used because of the similarity of exposure	33%	13%	14%
5 Intertidal area of barnacle coverage: (topographical area x percentage of intertidal rock area covered by barnacles): (row 3 x row 4)	$6.2 \times 10^4 m^2$	$7.9 \times 10^4 m^2$	$3.8 \times 10^4 m^2$	$6.7 \times 10^4 m^2$
6 Average number of adult barnacles per 25 cm^2 (Table 13)	15	39	15	5
7 The number of encrusting adult barnacles on a shore (row 5 x row 6 x 400)	3.7×10^8	1.2×10^9	2.3×10^8	1.3×10^8
8 Weight of barnacle material; average weight of an adult barnacle : 0.077 gm	$2.9 \times 10^7 gm$	$9.2 \times 10^7 gm$	$1.8 \times 10^7 gm$	$1.0 \times 10^7 gm$
9 Weight of barnacle material deposited per year: weight of barnacles row 8, divided by 3 years the average B. balanoides life-span in the U.K.	$9.7 \times 10^6 gm$	$3.1 \times 10^7 gm$	$6.0 \times 10^6 gm$	$3.3 \times 10^6 gm$
		Total weight for the Sound per year	$4.0 \times 10^7 gm$	
10 Thickness of barnacle material deposited per year: packing experiments show that the packing density is 0.69gm/cm3 for barnacle shells; planimetry gave the sublittoral areas cited herein	West coast of Iona from the subtidal zone to 20 m offshore depth: $\frac{\text{Area offshore to 20m } cm^3}{1.3 \times 10^{10} cm^2} \times \frac{1}{0.69 gm} \times \frac{9.7 \times 10^6 gm}{yr}$ $= 1.1 \times 10^{-3}$ cm/yr	Sound of Iona from the N. shores of Iona and the Ross of Mull to the S. shores of Iona and Erraid $\frac{\text{Area of the Sound}}{1.9 \times 10^{10} cm^2} \times \frac{cm^3}{0.69 gm} \times \frac{4.0 \times 10^7 \text{ gm total}}{yr}$ $= 3.1 \times 10^{-3}$ cm/yr		
11 Weight deposited per m^2 per year (row 9 ÷ sublittoral area)	$\frac{9.7 \times 10^6 gm}{1.3 \times 10^6 m^2} = \frac{8 gm}{m^2}$	$\frac{4.0 \times 10^7 gm}{1.9 \times 10^6 m^2} = \frac{21 gm}{m^2}$		

spores. Cabioch (1969) claims conceptacles form every 4-6 years in the Baie de Morlaix. Reproduction by vegetative means can also occur, whereby a piece of the algal structure (the whole structure is called a thallus) breaks off and forms another colony.

2. Spores released into the water undergo several changes in morphology until an encrusting disc is formed. This attaches to the substrate. Fragments from pre-existing thalli likewise attach themselves and begin new growth.

3. Growth is differentiated into four types of layers: the bottom-most is called a hypothallium where the calcified cell walls are oriented parallel to the substrate, a perithallium where the calcified cells are oriented perpendicular to the substrate, a meristem which is uncalcified (and where vegetative cell division occurs) and an uncalcified epithallium (produced by the meristem) which is equivalent to cover cells (Adey and MacIntyre, 1973; Alexandersson, 1974; Wray, 1977).

4. Growth proceeds periodically, Adey and McKibbin (1970) reporting that perithallial cells grow larger in the summer (especially June and July) than in the winter, for the forms P. calcareum and L. corallioides.

5. With maturation, branches develop of two types: dichotomous branching where the perithallial cells divide to form two equal branches with a symmetry plane between them; intercalary branching which originates along a branch away from the tips.

3.24.2 Analyses of algal sediment contribution.

Algal sediment contribution was studied by using a combination of in situ and laboratory studies. A diver-operated tow-board (see appendix 2 for a description of this technique), determined the size, shape of the algal deposit and also subdivided the maerl into zones of differing proportions of living to dead calcareous algae. These were separated, from field observations, into three tracts of 1) 0-30%,

2) 30% - 60% and 3) 60% - 100% living maerl cover (Table 18). From laboratory observations of samples collected from the area denoted 60% - 100% living calcareous algae it was noted that the actual living tissue occupied only 53% of the total area of the thalli (Table 19). Lacking other data on the fraction of living material in the sample, this factor is applied to each tract population (0-30%, 30-60% and 60-100% living tissue). Calculations show that there are 22,000 thalli ($\geq$ 1 cm in maximum axial length) per square metre; this was determined empirically from triplicate packing measurements in a laboratory, where the thalli were packed one layer deep. Tract population numbers are shown in Table 20. The average weight of a thallus, approximately 1 cm long, from the maerl area, is 0.13 g (n = 438 observations), the skeletal density is 2.04 (Table 11), and the average branch diameter is 2.2 mm (n = 100). From the work of Bosence (1976) the growth rate of Phymatolithon calcareum is 0.1 mm/yr at the branch tips. The weight added to each thallus (having an average of 4.6 branch tips; n = 100) = π x $(\text{radius})^2$ x growth increment x density x number of branches = π x 1.1 mm^2 x 0.1 mm x 2.04 gm/cc x 4.6 branches = 3.57 x 10^{-3} gm/thallus. Using the figures for numbers of thalli/m^2 derived earlier, the weight $CaCO_3$ production for P. calcareum has a maximum of 2.2×10^6g and a minimum of 2.7×10^5g. In the area of maximum productivity (tract No. 3) the productivity is 42 g/m^2 (Table 21).

3.25 Summary.

1. Balanus balanoides produces 4 x 10^4 kg $CaCO_3$/yr; 30 gm/planimetric m^2/yr.

2. Phymatolithon calcareum produces a maximum of 2 x 10^3 kg $CaCO_3$/yr; 20 gm/planimetric m^2/yr.

3. The "core" deposit of P. calcareum produces a maximum of

Table 18. Planimetric areas of the three tracts of living maerl cover

Tract	Areas (m^2)
1. 0-30% living maerl cover	1.3×10^5
2. 30-60% living maerl cover	1.8×10^4
3. 60-100% living maerl cover	1.9×10^3
	1.5×10^5 = Total area of maerl (0-100% living).

Table 19. Area of the thallus occupied by living (i.e. purple-coloured) tissue.

Method 1 : By % observation of thalli approximately 1 cm in maximum axial length.

		n	% observation	Product of maximum % living tissue	x % observations for each class	
class 1	75-100% living tissue	35	23	class 1	100% x 23%	= 23%
2	50- 75% living tissue	14	9	2	75% x 9%	= 7%
3	25- 50% living tissue	14	9	3	50% x 9%	= 5%
4	0- 25% living tissue	43	28	4	25% x 28%	= 7%
5	completely dead	47	31	5	0% x 31%	= 0%
		153	100			42% of total thalli area is living tissue

Method 2 : By weight % of population (specimens distinct from Method 1)

Population 1

		weight (gm.) of thalli in this class	%	Product of maximum % living tissue	x weight % for each class	
class 1	60-100% living tissue	8.99	67	class 1	100% x 67%	= 67%
2	30- 60% living tissue	0.78	6	2	60% x 6%	= 4%
3	5- 30% living tissue	0	0	3	30% x 0%	= 0%
4	0- 5% living tissue	3.63	27	4	5% x 27%	= 1%
		13.40				72% = total living tissue

Population 2

		weight (gm.)	%	Products		
class 1	60-100% living tissue	1.16	31	class 1	100% x 31%	= 31%
2	30- 60% living tissue	0.18	5	2	60% x 5%	= 3%
3	5- 30% living tissue	1.08	29	3	30% x 29%	= 9%
4	0- 5% living tissue	1.34	36	4	5% x 36%	= 2%
		3.76				45% = total living tissue

Average of 3 values =

53%

Table 20. Total numbers of living *Phymatolithon* thalli.

Part 1 : It was determined that the average amount of living tissue per thallus was 53%. This factor was then applied to the tracts of living maerl to provide an adjusted percentage of living maerl cover, mathematically calculated the amount of "100%" living thalli in a designated tract.

Tract		Adjusted values
1. 0- 30% living maerl cover	0 x 53%; 30% x 53% :	0 - 16 %
2. 30- 60% living maerl cover	30 x 53%; 60% x 53% :	16%- 32 %
3. 60-100% living maerl cover	60 x 53%; 100% x 53% :	32%- 53 %

Part 2 : Total numbers of living thalli are calculated from laboratory values for areal thalli density and the adjusted values of Part 1 of this Table.

Tract	Calculation = % living maerl x areal density x area	Number of "100%" living thalli: minimum		Number of "100%" living thalli: maximum
1. 0-16%	0x22,000 thalli etc. = 0; 16% x 22,000 thalli/m^2x1.3x$10^5$$m^2$ = 4.6x10^8 thalli	0	-	4.6×10^8 thalli
2. 16-32%	16%x22,000thalli/m^2x1.8x$10^4$$m^2$ = 6.3x10^7thalli; 32%x22,000 thalli/m^2x1.8x$10^4$$m^2$= 1.3x$10^8$ thalli	6.3×10^7 thalli	-	1.3×10^8 thalli
3. 32-52%	32%x22,000thalli/m^2x1.9x$10^3$$m^2$ = 1.3x10^7thalli; 52%x22,000 thalli/m^2x1.9x$10^3$$m^2$= 2.2x$10^7$ thalli	1.3×10^7 thalli	-	2.2×10^7 thalli
		7.6×10^7 thalli (Total minimum number of thalli)	-	6.1×10^8 thalli (Total maximum number of thalli)

Table 21. Productivity of the maerl tracts.

all	7.6×10^{7} thalli x 3.57×10^{-3} gm/thallus = 2.7×10^{5} gms $CaCO_3$ (minimum productivity)/yr.
all	6.1×10^{8} thalli x 3.57×10^{-3} gm/thallus = 2.2×10^{6} gms $CaCO_3$ (maximum productivity)/yr/$1.4 \times 10^{5} m^{2}$ = 16gm/m^2/yr
3. "core"	2.2×10^{7} thalli x 3.57×10^{-3} gm/thallus = 7.9×10^{4} gms $CaCO_3$ (maximum productivity)/yr/$1.9 \times 10^{3} m^{2}$ = 41gm/m^2/yr

80 kg $CaCO_3$/yr; 40 gm/planimetric m^2/yr.

3.26 Significance of the carbonate estimates.

Appreciable amounts of barnacle shell material are derived from the eulittoral shores of the Sound of Iona. If rates of sedimentation were similar to the present day since the end of glaciation, approximately 10,000 yrs B.P. (Gray and Lowe, 1977), then barnacles could produce a sediment deposit approximately 0.5 m thick over the entire Sound. This may be enough to account for much of the observed present-day sediment thickness.

It is believed that the size of the maerl deposit is mainly regulated by wave activity and tidal currents. While acknowledging the potential errors of the carbonate production estimate, the similarity in the barnacle and maerl production shows that there also may be sedimentary control: the maerl exists because of a delicate equilibrium between *Phymatolithon* production and barnacle production.

CHAPTER 4

SUMMARY

4.1 The study area encompassing the Columba and Colonsay Seas is characterized by erosion-resistant bedrock, island archipelagos, strong wave action and swift tidal currents. Seabed and land-surface areas have pronounced glacial sculpting along E-W Tertiary drainage passages and NE-SW trending faults.

Glacial basins and an irregular coastline act as receptacles for terrigenous sediment transport creating "basinal terrigenes". Indurated rock, shallow water and swift current areas are exploited by high producitivity organisms forming "island-margin carbonates".

4.2 The Sound of Iona one such island-margin deposit was studied in detail. The shallow Sound has been segregated into several bathymetric tracts; major ones are the southern platform, the central shoals, the northern platform and the peripheral deeper water area. The Sound was dominated by 80-90% bioclastic carbonate sand to gravel-size sediment. Relict glacial boulders and cobbles lie in the deeper water areas peripheral to the Sound. Thin section analyses of sand-size samples showed a sequence of abundance occurs which is barnacles $>$ terrigenes $>$ molluscs $>$ calcareous rhodophytes for both shore and sublittoral samples. Medium-size sand is pervasive, but calcareous rhodophyte gravel-size sediment is found on the northern platform of the Sound; fine sand is localized on the central shoals. Flume studies show that these fine sands are the most easily transported, but they are sequestered to a shoal nodal area by reversing flood and ebb tides. The calcareous rhodophytes (termed maerl) form a current-transport-resistant structure in an area of 3-sided wave shelter.

Shell breakdown studies show that barnacles breakdown most quickly from whole shell to sand-size sediment; they form little mud-size sediment. Maerl and molluscs break down much less quickly and form much fine grained sediment in the process. The swift currents in the Sound would wash this sediment from the Sound.

A hierarchy of bedforms is found on the platforms and the central shoals and range in magnitude from ripples, through megaripples to sand waves. Sand waves with wavelengths up to 380 m are found on or closely adjacent to the central shoals. A sand ribbon extends northwards from the central shoals to the northern platform. Diver's observations, aerial photographs and the historical maps, show that the time stability of the bedforms varies from minutes for small ripples to decades and centuries for the sand waves and the sand ribbon. The sand wave field containing the sand waves and the associated sand ribbon has existed for centuries.

Four dominant facies are recognized within and around the Sound: 1) relict boulder facies; 2) rippled sand facies; 3) sand wave and sand ribbon facies; and 4) the calcareous rhodophyte deposit named maerl; the alga Phymatolithon dominates it.

Hydraulic measurements show that the flood tide dominates the northern platform the ebb tide dominates the southern platform. This dominance is related to the submerged bathymetric highs of the central shoals which restrict tidal flow near the turn of the tides. Surface velocity studies show that both tides accelerate then decelerate on these shoals as they flow across; also, they accelerate through channels at the margins of the Sound. This acceleration is increased ($\geq$ 1.0m/sec) by an island causing a more northerly deflection of currents. Studies of the Sound during storm periods shows that the more severe storm wave attack originates from the Southern sectors. The gentle shallowing of the Sound causes the waves to break before or on the central shoals.

The facies are controlled by a combination of tidal current and wave action. Relict glacial material lies exposed in areas of high wave action and slow sedimentation. The rippled sand facies occur in the southern platform and shoal areas nearshore where tidal current and wave action create only small bedforms. The sand wave and sand ribbon facies forms by the drag of tidal currents streaming across the central shoals. The maerl (algal) facies forms in an area which is sheltered from waves by land on two sides and sand waves on a third side; the interlocking branches of the thalli enable them to grow without danger of erosion and transport.

Principal sediment transport, reflecting the dominant northwards flowing flood tide and the northwards moving storm waves, is to the north. The major transport paths are via the sand ribbons in the Sound.

Seismic (boomer) studies show that the thickest accumulation of Recent sediment is 2 m at the sandwaves of the central shoals. Thicknesses diminish laterally away from the sand wave area to 1 m on the northern platform to less than 1 m on the southern platform. Deeper penetration seismic (sparker) studies reveals layered sediment beneath the central shoals. Parabolic reflectors in the strata are consistent with the presence of cobbles and boulders; this is most probably relict glacial material. Further north in a depth transition zone from the northern platform and deep water areas are beds inclined at an apparent dip of 6-8^{o} and are mapped as glacial deltaic deposits.

4.3 Provenance studies were conducted of the three common sediment components, barnacles, molluscs and red calcareous algae. Spot and transect studies of the eulittoral zone of the Sound showed that Balanus balanoides was the most abundant calcareous organism. A comparison of four areas of the Sound showed that the hierarchy of Balanus density was E. coast of Iona (greatest gensity) $>$ Mull $>$ W. coast of Iona $>$ Erraid (lowest density). The hierarchy reflects the wave shelter of the east coast of Iona and the decreasing wave shelter for other areas. Eulittoral molluscs are locally abundant, but transect studies show that they are not areally important.

Infaunal, epifloral and epilithic molluscs inhabiting the eulittoral zone form extensive shell accumulations of gastropods, e.g. Gibbula, Littorina, Nassarius, Patina and bivalves, e.g. Lucinoma borealis, Lutraria lutraria, Mya truncata, Venerupis pullastra and Venus striatula.

Sublittoral organisms form rockhead and boulder-encrusting deposits of balanoid barnacles, calcareous serpulid worms, encrusting bryozoa. calcareous encrusting rhodophytes and mobile epilithic echinoderms, e.g. Echinus sp., Ophiocomina nigra, Ophiothrix sp., Crossaster papposus. Such deposits are found in the deeper water areas adjacent to the platform areas of the Sound. Few organisms save Glycymeris glycymeris and Spisula sp. are found on the southern platform because of its openess to severe wave attack, nor on the central shoals where the constantly shifting sand would be detrimental to most organisms. Mollusc density increases from the northern platform into the northern deeper water area and includes Arctica islandica, Cochlodesma praetenue, Cultellus pellucidus, Dosinia exoleta, Gari fervensis, Lucinoma borealis, Thracia phaseolina, Venus striatula and Aporrhais pespelicani.

The significance of these studies is that sediment produced by encrusting organisms particularly the barnacles, provides a substrate which is exploited by infaunal shelled organisms. Eulittoral barnacles would contribute much of this sediment; but artificial substrates show that the sublittoral barnacle Balanus crenatus could be an important contributor in areas where there are large sublittoral rock areas.

4.4 A carbonate production estimate of the eulittoral barnacle Balanus balanoides gave a figure of 4×10^4 kg deposited yearly within the Sound (i.e. within the seabed area laterally adjacent to Iona and Mull), or approximately 20 $g/m^2/yr$. The sublittoral calcareous rhodophyte Phymatolithon calcareum produces a maximum of 2×10^3 kg/yr for the deposit including three concentric tracts of living maerl deposits. The densest tract of living maerl produces approximately 40 g $CaCO_3/m^2/yr$. The maerl deposit may be areally controlled by the ambient sedimentation rate.

4.5 Facies of the Colonsay Sea include: 1) bare rock with echinoderms; 2) maerl facies; 3) megarippled sand derived from maerl; 4) and 5) current and wave rippled sand; 6) Modiolus gravel, a fine sediment super category including; 7) Turritella fine sand; 8) filamentous tube burrowed mud; 9) crustacean burrowed mud; and 10) spider crab mud, lastly a relict glacial overconsolidated clay facies. These facies are probably controlled by mechanisms similar to those observed in the Iona study.

4.6 Geological significance of this study.

Bjørlykke et.al. (1978) note that throughout geological time there have been many instances where the marine carbonates are found bedded with or overlying glacial deposits. References to such occurrences were noted in section 1.2 here. This study has also shown that there is an intimate relationship between glaciation and carbonate sedimentation. This relationship is manifest in the marine environment and in fresh-water lacustrine calcareous algal deposits on glaciated land surfaces (Cucci, 1974).

Sedimentation history of these occurrences can be summarized thus: glacial erosion sculpts an irregular topography of basins and highlands which act as barriers to sediment transport; when normal erosion resumes, terrigenous material is transported downslope into these basins; suitable localities located distally from the influence of sediment influx into these basins are exploited by carbonate-producing organisms.

APPENDIX 1. Expedition Data for the Columba-Colonsay Seas.

Location	Date	Vessel(s) Used	Principal scientist(s)	Purpose
Sound of Iona	19 July - 1 Aug 1975	Nektos: 4m Avon Searider (inflatable dinghy) with 24 hp engine	T. P. Scoffin M. Cucci	Reconnaissance sampling of dune, littoral and sub-littoral sediments.
Sound of Jura	Sept 1975	R.V. Calanus 76 feet, 75 ton research ship from SMBA Dunstaffinage	Brian Brown, University of Glasgow	Faunal and sediment sampling
Sound of Iona	19-30 July 1976	Nektos	M. Cucci, T.P. Scoffin	Hydrographic measurements, underwater light measurements, littoral faunal and floral studies.
Sound of Iona	19-24 July 1976	Calanus	G. Farrow, University of Glasgow	Barnett-Hardy suction bin sampling, sediment coring.
Colonsay Sea to Ardnamurchan (including Sound of Iona)	30 July - 10 Aug 1976	R.R.S. John Murray 134ft 595 ton research ship from N.E.R.C. Barry; inflatable dinghy	G. Farrow	Sediment sampling, underwater television hydrographic measurements, geophysical studies.
Sound of Iona	17 Sept - 12 Oct 1976	local dinghies 3-4m length with $2\frac{1}{2}$ hp engine	M. Cucci	Littoral population studies, current meter measurements.
Firth of Lorne	May, 1977	R.R.S. Challenger 180ft 1440 ton research ship from SMBA based in Barry	J. Hall, University of Glasgow	Sedimentological and geophysical studies.
Sound of Iona	3-14 Oct 1977	Calanus	M. Cucci	Biological, hydrographic, sedimentological and geophysical studies.
Coll, Tiree, Sound of Islay and Rockall	16 June - 5 July 1978	Challenger	T. P. Scoffin	Faunal, sedimentological, television and geophysical studies.
Coll, Tiree, Sound of Iona	14-28 Aug 1978	Nektos, Calanus	T. P. Scoffin	Reconnaissance sampling of dune, littoral and sub-littoral sediments, Sound of Iona underwater photography, digging in the maerl bank.

APPENDIX 2

Methods

A2.1 Position fixing.

Positing fixing for drift dive sampling and diver tow board surveys in the sublittoral areas of the Sound of Iona was established by triple bearing fixes. Errors were a few metres for nearshore stations but up to 150 m in the central Sound.

Shipboard work in 1976 aboard the R.R.S. John Murray utilized corrected Decca radio fixes (Chain 3 B North British) for station position determinations; positions were plotted using British Hydrographic Office Decca maps. Decca full daylight positional errors varied from 50 m in the Colonsay Sea area to 100 m in the Ardnamurchan area.

The Calanus utilized Decca and line-of-sight radar for the 1975 sampling cruise in the Sound of Jura; positional errors for this cruise are not known. The Decca system was subsequently removed from the Calanus. Hence the 1977 cruise in the Sound of Iona utilized range-finding radar only; this cruise had a positional error of about 150 m.

A2.2 Sediment sampling.

Diver sampling was initially undertaken from an anchored dinghy in the Sound of Iona; however this method was tiring, time-consuming and only 2-3 samples per day were collected. A more efficient technique was employed, termed "drift diving". A pair of divers were sent into the water from an unanchored boat. Divers would descend to the bottom, drifting with the current. One diver would collect a sample the other diver would act as a "buddy" lending assistance if necessary and also make seabed observations. Fatique was lessened and 7-12 samples per day could be obtained. Sublittoral sample collection was most intensive in the sheltered Sound. However, continued rough seas and dangerous diving conditions on the exposed western platform of Iona, limited diving to the collection of three samples.

Rock dredging operations from the John Murray used a 1-2 knot towing speed and a ratio of 3 lengths of wire to 1 length of vertical depth. The dredge had mouth dimensions of 1 m width by 0.3 m high attached to a weighted 5 mm nylon mesh protected by a flexible metal wire bag. The dredge mouth height prevented the sampling of material greater than 0.3 m; material finer than 5 mm tended to wash out unless the sediment was cohesive mud or unless the sample came from very shallow depths. The rock dredge was capable of sampling pebble to boulder-sized sediment, *in situ* rock, epilithic fauna and flora. The dredge bag could hold about 1 m^3 of sediment, but most dredge hauls were less than full volume.

Smith-McIntyre and Day grab samples obtain localized sediment samples between opposing snap-closing jaws. Sampling, done from a drifting Murray, was essentially vertical (versus the rock dredge which is lateral) with shallow penetration and small, 100 cm^3, volumes. The two samplers are similar in design but a Smith-McIntyre device used a spring-loaded trigger mechanism, while the Day sampler uses a simpler weighted trigger. The sampler obtained full volume samples approximately 50%; sampling was repeated if insufficient volume was obtained. The samplers were inadequate for sediment > 4 mm; the jaws would not close properly and fines would be lost. These samplers could sample flora and fauna provided the specimens were less than 10 cm in size.

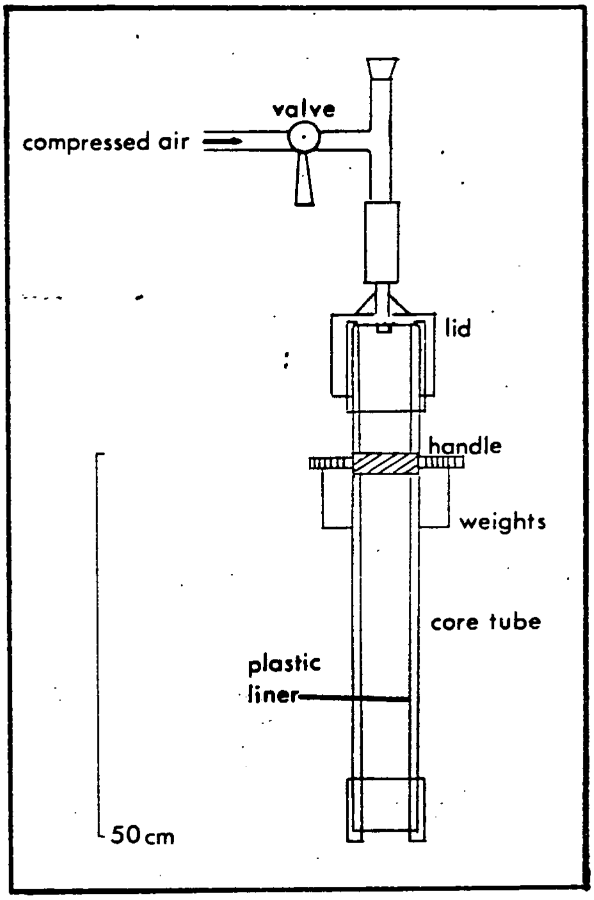
A Forster anchor dredge with mouth dimensions 26 cm wide, 28 cm high backed by a double thickness of 4 mm thick 50 cm deep nylon mesh, was utilized in the Sound of Iona. It differs from a rock dredge in that it is not towed; it is emplaced on the seabed like an anchor and it bites into the sediment by an engine thrust from the ship. This dredge sampled sediment ranging in size from gravel to small boulders, as well as intact epilithic fauna and flora. Dredge hauls were often full volume, i.e. 0.03 m^3.

Large-diameter, shallow-penetration cores and intact in situ organisms were obtained in the Sound of Iona using a Barnett-Hardy (Barnett and Hardy, 1967). This device utilizes a simple compressed air water pump attached to the top plate of a 60 cm high, 40 cm diameter pipe, which is open at one end. The open end of the cylinder is pushed into a few centimetres of sediment by a diver. Water is pumped from the cylinder and the external water pressure drives the cylinder into the sediment. When suitable volume (up to 0.06 m^3) is obtained the air pump is shut off, the bin removed, inverted and winched onto the deck. The coarseness of the sediment in the Sound made it difficult to retrieve intact sediment samples; only 2 samples out of 14 coring attempts were suitably intact to permit resin-impregnation.

The compressed-air water pump system from the Barnett-Hardy bin was modified for use on a perspex core 75 cm in length with an internal diameter of 8 cm and a maximum volume of 0.062 m^3 (Fig. 49). This device proved successful in all three attempts where it was used in medium-fine sand mixed with 5-10% volume of detrital coralline algae.

The size bias of the various samplers has been mentioned, but there is also a mixing bias. There are two types of mixing: vertical mixing and lateral mixing. Vertical mixing occurs during grab sampling where sediment from the sea bed surface is mixed with lower lying sediment. This feature may be minimal because of the shallow penetration of grab samples but it is most intensified with the Barnett-Hardy

Fig. 49. The perspex suction corer.



valve
compressed air
lid
handle
weights
core tube
plastic
liner
50 cm

suction bin where penetration depths reach to 0.5 m. Mixing can occur during subsequent inversion of this sampler. Lateral mixing is minimized with the aforegoing sampling techniques because they are very localized samplers. Lateral and vertical mixing occurs during dredge sampling. A Forster anchor dredge can be towed for distances up to 170 m, biting up to 0.5 m into sediment. The larger rock dredge may be towed for distances up to 1 km and have a similar depth of bite. It is probable that these dredges would sample several different biological environments and sedimentary substrates.

A2.3 Underwater imagery.

Underwater television observations of the Columba-Colonsay Seas utilized a Thompson camera and monitor and a National Panasonic ½" video tape recorder. The camera was protected in a small, rectangular metal housing. The housing was suspended a few centimetres above the bottom, or rested directly on the seabed. The camera provided a minimal viewing area of approximately 20 cm x 30 cm. The system was used at 72 stations at depths from 11 m to 115 m. Tapes from this television survey are housed with the Institute of Geological Sciences, Continental Shelf Unit, Murchison House, Edinburgh.

A2.4 Diver's observations in the Sound of Iona.

2.4.1 Drift diving.

The scuba diver responsible for underwater observations was interviewed in the dinghy at the end of each two man sampling dive. Information such as sediment type, sediment and rock areal cover, bedform parameters (e.g. ripple height, orientation, wavelength and asymmetry), presence and orientation of shells or living fauna, floral cover, water depth, current speed and direction estimates and any special features such as percentage living coralline alga cover, were transcribed onto a roughened perspex slate. Notes were transferred to a notebook once the party returned ashore for a permanent record.

2.4.2. Diver tow-board observations.

The rapidity and areal extent of diver's observations were greatly increased by the use of an underwater board (Fig. 50) towed at a speed of 2-3 knots behind the motor-powered dinghy. The tow-board was exclusively used over the Phymatolithon calcareum coralline alga beds which grow in the northern platform area of the Sound. For this operation an underwater trigger was mounted on the sledge and connected internally via a tow cable to a buzzer and light-receiver in the dinghy. A series of signals was devised so that the estimated percentage (0%, 30%, 60%, 100%) living algal cover count be transmitted from the towed diver to the dinghy. The alga data was recorded on a roughened perspex slate. During the three traverses, which were with the flood current and parallel to the shore, three observers were stationed at points along the shoreline. Simultaneous compass fixes were taken on the dinghy at intervals of 5 minutes. Additional fixes were made where living coralline algal cover was observed; these points were communicated to the shore observers by means of a flag signal given from the dinghy. Divers were changed after each traverse. For the tow-board studies six personnel were needed: three observers on shore taking compass fixes, a diver, an engine tender-signalman and a record keeper.

A2.5 Geophysical techniques.

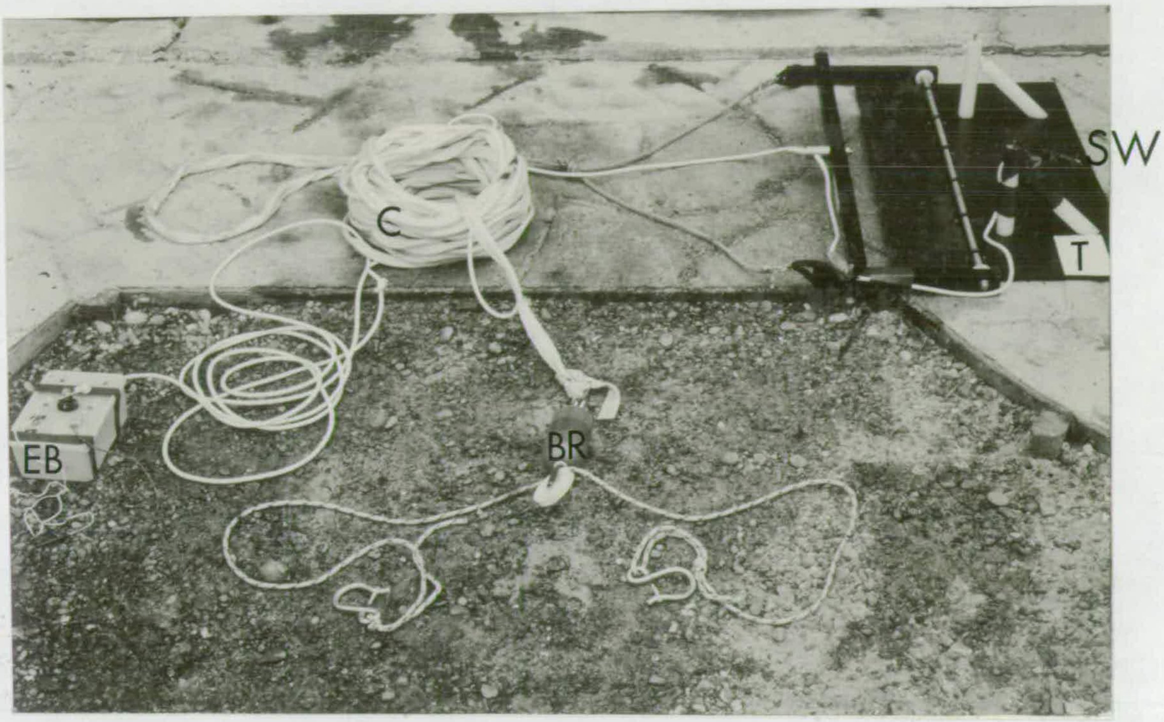
2.5.1 Introduction.

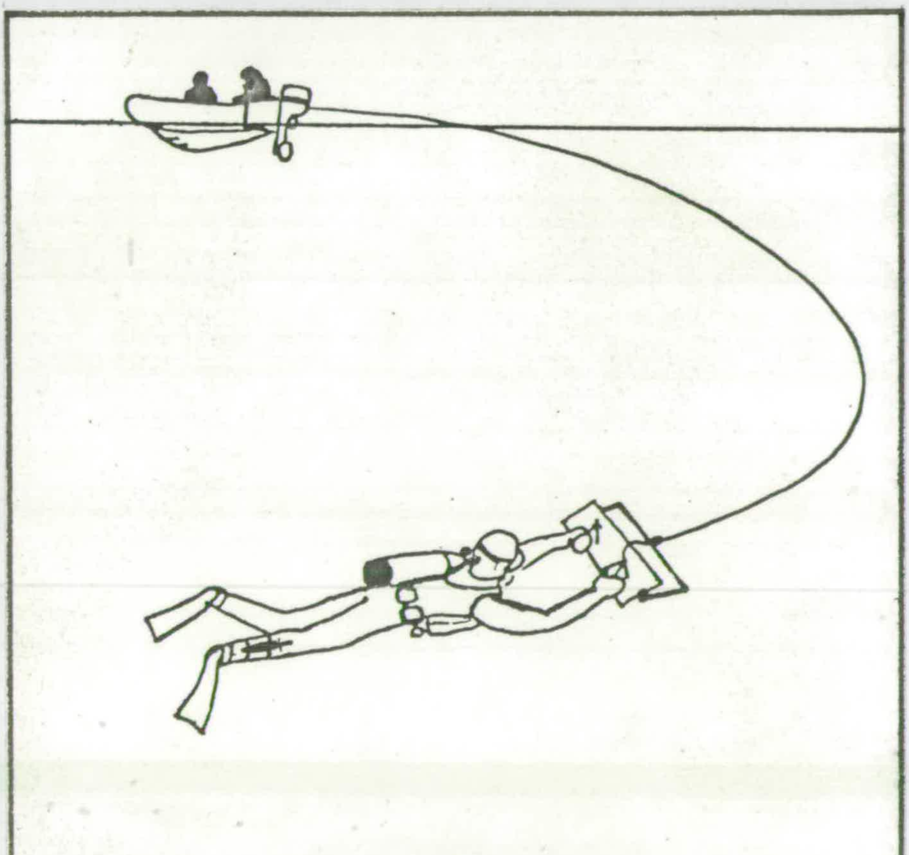
Echo-sounders and side-scan sonar respectively chart linear and lateral traverses of the seabed by the reflection of high frequency

Fig. 50. The underwater tow-board.

A. The tow-board (T), underwater switch (SW), transmitting and receiving electronics box (EB), tow cable (C) and bridle (BR).

B. Sketch of the tow-board in operation.


C
SW
T
EB
BR



sound. Two additional geophysical devices were used which enabled sediment and rock horizons to be discerned below the surface of the sediment. These devices are collectively termed sub-bottom profilers and they are specifically named a boomer and a sparker. With these devices a sound wave is directed into the sediment to different sonic horizons. It is then reflected back into the water column, collected by quartz crystal hydrophones and converted into graphic output. These devices are described in more detail below based on the author's data and McQuillin and Ardus (1977; c.f. illustrations therein).

These instruments were used aboard the Calanus at a tow-speed of 4-5 knots.

2.5.2 Echo sounders.

A portable Ferrograph echo sounder was used aboard the dinghy Nektos to study detailed seabed structure in the Sound of Iona. The working frequency was 143 KHz with a tow-speed of 2-3 knots. A keel mounted Kelvin-Hughes echo sounder was employed aboard the Calanus.

2.5.3 Side-scan sonar.

A Kelvin-Hughes MS-47 single-beam side-scan sonar was used around Iona. Operating frequency was 48 KHz. Maximum transmitting range was 300 m but in the shallow waters of the Sound, the actual range was about 150 m.

2.5.4 Boomer.

A Huntec boomer was used to study the detail of near-surface sediment structure. This device produces high frequency (3-8 KHz) sound at low power (165 joules) by the magnetic repulsion of a metal plate away from a coil. This device can detect sediment structures between 0.5 m and 1 m in thickness (i.e. the resolution is 0.5 m to 1 m).

2.5.5 Sparker.

An E. G. and G. sparker array was alternatively employed with the boomer to study deeper sediment and bedrock configurations in the Sound. A low frequency (400-700 KHz) sound wave is produced by a high power (500 joules) electrical discharge into the water. The discharge produces a spark which forms a gas bubble. The expansion of the gas bubble produces the sound wave. Resclution is about 2 m.

A2.6 Hydrographic data.

Currents were initially measured with dyes. However, this was feasible only for short term measurements and long term measurements were made using instrumental methods.

Surface current (velocities and directions) were measured using Plessey MO 27/2 direct reading units. Velocity, measured in ft/sec., was integrated over 28 seconds; accuracy was ±0.1 ft/sec or ±3% (whichever is the greater). Magnetic direction was obtained instantaneously with an accuracy of ± 5 degrees. The rotor units in these devices are horizontally mounted and were used with 18 Kg counterweights. The Plessey was used for velocity measurements at 10 minute intervals for up to 12 hours at depths of 2-4 m below the water surface.

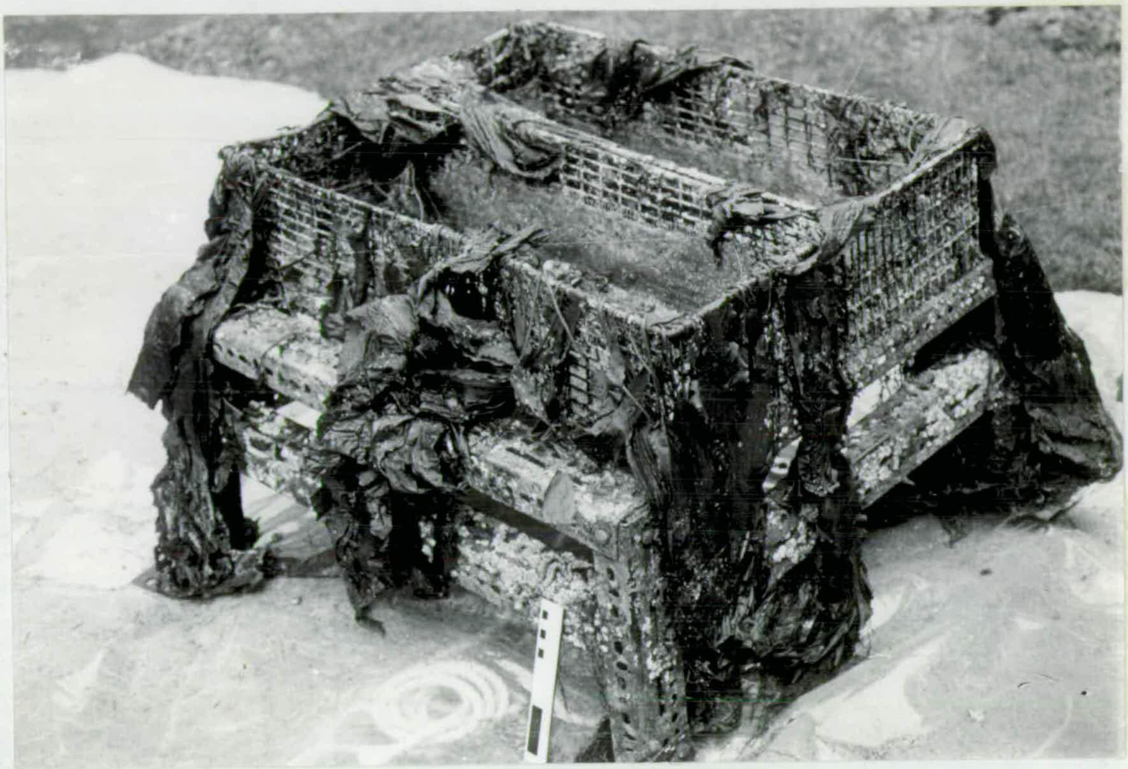
For the velocity profile determination at the maerl beds, three Plessey meters were suspended along the gunwales of the Calanus at 6.2 m, 4.3 m and 3.0 m above the bottom (initial heights). Velocity measurements were made at 10 minute intervals for 6 hours.

Recording current measurements were made by two Aanderaa RCM4 current meters. These devices employ a Savonius, i.e. vertically mounted rotors which measure velocity in m/sec. A rotating vane measures magnetic direction. Data is stored on a magnetic tape cartridge which, after retrieval is converted via a computer program into numerical output. Velocity was integrated over 5 minutes with an accuracy of $\pm$ 1 cm/sec or $\pm$ 2% (whichever is the greater). Instantaneous direction was measured with an accuracy of $\pm$ 5-7°. These devices were anchored to the seabed with a 320 Kg lead sinker with a vertical lift provided by a 0.8 m subsurface buoy (to keep the rotor vertical). Position was marked with a Dahn buoy equipped with a radar reflector and battery-powered flashing light.

A2.7 Artificial substrate.

A special frame was constructed to study carbonate encrustation and algal growth in the Sound of Iona (Fig. 51). The base consisted of a steel Dexion frame anchored to four cement blocks weighing about 10 Kg each. The Dexion held two wire mesh cages lined with nylon gauze, used for the algal growth studies. The apparatus was anchored to four marine concrete blocks and towed beneath the dinghy from the shore to a position at the mouth of the channel between Eilean Liath and Eilean nam Ban. At the drop point the cords binding the aquarium were cut simultaneously and the apparatus settled upright onto the seabed, at a depth of 6 m below O.D. Living coralline algae obtained earlier in the day from the northern sector of the Sound, were placed in several centimetres of seawater inside a plastic tub. Several grammes of Alizarin red-S were added to the water to stain the algae (after Barnes, 1970). The tub was covered to prevent possible death by sunlight bleaching and the algae were left to stain for two hours. The algae were removed to plastic containers filled with seawater. Divers transported the containers underwater to the substrate where they were tied down to the cages with short pieces of tagged, insulated electrical wire. After 1.25 years divers returned to the site,

Fig. 51. The artificial substrate after recovery.



attached ropes to the frame and raised the aquarium off the bottom. The aquarium was secured underneath the dinghy and taken back to the Calanus. It was later returned to Edinburgh for further study.

A2.8 Laboratory studies.

2.8.1 Thin section studies.

Raw sediment samples from Iona were treated with bleach to remove organic matter. The sample was inverted 30 times and a small 25 ml aliquot was removed. These aliquots were dried, inverted several times and sediment was sprinkled into the base of Teflon moulds. A 1:1 mixture of Araldite AY 105 resin and Versamid 140 A.I.D. hardener was poured into the moulds and allowed to set. After curing the resin impregnated samples were pushed out of the moulds and cemented to standard microscope slides using a mixture of three parts Epotek 301 resin to one part hardener. The samples were ground to a thickness of 30 μm and covered with a glass slide cemented by Canadian balsam. A 1.00 mm by 0.66 mm grid was used with a Swift point counter with 400 grains per thin section counted as recommended by Dryden (1931). Counts were tallied into the following categories: barnacle, mollucs, coralline alga, echinoderm, bryozoa, other grains (which includes uncommon and unidentifiable grains) and terrigenous grains. Grains were also examined for rounding using the techniques of Folk (1974) where 100 grains per thin section were examined from 37 stations. Two additional stations E4 and C5 consisting of pebble-sized sediment were examined by projection.

Sample components from the maerl area on the northern platform, too large to study by thin-section, were analyzed by weighing the constituent grain groups.

2.8.2 Scanning electron microscopy (SEM).

Selected samples from Iona and the Columba Sea were studied by SEM. Samples were soaked in distilled water overnight to remove adsorbed seasalts, drained and oven-dried. Samples were coated with a mixture of gold and palladium. Specimens were examined in a 5-30 kV Cambridge Mk 2 SEM.

2.8.3 X-ray diffraction.

Aliquots of sieved and dried material < 63 um sediment samples from the Colonsay Sea area, bulk sediments from IGS core SH69V and whole sediment from the sublittoral area of the Sound of Iona, were studied for major mineralogy on a Philips PW 1051 X-ray diffractometer. Samples were ground in an agate mortar and mounted with acetone. They were studied using Ni-filtered, Ca $K\alpha$ radiation at 36 KV and 20 mA, a slit system of 1°, 0.2°, 1°, a scan rate of 1° - 2° 2θ per minute, rate meter setting of 2, time constant setting of 4. Most samples were scanned 4° 2θ to approximately 50° 2θ. Carbonate samples from Iona were scanned from 20° - 40° 2θ. X-rays were interpreted by reference to Chao (1969); Mole percent $MgCO_3$ was computed from the curves of Goldsmith et al. (1961).

2.8.4 Carbonate densities.

The density of common carbonate shells was determined for material from the Sound of Iona. The shells were soaked in distilled water overnight to remove salt, drained and oven-dried. For large shells, or bulk samples, weight was determined using a Mettler top-loading balance, smaller shell material was weighed on an analytical balance. Volumes were measured using the weight gain caused by immersing but suspending the shell in a tared beaker or crucible filled with distilled water; the material was suspended using a fine gauge platinum wire. Volumes were calculated by converting the weight gain to cm^3

(Archimedes principal using a specific gravity of 1.00 for the distilled water). Densities were found by dividing the dry weight by the calculated volume. The small size of the barnacles precluded the use of this volume method. Instead volume was determined by the change in water level caused by immersing the shells in a graduated cylinder.

2.8.5 Special studies of *Phymatolithon calcareum*.

Bosence (1976) suggested that algal shape and branch structure of coralline algae was indicative of environment. His morphometric techniques were based on Sneed and Folk (1958). The technique repeated on Iona sand samples, consists of measuring an algal length along three mutually perpendicular axes, designated L, long; I, intermediate; S, short. Ratios of

$$\frac{S}{L} \quad \text{and} \quad \frac{L - I}{L - S}$$

were plotted on a triangular diagram (Fig. 47), with spheroidal, discoidal and ellipsoidal end-members.

2.8.6 Carbonate digestion by hydrochloric acid.

Bulk sediment samples were washed or centrifuged and dried according to the methods of McAllister (1958). The sample was placed into a pre-weighed Whatman #42 filter paper, and together they were weighed and placed into a sealed plastic liner fitted into a supported funnel. A solution of 20% $^{v}/_{v}$ BDH laboratory reagent grade hydrochloric acid, was added dropwise until dissolution was complete. The plastic liner was cut at the apex and the filter paper was drained and washed thirty times with distilled water. This was usually found to be adequate to remove soluble chloride precipitates on the filter paper. The plastic liner was removed after the sample was partly dry and the filter paper stiffened. The sample on the filter was oven-dried, cooled and reweighed. The % $CaCO_3$ was computed by the formula:

$\% \, CaCO_3 = \%$ soluble material =

$$\frac{(\text{original sample + filter paper, weight}) - (\text{insoluble residue + filter paper, weight})}{(\text{original sample + filter paper, weight}) - \text{filter paper weight}} \times 100$$

The carbonate in barnacle samples, used in productivity measurements was determined by similar methods. The carbonate in core SH69V was determined by using acetic acid digestion; this technique minimized hydrogen ion attack on clay crystal lattices.

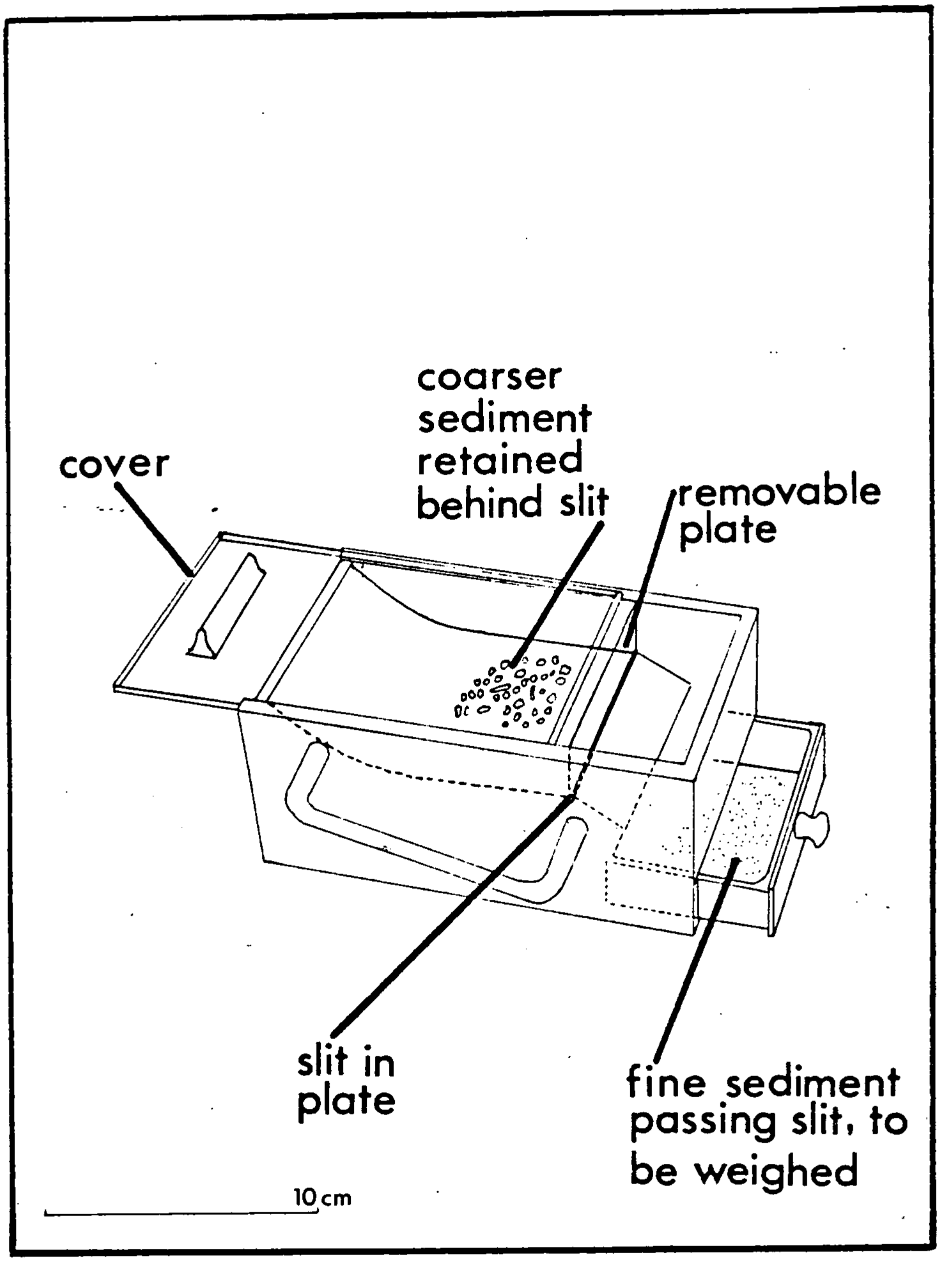
2.8.7 The height sorter.

A type of sizing device developed by Lees et al. (1969) was used as a rough estimate of sediment size. The device is termed a height sorter (Fig. 52). It consists of an aluminium box sealed with a perspex lid. Inside the box at the base of a sloping ramp is a removable metal plate. The plate has a cut-out basal edge which leaves a measured gap between it and the ramp. During operation a sample of 5-10 grams is introduced, the box is sealed and the grains are gently shaken down-slope against the plate. Grains smaller than the gap move through and are collected in a removable drawer beneath the ramp. Grains larger than the gap remain behind it and are collected and weighed. The next smaller gate is inserted and the process repeated. For the Iona sediments slit heights of 4, 2.8, 2.0, 1.4, 1.0, 0.7, 0.5, 0.3 and 0.1 mm were used; they are approximately 0.5ϕ intervals. It was found far faster to shake the sediment through the larger slit sizes of 4 - 1.4 mm, by hand because most sediment was of smaller size. The sediment in the remaining sizes were placed on a mechanical shaker for 5 minutes; it duplicated the gentle manual shaking.

2.8.8 Flume studies.

Three samples of sediment from Iona Sound were studied in a flume to discern current velocity thresholds for transport. An aliquot of

Fig. 52. The sediment height-sorter.


cover
coarser sediment retained behind slit
removable plate
slit in plate
fine sediment passing slit, to be weighed
10 cm

about 50 ml was placed on the glass base of the flume. A Kent-Lea Miniflo Probe 265-3 was placed approximately 1 cm upstream of the sample so that the centre of the impeller was level with the top of the sediment. Water was slowly added and velocity increased until 10% of the sediment volume was transported; velocity was further increased until 50% of the original sample was in motion. The probe velocity was noted in each case.

2.8.9 Shell abrasion experiments.

Four types of shell material from Iona Sound were studied for abrasion rates following the techniques of Chave (1960, 1964). The washed, whole, > 4 mm, shells were used. Their identities and initial starting weights are as follows: the littoral barnacle Balanus balanoides 8.96 g; the littoral gastropod Littorina littoralis 19.87 gm; the littoral limpet Patella sp. 71.74 gm; and the sub-littoral coralline alga Phymatolithon calcareum 72.48 gm. A sample was added to 1 l of distilled water in a plastic jar. Sufficient 1-1.5 cm (maximum axial length) chert pebbles were weighed and added so that there was an approximate 1:1 weight ratio of shell to pebbles. The sealed jar was affixed in a Bachofen System Schatz Turbula mixer for 40 to 80 hours, at 56 cycles per minute. One mixer cycle traces a closed spiral pattern of approximately 90 cm. A sample was wet-sieved using 4 mm, 2 mm and 63 um sieves at intervals of 0, 1, 2, 4, 8, 20 and 40 hour intervals (P. calcareum was abraded for 80 hours). The sieved portions were oven-dried, weighed and photographed.

2.8.9 Carbon 14 dating of shell sands.

Shell samples were prepared and analyzed for C-14 dating by Dr. D. D. Harkness of the Scottish Universities Research and Reactor Centre (SURRC), East Kilbride, Glasgow, Scotland. For the analysis whole, unabraded and unbored shells were used. The following discussion is from D. D. Harkness and S. Ladyman (SURRC, personal communications, 1977, 1978). Prior to C-14 assay the outermost 25 to 30 per cent by weight of each sample was discarded by physical scrubbing followed by a controlled acid leach (5 M HCl). Samples were converted to benzene (via CO_2, Lithium carbide and acetylene). Benzene is then used for C-14 activity measurement by liquid scintillation counting. The stable isotope correction is carried out by mass spectrometry of CO_2 on a VG Micromass 602 B double collector and inlet system and measured relative to a reference to an accuracy of $\pm$ 0.1 $^{o}/oo$.

APPENDIX 3. Carbonate percentages for samples from the Columba-Colonsay Seas as determined using 20% (by volume) HCl.

Note: med. = medium; crs. = coarse; BH = Barnett-Hardy suction bin; DG = Day grab sampler; FAD = Forster anchor dredge; GC = gravity corer; RD = rock dredge; SMG = Smith-McIntyre grab sampler.

Size scale used in this appendix:

Phi units	Size	Wentworth scale		
-5	32 mm	PEBBLE	GRAVEL	
-4	16 mm			
-3	8 mm			
-2	4 mm	GRANULE		
-1	2 mm	VERY COARSE SAND	SAND	
0	1 mm	COARSE SAND		
1	500 µm	MEDIUM SAND		
2	250 µm	FINE SAND		
3	125 µm	VERY FINE SAND		
4	62.5 µm	COARSE SILT	SILT	MUD
5	31 µm	MEDIUM SILT		
6	15.6 µm	FINE SILT		
7	7.8 µm	VERY FINE SILT		
8	3.9 µm	CLAY		
9	2 µm			
10	0.98um			

Appendix 3

R.V. Calanus sampling in the Sound of Jura : September, 1975.

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
Jura 66	77	83	pebble-size shells	FAD
Jura 80	59	22	gravel	FAD
Jura 97	73	30	v. crs. shell sand and gravel	FAD
Jura 99	26	45	muddy shell gravel	FAD
Jura 111	26	30	muddy shell gravel	FAD
Jura 131	165	$\bar{x}$:20 sd=0.2	clayey mud	FAD
Jura 134	37	30	muddy shell gravel	FAD
Jura 144	53	45	silty mud and shell gravel	FAD
Jura 147	135-117	84	shelly gravel	FAD

R.V. Calanus sampling in the Sound of Iona : 19-24 July, 1976.

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
M 1	12	$\bar{x}$:91 sd=4	crs. shell gravel (including P. calcareum)	BH
M 3	19	72	crs. shell gravel (including P. calcareum)	BH
M 4	21	86	crs. shell gravel (including P. calcareum)	BH
M 8	16	73	med.-crs. shell sand	FAD
N 1	21	84	med.-fine shell sand	FAD
N 2	8	80	crs. shell sand	Diver
N 4	14	70	med.-crs shell sand	BH
N 7	43	71	crs. shell sand	FAD
N 8	25	86	crs. sand-fine gravel	BH
O 2	7	90	crs. shell sand with shell gravel	FAD
O 3	7	60	med. shell sand with P. calcareum gravel	FAD
O 6	36	58	crs. shell sand with cobble-sized terrigenes	FAD
O 7	43	48	fine shell sand	FAD
O 8	40	53	med.-crs. shell sand	FAD
O 9	40	73	med.-crs. shell sand	FAD
O10	47	69	med. shell sand	FAD
O11	25	$\bar{x}$:72 sd=1	med. shell sand	FAD

Appendix 3.

R.V. Calanus sampling in the Sound of Iona : 19-24 July, 1976 (cont)

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
014	8	90	shelly gravel (including *P. calcareum*)	FAD
015	8	81	med. shell sand (with *P. calcareum* gravel)	FAD
016	16	81	med. shell sand with shell gravel	FAD
017	16	$\bar{x}$:90 sd=2	med. shell sand	FAD
018	21	64	crs. shell sand and gravel (including *P. calcareum*)	FAD
019	19	46	crs. shell gravel with pebble-sized terrigenes	FAD

R.R.S. John Murray sampling in the Columba-Colonsay Seas : 30 July 10 August, 1976.

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
JM 5	55	15	silt-rich mud	RD
JM 14	16	22	fine-med sand	SMG
JM 15	25	31	silty-mud	SMG
JM 16	22	31	sandy mud	SMG
JM 17	21	32	sandy mud	SMG
JM 18	15	39	sandy mud	DG
JM 20	16	32	med-crs. sand	SMG
JM 21	16	34	med-crs. sand	SMG
JM 22	16	95	med-crs. sand	SMG
JM 23	29	27	silty-sand	SMG
JM 24	37	31	silty-sand	SMG
JM 25	37	40	silty-sand	SMG
JM 26	37	48	silty-sand	SMG
JM 27	37	43	med. sand	SMG
JM 30	10	16	med. sand	SMG
JM 31	10	16	med. sand and gravel	SMG
JM 32	8	17	med. sand and gravel	SMG
JM 37	23	41	med. sand and gravel	SMG
JM 38	23	$\bar{x}$=84 sd=4	muddy gravel with *P. calcareum*	RD
JM 39	23	67	muddy gravel with *P. calcareum*	RD

Appendix 3.

R.R.S. John Murray sampling in the Columba-Colonsay Seas : 30 July - 10 August, 1976 (cont)

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
JM 41	20	49	fine-med sand	SMG
JM 42	20	57	crs.-sand and gravel	SMG
JM 43	20	87	gravel (barnacle-rich)	SMG
JM 50	49	40	med. sand	SMG
JM 51	19	43	med. sand	SMG
JM 52	19	43	sandy gravel	SMG
JM 53	22	49	silty fine sand	SMG
JM 54	38	44	med. sand	SMG
JM 55	33	36	med. sand	SMG
JM 56	22	36	crs. sand	SMG
JM 57	27	32	silty fine sand	SMG
JM 58	37	33	silty fine sand	SMG
JM 59	86	40	muddy gravel	SMG
JM 60	101	43	silty mud	SMG
JM 61	97	40	silty mud	SMG
JM 62	31	45	silty mud	SMG
JM 63	46	39	muddy gravel	SMG
JM 64	53	33	med. sand	SMG
JM 65	30	36	med.-crs sand	SMG
JM 66	49-41	33	silty-mud	DG
JM 67	32-28	40	silty-mud	DG
JM 68	32	35	sandy mud	DG
JM 69	26	40	fine-med. sand	DG
JM 70	33	32	sandy silt	DG
JM 71	38	39	fine-med. sand	DG
JM 72	35	38	med. sand	DG
JM 73	46	38	muddy sand	DG
JM 74	32	34	muddy sand	DG
JM 75	27	31	fine-med. sand	DG
JM 76	26	40	med. sand	SMG
JM 77	26	38	muddy sand	SMG
JM 78	55	33	clayey mud	SMG
JM 79	49	11	crs.-v. crs. sand	SMG
JM 80	55-66	32	silty fine sand	DG
JM 81	40	19	fine-med. sand	DG

Appendix 3.

R.R.S. John Murray sampling in the Columba-Colonsay Seas : 30 July - 10 August, 1976 (cont)

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
JM 82	42	16	med. sand	DG
JM 83	43	14	med. sand	DG
JM 84	44	15	med. sand	DG
JM 85	45	10	med. sand	DG
JM 92	75	39	fine sand and mud	SMG
JM 93	76	43	fine sand and mud	SMG
JM 95	67	83	muddy pebbles	RD
JM 97	86	61	muddy gravel	RD
JM102	60-55	83	med. sand	SMG
JM106	59	100	cobbles	RD

R.R.S. Challenger sampling in the Firth of Lorne area : May, 1977.

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
CH 1	26	$\bar{x}$:59 sd:0.1	crs. sandy mud	GC
CH 3	55	21	silty mud	GC
CH 5	115	7	pebbly mud	GC
CH 6	43-40	54	muddy pebble	GC
CH 7	75	37	muddy gravel	GC
CH 9	38-40	59	sandy mud	GC
CH 12	137-130	10	clayey mud	GC
CH 13	100	9	clayey mud	GC
CH 16	121-126	37	clayey mud	GC
CH 17	118	40	muddy sand and gravel	GC
CH 18	53	14	brown mud	GC
CH 23	37	18	brown mud	GC
CH 25	50	30	muddy sand and gravel	GC
CH 26	43	22	muddy sand and gravel	GC
CH 27	52	38	muddy sand and gravel	GC
CH 28	67	71	muddy gravel with pebbles	GC
CH 30	43	26	muddy gravel	GC
CH 31	40	53	muddy sand and gravel	GC
CH 32	140	11	sandy mud	GC
CH 39	?	30	muddy gravel	GC

R.R.S. Challenger sampling in the Firth of Lorne area : May, 1977 (cont)

Sample	Depth (m)	% $CaCO_3$	Sediment size	Collecting technique
CH 40	42	25	terrigene-rich gravel	GC
CH 41	23	24	terrigene-rich gravel	GC
CH 42	23	19	muddy cobbles	GC
CH 44	30	59	pebbly crs. sand	GC
CH 47	85	76	silty crs sand	GC
G 1	26	$\bar{x}$:36 sd=1	silt-rich mud	DG
G 2	32	40	silt-rich mud	DG
G 3	55	29	silt-rich mud	DG
G 4	53	30	fine sand and silt	DG
G 5	125	28	silt-rich mud	DG
G 6	36	45	silt-rich mud with gravel-sized shells	DG
G 7	75	27	silt-rich mud	DG
G 8	35	37	fine sand	DG
G 9	38-40	18	fine-med sand with gravel-sized shells	DG
G 10	50-51	27	med. sand	DG
G 11	85	26	silt-rich mud	DG
G 12	130	31	muddy gravel	DG
G 13	100	44	mud with crs gravel-sized shells	DG
G 16	121-126	47	mud with crs gravel-sized shells	DG
G 17	118	19	silt-rich mud	DG
G 18	53	18	med. sand	DG
G 19	71-72	30	silt	DG
G 20	86	32	silt	DG
G 21	135	30	silt	DG

APPENDIX 4.1a Thin section percentages for the Sound of Iona components.

Beach (+ Dune = A3, A8, B15, B17, C7, F9)

	Spl.	cirriped	mollusc	calcareous rhodophyte	echinoderm	foram-inifera	bryozoa	other	terrigene
	A2	78.25	6.00	0.75	5.00	0	0	1.25	8.75
Dune	A3	73.50	4.00	0.25	0	0	0	2.00	20.25
	A4	27.50	4.00	0	0	0	0	2.00	66.50
	A5	58.85	5.74	0.25	0.50	0	0	2.00	32.67
Dune	A8	76.50	3.50	0	0.50	0	0	0.75	18.75
	A9	74.25	3.00	0	0.75	0	0	1.25	20.75
	B1	72.50	9.00	1.25	3.00	0.75	0.50	1.50	11.50
	B2	66.25	5.75	0	0.50	0	0	3.00	24.50
	B3	52.00	6.25	0	2.00	0.50	0	6.50	32.75
	B4	64.50	8.25	0.50	1.25	0	0	4.25	21.25
	B5	88.25	1.25	0	0.50	1.00	0	1.50	7.50
	B6	84.75	4.00	0	2.75	0.50	0	4.25	3.75
	B7	pebbles not analyzed							
	B8	61.35	4.24	0.25	0.25	0.25	0	1.00	32.67
	B9	59.60	4.24	0	0	0	0	0.75	36.41
	B10	80.25	1.25	0	0.75	0	0	1.75	16.00
	B11	79.75	6.00	1.25	1.25	0.25	0	2.25	9.25
	B12	pebbles not analyzed							
	B13	67.33	14.71	1.25	1.00	0.25	0	3.24	12.22
	B14	64.25	9.25	0	1.25	0.25	0	0.50	24.50
Dune	B15	58.00	7.75	0	0.50	0	0	5.00	28.75
	B16	62.25	11.00	0.50	1.75	0	0	3.00	21.50
Dune	B17	60.00	21.00	0	0.25	0	0	2.25	16.50
	B18	65.50	16.25	0.75	0.25	0	0	3.50	13.75
	C1	54.25	25.00	0.25	4.50	3.50	0.25	6.00	6.25
	C5	pebbles not analyzed							
	C6	73.00	4.25	0	1.50	0	0	1.00	20.25
Dune	C7	59.25	17.75	0.25	0.50	0.50	0	8.00	13.75
	E8	16.00	3.00	0	0	0	0	8.75	72.25
	E9	large shells not analyzed							
	E10	13.25	5.00	0	0.50	1.00	0	2.75	77.50
	E11	23.00	5.25	0	1.00	0.50	0	5.25	65.00
	E12	pebbles not analyzed							
	E13	8.33	4.51	0	0.35	0	0	2.43	89.38
	F6	18.47	5.41	1.91	5.73	0	0	11.78	56.69
	F7	grain counts too small n=52							
	F8	61.69	2.60	5.19	2.60	0	0	18.18	9.74
Dune	F9	43.75	19.00	2.00	4.00	0	0	5.25	26.00
	L5	31.75	36.25	0	3.50	8.50	0.25	12.25	7.50

n = 33

	cirriped	mollusc	calcareous rhodophyte	echinoderm	foram-inifera	bryozoa	other	terrigene
$\bar{x}$	56.91	8.620	0.503	1.460	0.538	0.030	4.095	27.822
sd	22.00	2.750	1.013	1.566	1.569	0.104	3.919	22.314
cv	38.66%	89.905%	201.4%	107.275%	291.681%	342.498%	95.705%	80.060%

Dune only n = 6

	cirriped	mollusc	calcareous rhodophyte	echinoderm	foram-inifera	bryozoa	other	terrigene
$\bar{x}$	61.83	12.17	0.42	0.96	0.08	0	3.88	21.75
sd	11.86	7.97	0.79	1.50	0.20	-	2.69	4.65
cv	19.18%	65.47%	188.4%	156.88%	244.95%	-	69.34%	21.38%

Beach only n = 27

	cirriped	mollusc	calcareous rhodophyte	echinoderm	foram-inifera	bryozoa	other	terrigene
$\bar{x}$	55.82	7.83	0.52	1.57	0.64	0	4.14	29.47
sd	23.70	7.63	1.07	1.59	1.72	-	4.18	24.33
cv	42.46%	97.38%	204.7%	100.9%	269%	-	101.0%	82.55%

Appendix 4.1b Thin section percentages for the Sound of Iona components.

Sublittoral

Spl	cirriped	mollusc	calcareous rhodophyte	echinoderm	foram-inifera	bryozoa	other	terrigene
A1	59.75	20.25	1.42	6.17	1.67	0	4.92	5.75
A6	62.98	22.10	5.52	1.66	0	0	3.85	3.87
A7	56.19	8.76	25.00	1.29	0	0	3.09	5.67
C2	69.75	10.75	1.25	2.50	0.5	0	1.25	14.00
C3	68.75	11.75	0	1.50	0	0	2.50	15.50
C4	68.00	11.00	0	1.25	0	0	10.50	9.25
D1	49.13	10.97	0	1.50	0	0	6.98	31.42
D2	56.87	17.03	0	4.12	0	0	4.12	17.86
D3	30.50	10.25	0	2.25	0	0	7.75	49.25
D4	large shells not analyzed							
D5	large shells not analyzed							
D6	large shells not analyzed							
E1	60.50	12.61	2.52	3.36	0	0	3.08	17.93
E2	29.93	8.10	15.14	2.11	0	0	19.37	25.35
E3	52.00	17.00	0.25	3.50	0	0	8.00	19.25
E4	Phymatolithon calcareum not analyzed							
E5	bivalves not analyzed							
E6	extra P. calcareum							
E7	soft plants not analyzed							
F1	69.97	5.12	11.6	2.39	0	0	3.41	7.51
F2	P. calcareum not analyzed							
F3	40.78	5.88	33.33	3.14	0	0	12.55	4.31
F4	soft plants							
F5	53.02	7.76	9.48	2.16	0.43	0	18.10	9.05
G1	55.34	9.55	0.84	1.40	0	0	1.40	31.46
G2	62.11	12.28	2.46	5.26	0	0	1.05	16.84
G3	large shells and P. calcareum not analyzed							
G4	43.25	16.00	6.50	1.25	0	0	1.25	31.75
G5	62.59	9.98	2.74	1.25	0	0	2.74	20.70
G6	39.25	22.50	2.25	1.50	0	0	4.75	29.75
H1	58.68	16.80	4.41	2.20	0	0	1.93	15.98
H2	61.00	15.25	2.00	1.25	0	0	2.00	18.50
H3	42.40	13.60	10.67	1.60	0	0	1.33	30.40
H4	55.50	13.00	6.75	2.00	0	0	3.00	19.75
H5	P. calcareum not analyzed							
H6	P. calcareum and shells not analyzed							
H7	41.75	13.50	33.00	1.50	0	0	2.25	8.00
H8	46.88	9.98	34.16	0.25	0	1.00	4.74	3.24
H9	67.83	8.48	4.24	0.75	0	0	4.49	14.29
H10	55.25	12.75	10.25	0.50	0	0	8.50	12.75
H11	43.18	13.09	29.53	0.84	0	0	7.80	5.57
H12	P. calcareum not analyzed							
I1	60.06	9.09	1.10	1.10	0	0	12:12	16.53
I2	54.23	10.20	2.62	1.46	0	0	14.58	16.91
I3	51.50	11.00	5.25	2.00	0	0.25	9.75	20.25
I4	47.75	10.25	3.25	4.00	0	0.25	4.75	29.75
I5	61.22	7.58	5.54	2.92	0	0	3.21	19.53
I6	71.66	8.47	4.89	2.28	0	0	0.33	12.38
I7	58.10	11.22	2.49	3.24	0	0	1.75	23.19
I8	57.50	13.50	0.75	2.75	0	0	2.50	23.00
J1	56.50	12.75	10.50	3.50	0.25	0	7.25	9.25
J2	49.00	7.75	13.75	0	0	0	9.75	19.75
J3	44.50	13.25	5.75	2.00	0.25	0	7.25	27.00
J4	63.50	6.00	2.25	1.75	0	0	9.75	16.75
K1	71.25	8.25	1.50	3.00	0	0.25	6.75	9.00
K2	58.75	3.25	3.75	4.50	0	0	4.25	25.50
K3	56.36	12.47	1.25	2.99	0	0	4.24	22.69
K4	41.50	17.00	4.75	1.50	0	0	5.25	30.00
K5	67.00	8.00	2.25	3.00	0	0	8.75	11.00
K6	6.00	6.00	0.50	1.50	0	0	1.75	84.25
K7	58.25	15.50	6.00	3.75	0	0.25	3.25	12.50
L1	45.00	7.50	9.25	2.50	0	0	8.50	27.25
L2	42.64	14.47	2.03	3.30	0.25	0	7.61	29.70
L3	55.53	12.37	15.00	1.32	0.26	0	7.89	7.63
L4	22.22	7.07	34.68	1.35	0	0	8.75	25.93
n = 52								
$\bar{x}$	53.14	11.520	7.585	2.234	0.069	0.048	5.898	19.512
sd	12.88	4.144	9.679	1.239	0.252	0.179	4.255	13.153
cv	24.23%	35.971%	127.613%	55.468%	362.407%	371.832%	72.144%	67.410%

Appendix 4.2 Thin section percentages for the Sound of Iona, recalculated for cirriped , mollusc, rhodophyte and echinoderm categories on a terrigene free basis

Sublittoral Terrigene free (Foraminifera, bryozoa and "others" omitted)

Spl.	cirriped	mollusc	calcareous rhodophyte	echinoderm
A1	64	21	1.5	6.6
A6	66	23	5.7	1.8
A7	59	9.4	27	1.4
C2	81	13	1.5	2.9
C3	82	14	0	1.8
C4	75	12	0	1.4
D1	71	16	0	2.1
D2	69	21	0	5.0
D3	61	20	0	4.5
D4	large shells not analyzed			
D5	large shells not analyzed			
D6	large shells not analyzed			
E1	74	16	3.0	4.2
E2	40	11	20	2.8
E3	64	21	0.31	4.3
E4	_Phymatolithon calcareum_ not analyzed			
E5	bivalves not analyzed			
E6	_P. calcareum_ not analyzed			
E7	soft weed not analyzed			
F1	76	5.5	13	2.6
F2	_P. calcareum_ not analyzed			
F3	43	6.2	34	3.1
F4	soft plants not analyzed			
F5	58	8.6	10	2.4
G1	80	14	1.2	2.0
G2	75	14	3.0	6.4
G3	_P. calcareum_ and shell not analyzed			
G4	63	23	9.6	1.9
G5	80	13	3.4	1.7
G6	56	33	3.3	2.1
H1	70	20	5.2	2.6
H2	75	19	2.5	1.5
H3	60	20	16	2.3
H4	70	16	8.5	2.5
H5	_P. calcareum_ not analyzed			
H6	_P. calcareum_ and shells not analyzed			
H7	45	15	36	1.6
H8	48	10	35	0.26
H9	79	9.9	4.9	0.88
H10	63	15	11	0.57
H11	46	14	31	0.89
H12	_P. calcareum_ not analyzed			
I1	72	11	1.3	1.3
I2	65	12	3.1	1.8
I3	65	14	6.3	2.5
I4	69	14	4.7	5.7
I5	76	9.5	6.9	3.6
I6	82	9.7	5.6	2.6
I7	75	14	3.3	4.2
I8	75	18	0.97	3.6
J1	63	14	12	3.9
J2	61	9.8	18	0
J3	62	18	8.0	2.7
J4	77	7.2	2.8	2.2
K1	78	9.1	1.7	3.3
K2	80	4.5	5.1	6.1
K3	73	16	1.7	3.9
K4	60	24	6.9	2.1
K5	75	9.0	2.6	3.4
K6	38	38	3.1	9.4
K7	67	18	6.9	4.4
L1	62	10	13	3.4
L2	61	20	2.9	4.7
L3	61	13	16	1.4
L4	30	9.6	47	1.9
n = 52				
$\bar{x}$	66	15	9.2	3.0
sd	12	6.4	11	1.8

Appendix 4.3

Thin section percentages recomputed on a terrigene-free basis

Beach = Terrigene free (Foraminifera, bryozoa and "others" omitted)

Spl.	cirriped	mollusc	calcareous rhodophyte	echinoderm
A2	86	6.6	0.82	5.5
A4	85	12	0	0
A5	87	8.5	0.37	0.74
A9	94	3.8	0	0.95
B1	83	10	1.4	3.4
B2	88	7.7	0	0.67
B3	78	9.3	0	3.0
B4	82	11	0.63	1.6
B5	96	1.4	0	0.54
B6	89	4.2	0	2.9
B7	pebbles not analyzed			
B8	91	6.3	0.37	0.37
B9	92	6.6	0	0
B10	95	1.5	0	0.89
B11	88	6.6	1.4	1.4
B12	pebbles not analyzed			
B13	76	17	1.5	1.1
B14	85	12	0	1.7
B16	79	14	0.64	2.2
B18	77	19	0.87	0.29
C1	57	27	0.27	4.8
C5	pebbles not analyzed			
C6	91	5.4	0	1.9
E8	57	11	0	0
E9	large shells not analyzed			
E10	59	23	0	2.3
E11	66	15	0	2.9
E12	pebbles not analyzed			
E13	52	28	0	2.2
F6	42	13	4.4	13
F7	grain count too low n = 52			
F8	69	2.9	5.8	2.9
L5	35	39	0	3.8
n = 27				
$\bar{x}$	77	12	0.68	2.5
sd	17	8.9	1.4	2.8

Dune = Terrigene free (Foraminifera, bryozoa and "others" omitted)

Spl.	cirriped	mollusc	calcareous rhodophyte	echinoderm
A3	93	5	0.31	0
A8	94	4.3	0	0.62
B15	82	11	0	0.70
B17	72	25	0	0.30
C7	69	21	0.29	0.58
F9	59	26	2.7	5.4
n = 6				
$\bar{x}$	79	15	0.55	1.3
sd	15	9.8	1.1	2.0

Appendix 4.4 Northern platform 2 : maerl area; weight percentages of sample constituents.

Note: n.o. = not observed, n.c. = not calculated.

Spl.	Cirripede	mollusc	calcareous rhodophyte	echinoderm	foraminifera	bryozoa	other	terrigene	sand and gravel
E4	tr (0.02)	2.2	81.38	n.o.	n.c. in sand and gravel fraction	n.c.	tr (0.02) (serpulids)	in sand and gravel fraction	16.38
F2	tr (0.22)	tr (0.56)	92.86	n.o.	n.c. in sand and gravel fraction	n.c.	tr (0.02) (serpulids)	in sand and gravel fraction	6.34
H5	n.o.	tr (0.26)	99.74	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
H6	tr (0.69)	23.40	47.12	1.52	n.c. in sand and gravel fraction	n.c.	n.o.	n.o.	27.27
H12	tr (0.02)	2.39	93.18	n.o.	n.c. in sand and gravel fraction	n.c.	tr (0.02)	1.89	2.49

APPENDIX 5. Calculation of eulittoral zone rock relief factors.

Station	Linear measure 1 Parellel to shore	Linear measure 2 Perpendicular to shore	Linear Area	Contour measure 1 Parellel to shore	Contour measure 2 Perpendicular to shore	Contour Area	Areal Relief Factor: Contour Area / Linear Area
1Y Iona	4.6m	4.6m	21.2m^2	5.7m	5.8m	33.1m^2	1.6
2Y Iona	4.6m	4.6m	21.2m^2	5.3m	9.4m	49.8m^2	2.3
3Y Iona	4.6m	4.6m	21.2m^2	5.2m	7.7m	39.9m^2	1.9
4Y Iona	4.6m	4.6m	21.2m^2	5.2m	5.7m	29.8m^2	1.4
5Y Iona	4.6m	4.6m	21.2m^2	5.3m	6.0m	31.8m^2	1.5
6Y Iona	4.6m	4.6m	21.2m^2	5.5m	6.2m	34.1m^2	1.6
4S Iona	7.0m	8.3m	58.1m^2	8.0m	11.0m	88.0m^2	1.5
							Average relief factor 1.7
1S Mull	5.0m	7.0m	35m^2	6.5m	8.0m	52.0m^2	1.5
2S Mull	5.0m	5.8m(est)	28.9m^2	7.1m	6.6m	46.9m^2	1.6(est.)
3S Mull	5.0m	7.0m	35m^2	8.4m	7.4m	62.2m^2	1.8
							Average relief factor 1.6
1 Erraid	2.8m	2.9m	8.1m^2	5.3m	5.4m	28.6m^2	3.5
2 Erraid	3.1m	3.1m	9.6m^2	4.7m	5.2m	24.4m^2	2.5
3 Erraid	5.0m	18.0m	90.0m^2	12.8m	21.0m	268.8m^2	3.0
							Average relief factor 3.0
4 Erraid 6 Erraid	Boulders, max. length 1m areal data not computed.						

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Calcareous sediments on the nearshore continental shelf of western Scotland

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SYNOPSIS

The highest carbonate values are associated with exposed coasts of Lewisian gneiss, reaching 95% $CaCO_3$ in SW Tiree: around Iona average values are 80 to 85% $CaCO_3$. Maximum values of 60 to 70% on Islay indicate a regional gradient which reflects a reduced fetch southwards, and a greater input from reworked glacial drift and fluvial material.

High energy carbonate deposits are distinguished by the low diversity of their components, nearly all coming from fragmented molluscs and barnacles. Low energy carbonates have diverse components, with foram and echinoid values each reaching 10%. The ratio $\frac{\text{Barnacles}}{\text{Echinoids + Forams}}$ most easily separates the two facies (high energy mean = 18·5: low energy mean = 2·1).

In the immediate offshore tidal-swept zones such as the Sound of Iona barnacles are the most important contributors to the sediment.

Most of the carbonate is fresh and by its relationship to contemporary shore ecology can be shown to be of present-day origin. Offshore, however, relict grains are widespread. Their pitted surfaces are inhabited by very abundant diatoms, and it is tentatively suggested that local carbonate dissolution may be caused by them. Additionally they represent a much more abundant source of silica for eventual silicification of the carbonate than do sponge spicules, which are rare.

INTRODUCTION

Limestones formed from the breakdown of fossil débris are very widespread throughout the geological record. Most work on possible modern analogues has concentrated in tropical areas like the Persian Gulf (e.g. Purser 1973) and the Bahama Banks (e.g. Purdy 1963). Bioclastic calcareous deposits, however, are far from restricted to the tropics, as has been shown by the work of Boillot (1964, 1965) off Brittany, and Keary (1967), Lees *et al.* (1969) and Pendlebury *et al.* (1976) off Ireland. Surprisingly, the famous shellsand beaches of Scotland have not hitherto attracted the attention of geologists, save for brief notes by Raymond and Hutchins (1932) on a beach near John o' Groats, and by Haldane (1939) on the 'coral' sands of Dunvegan, Skye.

The present study was begun with the aim of identifying the dominant organisms contributing to the nearshore carbonate fraction of the bottom sediments. Additionally we hoped to evaluate the relative susceptibility of each skeletal component to disintegration, whether by biological attack or by physical processes such as wave and current transport. By using this information on ancient limestones we might therefore arrive at estimates of the degree of transport and palaeoecological mixing represented by any given deposit.

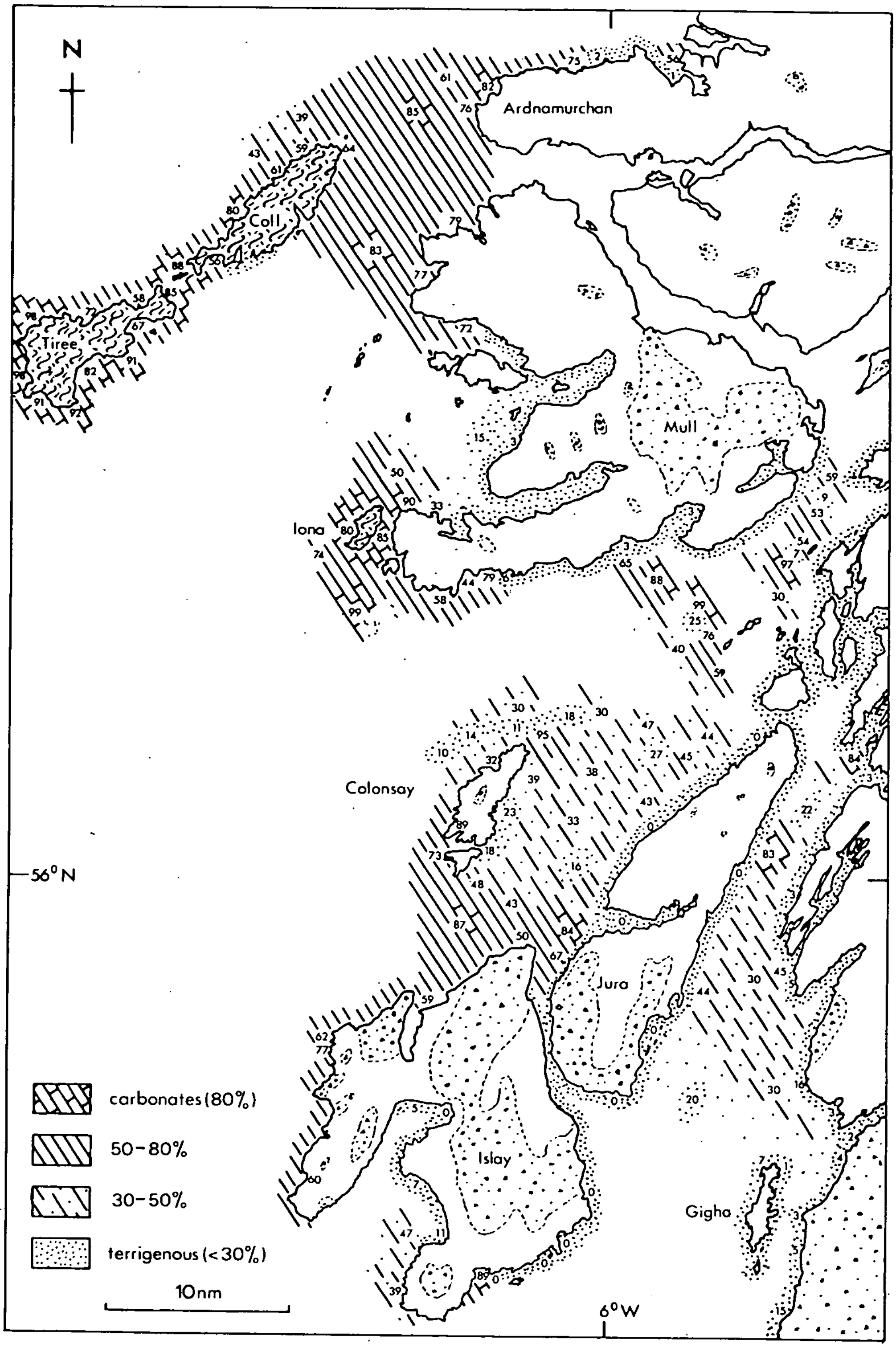

FIG. 1.—Map showing the regional distribution of carbonate in bottom sediments between Ardnamurchan and Gigha. Beach data principally from Ritchie (personal communication 1977 and *in lit.*) and our own observations. Offshore data from samples collected by Brown, Whittington, Dobson and ourselves. [Figures obtained by acid digestion: chiefly analysed by MC] Material from 'John Murray' cruise 10, 1976, 'Edward Forbes' cruise 14A, 1976, 'Challenger' cruise 8, 1977, and from four 'Calanus' cruises is plotted. Outcrop of Lewisian gneiss from Binns *et al.* (1974)
Drift (shown approximately) is from IGS (1977).

REGIONAL DISTRIBUTION OF CALCAREOUS SEDIMENTS

Fig. 1 shows the correlation between exposed sites and % $CaCO_3$ in the nearshore sediments. All west-facing promontories have high values. Landwards of these (e.g. Firth of Lorne) beaches become terrigenous, even though carbonate values are high offshore. In certain instances, anomalously low offshore values can be shown to reflect the erosion of underlying glacial outwash sands (e.g. Tarbert Bank, off Jura, Farrow *et al.* 1978).

The highest carbonate values are associated with the outcrop of Lewisian gneiss, reaching a peak in the 95% pure beaches of SW Tiree. The regional trend continues out of the area shown on fig. 1 to a further area of very high carbonate in the Outer Hebrides, again associated with gneiss and highly exposed conditions. Values are lower towards the south, maximum values being 60–70% on Islay. This may reflect an increased input from the erosion of glacial drift, particularly on Kintyre, though the maximum fetch is also very much reduced here.

Much of the offshore area has intermediate carbonate values of 20–50%, and thus represents the modern equivalent of the widespread calcareous shales and sandstones of the past—an oft neglected group of sediments.

Since extensive sample coverage is available for beaches (Crofts *et al.* 1974; Mather *et al.* 1972, Ritchie *et al.* 1974) and offshore (Binns *et al.* 1974) our own work has been on a more intensive scale, concentrating on the following areas:–

1) Sound of Iona—an area of very high carbonate sediment with a gneissose or granitic basement:
2) Ardnamurchan—another high carbonate area, but mostly with a basaltic basement:
3) NE Orkney Islands—probably the purest inner shelf carbonate, with an Old Red Sandstone sedimentary basement and some glacial deposits:
4) Colonsay—Islay—Jura—an essentially low-medium carbonate area with local highs; basement usually thick Quaternary sediment, including glacial drift.

TECHNIQUES OF STUDY

The bottom sediments were either sampled by hand; divers skimming the lip of a 1 litre polythene bottle over the upper 6 cm of sediment; or they were obtained by Smith/McIntyre Grab, Day Grab or Anchor Dredge, from a research vessel, either the 'Calanus' or the 'John Murray'. For most of the offshore stations each sample was preceded by geophysical traversing (to obtain the internal structure of sand bodies and for side-scan sonar mapping) and underwater television examination. We consider this important, inasmuch as the constituent particles of a sediment will differ radically between, for example, the crests and trough of a megaripple. Underwater television (and still photography) permits some appreciation of whether a sample can be regarded as representative of a particular area. Side-scan sonar gives an indication of how widespread such an area is in terms of adjacent features such as rock outcrops.

Back in the laboratory samples were washed, over dried at 100°C and analysed for their principal components. We considered that little point would be served by routine granulometric analysis, since with locally derived material, results say little about hydrodynamic regime. Most of the carbonate is of sand or gravel grade and can con-

TABLE 1

Summary of regional averages of principal carbonate components in sediments from the inner continental shelf of western Scotland

Locality	%$CaCO_3$	Barnacles	Molluscs	Calcareous Algae	Echinoids	Crinoids	Bryozoa	Serpulids	Forams	Environment
Iona	83	34	42	2	3	0	1	tr	1	beach and Sound
Ardnamurchan (west)	82	46	29	2	4	0	tr	0	1	beach
Ardnamurchan (north)	73	33	23	2	6	0	1	0	8	beach
NW Mull	76	16	45	1	7	0	1	0	5	beach
Iona	89	50	23	tr	5	tr	3	8	tr	offshore rock
Firth of Lorne	87	39	33	tr	5	4	4	5	tr	offshore rock

veniently be analysed in graduated trays by binocular microscope. Point counting of grains along traverses (sands) or box counting (for gravels) was used. Depending on the number of components, 500 (for up to 5) or 1000 (for up to 11) points were counted.

Highly polished grains, particularly of sand grade, are very difficult to identify. Many samples, therefore, were impregnated and thin sections prepared: other samples were stub mounted for SEM examination. Both techniques assisted in distinguishing between mollusc and barnacle fragments, though the possibility of error still remains.

Grains were identified according to the criteria elaborated by Milliman (1974, Appendix I, II).

Principal Components

Results of principal components analysis are available from three of the four areas, the Orkneys material having yet to be processed. Data are most complete for the Sound of Iona and for beach and nearshore regions of Mull and Ardnamurchan. A summary is given as table 1; full results may be obtained from the senior author. Eleven components were tabulated: they are illustrated on plates 1, 2, 3. Two, molluscs and barnacles, far outweigh the remaining nine, of which echinoids are the most important. The averages given in table 1, however, subsume a greater variation than is at first apparent. Many of these variations are of a quite local nature, and demonstrate clearly by their relationship to contemporary shore ecology that much of the carbonate sediment is genuinely of recent origin.

Local Variations in Principal Components and in Total % Carbonate

1) *Exposure contrasts on Iona*

The Iona area is a major producer of calcareous sediment (fig. 2). Fig. 3 shows the average compositions of the two contrasted sets of beach samples from exposed and sheltered coasts: representative grains are illustrated on Pl. 1; 3A, B. Highly polished grains of molluscan and barnacle origin are normal on exposed beaches not only on Iona but throughout the Hebrides, on Tiree and Barra (particularly). Fragile grains, such as those of echinoids, molluscan spat, forams or bryozoa are missing, but on the sheltered beaches these are well developed, with a clear component originating from the local seaweed. One uniquely diverse sediment (Pl. 1) consists of 11% bryozoa and 13% *Spirorbis* together with 45% molluscan spat. In this sample, barnacles account for a mere 5%. These fine examples of local ecological control on the resulting carbonate sediment belie the difficulties in explaining the balance of components in offshore sediments in the Sound of Iona. Table 2 shows that barnacles are twice as abundant in the Sound, even being more abundant here than on the exposed beaches. These are not all relict grains, many being very fresh, and it appears that sublittoral production of barnacles may be high.

Lithothamnium is the most distinctive component of many of the Sound sediments (Pl. 2F), though its distribution is patchy. The main centre of active dispersal of live

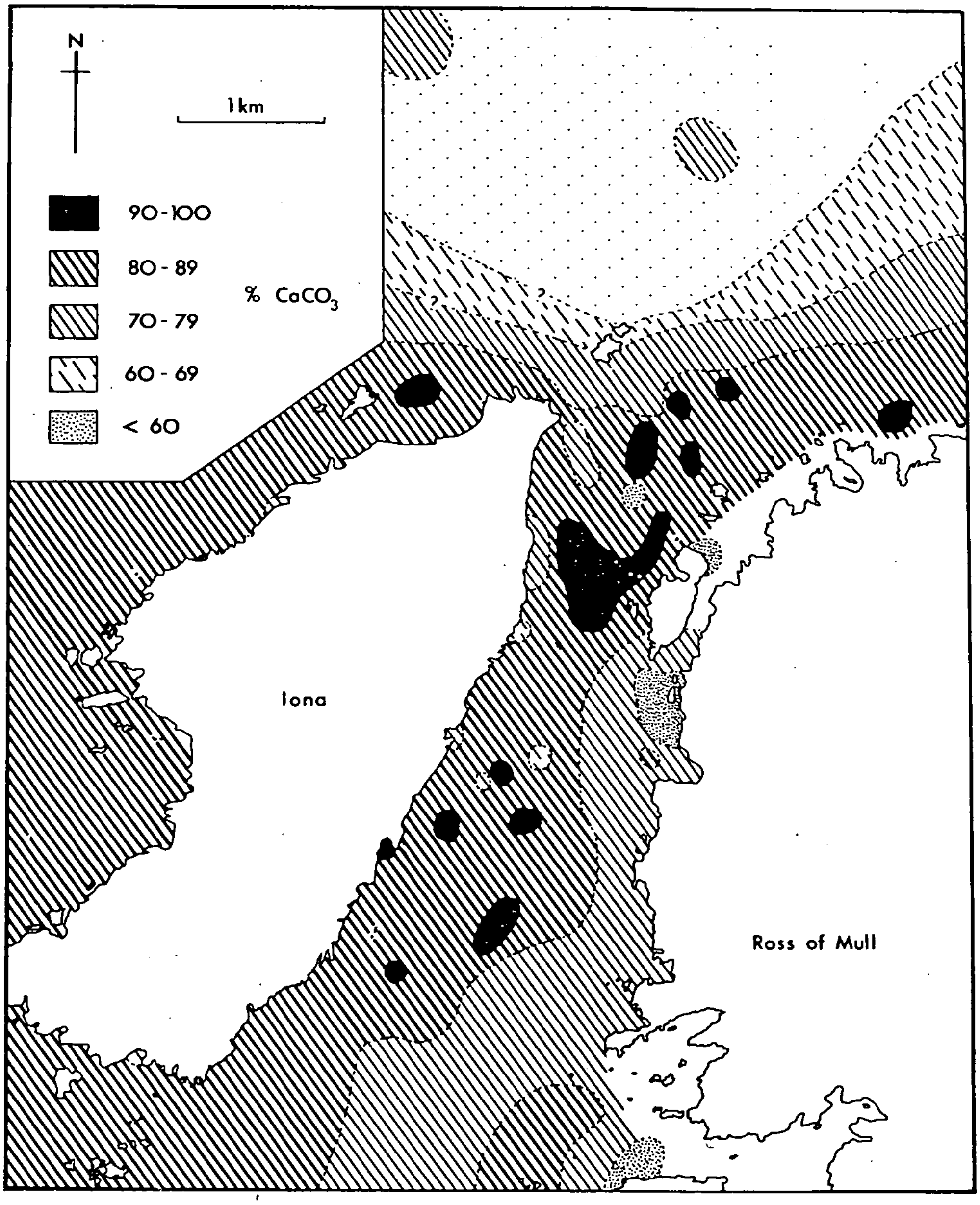

FIG. 2.—Map showing the variation in total carbonate in bottom sediments of the Iona area. Based on 85 samples. [Figures chiefly obtained by point counting (GEF), some peripheral values by acid digestion (MC).]

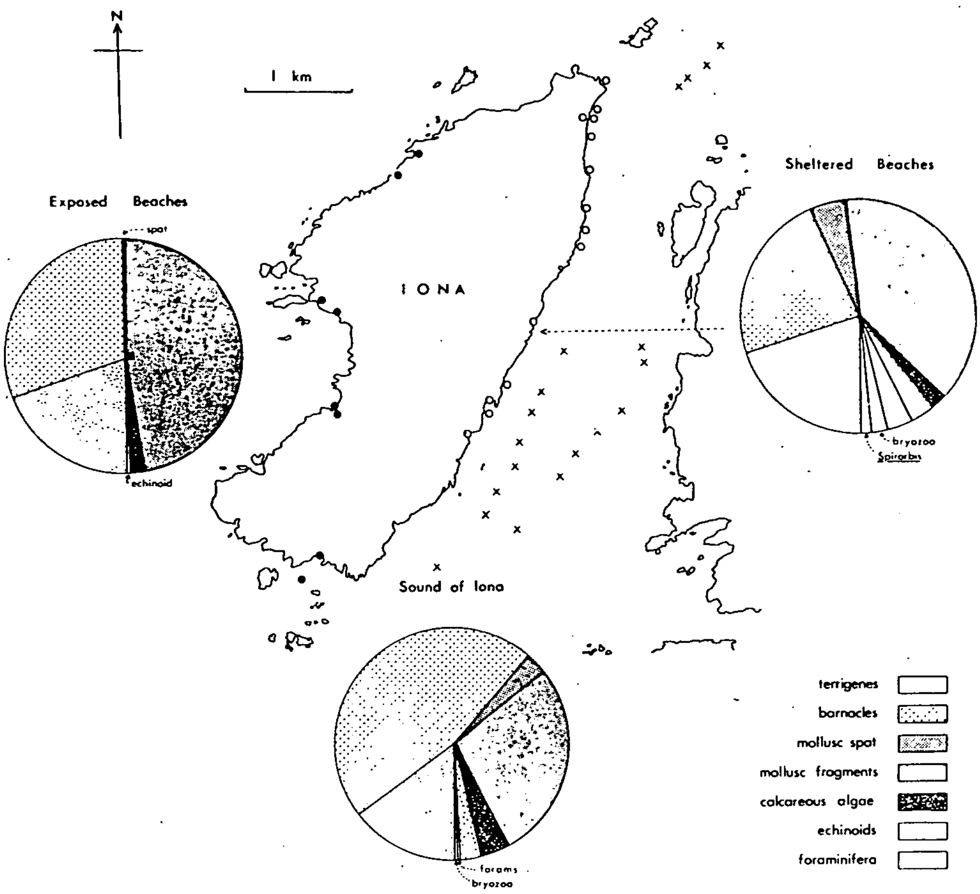

FIG. 3.—*Pi* diagrams showing the variation in principal carbonate components from Iona between exposed beaches, sheltered beaches and the tidal Sound. Diagrams are averages for the stations plotted.

algae is in the north of the Sound, where 100% pure algal deposits occur. [The occurrence of *Lithothamnium* in a wider context is being treated in a separate paper.]

2) *Component variation across individual beaches on Mull and Ardnamurchan*

The beaches to be dealt with are shown, on fig. 4. The highest energy beach is Sanna, 2 miles NE of Ardnamurchan Point. Port Bàn is exposed to the north, while of the two Mull beaches, Calgary Bay is not as exposed as its WSW facing would suggest, since it is strongly embayed. Beaches in the vicinity of Port an t'Struthain show a striking gradation from white carbonate to black basaltic sands.

a) *Sanna Bay*

Three examples from a transect near the northern end of the Bay were analysed: the results, given in table 3, are portrayed on fig. 5. It is notable that the sample from near rocks, rather than being richer in terrigenes, is richer in carbonate, particularly barnacles. Also evident is a relative increase in echinoid remains up the beach, possibly a

TABLE 2

Principal carbonate components in sediments from Iona

Environment	n	%$CaCO_3$	Barnacles	Molluscs (spat/ fragments)	Lithothamnium	Echinoids	Forams	Bryozoa	Spirorbis	Energy level
Western beaches (exposed)	8	80	30	48 (tr/48)	1	tr	0	0	0	high wave action
Eastern beaches (sheltered)	14	80	23	44 (5/39)	2*	4	3	2	1	low wave action
Sound of Iona (tidal)	19	85	46	31 (3/28)	4	3	tr	tr	tr	high current action

* Includes *Corallina*.

TABLE 3

Principal carbonate components in beach sediments from Sanna Bay, Ardnamurchan

Tidal Height	Situation	%$CaCO_3$	Barnacles	Molluscs (spat/ frags.)	Lithothamnium	Echinoids	Forams	Bryozoa	HM No.
LWMOT	*Arenicola* Sand	71	42	24 (1/23)	1	2	1	tr	*R12205*
MTL	near rocks	94	61	23 (8/15)	2	5	3	0	*R12204*
HWST	berm	83	34	39 (tr/39)	2	6	1	1	*R12206*

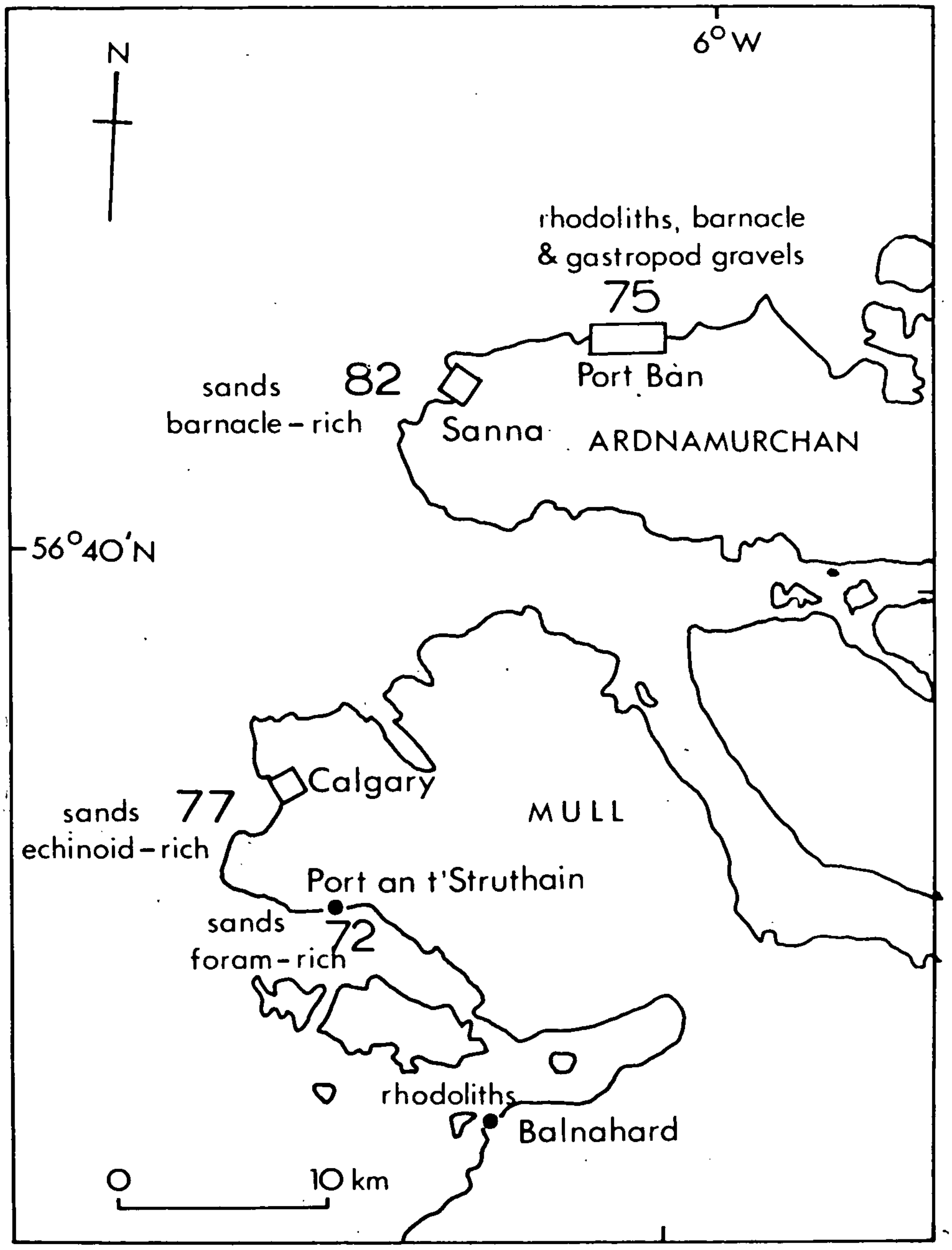

FIG. 4.—Map showing the localities on Mull and Ardnamurchan where detailed investigations of carbonate sedimentation have been undertaken.

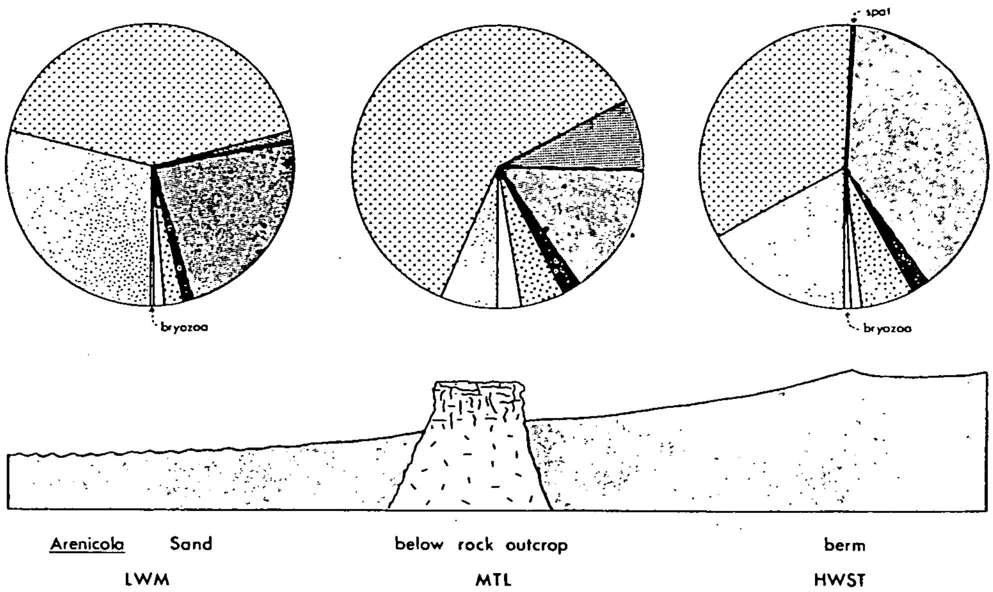

FIG. 5.—Shore transect across N sector of Sanna Bay, Ardnamurchan, showing variation in principal carbonate components. (Key as for Fig. 2.)

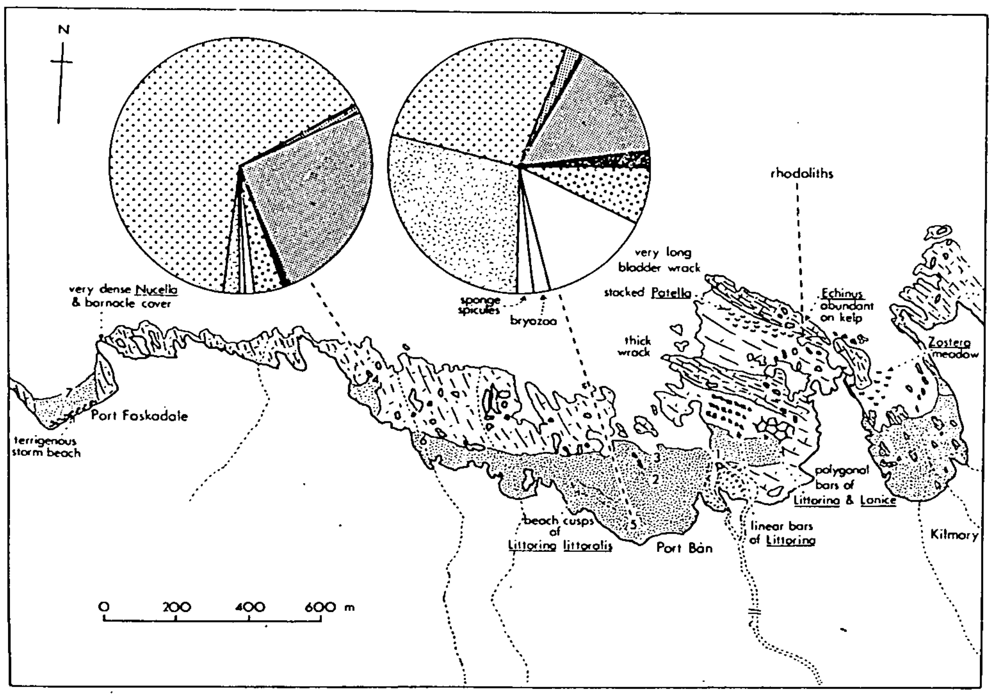

FIG. 6.—Simplified sketch map of northern coast of Ardnamurchan between Port Faskadale and Kilmory, showing aspects of the shore ecology and the carbonate components of a high energy gravel and a moderate energy sand. The localities of the samples tabulated in table 4 are shown, together with the rhodolith occurrence illustrated on Pl. 4A. (Key as for Fig. 2.)

reflection of the ease with which their porous remains are transported compared with the heavier barnacle plates.

b) *Port Bàn area, north coast of Ardnamurchan*

The stretch of coast between Kilmory and Faskadale is magnificent in its contrast between massive black agglomerates and a diversity of white carbonate sediments. Fig. 6 illustrates the various sediment types that have been recognised. Most singular are the doughnut-like algal encrustations which have grown around eroded limpets (Pl. 4A). [Similar rhodoliths (Bosellini *et al.* 1971) also occur at Balnahard on Mull (Pl. 4B) where their nuclei are *Littorina* gastropods.] Gravels are again barnacle-rich, but often with a major component of *L. obtusata*, which gives them a striking brown colour. Skin-diving observations offshore provide an explanation for the high gastropod component, for a succession of rock platforms provides the basis for a very flourishing algal population. The barnacles are driven eastwards by wave action from near vertical cliffs east of Port Faskadale (fig. 6).

Several sediments here, not of especially low energy, have more than 10% forams, and the sediments generally are much richer in forams than those at Sanna. The proportion of echinoid material is also comparatively high. The *Pi* diagrams on fig. 6 seem essentially to reflect the contrast between two grain populations with quite different hydrodynamic properties, the fine terrigenous material associating with the lighter foram and echinoid grains. There is some suggestion in the figures that foram and echinoid values move in unison (table 4), though this is not completely so in Calgary Bay on Mull.

c) *Calgary Bay, NW Mull*

Data are available for a complete traverse from offshore kelp beds to the backshore (table 5). Total percent carbonate increases up the shore until the backshore where it drops sharply by 20%. Concomitantly there is a fall-off in both barnacle and foram components. Except for the backshore records the echinoid and foram values are again in unison, as at Port Bàn. The explanation for this drop-off is to be found in the wind action to which the backshore is subjected. This drives the lightest (foram) component onward towards the dunes. [Dunes almost wholly composed of the foram *Cibicides* occur on the Island of Eigg.]

It would seem that at the time of collection (in mid-summer with negligible wave action) previous winds were sufficient to remove forams, but not echinoid or mollusc fragments (to the same degree). The heavier terrigenous grains therefore remain, relatively enriched because of insufficient wave energy to transport the more massive barnacle plates farther onshore than the crest of the mid-tide sand-bar.

At 10% the accreting sediment of the bar is the richest in echinoid remains yet encountered, reflecting a dense *Echinocardium* population at and beyond LWST.

The *Echinocardium* sand itself is strikingly rich in well preserved opaline tetrad sponge spicules (Pl. 1E), which suggests a relatively low energy level of accumulation, since the spicules, if present at all in sediments from more exposed sites, are always fragmentary and frosted.

TABLE 4

Principal carbonate components in beach sediments between Kilmory and Faskadale, Ardnamurchan

Position on Fig. 6	%$CaCO_3$	Barnacles	Molluscs (spat/frags)	Lithothamnium	Echinoids	Forams	Bryozoa	HM no.
1) base of barnacle covered rock LWST	77	47	14 (4/10)	2	6	8	tr	*R12207*
2) LWNT surface	77	29	29 (1/28)	tr	6	10	1	*R12211*
3) LWMOT *Arenicola* sand	51	19	26 (1/25)	0	3	2	tr	*R12212*
4) LWMOT gravel	98	65	27 (1/26)	tr	4	1	tr	*R12217/8*
5) HWNT	71	27	17 (2/15)	2	7	14	2	*R12213*
6) near stream mouth	62	13	25 (1/24)	4	7	12	1	*R12214*
7) LWMOT high energy bay	36	8	22 (0/22)	1	2	1	1	*R12219*

TABLE 5

Principal carbonate components in beach sediments from Calgary Bay, Isle of Mull

Position	%$CaCO_3$	Barnacles	Molluscs (spat/ frags)	Lithothamnium	Echinoids	Forams	Bryozoa	HM no.
sand patch between kelp	74	25	39 (16/23)	1	3	3	2	*R12191*
Echinocardium sand* ELWST	69	4	46 (1/45)	tr	7	7	1	*R12192*
surface of plane bed LWST	82	13	51 (1/50)	tr	7	9	tr	*R12193*
crest of accreting bar MTL	88	24	47 (3/44)	1	10	5	tr	*R12194*
backshore	69	14	43 (1/42)	2	7	1	0	*R12195*

* Includes 3% siliceous sponge spicules.

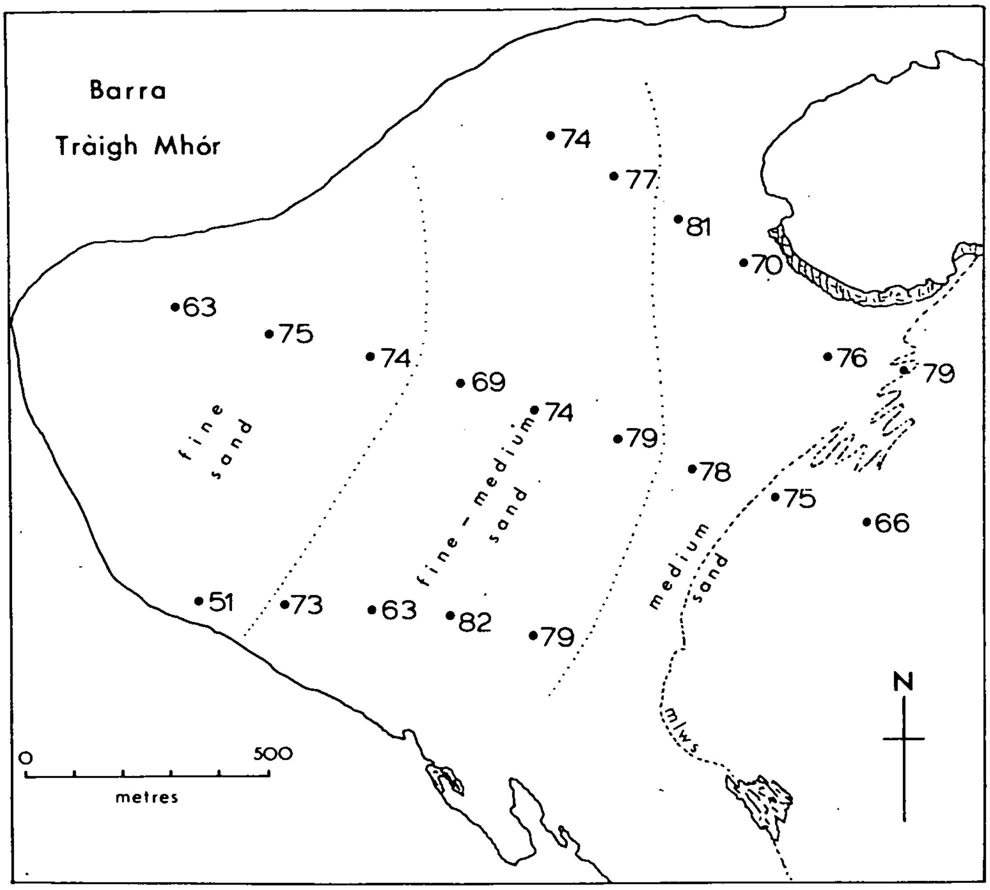

FIG. 7.—Map showing variation in total percentage carbonate across a single large beach. Traigh Mhor. Barra.

The high percentage of small gastropods in the sample from between kelp blades recalls the low energy beach samples from the east coast of Iona.

VARIATION IN TOTAL PERCENTAGE CARBONATE ACROSS A SINGLE LARGE BEACH (Traigh Mhor, Barra)

All the beaches recorded so far have been comparatively small, and have shown considerable variation in carbonate composition. Before leaving the shore to consider offshore samples it is of some importance to ascertain variability in the purity of carbonate across much larger areas of the shore. These occur on Tiree but are particularly well developed in the Outer Hebrides.

The most complete data we have available are for Traigh Mhor, the large beach at the NE end of the Island of Barra. Farrow (1974) has described the ecology of the dominant *Cardium* population and the processes of sedimentation. Total carbonate determinations were made by acid digestion of samples from 20 stations. The results are shown in fig. 7. Values vary but slightly about a mean figure of 73% $CaCO_3$, a figure strikingly similar to other beaches of relatively sheltered aspect on Mull and Ardnamurchan (fig. 4). Except for samples from near shellbanks, the mean grain size shows a systematic down-beach increase from fine to medium sand.

HIGH-ENERGY VS. LOW-ENERGY BEACH CARBONATES

Re-arranging the data for the various beaches given in tables 2 to 5 according to degree of exposure gives the results shown in table 6. At 82% $CaCO_3$ the exposed beaches are slightly more calcareous than the protected beaches, and are also strikingly less diverse in their constituents, molluscan and barnacle débris comprising 95% of the total carbonate. The most ready way of differentiating the two seems to be to use the ratio:

$$\frac{\text{Barnacles}}{\text{Echinoids and Forams}}$$

This averages 18·5 for the exposed beaches compared with 2·1 for protected beaches.

This ratio is significant both on ecological and hydrodynamic grounds. Barnacles are the dominant rocky shore epifauna on all exposed coasts, nowhere better seen than at Fingal's Cave, Staffa, on the vertical columns of basalt. Forams, in contrast, require a relatively stable soft substrate. The echinoid category unfortunately includes both epifaunal and infaunal types, but the epifaunal types do not come close inshore at the most exposed sites.

The hydrodynamic contrast is sharp, between massively partitioned barnacle plates and porous and much lighter echinoid and foram tests.

Thus the higher energy areas will tend to produce more barnacles and wave action will be sufficient to transport them up exposed beaches. Fewer barnacles will be present on more sheltered coasts, giving greater seaweed cover (which itself reduces the wave energy), so that any barnacles present offshore do not get transported onto leeward beaches.

OFFSHORE CARBONATES OF THE INNER SHELF

Table 7 shows the principal carbonate components in sediments obtained from isolated rock pinnacles off Mull. Again they can be classified into 'high' and 'low' energy categories, though the differences between the samples seem to reflect not so much geographical exposure contrasts as ecological ones created by the presence or absence of a baffle of *Laminaria*. Again, barnacles are dominant; many grains being of a relict aspect. Sample 23, with 12% crinoids, is noteworthy.

These isolated cases of high carbonate are surrounded by a widespread belt of muddy sand averaging between 30 and 40% $CaCO_3$.

The carbonate is not all concentrated in the coarser fraction—30% of the silt and clay is carbonate. This mud is shown by X-ray diffractometry to be low-Mg calcite. Under the SEM it does not show any signs of dissolution (Dr T. Alexandersson personal communication 1977). The most probable source is from barnacles, for although

TABLE 6

Comparision of high and low-energy beach carbonates

	%$CaCO_3$	Barnacles	Molluscs	Echinoids	Forams	Barn / Ech. & For.	Locality	B + M / % $CaCO_3$
	80	30	48	tr	0	∞	Iona (mean of 8)	97
HIGH	82	46	29	4	1	9·2	Sanna (mean of 3)	91
ENERGY	98	65	27	4	1	13·0	Port Ban no. 4	94
	(82)	(37)	(41)	(2)	(tr)	(18·5)	(Mean of 12)	(95)
	80	23	44	4	3	3·3	Iona (mean of 14)	84
	77	29	29	6	10	1·8	Port Ban no. 2	75
LOW	71	27	17	7	14	1·3	Port Ban no. 5	62
ENERGY	77	16	45	7	5	1·3	Calgary (mean of 5)	79
	72	16	36	5	11	1·0	Port an t'Struthain (mean of 2)	72
	(78)	(21)	(41)	(5)	(5)	(2·1)	(Mean of 23)	(79)

TABLE 7

Principal carbonate components in sheil-sand from isolated rock pinnacles in the Firth of Lorne and around Iona

Locality (Depth)	%$CaCO_3$	Barnacles	Molluscs (spat/frag.)	Calcareous Algae	Echinoids	Crinoids	Bryozoa	Serpulids	Forams	Aberystwyth dive no.
1½nm S of Carsaig (33 m)	63	26	37 (1/36)	0	tr	0	0	0	0	*54*
3¼nm SSE Carsaig (33 m)	88	35	31 (4/27)	1	7	0	8	5	1	*24*
6 nm SE of Carsaig (25 m)	99	63	18 (4/14)	0	3	12	1	2	tr	*23*
2½ nm W of Seil Is. (26 m)	97	32	45 (9/36)	0	8	tr	2	7	1	*20*
1¼ nm WNW of Ard Tun (18m)	95	55	24 (8/16)	1	7	0	2	6	tr	*41*
1¼ nm WSW of Iona (22 m)	74	54	17 (1/16)	0	2	0	1	tr	0	*34*
NW Torran Rocks (22 m)	99	42	28 (4/24)	0	4	1	6	18	0	*51*
Average offshore rock	88	44	29	tr	4	2	3	5	tr	

certain layers of many mollusc shells are composed of low-Mg calcite (Taylor *et al.* 1969), we would have expected some aragonite mud also to have been present had it been of molluscan origin. However, the possibility that any aragonite might have been completely removed by solution must be considered, though we do not think it likely.

Relict Carbonate Grains

There is little doubt that nearly all the beach carbonate, particularly that from protected beaches, is of present-day origin. There is some possibility that the well-rounded barnacle/mollusc grains of exposed beaches could be concentrated residue of fragmented relict grains, though SEM work shows the grains to be unbored and often with unaltered microstructure (Pl.3B).

Offshore, however, thoroughly 'moth-eaten' grains are common (Pl. 3, C, D. E) identifiable examples belonging to barnacles, mollusc hinges, *Lithothamnium*, serpulids and echinoids. Algal and clionid sponge borings are all pervasive. Concentrations of interstitial diatoms are particularly high both in original cavities (e.g. barnacle 'chambers', Pl. 1H) and in borings (Pl. 3F. G), and it is tempting to speculate that they may be an important factor in the early diagenesis of this skeletal material, possibly creating acidic microenvironments where carbonate solution could take place (Pl. 5). Though relict grains may be extremely pitted there is never any suggestion of physico-chemical solution, such as would result from seawater under-saturated in carbonate. Diatoms appear to be so abundant in these relict grains that they represent a potential source of easily mobilised silica for the future silification of the carbonate. They are certainly far more abundant than sponge spicules—a source often appealed to in supplying the necessary silica.

Discussion

Production of barnacle débris

Barnacles constitute the major contributor to the calcareous sediments in many offshore areas such as the Sound of Iona and the Passage of Oronsay. Though relict grains do occur, the majority of the barnacles seem to be of recent origin (Pl.2D, E). It is premature to offer an embracive explanation for their dominance since many factors may be involved, but grazing by regular echinoids and removal in the holdfasts of *Laminaria* are both frequently observed. A further factor possibly of great significance in areas of dense settlement is the competitive elongation of adjacent barnacles. When growing under these conditions the barnacles not only produce more carbonate in unit time, but also are much less firmly attached to the substratum.

A final factor concerns the structure of the barnacle skeleton. Being very much more solid than, for example, echinoid or nacreous molluscan grains (particularly the carinate plates) they will undoubtedly resist prolonged transport better than most other skeletal grains. Therefore we might predict that with extended reworking a shelf sediment might become steadily enriched in its barnacle percentage. But this is to assume, additionally, that barnacle plates have a low susceptibility to biological attack from a multiplicity of borers, such as blue-green algae and the sponge *Cliona*. We need far more data on this point. Radiocarbon dates, in progress, should illuminate the problem of the age of this material.

The most attractive hypothesis that can be put forward to date to account for high rates of production of barnacle débris is based on evidence from the southern part of the Sound of Iona, from the work of Boillot (1964, 1965) and Reineck *et al.* (1976) and from an appreciation of the significance of the rare event in Geology. Ager (1974) has recently argued that the single severe storm acting perhaps only once in several hundred or even a thousand years may do more to leave a preservable record than the day-to-day 'gentle rain from heaven'—style of sedimentation. (This is indeed something to remember for those of us traditionally engaged in field observations over the summer vacation, since it suggests we are wasting our time!).

Fig. 8 is an attempt to show what the consequences could be of a severe storm acting over a wide area of barnacle encrusted cobbles. The fact that below a certain cobble size

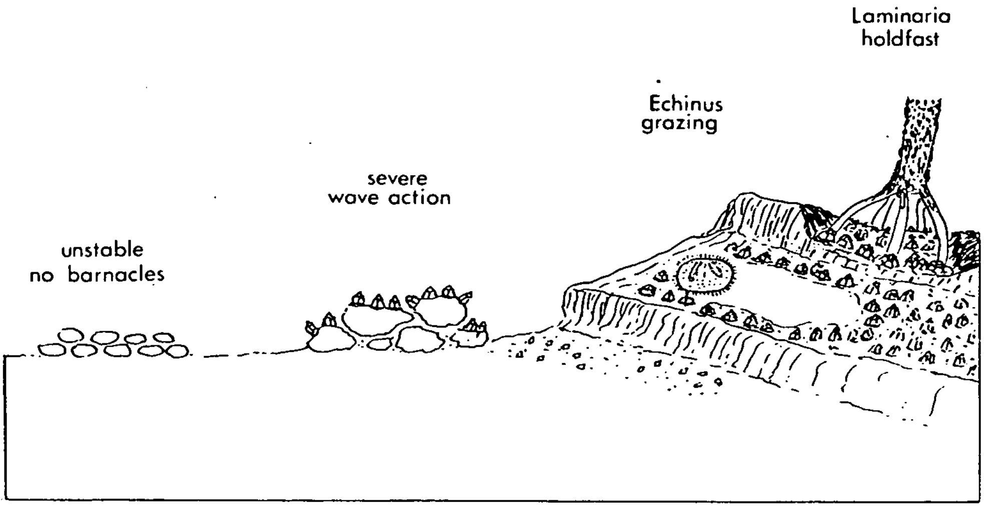

FIG. 8.—Cartoon illustrating three processes involved in the production of barnacle debris. Maximum production is thought possibly to occur through storms periodically disturbing zones of encrusted cobbles.

only basal attachment discs of barnacles were recorded in our surveys in 1975 and 1976 testifies to their recent removal by some means. For the sake of argument we have assumed storms to be responsible while recognising the grazing activities of echinoids. To produce the maximum amount of barnacle débris would require a greater incidence of storms than envisaged by Ager for his 'tempestite' deposits: one every ten years would be ideal! Of course, storms are relative, and in fact we are probably invoking the kind of 'once in 50 years' event for which Reineck *et al.* (1968) consider they have a well preserved record in the southern North Sea.

The relative paucity of echinoderm débris

After many underwater television traverses in the Inner Hebrides, particularly between Mull and Coll, one is left with a vivid impression of forests of ophiuroids, and echinoids peppering the more bouldery areas. Their débris in the resulting sediments, however, is far less impressive, indeed we have yet to identify ophiuroid plates from over 100 samples so far examined: echinoid plates and spines have never yet exceeded 10%.

This is staggering when one considers that the Pennines are built largely of echinoderm débris in the shape of the Carboniferous Limestone. How incredibly abundant must the crinoids have been on the Palaeozoic shelf (even when one considers that balanid barnacles had yet to evolve, and that the brachiopods had still to be ousted by the superior carbonate producing bivalves).

FUTURE RESEARCH

Further cruises are needed to determine over how much of the shelf barnacle débris is a major sediment contributor. We need additional photographic traverses across shelves of varied exposure and topography to assess the potential skeletal contributions from the whole range of epifauna. One might predict, for example, a belt of serpulid-enrichment in a slightly deeper zone to that dominated by barnacles, unless relict contamination is an important factor.

The use of submersibles to monitor colonisation experiments on a variety of substrata at depths extending beyond divable range would make a major contribution to our understanding of process rates.

We also need much more detailed work on the mechanism of fragmentation of the skeletal material. Which are the key 'weakening' organisms? How long does it take for a grain to acquire its 'moth-eaten' appearance?

Most critically we need to know the geometry of the deposits. Vibro-cores are essential here, for although we can gauge thickness from pinger and sparker records, we cannot determine how the calcareous components vary with depth. Are these substantial carbonate deposits or simply a veneer on a terrigenous base? We must turn to other areas like the Orkneys for more information on rates of accumulation of major sand bodies, in comparison with which the areas of accumulation in the Inner Hebrides can be seen to be relatively localised, though informative in their close relationship between local ecology and sediment type.

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REFERENCES

AGER, D. V., 1974. Storm deposits in the Jurassic of the Moroccan High Atlas. *Palaeogeogr. Palaeoclim. Palaeoecol.*, **15**, 83–93.

BINNS, P. E., MCQUILLIN, R. and KENOLTY, N., 1974. The geology of the Sea of the Hebrides. *Rep. Inst. Geol. Sci.*, **73/14**.

BOILLOT, G., 1964. Étude géologique de la Manche occidentale, fonds rocheux, dépôts Quaternaires, sédiments actuels. *Annls Inst. Oceanogr. Paris*, **42**, 1–219.

——. 1965. Organogenic gradients in the study of neritic deposits of biological origin: the example of the western English Channel. *Mar. Geol.*, **3**, 359–367.

BOSELLINI, A. and GINSBURG, R. N., 1971. Form and internal structure of recent algal nodules (rhodolites) from Bermuda. *J. Geol.*, **79**, 669–682.

CROFTS, R. S. and RITCHIE, W., 1974. Beaches of mainland Argyll. Dept. Geogr. Univ. Aberd.

FARROW, G. E., 1974. On the ecology and sedimentation of the *Cardium* shellsands and transgressive shellbanks of Traigh Mhor, Island of Barra, Outer Hebrides. *Trans. Roy. Soc. Edinb.*, **69**, 203–229.

——. SCOFFIN, T. P., BROWN, B. J. and CUCCI, M., 1978. An underwater television survey of facies variation on the inner Scottish shelf between Colonsay, Islay and Jura, *Scott. J. Geol.* in press.

HALDANE, D., 1939. Notes on the nullipore or coralline sands of Dunvegan, Skye. *Trans. Edinb. Geol. Soc.*, **13**, 442–444.

INSTITUTE OF GEOLOGICAL SCIENCES, 1977. Geological Survey Ten Mile Map: north sheet (1st Edn: Quaternary) 1:625000.

KEARY, R., 1967. Biogenic carbonate in beach sediments of the west coast of Ireland. *Sci. Proc. Roy. Dublin Soc.*, **A3**, 75–85.

LEES, A., BULLER, A. T. and SCOTT, J., 1969. Marine carbonate sedimentation processes, Connemara, Ireland. *Reading Univ. Geol. Rep.*, 2.

MATHER, A. and CROFTS, R., 1972. The beaches of west Inverness-shire and north Argyll. Dept. Geogr. Univ. Aberd.

MILLIMAN, J. D., 1974. *Recent sedimentary carbonates.* Pt 1: Marine Carbonates. Springer, Berlin.

PENDLEBURY, D. C. and DOBSON, M. R., 1976. Sediment and macrofaunal distributions in the eastern Malin Sea, as determined by side-scan sonar and sampling. *Scott. J. Geol.*, **11**, 315–332.

PURDY, E. G., 1963. Recent calcium carbonate facies of the Great Bahama Bank. Pt II. Sedimentary Facies. *J. Geol.* **71**, 472–497.

PURSER, B. H., 1973. *The Persian Gulf: Holocene carbonate sedimentation and diagenesis.* Springer, Berlin.

RAYMOND, P. E. and HUTCHINS. F., 1932. A calcareous beach at John o' Groats, Scotland. *J. Sedim. Petrol.*, **2**, 63–67.

REINECK, H-E. and DORJES, J., 1976. Geologisch-biologische Untersuchungen an Gerollstranden und—verstränden der Costa Brava, Mittelmeer. *Senckenberg. Marit.*, **8**, 111–153.

——. DORJES, J., GADOW, S. and HERTWECK, G., 1968. Sedimentologie, Faunenzonierung und Faziesabfolge vor der Ostkuste der inneren Deutschen Bucht. *Senckenberg. Lethaea*, **49**, 261–309.

RITCHIE, W. and CROFTS, R. S., 1974. Beaches of Islay, Jura and Colonsay. Dept. Geogr. Univ. Aberd.

TAYLOR, J. D., KENNEDY, W. J. and HALL, A., 1969. The shell structure and mineralogy of the Bivalvia. Introduction: Nuculacea-Triganiacea. *Bull. Brit. Mus. (Nat. Hist.) Zool. Suppl.*, **3**.

Explanation of Plates

Plate 1.—SEM photographs of principal bioclastic components in carbonate sediments from protected beaches on E coast of Iona. All samples from locality L5, except for *D* (A1).

A: obliquely worn *Echinocardium* plate (irregular echinoid)
B: serpulid worm *Spirorbis* (flattened side originally attached to *Fucus*)
C: cheilostome bryozoan *Scrupocellaria* sp.
D: cyclostome bryozoan *Crisia* sp.
E: siliceous tetrad sponge spicule
F: benthic foraminiferan, *Elphidium* sp.
G: fresh, unbored surface of calcareous alga *Corallina*
H: abundant benthic diatoms (siliceous) in primary chambers of barnacle lateral plate: *Surirella*-like forms are present

Plate 2.—SEM photographs of principal skeletal contributors to actively forming carbonate sediment from the northern Sound of Iona (station H9).

A: fresh, unabraded test of the irregular echinoid *Echinocyamus*
B,C: fresh, unbored spatulate spine of irregular echinoid
D: fresh carinate barnacle plate, showing characteristic rows of perforations
E: internal view of barnacle lateral plate, with adjacent highly porous echinoid plate (?madreporite)
F: calcareous alga *Lithothamnium* sp., showing early bored and serpulid-encrusted growth overlapped by fresh new growth
G,H: small, well preserved gastropods.

The epifaunal material has been transported by tidal currents and forms the substrate for the *in situ* infaunal remains.

Plate 3.—SEM photographs comparing the surface texture of high energy (SW coast) and relict (centre of Sound) carbonate grains.

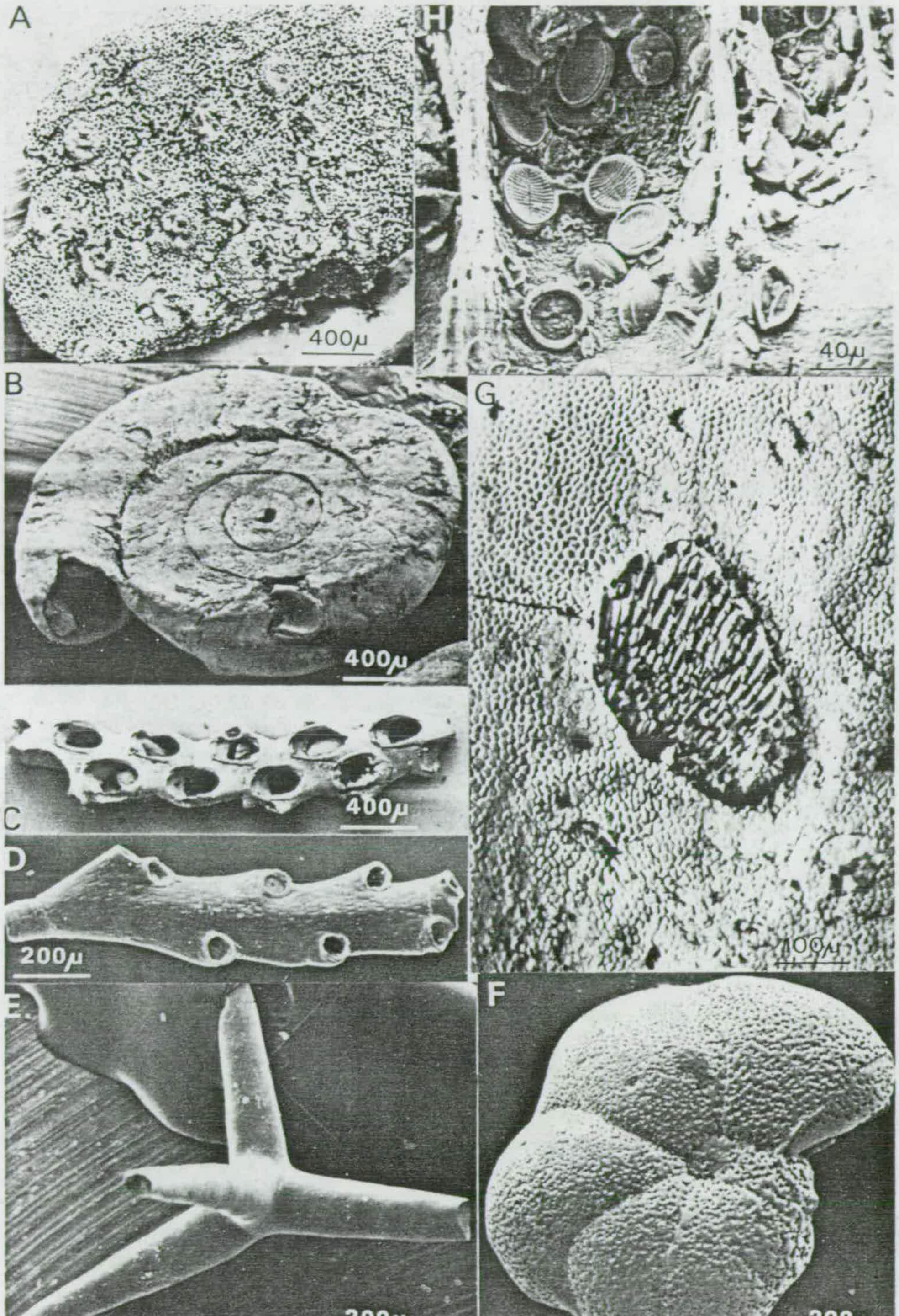
A: well rounded, smoothed grain from exposed shore (locality J3)
B: unaltered nacreous microstructure of *A* indicates an aragonitic bivalve
C: probable algal borings into cardinal tooth of relict bivalve (locality H11)
D: probable algal borings into relict barnacle plate (locality D4)
E: varying stages in the breakdown of a regular echinoid spine: nature of borer uncertain (D4)
F: highly pitted surface of relict barnacle grain, showing corroded texture of siliceous *Campylodiscus*-like diatom (D4)
G: concentration of two generations of adherent benthic diatoms in chamber of relict barnacle (*cf.* Pl.1H); *Surirella*-like forms may be recognised.

Plate 4.—Algal nodules (*rhodoliths*) from Mull and Ardnamurchan.

A: morphogenetic sequence showing encrustation of eroded *Patella* shells (Port Ban, Ardnamurchan: locality on fig. 6)
B: morphogenetic sequence showing encrustation of *Littorina* shells, during life and when occupied by hermit crabs except for final stage of development (Balnahard, Mull)
C: mature rhodolith, nature of nucleus unknown (Mull)
D: thin section of thoroughly bored *Littorina* encrusted internally by unbored serpulid worm: rudimentary external algal encrustation (Mull)
E: thin section showing internal growth features of large rhodolith from Mull: the very open structure is created partly by nodose growth and partly by boring. The nucleus is a pebble of vesicular basalt.

Plate 5.—Stereopairs of benthic diatoms from relict *Lithothamnium* twig (locality H11: Sound of Iona)

above: *Cocconeis*-like diatom from pitted surface appears to be surrounded by corroded 'moat'
below: *Diploneis*-like diatom from within cavity: again there is the suggestion of a corroded texture immediately around the diatom.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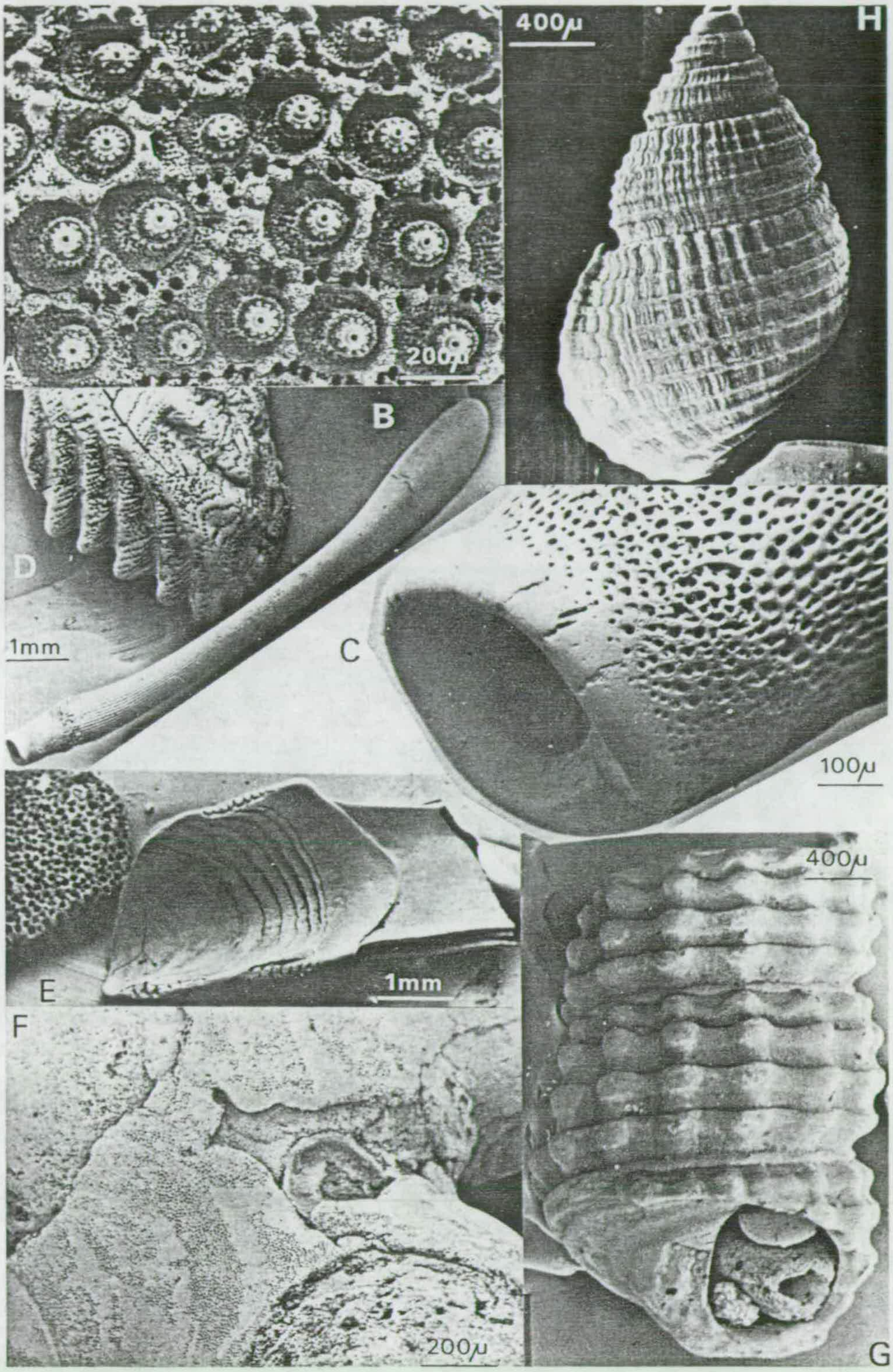
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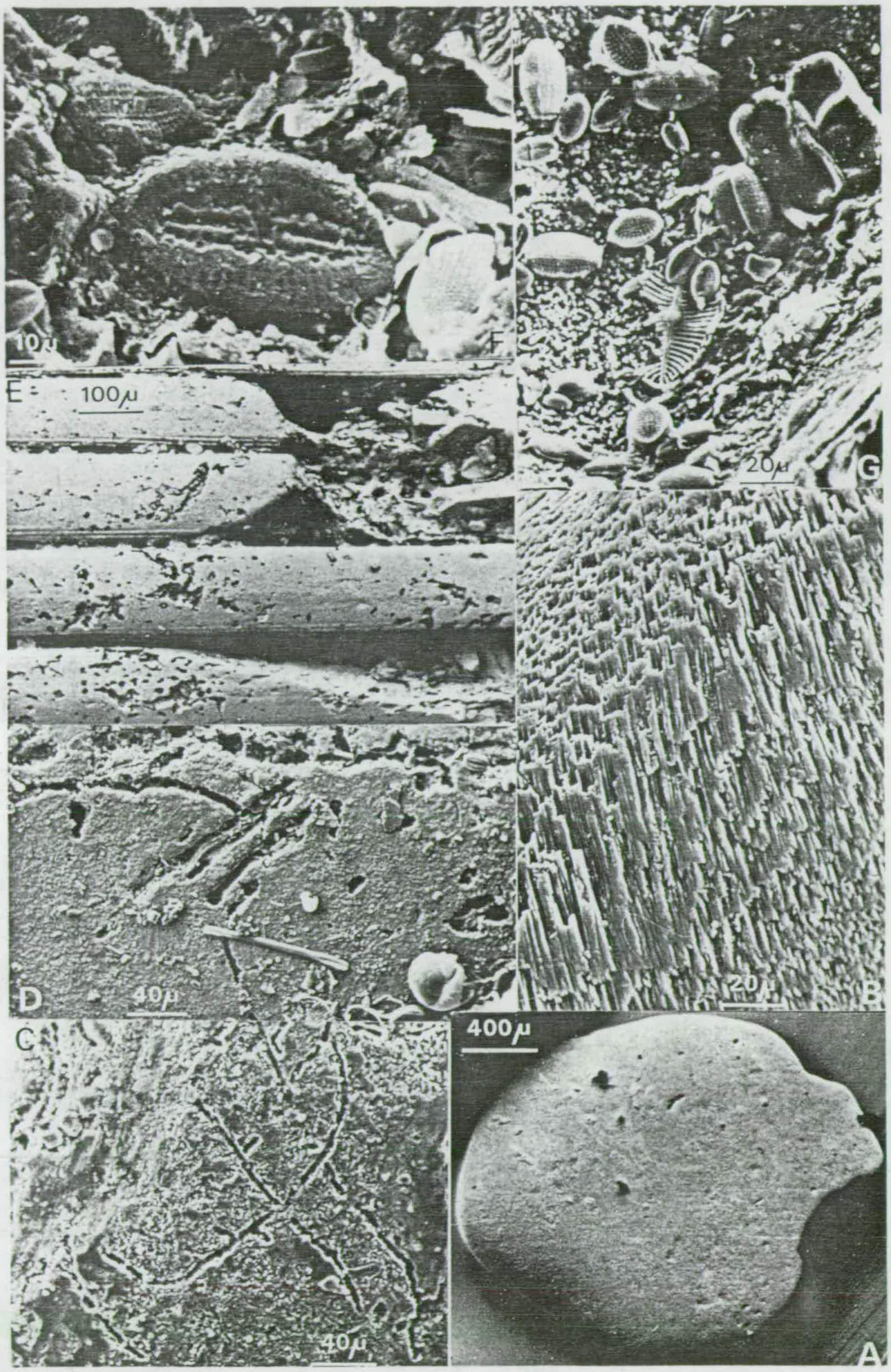
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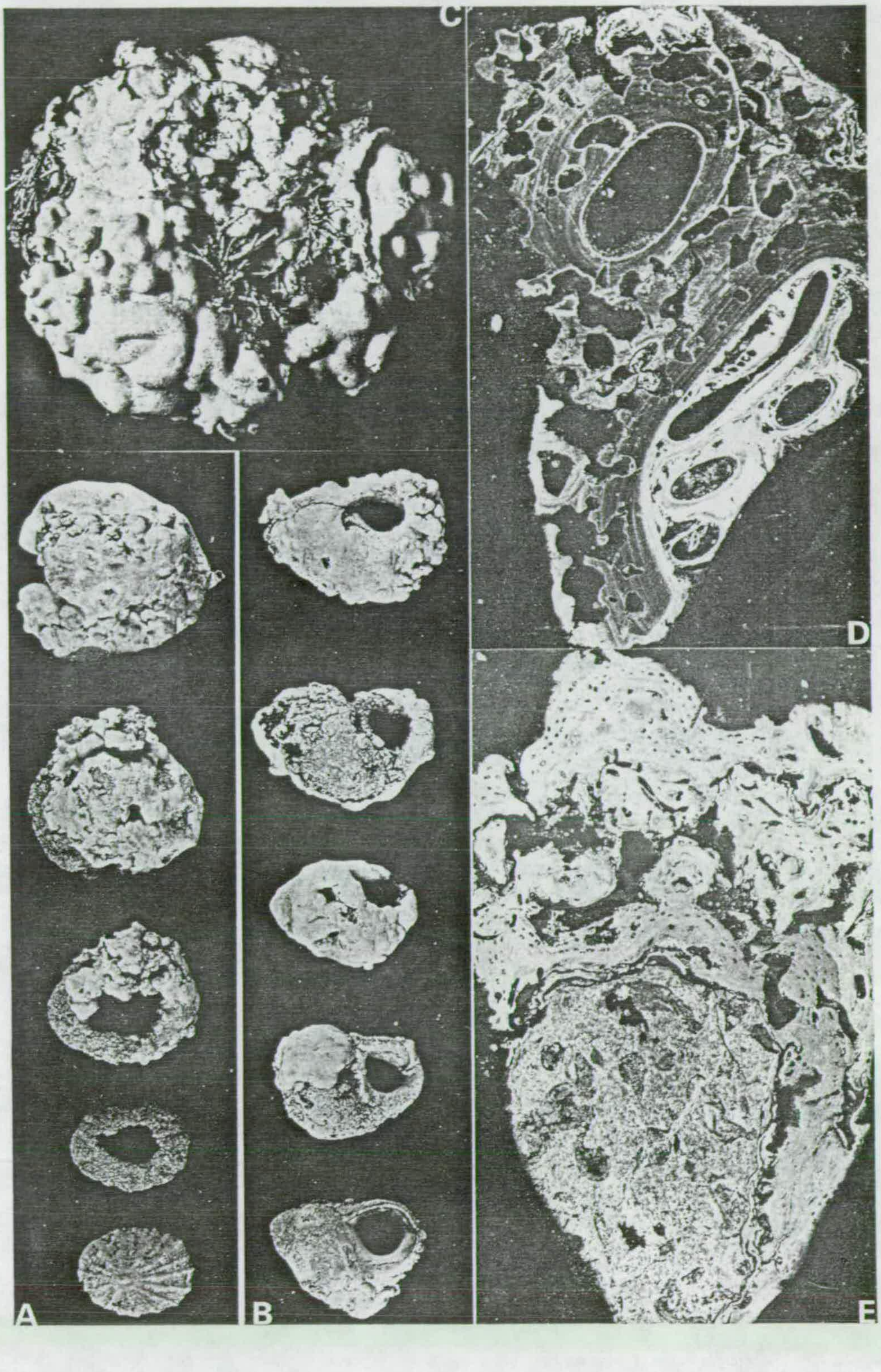
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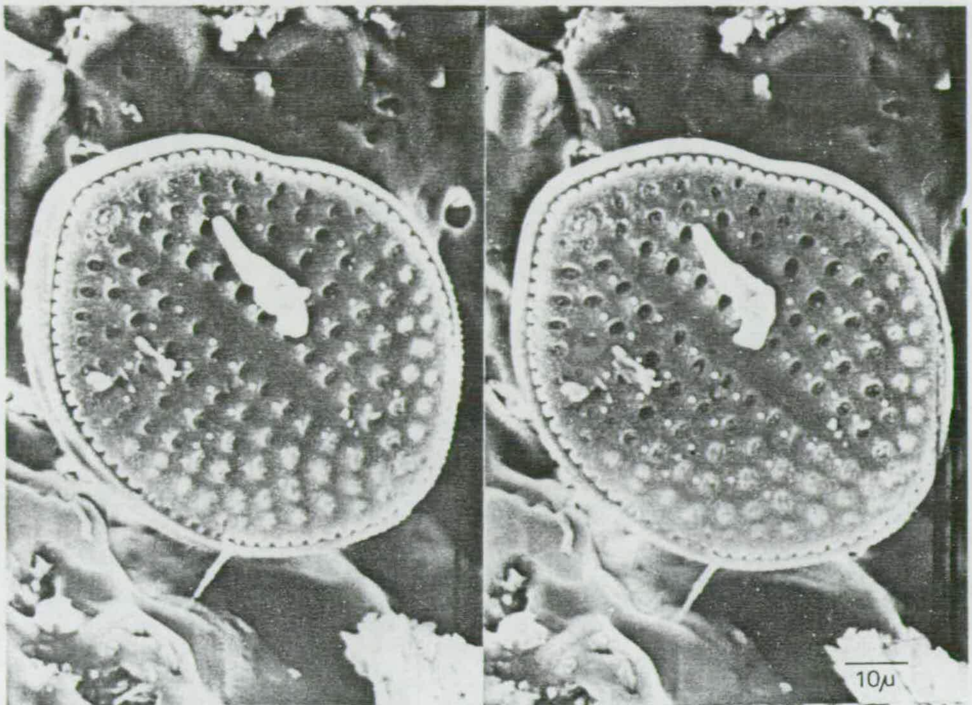
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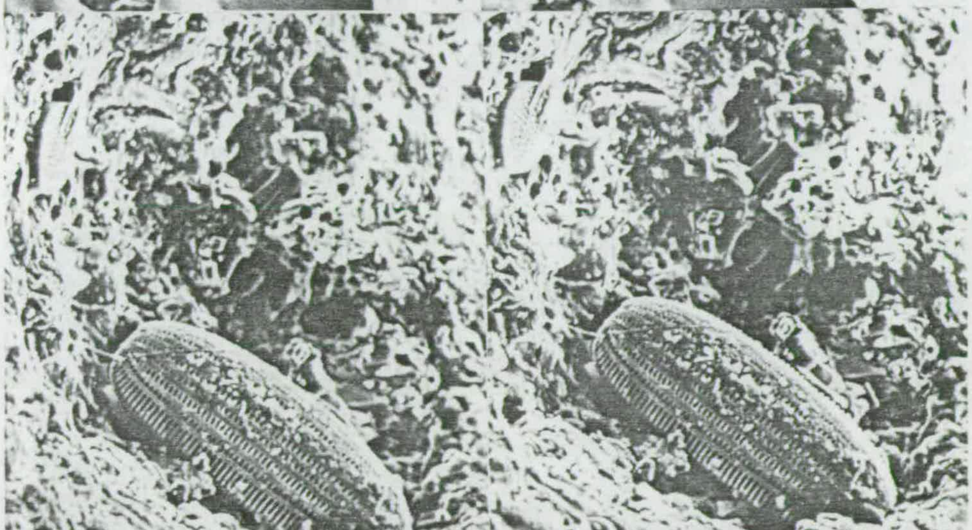
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An underwater television survey of facies variation on the inner Scottish shelf between Colonsay, Islay and Jura

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SYNOPSIS

Using underwater television, eleven recurrent bottom facies have been identified and mapped over an area of about 250 km². Bare rock areas are rare: *Turritella*-rich fine sands with trails, and crustacean-burrowed muds widespread. Coarse sands, fining northwards from megaripple fields in the Sound of Islay and the Passage of Oronsay are dominantly of biogenic origin. The kelp *Laminaria saccharina* was seen rooted in gravelly parts of the megaripple field in the former area (one of strong tidal currents but reduced wave action) where the calcareous alga *Lithothamnium* is an important contributor. Barnacles and molluscs dominate in the latter region, which is more exposed to Atlantic swell. Extensive spreads of *Modiolus* seem to rest on a tough clay surface, possibly of eroded late-Glacial material which also probably underlies Tarbert Bank, since it crops out along its eastern margin. The rippled sand body located on the Bank could represent residual outwash.

Facies analysis by combined underwater television and grab/dredge/box coring is optimal for shelf waters of intermediate depth (10–100 m): it reveals particularly well vagile epifauna, normally missed by conventional grabbing. In addition, it permits sediment/faunal samples to be studied in a truer perspective.

Differentiation of facies by television scores over bottom sampling in higher energy, coarser sediments; but in lower energy muds and fine sands of the level bottom, where infauna dominate, biofacies analysis by faunal clustering and resin impregnation of internal structures will probably achieve greater refinement.

INTRODUCTION

One of the most important aims of working on modern-day environments is to help in interpreting ancient sedimentary rocks. Divers can observe processes in shallow water but underwater television observations of the seabed can be made over wider areas, and in deeper water.

Underwater television was first tested in the U.S.A. in 1947 and experimental work was carried out from 1948 onwards by H. Barnes at the then Scottish Marine Biological Association Station at Millport. Its importance in biological studies has been shown by Barnes (1959; Stevenson 1967; Nishimura and Hara 1968; Chapman and Rice 1971; Machan and Fedra 1975; Holme and Barrett 1977). Stanley and Fenner

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(1973) report not only on sedimentary structures and bottom lithology but also on such items as bottom firmness, amount of suspended material, percentage of shell fragments and the live fauna encountered. Underwater television has proved to be an essential tool in the operation of both manned and unmanned submersibles, with much of this submarine work being undertaken on the Scottish shelf (Eden *et al.* 1971, 1973).

The Inner Hebridean shelf between Colonsay, Islay and Jura (Fig. 1) has been little sampled, though several geophysical surveys have been carried out, mainly by the Institute of Geological Sciences as part of their continental shelf programme. A small number of samples was collected by them from the north of the area and a borehole (BH 71/9) was drilled E of Colonsay (Binns *et al.* 1974).

Methods

In the summer of 1976 we set out in the RRS *John Murray* to study the ecology and sedimentology of parts of the Inner Hebrides concentrating on the carbonates. The project involved surveying by pinger and side-scan sonar, sediment/faunal analysis, and seabed mapping by diving and underwater television. The purpose of this paper is to report on the underwater television mapping.

At most of the seventy-one combined underwater television/grab or dredge stations (Fig. 1) an average of 10 minutes recorded coverage was considered adequate but in areas of strong currents this was sometimes shortened because of undue drifting. A "Spirotechnique" camera was used in conjunction with Thomson monitor and National VTR, recording on ½-in Scotch tape. The camera was housed in a simple rectangular frame, and this was normally suspended a few cm vertically above the seabed, or else rested directly on the bottom, giving a detailed vertical view of a minimum area 26 × 18 cm. The camera proved sufficiently sensitive to be used without artificial light in depths of up to 30 m. Visibility was very good with the sea calm, though a long wavelength swell often caused the camera to saltate.

The tapes (totalling 11 hours), together with transcripts of station commentaries, are lodged with I.G.S. C.S.N.U. at Murchison House, Edinburgh.

Results

Since large rock outcrops or bouldery areas were rare in this ground, we recorded few sharp facies changes. All the boundaries shown on the facies map (Fig. 2) are gradational, being particularly diffuse between the wave-rippled sand, *Turritella* sand and burrowed-mud facies. The areas of stiff clay (possibly late-Glacial) are more sharply defined, and limited to the eastern margin of Tarbert Bank.

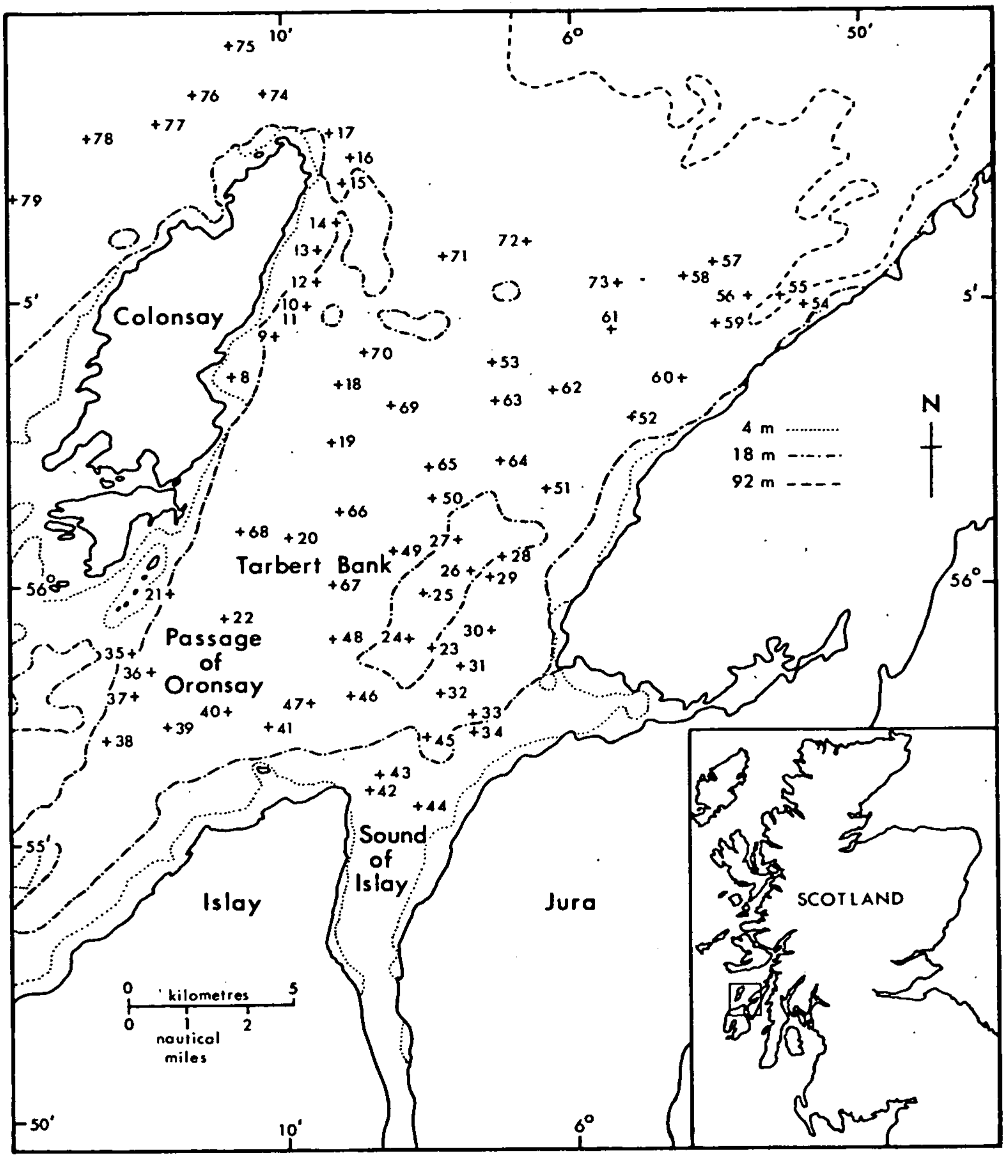

FIG. 1. Map showing the location of underwater television stations and the regional bathymetry.

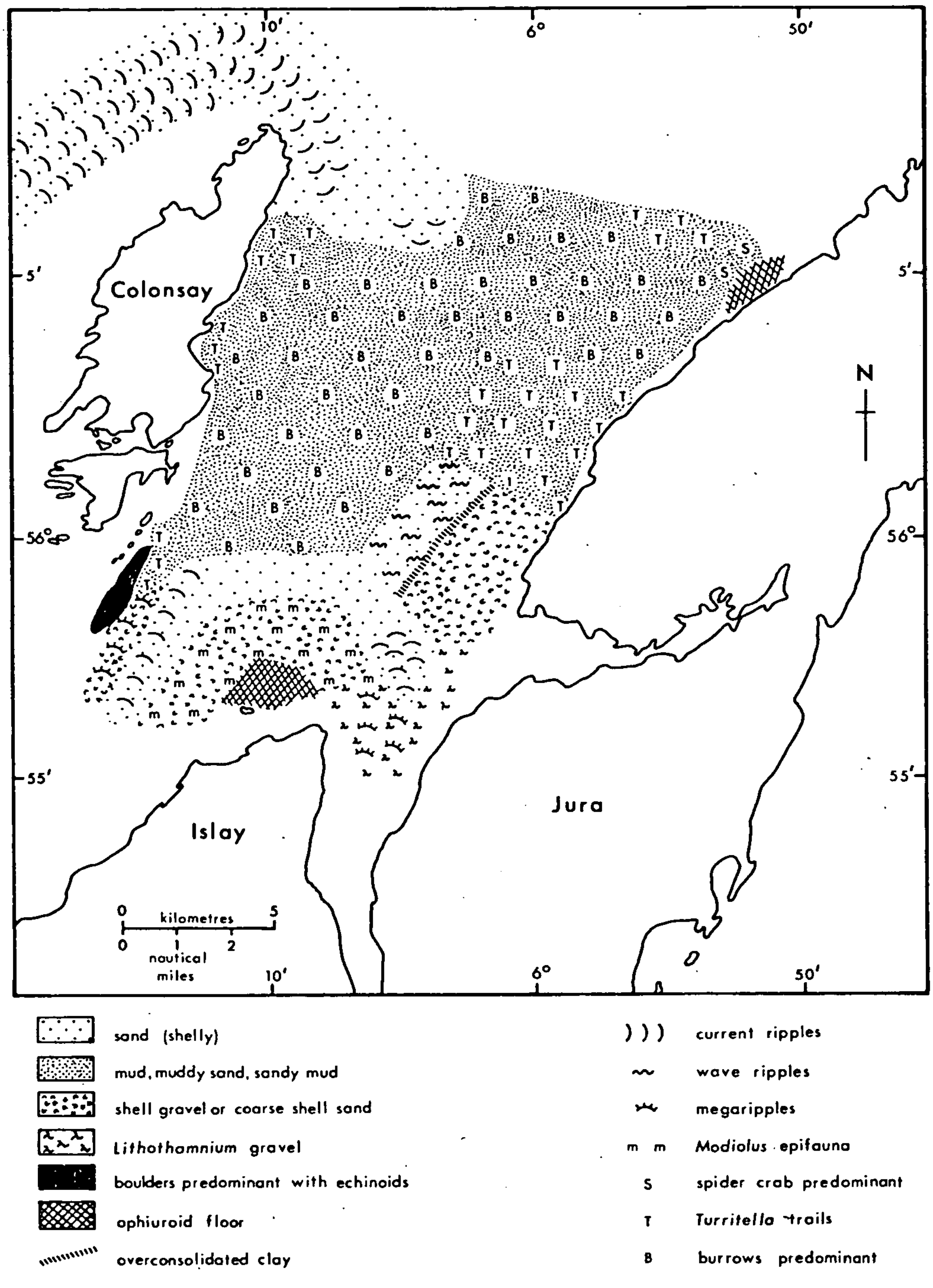

FIG. 2. Generalized facies map incorporating lithology, sedimentary structures and biogenic features: based on the 71 stations shown on Figure 1.

Distinguishing between facies

The criteria used to distinguish between the various facies are shown on Table 1. The more important are:

1. Physical sedimentary structures (notably ripple type).
2. Biogenic sedimentary structures (notably trails, burrows, 'worm' tubes and pellets).
3. Common (identifiable) skeletal remains (notably gastropods, bivalves, echinoderms and *Lithothamnium*).

The mobile epifauna, although often spectacular are not used as a facies discriminant as they are less closely related to the sea bottom (but see Table 1). In particular we found starfish (*Asterias rubens; Luidia ciliaris*) and swimming crabs (*Macropipus* [*Portunus*] *depurata*) very widespread. Though there was considerable variation in the density and type of seaweed to be seen, we have not based our facies on this principally because of the very low fossilization potential of the soft algae. This is not to deny their significance, which will emerge later.

Many of the organisms seen, and referred to below, are to be found in Campbell and Nicholls (1976) and Barrett and Yonge (1972).

(i) *Bare rock with echinoderms.* This facies is not widespread (Fig. 2). The two stations in shallow water (26 m) clearly showed that production of carbonate comes not only from the rock epifauna, where veritable forests of ophiuroids, apparently several individuals deep, at first sight (Fig. 3) resemble a tangled mass of seaweed; but also from sea urchins and gastropods grazing on long kelp fronds. A further source of carbonate consists of epifauna cemented to the rough stems of *Laminaria hyperborea* (being smooth, the stems of *L. digitata* are not encrusted): barnacles, serpulids and bryozoa dominate. The scavenging gastropod *Buccinum undatum* and the predatory starfish *Asterias rubens* and *Solaster endeca* were conspicuous.

The ophiuroids were mostly *Ophiothrix fragilis*, but with rare *Ophiocomina nigra* also present. Their habit of resting *en masse* with arms raised aloft in filter-feeding attitude is common. It is a strikingly crinoid-like mode of life for a group normally considered predatory, presumably in adaptation to the considerable tidal currents seen at both localities.

Areas of isolated boulders rather than rock platforms (possibly winnowed boulder clay) are normally dominated by echinoids rather than ophiuroids, together with *Alcyonium*, a coelenterate yielding small calcareous sclerites on death.

(ii) *Megarippled sand.* This facies occurs in the southern Passage of Oronsay, and at the northern end of the Sound of Islay (Fig. 2). It was seen as deep as 67 m, but the mean depth for six stations was 30 m. Because of the small field of view of the camera it was not always easy to appreciate whether the sandy or shelly substrate was megarippled. Characteristically, however, megaripples were recognized by lines of coarse shell debris and single valves (sometimes with slight edgewise stacking) marking the troughs, with the crests appearing finer and of sand. Wavelengths of

TABLE 1 Underwater Television Facies Analysis: Colonsay, Islay, Jura. FARROW et al.

FACIES	(number of stations)	Depth (uncorrected) mean	range	DEFINITIVE CRITERIA	Associated Live Fauna (including traces)	Dead Shells (conspicuous)	Shell orientation	Sediment type (field terms)
i) Bare rock with echinoderms	(3)	45m	(22-86)	ophiuroid forests/ echinoids	Buccinum, Asterias	-	-	rock
ii) Low amplitude megaripples	(6)	31m	(11-67)	λ = 1m: troughs shelly, crests sandy	Macropipus depurator starfish: Chlamys	Arctica, Ensis Pecten	single valves much fragmentation, some edgewise stacking	gravel - cs sand
iii) Current-rippled sand	(13)	41m	(20-55)	linguoid or asymmetrical ripples with Lanice tubes	Macropipus depurator hermit crabs: Pecten	Ensis, Arctica Dentalium	large valves concave up, small valves convex up	cs sand
iv) Wave-rippled sand	(4)	12m	(10-14)	sharp-crested symmetrical ripples	Fish: hermit crabs starfish	Arctica, Ensis, Pecten	many conjoined valves, concave up	sand
v) Turritella fine sand	(8)	28m	(17-50)	hermit-crab trails, Turritella shells 'mat-stabilized' sand surface with occasional burrow holes	lugworm casts: hermit crabs. Macropipus depurator: starfish: sunstars: Anseropoda placenta: trochids: Callionymus: brittle stars: Buccinum faecal pellets: Sea Pens: Lanice: sand volcanoes: Pecten: Scrupa cellaria	fresh Arctica Ensis	conjoined valves concave up with valves broken by predation	fine sand
vi) Filamentous-tube burrowed mud	(10)	33m	(23-39)	stabilizing mat of small filamentous tubes: Sea Pens: crab trails: burrow holes: faecal pellets: occasional mud volcanoes	Macropipus: starfish: flounder: hermit crabs: (Nephrops, Goneplax)	Arctica Turritella Buccinum	conjoined valves concave up broken by predation	mud - fine sand
vii) Crustacean-burrowed mud	(12)	48 m	(30-107)	abundant large and small burrow holes: mud volcanoes: trails radiating from burrows: Sea Pens	Goneplax: Nephrops: Antennularia: Virgularia: Pandalus: Macropipus: Buccinum: Munida: Lumpenus lumpraetiformis and Lesseurigobius in burrow holes: faecal pellets	rare		mud
viii) Spider-crab mud	(1)	115m	-	abundant spider crabs and feathery sea pens	Munida bamffica: Hyas araneus: Macropodia Inachus: Ophiura texturata: Pennatula with attached Antedon	-	-	mud
ix) Overconsolidated clay	(2)	25m	(23-28)	scour marks, clay balls: highly corroded and encrusted Arctica shells	Chaetopterus: sunstars	Arctica	variable, bored and encrusted	clay
x) Modiolus gravel	(3)	25m	(22-30)	large single valves of Modiolus forming shell pavement resting on firm clay	Buccinum: brittle stars: sunstars: starfish: Modiolus clumps	Modiolus	many convex up with some imbrication: others heavily encrusted with serpulids and barnacles	gravel
xi) Lithothamnium gravel	(2)	20m	(15-25)	stick-like gravel with kelp and razor shells	Pecten maximus	Ensis	convex up single valves	gravel

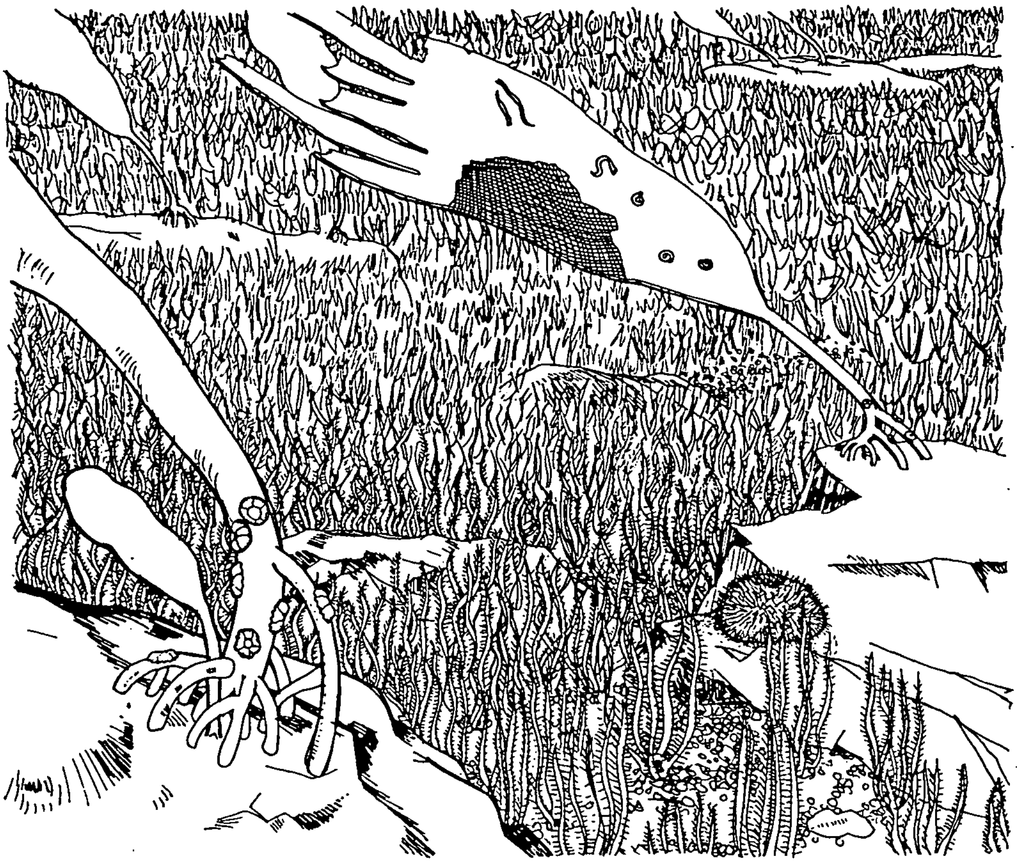

FIG. 3. Artist's reconstruction of rocky seafloor, at a depth of about 25 m, showing weed-like appearance of dense ophiuroid cover, calcareous epifauna on kelp, and grazing echinoid. Composite, drawn from videotape replays by Norman Aikman. Typical of region N of Islay (55°57'N 6°10'W).

around 1 m and amplitudes of approximately 10 to 20 cm were common: the sediments were clearly well-washed.

The only shells commonly not in a fragmented state, but presented as paired, conjoined valves, were razor shells and scallops (*Ensis* sp. and *Pecten maximus*). Both are active bivalves capable of coping with excessive sediment.

In the shallow Sound of Islay stations (11 or 12 m depth) *Lithothamnium* gravel is an obvious component of the substrate. Here enormous fronds of the seaweed *Laminaria saccharina* were seen rooted amongst the gravel and effectively stabilizing parts of the megaripple field (Fig. 4). The fronds, seeming longer than the water was deep, extended fully downcurrent and provided shelter for abundant *Macropipus* crabs. The scene was completed by clusters of live *Chlamys* and the ubiquitous *Asterias*.

(iii) *Current-rippled sand.* Linguoid and asymmetrical, straight crested rippled sands were found in two belts. One straddling the northern tip of Colonsay; the other in the south, an extension of the Passage of Oronsay megaripple field (Fig. 2). The mean depth for the thirteen stations in this facies was 41 m. Typically, wavelength varied between 10 and 26 cm, and amplitude 2 to 4 cm. Over wide areas of the northern region a thin carpet of rippled sand appeared to be migrating over a shelly base. Agglutinated tubes of the sand-mason worm *Lanice conchilega*, both protruding and prostrate, seemed almost confined to this facies. Paired *Ensis* valves were seen, together with derived tubes of *Dentalium*, possibly originating from nearby lower energy facies. Large valves of *Arctica* appeared concave up, while associated smaller shells were often convex up—possibly a response to relatively weak tidal currents. (There is a very real possibility, nevertheless, that the concave up valves are more

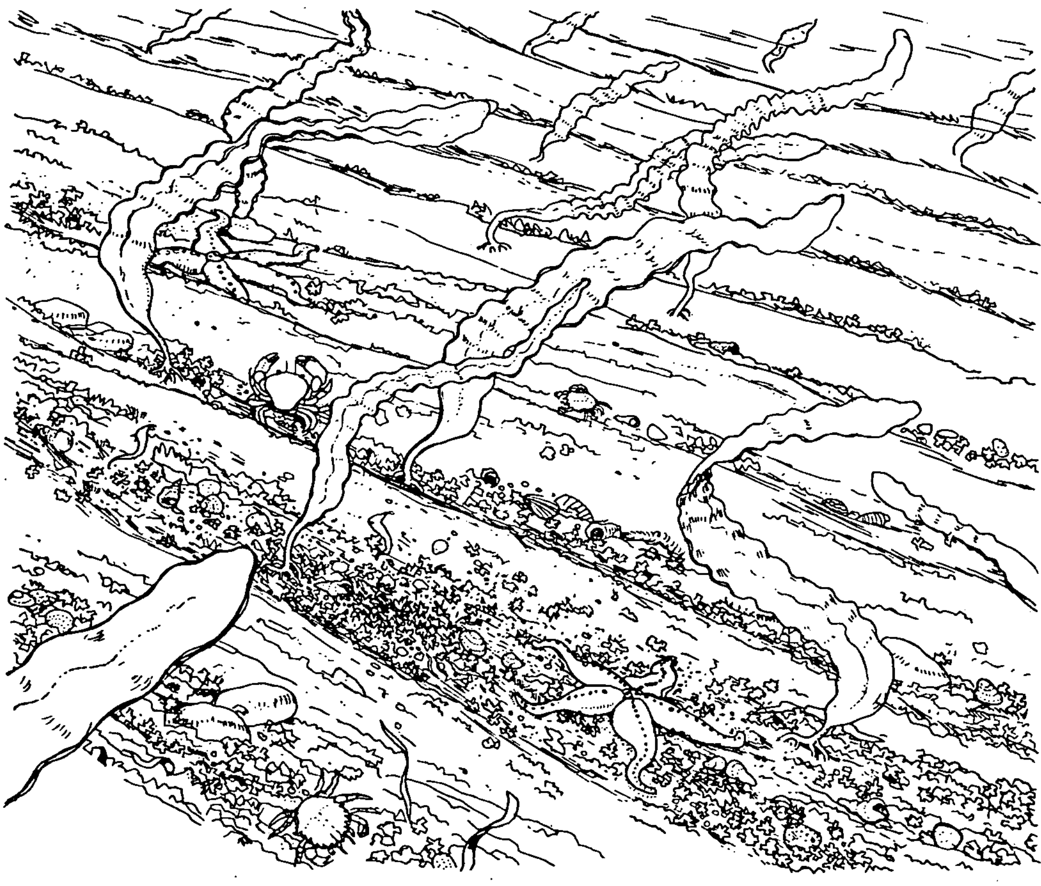

FIG. 4. Artists' reconstructions of gravelly megaripples at the N end of the Sound of Islay, 11 m depth (composed principally of *Lithothamnium* débris) partly stabilized by the kelp *Laminaria saccharina*:
(a) oblique view by Norman Aikman

noticeable than those which are convex up, especially when fresh. Large convex up algal-encrusted *Arctica* shells look at first sight remarkably similar to well-rounded stones.) Hermit crabs and *Macropipus*, though common, very rarely leave any visible traces of their movement over the surface (*cf.* facies v and vi). *Pecten maximus* completes the conspicuous epifauna.

(iv) *Wave-rippled sand.* Symmetrically rippled sands occur principally over the wide area of Tarbert Bank at depths of around 11 m. (Fig. 2). Interference and ladder rippling is common as a result of wave-induced swell and tidal currents at the time of observation being approximately at right angles. Ripples are shorter (6 to 15 cm) and higher (2 to 4 cm) than in the current-rippled areas. Starved ripples again

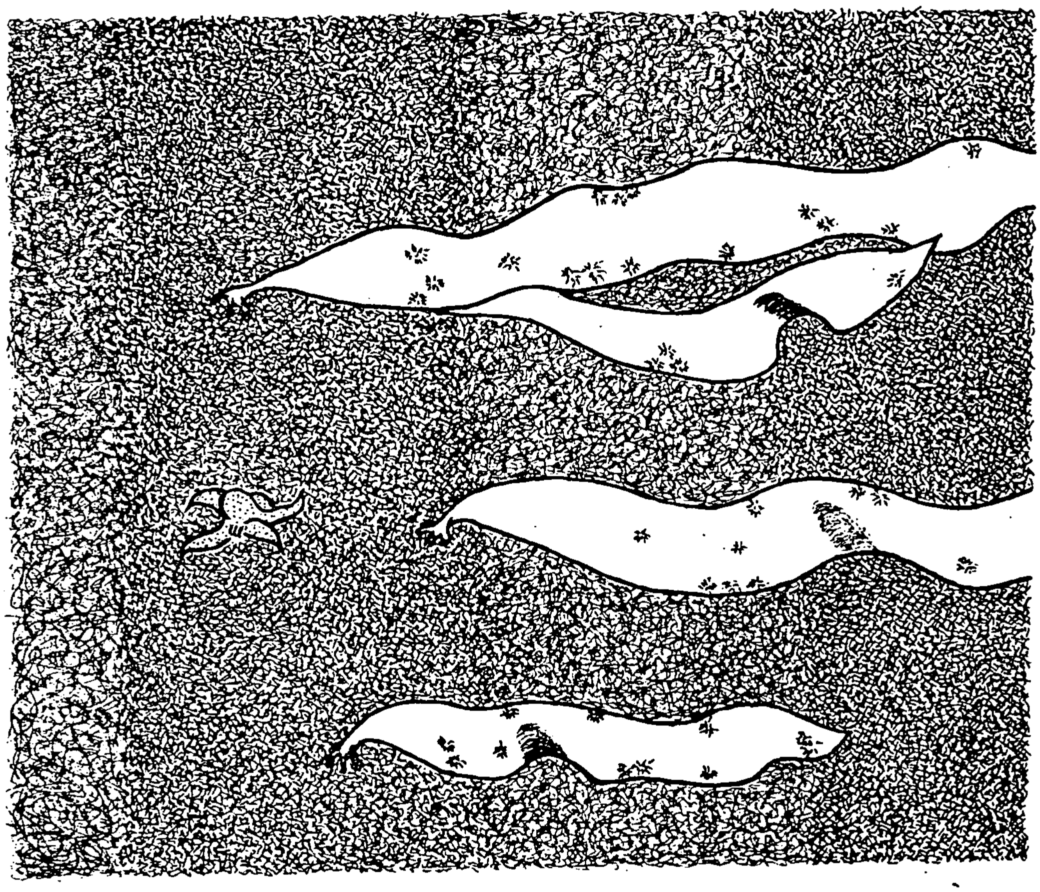

FIG. 4(b) vertical view by Maureen Roberts Drawn from single VTR sequence. (55°55′N 6°07′W).

occur, together with widespread markings perpendicular to the ripple crests made by drifting seaweed, often with cobbles or shells attached. Mollusc valves, large and small, were conspicuously concave up, many of them conjoined, *Arctica* being relatively more abundant than *Ensis* (the reverse of the situation in current-swept areas).

Starfish (*Asterias rubens* and *Luidia ciliaris*) were often seen in 'hunched up' feeding position, and hermit crabs observed scavenging; though neither left clear traces in the sediment of their activity. The occasional lugworm cast hinted at a cryptic infauna.

(v) *Turritella fine sand*. The distinction between this facies and the preceding one is based on the replacement of physically produced sedimentary structures (ripples) by those of biogenic origin (trails and pellets). This was one of the most frequently encountered facies (Fig. 2) occurring at a mean depth of 28 m—only slightly deeper than the previous sandy facies. The hallmark of this facies consists of the conspicuous trails made by hermit crabs which inhabit dead shells of *Turritella communis*. The possibility exists that some of these gastropods could be inhabited by the sipunculid worm *Phascolion strombi* (Campbell and Nicholls 1976, p. 137). The sediment surface is not rippled, despite in some cases the presence of moderate bottom currents (indicated by drifting weed). Darker patches, several metres in diameter, may represent a diatom-rich gelatinous mat of the type recorded by Bathurst (1967) from the Bahamas. This might explain the presence of trochid gastropods (algal grazers) which were not noted in adjacent facies, though there is an alternative possibility that they arrived attached to kelp fragments, deposited in this facies during storms: very large bits of drifted kelp were encountered.

This facies has considerable diversity (judged solely by the criterion of television analysis). Very fresh conjoined *Arctica* valves frequently bear evidence of damage by predation, possibly by *Macropipus*, which is commonest in this facies.

Live scallops were again noted, more frequently than elsewhere. The starfish were more varied than in other facies, including additionally cushion stars (*Anseropoda placenta*) and sunstars (*Crossaster papposus*). Faecal pellets often seemed the centre of attraction for the hermit crabs; convergent radiating trails being the result. *Buccinum undatum* represented another scavenger.

Partly infilled, concave up *Arctica* shells showed that normal sedimentation in this facies was dominantly vertical, out of suspension, rather than lateral. This facies graded in places into the next, where sea pens and burrow openings began to become frequent. Normally, however, they were rare in this facies.

(vi) *Filamentous-tube burrowed 'mud'*. Three burrowed 'mud' facies have been differentiated, though for clarity, they are shown collectively on figure 2 ('mud' is a field term here, and probably includes silt and fine sand). The first and shallowest of the three (mean depth 34 m for 10 stations) was characterized by a mat of small tubes 2 or 3 millimetres in diameter, most commonly revealed around the margins of burrow openings, which were far steeper than they would be without the mat stabilization.

We could not discern the nature of the tube-building organism. The closest illustration we have been able to locate is of the tubes of the tiny amphipod *Haploops tubicola*, initially described by Petersen (1918, Pl. VIII) and figured by Thorson (1957, p. 517) from soft clay 27 m deep in the Kattegat; but tubicolous polychaetes could be responsible.

Crab trails were conspicuous. They include large bilobed trails made by reversing crabs; and faecal pellets and faecal strings. Sea pens were common with occasional mud volcanoes (probably the work of callianassid crustaceans). Shells broken by predation were again conspicuous.

(vii) *Crustacean-burrowed mud.* A very high density of burrow openings typifies this facies, which occurs throughout the central part of the area (Fig. 2) in water averaging 48 m deep. The sea-floor may have a chaotic cratered topography where the burrow openings are adjacent to large mud volcanoes. Elegant, elongate sea pens (*Virgularia mirabilis* and *Funiculina quadrangularis*) were conspicuous associates (Fig. 5). Burrow openings took two forms: the larger, sometimes oblique, were those of the scampi, *Nephrops norvegicus*: the smaller, often in clusters of five, were of the crab *Goneplax*. In addition, several fish were seen occupying *Nephrops* holes (Table 1). Around others, hydroids could be seen. Pandalid shrimps were often seen darting across the T.V. frame, but in general there was little evidence of mobile epifauna (except for the occasional *Macropipus* and *Buccinum*) or shell material.

The most distinctive traces of this facies were the radiating ones made by *Nephrops*. Faecal castings were again noticeable and seemed to 'stick' to the sediment surface.

(viii) *Spider-crab mud.* At 115 m it was the deepest station possible with our equipment—and one of the most diverse. Sea pens were again noticeable, but in this facies the wider, feathery-looking *Pennatula phosphorea* occurred (sometimes with the crinoid *Antedon bifida* attached near the top). The brittle star *Ophiura texturata* was also common. Trails made by a variety of long-legged crustaceans (*Macropodia, Inachus, Hyas*) were dominant over other traces.

(ix) *Overconsolidated clay.* Tough clay, showing clear indications of undergoing present-day erosion, forms a belt on the eastern side of Tarbert Bank (Fig. 2). At a remarkably constant depth of between 23 and 28 m, the facies may represent late-Glacial "Clyde Beds" material. Scoured and partly undercut grooves could be seen, with clay balls adjacent, and washed out tubes of *Chaetopterus*. Large, severely corroded, serpulid encrusted, *Arctica* valves were very common in patches.

(x) *Modiolus gravel.* Extensive spreads of the horse mussel *Modiolus modiolus* occurred on a clayey substrate immediately north and northwest of Post Rocks, Islay (Fig. 2)—at precisely the same depth as facies ix. That they were not simply a remanié deposit produced by the winnowing of Clyde Beds-like clay was indicated by the widespread occurrence of typically byssate clumps of live *Modiolus* (Fig. 6). Much of the bottom initially looked very stony, but on close view during replay the "stones" could be seen to be single convex up valves of *Modiolus*, some even tending to show imbrication. In contrast, other *Modiolus* valves were richly encrusted with serpulids and barnacles. *Buccinum* was more abundant in this facies than elsewhere, with brittle stars and starfish also present.

(xi) *Lithothamnium gravel.* At the N end of the Sound of Islay, again at a 25 m depth (Fig. 3) and seeming to rest on a clayey bottom, was a rich spread of *Lithothamnium* gravel, much of it probably living (seen in the dull colour compared with the brilliant white of the dead; Bosence 1976, p. 372). An additional finer grained occurrence at 15 m, together with abundant *Lithothamnium* debris in the gravelly, megarippled areas nearby, suggests that the alga is not so restricted in substrate as is *Modiolus*. Kelp, *Macropipus* and *Ensis* valves were persistent associates, as in the megarippled areas.

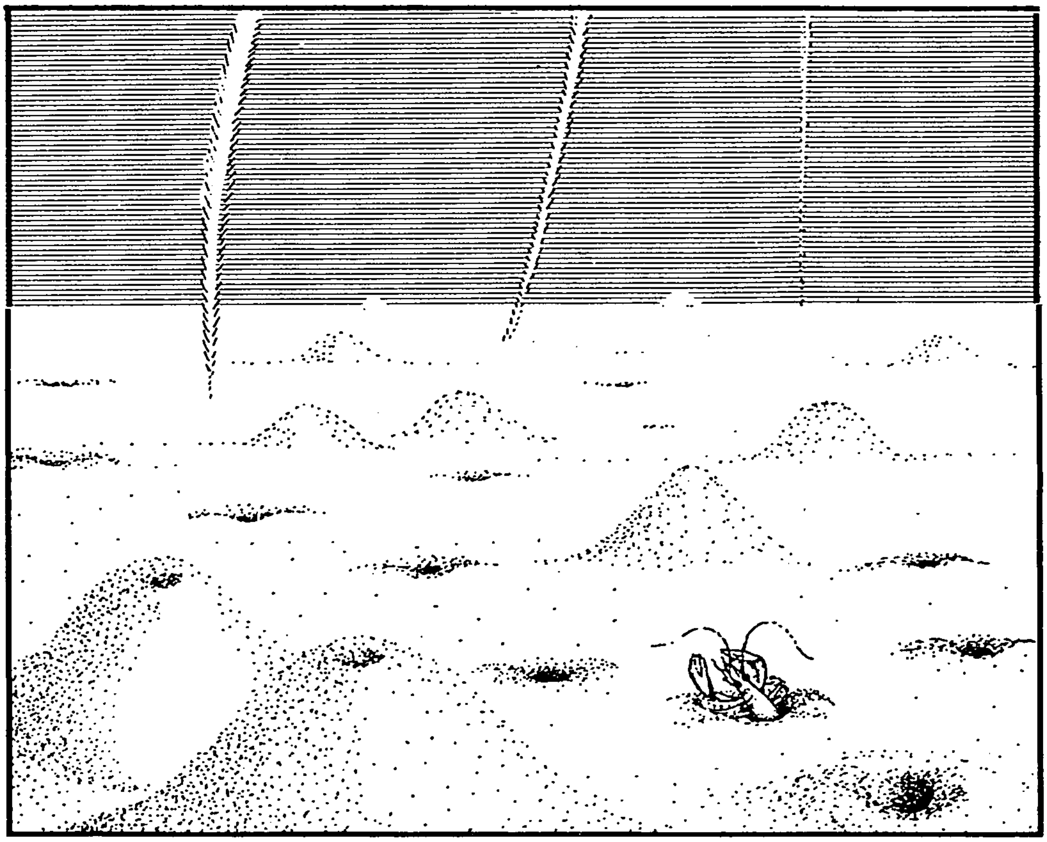

FIG. 5. Artists' reconstructions of crustacean burrowed mud facies, widespread in the central part of the area at an average depth of 48 m; showing burrow entrances of *Nephrops norvegicus* (scampi), mud volcanoes (probably produced by burrowing thalassinidean shrimps) and the tall sea-pens *Funiculina*. Drawn from single VTR sequences:
(a) general oblique view by William Senior (similar scale to figs. 3 and 4a): relatively low level of burrowing activity

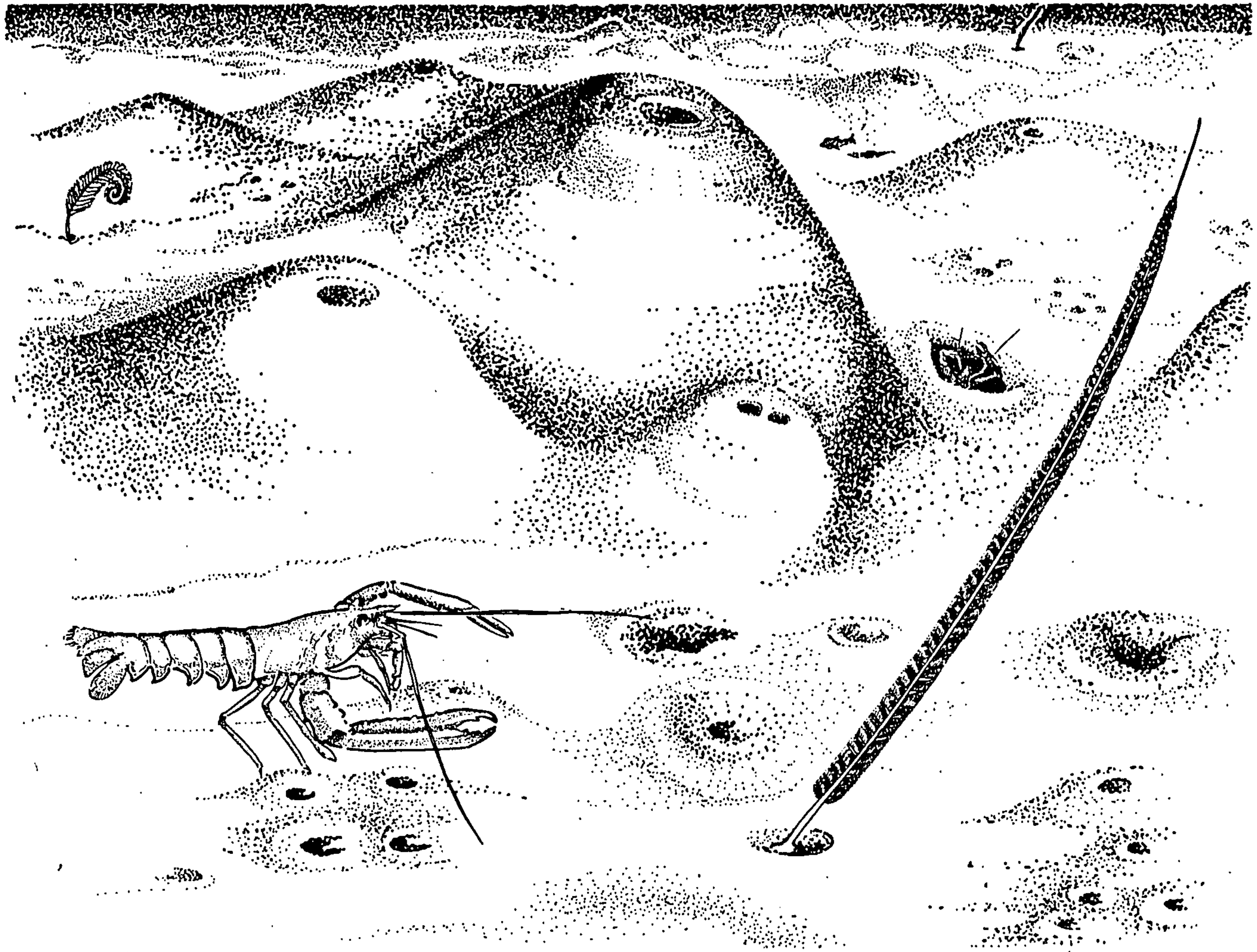

FIG. 5. (b) detailed view by Jill Clokie (similar scale to fig. 6): high level of burrowing activity (56°05′N 6°00′W).

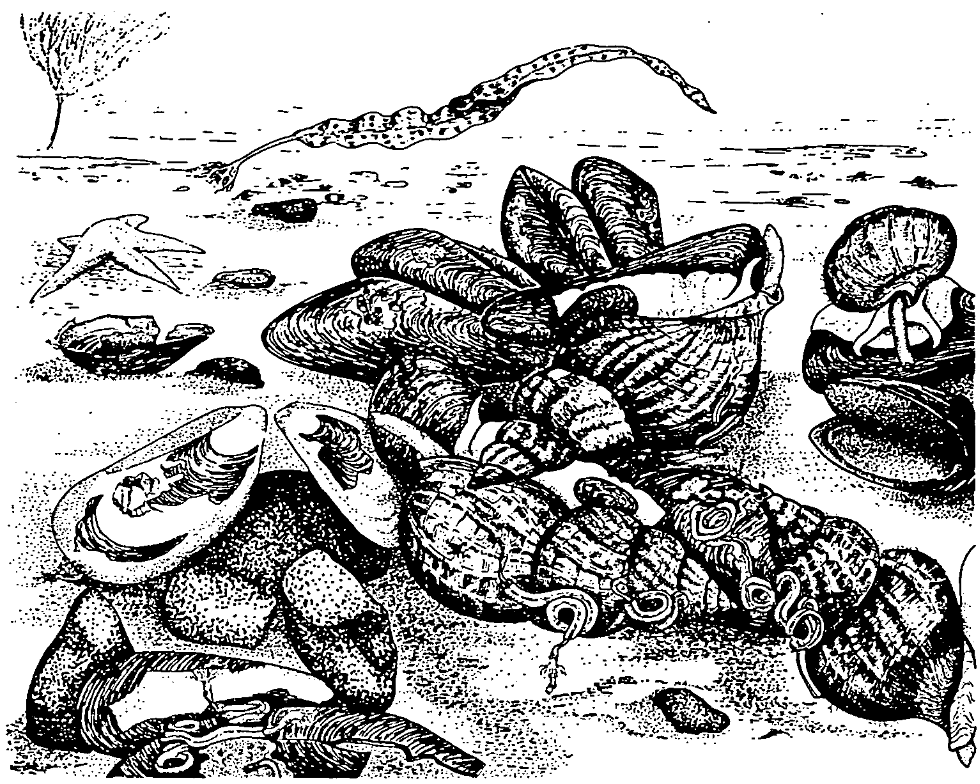

FIG. 6. Artist's reconstruction of *Modiolus* bed N of Islay, 23 m depth, showing a cluster of *Buccinum undatum* (whelks) feeding over a byssate clump of the horse mussel *Modiolus modiolus*. Drawn by Jill Clokie from single VTR sequence. (55°58'N 6°10'W)

PROCESSES, PRODUCTS AND FOSSILIZATION POTENTIAL

Many of the sedimentary processes we observed during our television survey were biogenically influenced in some way. In particular, the influence of the larger kelp species on present-day patterns of sedimentation seems of great significance. They cannot be ignored either as producers of carbonate sediment (from their calcareous epifauna) or as transporters of clasts up to cobble size—or even as stabilizers of very slow-moving bedforms (including megaripples). Whether we shall ever be in a position to determine the rôle played by the soft algae in former times remains to be seen, but their fossilization potential must be extremely low. (A very rare occurrence from Greenock is given by Brett and Norton 1969).

Two particular soft algae, *Laminaria hyperborea* and *L. saccharina*, are important. The former is found in rocky or bouldery areas, usually exposed to wave action: the latter occurs in more sheltered areas, often in sounds strongly swept by the tide. *L. hyperborea* has a rough stem that supports a particular epifauna of barnacles, serpulids and bryozoa, and fronds which are grazed particularly by regular echinoids and trochid gastropods. Carbonate production comes therefore from three very distinct parts of any one plant: (i) the holdfast (ii) the stem (iii) the frond. On death of the plant the first two parts produce debris of sessile animals—these are the perennial parts of the plant, maybe living for eight years, though usually about four (Kain 1963). The frond, however, has an effective life of only five to seven months (Thorson 1971, p. 108) and this supports essentially motile animals (with the exception of the bryozoan *Membranipora*). The high primary frond productivity leads to a much higher motile calcareous epifauna than would be present in the absence of the algae.

We have seen *L. saccharina* rooted in *Lithothamnium* gravel in megarippled areas. This species normally prefers gravelly rather than rocky substrates (T. Norton pers. comm. 1977). It therefore tends to stabilize the bedform, and its very presence hints at insubstantial mobility of the megaripples over a period of several years.

Because of their contrasted substrate preference, when these two algae break free they tend to transport different types of clast, *L. saccharina* moves clumps of *Modiolus*, large *Arctica* shells and *Lithothamnium* gravel, whereas *L. hyperborea* moves large cobbles. Storms may not be needed to uproot the algae, since as they grow they naturally get more buoyant through the larger surface area of frond exposed to wave and current action. Large accumulations of kelp are produced by storms, however, with extremely important palaeoecological consequences. The kelp is deposited in great masses in low energy areas (typically muddy sand). The motile kelp epifauna may not perish immediately but may mix with the *in situ* dominantly infaunal community. In the fossil record, such a mixed community would be difficult to detect in view of the almost zero fossilization potential of the algae themselves. Such storm beds of kelp might additionally be expected to produce a highly organic lens of sediment within the local sequence.

Another group of algae also play a stabilizing rôle—on the fine sand of the level bottom. The television showed that over wide areas some kind of mat, probably diatom-rich, was preventing ripple marks from forming despite the presence of moderate bottom currents. The mat areas had a greater density and diversity of epifauna than adjacent rippled sands, particularly of predatory starfish. The similarity to Bathurst's (1967) subtidal gelatinous mat from the Bahamas is striking. Here again, it is very doubtful whether the mat would be preserved in the fossil record.

The traces of epifaunal activity vary dramatically in their fossilization potential. Crabs, hermit crabs and starfish failed to leave any observable traces in the coarser sand facies, though they were common there. Although less common in the muddier facies, the crabs left conspicuous trails. We would therefore expect indications of vagile epifauna in comparable sandstones from the rock record to be at best a cryptic bioturbation, with a very poorly preserved, fragmented body fauna. The real abundance of vagile compared with sessile epifauna may have been very much greater than counts of the relative abundance of the appropriate fossils (say trilobites and brachiopods) would suggest.

Facies Synthesis

In a comparatively small area, eleven facies have been recognized. Three of these seem related to a substrate of consolidated late-Glacial clay all about 25 m deep. The rocky facies is insufficiently developed to merit discussion. The remaining seven facies portray the classic gradation of clastic sediments from high to low energy; three facies showing evidence of bedload movement, and four the very clear dominance of vertical sedimentation out of suspension. It might be expected that this transition relates directly to water depth, but examination of Table 1 shows this not to be so. Firstly, megaripples occur as deep as 67 m whereas burrowed mud facies occurs as shallow as 23 m; and secondly there is no clear depth differentiation between three of the four sand facies where similar ranges occur between 11 and 67 m. In this area the major control on facies is the location of land masses which influence wave and current forces. The island of Colonsay shelters the area to the east from strong wave action such that mud facies may be seen extending close inshore, whereas in the exposed area just to the north current-rippled sand appears at the same depth. The juxtaposition of the islands of Jura and Islay concentrate the tidal streams responsible for the megarippled sands to the SE of the area.

This evidence illustrates the caution which must be adopted when deducing depth of water from facies evidence in shelf sedimentary rocks. As great a facies variation—*within the confines of the inner continental shelf*—is shown in Recent sediments here as is shown for example by many Palaeozoic sedimentary rocks of Britain where the epithets 'shelf' and 'basin' are of fundamental palaeogeographical import. Indeed, on this part of the Scottish shelf, facies that might possibly be interpreted in the stratigraphic record as of 'basinal' aspect dominate over those of 'shelf' type. The term 'basinal' would thus appear to have little meaning in terms of contemporary depth or structure.

The oversimplification of relating facies to depth possibly results from our tendency to consider palaeogeographic boundaries as regular linear features with land on one side and progressively deepening water on the other. The recent glacial sculpturing of the Inner Hebridean shelf makes its anatomy inappropriate for drawing too elaborate uniformitarian analogies but nevertheless the study of the Recent Hebridean facies teaches a lesson of caution when interpreting conditions on ancient shelves.

Acknowledgements

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REFERENCES

BARNES, H. 1959. *Oceanography and Marine Biology*. London.

BARRETT, J. and YONGE, C. M. 1972. *Collins pocket guide to the sea shore*. London.

BATHURST, R. G. C. 1967. Subtidal gelatinous mat, sand stabilizer and food: Great Bahama Bank. *J. Geol.* **75**, 736–8.

BINNS, P. E., McQUILLIN, R. and KENOLTY, N. 1974. The geology of the Sea of the Hebrides. *Rep. Inst. Geol. Sci.*, No. 73/14.

BOSENCE, D. W. J. 1976. Ecological studies on two unattached coralline algae from Western Ireland. *Palaeontology*, **19**, 365–95.

BRETT, D. W. and NORTON, T. A. 1969. Late glacial marine algae from Greenock and Renfrew. *Scott. J. Geol.* **5**, 42–8.

CAMPBELL, A. C. and NICHOLLS, J. 1976. *The Hamlyn guide to the seashore and shallow seas of Britain and Europe*. London.

CHAPMAN, C. J. and RICE, A. L. 1971. Some direct observations on the ecology and behaviour of the Norway lobster *Nephrops norvegicus*. *Marine Biol.* **10**, 321–9.

EDEN, R. A., ARDUS, D. A., BINNS, P. E., McQUILLIN, R. and WILSON, J. B. 1971. Report on geological investigations with a manned submersible off the west coast of Scotland, 1969–70. *Rep. Inst. Geol. Sci.* No. 71/16.

——, DEEGAN, C. E., RHYS, G. H., WRIGHT, J. E. and DOBSON, M. R. 1973. Geological investigations with a manned submersible in the Irish Sea and off western Scotland 1971. *Rep. Inst. Geol. Sci.* No. 73/2.

HOLME, N. A. and BARRETT, R. L. 1977. A sledge with television and photographic cameras for quantitative investigation of the epifauna on the continental shelf. *J. mar. biol. Assoc.* U.K. **57**, 391–403.

KAIN, J. M. 1963. Aspects of the biology of *Laminaria hyperborea* II. Age, weight and length. *J. mar. biol. Ass.* U.K., **43**, 129–51.

MACHAN, R. and FEDRA, K. 1975. A new towed underwater camera system for wide-range benthic surveys. *Marine Biol.* **33**, 75–84.

NISHIMURA, M. and HARA, M. 1968. Utilization de la télévision sous-marine au Japan. *Rev. Hydrog. int.* **45**, 125–34.

PETERSEN, C. G. J. 1918. The sea bottom and its production of fish-food. A survey of the work done in connection with the valuation of the Danish waters from 1883–1917. *Rep. Dan. biol. Stn. 25*, 62 pp. 10 pl.

STANLEY, D. J. and FENNER, P. 1973. Underwater television survey of the Atlantic Outer Continental Margin near Wilmington Canyon. *Smithsonian Contrib. Earth Sci.* No. 11.

STEVENSON, R. A. 1967. Underwater television. *Oceanol. int.* **2**, 30–5.

THORSON, G. 1957. Bottom communities (sublittoral or shallow shelf). *Geol. Soc. America Memoir* **67**, (ed. Hedgpeth, J. W.) pp. 461–534.

——, 1971. *Life in the sea*. London.

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THE COORDINATION OF DIVING AND SHIPBOARD TECHNIQUES IN INVESTIGATIONS OF CARBONATE SEDIMENT DEPOSITION ON THE WEST COAST OF SCOTLAND

(Manuscript submitted to Progress in Underwater Science)

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ABSTRACT

Geological studies of sediments on the west Scottish Shelf necessitate collecting a range of information including:- observations of the nature of surface and buried sediment; the types and quantities of organisms producing, and living on and in, this sediment; the morphology of the sea bed; internal structure of the sediment pile; and the prevailing physical conditions. To build an overall picture of the nature of the deposits and the processes responsible for their specific characteristics requires direct observations from within the water by scuba divers and indirect observations obtained using shipboard techniques. The two approaches complement and supplement each other. They complement each other where both diver and ship can survey the same area using different techniques and scales of observation, and supplement each other where the diver can operate in an area inaccessible to the ship and the ship can operate in an area inaccessible to the diver. Shipboard techniques provide data rapidly over fairly broad areas including the collection of recorded images on video tape or film by underwater television and film cameras, surface sediment sampling by grabbing and dredging, subsurface sampling by coring, seabed and subsurface profiling by marine geophysical techniques such as side-scan sonar, precision echo sounding, pinger, boomer and sparker seismic methods. Diving

techniques provide detailed observations of local areas and ground-truths for the interpretation of data collected indirectly from ships. At the planning stage the marine geologist is concerned with how best to blend these various techniques to produce the most successful programme for his study.

INTRODUCTION

The electronic devices briefly described here are standard tools for the marine geologist but there may be groups of divers who are not familiar with the scope of these instruments and the potential they hold for their studies. This article is principally aimed at such workers. For details of the technical aspects of these geophysical instruments see McQuillin and Ardus (1977).

In a study of the accumulation of carbonate sediments on the shelf and coast of western Scotland the following five characteristics of the area have received our closest attention:-

(i) The types of sediment on the sea bed

(ii) The types of organisms producing calcareous sediments

(iii) The physical conditions prevailing

(iv) The nature and configuration of the sea bed

(v) The nature of the sediment pile

It has been found that a combination of diving and shipboard techniques provides the most valuable data for this investigation.

SCUBA DIVER OBSERVATIONS

Scuba divers have been able to make direct observations relating to each of these five aspects mentioned above.

(i-ii) Surveys of sediment and organism distributions were undertaken in shallow water by drift-diving and by tow-board methods. Both methods were ideal for rapid reconnaissance of small shallow areas (about $\frac{1}{4}$ km^2 per dive in water 10 m deep) but they suffered from difficulties in position fixing. The tow-board method with its system of electric light and buzzer signals from diver to dinghy allowed a degree of communication enabling sea bed mapping without surfacing during the dive.

(iii) Measurements of prevailing physical conditions were greatly hampered by currents stronger than 50 cm/sec (1 knot). Strong tidal currents and heavy waves restricted the operation of sensitive instruments such as the recording light meter which measured both the quantity and quality of light during investigations of the light requirements of calcareous algal deposits. Current measurements were best done from boats but stopwatch timing of the travel of dye in water was used to supplement current meter observations of the speed and nature of water movement over sand waves.

(iv) Sea bed structures were measured directly but also experimentation on the sea bed with planted blocks and stakes were undertaken by scuba divers to further understanding of sediment production and transport. However major changes in sedimentary structures occurred during the swiftest part of the tidal cycle and in storms, that is during the time most difficult to view them directly by diving.

(v) The internal structure of accumulating sediment was elucidated by scuba diver-operated coring at locations of special interest. Manual piston coring and suction-assisted box coring give shallow (50 cm maximum in coarse sand) recovery of sediment. The cores were sliced and peels made by resin impregnation of a vertical surface to reveal internal structures (Figure 1).

Figure 1 here

Figure 1. Resin-impregnated peel of suction-assisted core of coarse shelly sediment from the Sound of Iona revealing biogenic structures. Scale: white rectangle at base of photograph is 1 cm wide.

Limitations of scuba diver observations

The major constraints on the diver's scope of operations were the depth and sea conditions. But even in shallow areas the cold water restricts the stay underwater and thick wet-suits hinder handling intricate equipment. Even using a tow-board the area that a diver could survey in one dive gave inadequate detail or coverage to complete the task in the time available. The diver's scale of observation varied with the light and clarity of the water: normally he could record (on a slate or photograph) fine detail on the scale of centimetres to metres ideally, but larger features of the order of magnitude of 10's to 100's of metres were beyond his scope. Whilst having the distinct advantage of being able to take a second look at some feature of special interest on the sea bed the divers visual scientific observations were countered by being both subjective and generally poorly recorded. Sub-bottom sampling gear operated manually by divers was inadequate to do no more than scratch the surface, for information on deeper structures beneath the sea bed, shipborne geophysical techniques had to be adopted.

DATA COLLECTED BY SHIPBORNE TECHNIQUES

Samples of sediment and fauna were collected from boats by various grabbing and dredging methods, and gravity coring gave a further record of the sub-bottom deposits. Shipborne sampling methods (in contrast to diver sampling) suffered from not knowing the relation of the sample to the overall picture and how representative this sample is of the typical sea bed. This was overcome to a large extent by surveying the sample area with underwater television. The system of underwater television, with coordinated still film camera was used from a research vessel. The T.V. camera, mounted on a frame with lights and a neighbouring 70 mm still camera, was suspended from the slowly drifting ship (Figure 2) and shipboard monitors show pictures of the sea bed.

Figure 2 here

Figure 2. Schematic diagram of electronic devices operated from research vessel, cut away to reveal the relative depths of penetration of towed seismic instruments. Although all illustrated in this one summary diagram these devices would not be operated simultaneously.

The depth of operation was limited by the strength of the housing and the length of cable to 500 m. The T.V. system offers continuous video images of the sea bed (from about 50 cm to 3 m elevation above the bottom determined by the light source and camera focussing) which can be recorded for later playback. An attached flash and still camera produced photographic images with much better resolution than T.V., of objects of special interest (Figure 3); each flash was recorded on the video tape and readily allowed the later placing of still pictures into the overall scene.

Figure 3 here

Figure 3. Deep underwater 70 mm camera photograph of muddy sea bed with sea pens at 50 m depth east of Colonsay. The 10 cm high mounds are produced by the burrowing activity of the Norwegian lobster Nephrops sp.

Videotape records were supplemented by verbal descriptions made not only at the original recording but during later playback by viewers. The video system recorded sediment type, organism distribution (both sessile and vagile), sea bed configuration from which measurements were made, processes operating at the time such as ripple migration or feeding behaviour of animals.

In order to scan a wider area rapidly, sonic devices were employed which give a continuous track along the ships course. (Figure 2). These instruments can usually be used in bad seas up to Force 6 and can be towed at 4 to 7 knots with no adverse effects on the record. The side scan sonar transmitter sends a narrow beam of acoustic signals in an arc oblique to the sea bed in a direction at right angles to the ships course (Figure 2). The time taken for the echo to return to a receiver on the ship from obstacles on the sea bed struck by the beam is measured and plotted as a line of varying densities on a read-out on board the ship (Figure 4). As the transmitter moves it sends out the beam continuously and the read-out builds line by line to produce an image having the appearance of a three dimensional picture of the sea bed (Figure 4).

Figure 4 here

Figure 4. Side-scan sonograph of folded and faulted rock outcrop at 35 m depth north of Sanday, Orkney.

Besides offering valuable data on sea bed morphology this device can pin point areas of special interest for later diver investigation. The array of tones produced on the sonograph can be accurately interpreted once a diver investigates the actual nature of the sea bed producing the characteristic dense and light patterns on the record. By this means mud bottoms can be distinguished from those covered by, for example, gravel, sand, weed, coral or rock. The diver obtains the ground-truths necessary in interpreting sea bed type from sonographs in a similar way to that in which study of a long core of sediment helps the fuller understanding of a seismic profile.

Seismic profiles along transects enable the sub bottom structure to be surveyed rapidly. Various types of equipment are used to send signals to the sea bed and beyond for reflection back from distinctive layers or structures to the recording device on the ship. The depth of penetration into the sediment and the resolution of the structure revealed there,,vary according to the amount and type of energy emitted from the instrument towed by the ship. In our studies we used three instruments:- a pinger, a boomer and a sparker (Figure 2) which in order, give increasing depth of penetration. The pinger readout shows detail at shallow depth below the sea bed, giving good records of large-scale sedimentary structures in unconsolidated sediments. It also effectively locates pockets of sediment on an undulating rocky sea bed (Figure 5). From this a good indication can be obtained of the distribution of substrates available for epifaunal and infaunal colonization. At shallow depths such pinger records could save valuable time for a diver searching either for pockets of loose sediment to sample or outcrops of in-situ rock to map.

Figure 5 here

Figure 5. Pinger profile of pockets of loose sediment on an undulating rocky outcrop off Ardnamurchan peninsula. Vertical distance between dashed horizontal lines is approximately 25 m.

The boomer and sparker (Figure 2) records give greater penetration and can indicate deeply buried accumulations of sediment and rock (Figure 6)

Figure 6 here

Figure 6. Sparker profile of buried glacial deltaic sediment, N. Sound of Iona. Vertical distance between horizontal lines is approximately 40 m.

DISCUSSION

It is obvious that a scuba diver can get to places inaccessible to a research vessel (in-shore, shallow water) and a research vessel can work in places inaccessible to the scuba diver (deep, rough water), and in this respect the observations recorded by the two complement each other. But the object of this note has been to suggest how the use of both diving and shipboard techniques each can help the other to make fuller use of the results obtained. Coordinating diving and shipboard techniques stretches the scope of the study beyond the limits of each, and further, enables a more rapid and comprehensive survey of the area by either alone. The sequence of observations should be considered at the planning stage so as to make the most effective use of resources.

REFERENCE

McQuillin, R. and D.A. Ardus (1977). Exploring the geology of shelf seas. London: Graham and Trotman Ltd. 234 pp.

REFERENCES

Adey, W. H. 1970. The effects of light and temperature on growth rates in boreal-subarctic crustose corallines. J. Phycology, vol.6. p.269-276.

Adey, W. H., and Adey, P. J. 1973. Studies on the biosystematics and ecology of the epilithic crustose corallinaceae of the British Isles. British Phycol.Jour.vol.8.p.343-407.

Adey, W. H., and McIntyre, I. G. 1973. Crustose coralline algae: a re-evaluation in the geological sciences. Bull. Geol. Soc. Am. vol. 84. p. 883-904.

Adey, W. H., and McKibbin,D.L. 1970. Studies on the maerl species Phymatolithon calcareum (Pallas) nov. comb. and Lithothamnium coralloides Crouan in the Ria de Vigo. Botanica Marina, vol 13. p. 100-106.

Admiralty Tidal Stream Atlas. 1973. Published as Tidal Stream Atlas, north coast of Ireland, West coast of Scotland. No. 218. Hydrographic Dept. U.K. Taunton.

Alexandersson, T. 1974. Carbonate cementation in coralline algal nodules in the Skagerrak, North Sea: biochemical precipitation in undersaturated waters. J. Sedim. Petrol., vol. 44. p. 7-26.

Alexandersson, T. 1972. Micritization of carbonate particles: processes of precipitation and dissolution in modern shallow-marine sediments. Bull. Geol. Inst. of U. Uppsala. New Series, vol. 3, No. 7. p. 201-236.

Allen, J. R. L. 1968. Current ripples. North-Holland Pub. Co. Amsterdam. 433p.

Allen, J. R. L. 1970. Physical processes of sedimentation. George Allen and Unwin Ltd. London. 248p.

Bailey, E. B.; Clough, C. T.; Wright, W. B.; Richey, J. E., and Wilson G. V. 1924. Tertiary and post-Tertiary geology of Mull, Loch Aline and Oban. Memoirs of the Geological Survey, Scotland. H. M. Stationery Office, Edinburgh. 445 p.

Barnes, R. D. 1966. Invertebrate zoology. W. B. Saunders. Philadelphia and London. 632p.

Barnes, D. J. 1970. Coral skeletons: an explanation of their growth and structure. Science, vol. 170. p. 1305-1308.

Barnett, P. R. O., and Hardy, B. L. S. 1967. A diver-operated quantitative bottom sampler for sand macrofaunas. Helgoländer wiss. Meeresuntes vol. 15 p390-398.

Barrett, J., and Yonge, C. M. 1958. Collins pocket guide to the sea shore. Collins. London. 272p.

Bathurst, R. G. C. 1975. Carbonate sediments and their diagenesis: Developments in sedimentology, vol. 12. Elsevier Sci. Pub. Co. Amsterdam 2nd ed. 658p.

Belderson, R. H. 1964. Holocene sedimentation in the western half of the Irish Sea. Marine Geol., vol. 2. p.147-163.

Belderson, R. H., and Kenyon, N. H. 1969. Direct illustration of one-way sand transport by tidal currents. J.Sedim.Petrol., vol. 39. p. 1249-1250.

Belderson, R. H.; Kenyon, N. H., and Stride, A. H. 1971. Holocene sediments on the continental shelf west of the British Isles. In: F. M. Delaney (ed.) ICSU/SCOR Working party 31 Symposium, Cambridge 1970: The geology of the East Atlantic Continental margin. Rep. Inst. Geol. Sci. No. 70/14. p. 157-170.

Belderson, R. H.; Kenyon, N. H.; Stride, A. H., and Stubbs, A. R. 1972. Sonographs of the sea floor: a picture atlas. Elsevier Sci Pub. Co. Amsterdam. 185p.

Binns, P. E.; Harland, R., and Hughes, M. J. 1974a. Glacial and post-glacial sedimentation in the Sea of the Hebrides. Nature, vol.248. p. 751-754. Refs. 1974a, b shown in text as Binns et al. (1974).

Binns, P. E.; McQuillin, R., and Kenolty, N. 1974b. The geology of the Sea of the Hebrides. Rep. Inst. Geol. Sci. No.73/14. 43p.

Binns, P. E.; McQuillin, R.; Fannin, N. G. T.; Kenolty, N., and Ardus, D. A. 1975. Structure and stratigraphy of sedimentary basins in the Sea of the Hebrides and the Minches in A. W. Woodland (ed.) Petroleum and the continental shelf of north-west Europe. Applied Science Pub. Ltd., Essex, England. p. 93-102.

Bishop, P. 1977. Glacial and post-glacial sedimentation in the Minches, North West Scotland. Unpub. Ph.D. thesis. U. London, U.College, Dept. of Geology. 193p.

Bjørlykke, K.; Bue, B., and Elverhøi, A. 1978. Quaternary sediments in the northwestern part of the Barents Sea and their relation to the underlying Mesozoic bedrock. Sedimentology, vol. 25. p. 227-246.

Blanc, J. J. 1958. Resultants scientifiques des campagnes de la Calypso; V11. Etudes sur le seuil Siculo-Tunisien; 31 Sedimentologie sous-marine du detroit Siculo-Tunisien, campagne de la Calypso (Aout-Septembre, 1954). Ann. Inst. Ocean. T.34. p. 91-126.

Bosence, D. W. J. 1976. Ecological and sedimentological studies on some carbonate sediment producing organisms, Co. Galway, Ireland. Unpub. Ph.D. thesis. U. of Reading, Dept. Geology. 141 p.

Bowes, G. E., and Smith, M. H. 1969. Marine geological research in the west of Scotland. An interim report. University of Strathclyde, Applied Geology Research Report No. 1. 14 p.

Brill, K. G. 1956. Cyclic sedimentation in the Permian system of Tasmania. Papers and Proc. Roy. Soc. of Tasmania. Vol.90. p.131-140.

Brown, B. J. 1979. Shell transport and community recognition in modern shelf seas. Unpub. Ph.D. thesis. U. Glasgow, Dept. Geology. 2 volumes. 1012p. total.

Brown, B. J., and Farrow, G. E. 1978. Recent dolomitic concretions of crustacean burrow origin from Loch Sunart, west coast of Scotland. Jour. Sedim. Petrol., vol. 48. p. 825-833.

Cabioch, J. 1969. Les fonds de maerl de la baie de Morlaix et leur peuplement vegetal. Cah. Biol. Mar., vol. 10. p. 139-161.

Cabioch, J. 1970. Le maerl des cotes de Bretagne et le probleme de sa survie. Penn ar Bed., vol. 7. p. 421-429.

Cabioch, J. 1972. Étude sur les Corallinacees. II. La morphogenese consequences systematiques et phylogenetiques. Cah. Biol. Mar., vol. 13. p. 137-288.

Campbell, A. C., and Nicholls, J. 1977. The Hamlyn guide to the sea shore and shallow seas of Britain and Europe. The Hamlyn Pub. Gp. Ltd. London. 320p.

Carey, S. W., and Ahmad, N. 1961. Glacial marine sedimentation. In G. O. Raasch (ed.) Geology of the Arctic: Proceedings of the First International Symposium on Arctic Geology. U. Toronto Press. p. 865-894.

Carrigy, M. A. 1956. Organic sedimentation in Warnbro Sound, West Australia. J. Sedim. Petrol., vol. 26. p. 228-239.

Carrigy, M. A., and Fairbridge, R. W. 1954. Recent sedimentation, physiography and structure of the continental shelves of western Australia. J. of the Royal Society of Western Australia, vol. 38. p. 65-95.

Caston, G. F. 1976. The floor of the North Channel, Irish Sea: a side-scan sonar survey. Rep. Inst. Geol. Sci. No. 76/7. 16p.

Caulet, J. P. 1972. Recent biogenic calcareous sedimentation on the Algerian continental shelf. In. D. J. Stanley (ed.) The Mediterranean Sea. Dowden Hutchison & Ross Inc. Stroudsburg, Pa. p.261-277.

Channon, R. D. 1971. Storm and current sorted sediments of the continental shelf southwest of England. Unpub. Ph.D. thesis. U. Bristol, Dept. Geology. 378p.

Channon, R. D., and Hamilton, D. 1976. Wave and tidal current sorting of shelf sediments southwest of England. Sedimentology vol23 p.17-42

Chao, G. Y. 1969. 2θ (Cu). Table for common minerals. Geological Paper 69-2. Carleton U. 42p.

Chave, K. E. 1960. Carbonate skeletons to limestone: Problems. Trans. N.Y. Acad. Sci. Ser. II, vol. 23. 14-24.

Chave, K. E. 1964. Skeletal durability and preservation. In: J. Imbrie and N. D. Newell (eds.), Approaches to Paleoecology. John Wiley and Sons Inc., N.Y. p. 377-387.

Chayes, F. 1956. Petrographic modal analysis. John Wiley and Sons Inc, New York. 113p.

Connell, J. H. 1961. The influence of interspecific competition and other factors on the distribution of the barnacle Chthamatus stellatus. Ecology, vol. 42. p. 710-723.

Craig, E. H. C.; Wright, W. B., and Bailey, E. B. 1911. The geology of Colonsay and Oronsay with part of the Ross of Mull. Memoirs of the geological survey, Scotland vol. 35. 109 p.

Craig, R. E. 1959. Hydrography of Scottish coastal waters. Marine Research No. 2. Scottish Home Dept. H. M. Stationery Office, Edinburgh. 30p.

Cucci, M. A. 1974. Chara - production of sediment in Preble Green Lake, Cortland County, New York. Unpub. Master of Science thesis, Syracuse U. (N.Y., USA) Dept. Geology.

Cunningham, R. J. H. 1851. Geognostical description of Iona. Unpub. manuscript housed with Royal Highland and Agricultural Society, Ingliston, nr. Edinburgh, Scotland.

Dalrymple, R. W.; Knight, R. J., and Lambiase, J. J. 1978. Bedforms and their hydraulic stability relationships in a tidal environment, Bay of Fundy, Canada. Nature, vol. 275. p. 100-104.

David, T. W. E. 1950. The geology of the Commonwealth of Australia, vol. 1. Edward Arnold and Co., London. 747p.

Dobson, M. R.; Evans, D., and Whittington, R. 1975. The offshore extension of the Loch Gruinart Fault, Islay. Scott. J. Geol., vol. 11. Pt. 1. p. 23-35.

Draper, L., and Herbert, J. P. 1976. Visual wave observations in Scottish Waters 1968-1976. Report No. 29. N.E.R.C. Instit. Oceanographic Sciences.

Dryden Jr., A. L. 1931. Accuracy in percentage representation of heavy mineral frequencies. Proc. Natn. Acad. Sci. U.S.A., vol.17. p. 233-238.

Eden, R. A.; Ardus, D. A.; Binns, P. E.; McQuillin, R., and Wilson, J. B. 1971. Geological investigations with a manned submersible off the west coast of Scotland 1969-1970. Rep. Inst. Geol. Sci. No. 71/16. 49p.

Eden, R. A., and Binns, P. E. 1973. The role of divers and submersibles in geological mapping of the continental shelf around Scotland 1967-1972. In. Science Diving International. British Sub Aqua Club, London. p. 210-214.

Eden, R. A.; Deegan, C. E.; Rhys, G. H.; Wright, J. E., and Dobson, M. R. 1973. Geological investigations with a manned submersible in the Irish Sea and off western Scotland 1971. Rep. Inst. Geol. Sci. 73/2. 27p.

Emery, K. O. 1968. Positions of empty pelecypod valves on the continental shelf. J. Sedim. Petrol., vol. 38. p. 1264-1269.

Emery, K. O.; Butcher, W. S.; Gould, H. R., and Shepard, F. P. 1952. Submarine geology off San Diego, California. J. Geology, vol. 60. p. 511-548.

Farrow, G. E.; Cucci, M. A., and Scoffin, T. P. 1978. Calcareous sediments on the nearshore continental shelf of western Scotland. Proc. Roy. Soc. Edinburgh 76B. p. 55-76.

Farrow, G. E.; Scoffin, T. P.; Brown, B. J., and Cucci, M. A. 1979. An underwater television survey of facies variation on the inner Scottish shelf between Colonsay, Islay and Jura. Scott. J. Geol. vol. 15. p. 13-29.

Ferentinos, G. K. 1976. Sediment distribution and transport processes on the Outer continental shelf of the Hebridean Sea. Marine Geology, vol. 20. p. 41-56.

Folk, R. L. 1974. Petrology of sedimentary rocks. Hemphill Publ. Co. Austin, Texas. 182p.

Folk, R. L. 1976. Rollers and ripples in sand, streams and sky; rhythmic alteration of transvers and longitudinal vortices in three orders. Sedimentology, vol. 23. p. 649-669.

Folk, R. L., and Robles, R. 1964. Carbonate sands of Isla Perez, Alacron reef complex, Yucatan. J. Geology, vol. 72. p. 255-292.

Fretter, V., and Graham, A. 1962. British prosobranch molluscs. Ray Society. London. 755p.

Gill, E. D. 1948. Geology of the Point Lonsdale-Queenscliff Area, Victoria. Victorian Naturalist, vol. 65. p. 38-46.

Gillham, M. E. 1957. Coastal vegetation of Mull and Iona in relation to salinity and soil reaction. J. Ecol., vol. 45. p. 757-778.

Goldsmith, J. R.; Graf, D. L., and Heard, H. C. 1961. Lattice constants of the calcium-magnesium carbonates. Am. Miner., vol. 46. p. 453-457.

Gray, J. M., and Brooks, C. L. 1972. The Loch Lomond readvance moraines of Mull and Menteith. Scott. J. Geol., vol. 8. Pt.2. p. 95-103.

Gray, J. M., and Lowe, J. J. (eds.) 1977. Studies in the Scottish late glacial environment. Pergamon Press, Oxford. 197p.

Guilcher, A., and King, C. 1961. Spits, tombolos and tidal marshes in Connemara and west Kerry Ireland. Proc. Roy. Irish Acad., vol. 61 section B. p. 283-338.

Gunatilaka, H. A. 1972. A survey of the geochemistry and diagenesis of Recent carbonate sediment from Connemara, Western Eire. Unpub. Ph.D. thesis. Reading U., Dept. Geology. 125p.

Harland, W. B. 1964. Evidence of Late Precambrian glaciation and its significance. In: A.E.M. Nairn (ed.) Problems in Paleoclimatology. Wiley Interscience, New York. p. 119-149.

Herdman, W. A. 1895. The Marine zoology, botany and geology of the Irish Sea - Third report of the committee. Brit. Assoc. Adv. Sci. Rep. p. 455-467.

Holzman, J. E. 1952. Submarine geology of Cortez and Tanner Banks. J. Sedim. Petrol., vol. 22. p. 97-118.

Horowitz, A. S., and Potter P. E. 1971. Introductory petrography of fossils. Springer-Verlag, Berlin. 302p.

Hoskin, C. M., and Nelson Jr., R. V. 1969. Modern marine carbonate sediment, Alexander Archipelago, Alaska. J. Sedim. Petrol., vol.39. p. 581-590.

Houbolt, J. S. H. C. 1968. Recent sediments in the southern bight of the North Sea. Geologie en Mijnbouw, vol. 47. p. 245-273.

Inman, D. L. 1949. Sorting of sediments in the light of fluid mechanics. J. Sedim. Petrol, vol. 19. p. 51-70.

Jardine, W. G. 1977. The Quaternary marine record in southwest Scotland and the Scottish Hebrides. In: C. Kidson and M. J. Tooley (eds.) The Quaternary History of the Irish Sea. Geol. J. Liverpool. Special Issue No. 7. p. 99-118.

Johnson, D. W. 1919. Shore processes and shoreline development fascimile of 1919 ed. reprinted 1965. Hafner Pub. Co. New York. 584p.

Kelling, G., and Stanley, D. J. 1972. Sedimentation in the vicinity of the Strait of Gibralter. In: D. J. Stanley (ed) The Mediterranean Sea. Dowden, Hutchinson & Ross Inc. Strondsburg, Pa. p. 489-519.

Kennedy, W. Q. 1946. The Great Glen Fault. J. Geol. Soc. London, vol. 102. p. 41-76.

Kenyon, N. H. 1970. Sand ribbons of European tidal seas. Mar. Geol. vol. 9. p. 25-39.

Kenyon, N. H., and Stride, A. H. 1970. The tide-swept continental shelf sediments between the Shetland Isles and France. Sedimentology, vol. 14. p. 159-173.

Kerr, P. F. 1959. Optical mineralogy. McGraw Hill Book Co. New York. 442p.

Kitching, J. A. 1935. An introduction to the ecology of intertidal rock surfaces on the coast of Argyll. Trans. Roy. Soc. Edin., vol. 58. p. 351-374.

Komar, P. D. 1976. Beach processes and sedimentation. Prentice-Hall Inc. Englewood Cliffs, N. J. 429p.

Lees, A.; Buller, A. T., and Scott, J. 1969. Marine carbonate sedimentation processes, Connemara, Ireland. Reading U. Geological Reports No. 2. 64p.

Lees, A., and Buller, A. T. 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Marine Geol. vol.13. p. M67-M73.

Lewis, J. R. 1964. The ecology of rocky shores. The English Universities Press Ltd. London. 323p.

Lovell, J. P. B. 1979. Composition of Holocene sands of Mull and adjacent offshore areas: a study of provenance. Rep. Inst. Geol. Sci. No. 79/2. 9p.

McAllister, R. F. 1958. Rapid removal of marine salts from sediment samples. J. Sedim. Petrol., vol. 28. p. 231-232.

Macculloch, J. 1824. The Highlands and Western Isles of Scotland. containing descriptions of their scenery and antiquities... in letters to Sir Walter Scott. Four volumes. London Longman, Hurst, Rees, Orme, Brown and Green. Vol. 4. 480p.

Mackenzie Sr., M. 1776. Nautical descriptions of the west coast of Great Britain, from Bristol Channel to Cape-Wrath. Mount and Page and various other publishers, London, 69p; (Iona sand banks, p.42); With accompanying atlas: A maritim (sic) survey of Ireland and the west coast of Great Britain. Vol. 2. 31 charts (Sound of Iona: charts 21 and 23).

McQuillin, R., and Ardus, D. A. 1977. Exploring the geology of shelf seas. Graham and Trotman Ltd. London. 234p.

Majewske, O. P. 1969. Recognition of invertebrate fossil fragments in rocks and thin sections. E. J. Brill. Leiden. 101p.

Malcolm, S. J. 1979. The geochemistry of Recent sediments from Loch Etive, Scotland. Unpub. Ph.D. thesis, U. Edinburgh, Dept Geology. approx. 100p.

Mather, A., and Crofts, R. 1972. The beaches of west Inverness-shire and north Argyll. U. Aberdeen. Dept. Geography. 201p.

Milliman, J. D. 1974. Marine Carbonates. Springer-Verlag, Berlin. 375p.

Milliman, J. D.; Weiler, Y., and Stanley, D. J. 1972. Morphology and carbonate sedimentation on shallow banks in the Alboran Sea. In: D. J. Stanley (ed) The Mediterranean Sea. Dowden, Hutchinson & Ross Inc. Stroudsburg, Pa. p. 241-259.

Nelson, C. S. 1978. Temperate shelf carbonate sediments in the Cenozoic of New Zealand. Sedimentology, vol. 25. p. 737-771.

Nesteroff, W. 1965. Recherches sur les sediments marins actuels de la region d'Antibes. Masson et Cie, Paris. Nouvelle serie. T.43. 135p.

Niino, H. and Emery, K. O. 1961. Sediments of shallow portions of East China Sea and South China Sea. Bull. Geol. Soc. Am., vol. 72. p. 731-762.

Pendlebury, D. C. 1974. Recent sediments, shelly fauna and foraminifera of the Malin Sea. Unpub. Ph.D. thesis. U. Coll. Wales, Aberystwyth.

Pendlebury, D. C., and Dobson, M. R. 1976. Sediment and macrofaunal distrubitions in the eastern Malin Sea, as determined by side-scan sonar and sampling. Scott. J. Geol., vol. 2. Pt. 4. p.315-332.

Pennant, T. 1776. A tour in Scotland and voyage to the Hebrides PartI. B. White Pub. London. 439p.

Petersen, G. H. 1966. Balanus balanoides (L.) (Cirripedia) Life cycle and growth in Greenland. Meddelelser om Grønland bd. 159. nt.12. 114p.

Pettijohn, F. J. 1975. Sedimentary Rocks. 3rd edition. Harper and Row, New York and London. 628p.

Price, J. H., and Tittley, I. 1978. Marine algae (excluding diatoms) In: A. C. Jermy and J. A. Crabbe (eds.) The island of Mull, a survey of its flora and environment. British Museum (Natural History) London.

Price, N. B., and Calvert, S. E. 1973. A study of the geochemistry of suspended particulate matter in coastal waters. Marine Chemistry, vol. 1. p. 169-189.

Raymond, P. E., and Hutchins, F. 1932. A calcareous beach at John O'Groats, Scotland. J. Sedim. Petrol., vol. 2. p. 63-67.

Raymond, P. E., and Stetson, H. C. 1932. A calcareous beach on the coast of Maine. J. Sedim. Petrol., vol. 2. p. 51-62.

Rayner, D. 1971. The stratigraphy of the British Isles. Cambridge U. Press. 453p.

Reading, H., and Walker, R. G. 1966. Sedimentation of Eocambrian tillites and associated sediments in Finnmark, Northern Norway. Paleogeogr. Palaeoclim. Palaeoecol., vol. 2. p. 177-212.

Reineck, H. E., and Singh, I. B. 1975. Depositional Sedimentary environments. Springer-Verlag, Berlin. 439p.

Robinson, A. H. W. 1958. The charting of the Scottish coasts. The Scott. Geographical Mag., vol. 74. No. 2. p. 116-127.

Robinson, A. H. W. 1962. Maritime cartography in Britain (A history of the sea chart to 1855). Leicester U. Press (University Press Oxford). 222p.

Sacheverell, W. 1688. An account of the Isle of Man, with a voyage to I-columb-kill, Manx Society, Douglas, Isle of Man: (published 1859) p. 95-109.

Schäfer, W. 1972. Ecology and palececology of marine environments. trans. by Irmgard Oertel, ed. by G. Y. Craig. Oliver and Boyd, Edinburgh, 568p.

Schermerhorn, L. J. G. 1974. Late Precambrian mixtites. Glacial and/or nonglacial? Am. J. Sci., vol. 274. p. 673-824.

Scholl, D. W. 1960. Relationship of insular shelf sediments to sedimentary environment and geology of Anacapa Island, California. J. Sedim. Petrol, vol. 30. p.123-139.

Shirley, J. 1964. An investigation of the sediments of the continental shelf of New South Wales, Australia. Geol. Soc. Aust. Jour., vol. 11. p. 331-341.

Sissons, J. B. 1967. The evolution of Scotland's scenery. Oliver and Boyd, Edinburgh. 259p.

Sissons, J. B. 1976. Scotland. Methuen and Co. London. 150p.

Slatt, R. M. 1974. Continental shelf sediments off eastern Newfoundland: a preliminary investigation. Canadian J. of Earth Sciences, vol. 11 No. 3. p. 362-368.

Slatt, R. M. 1977. Late Quaternary terrigenous and carbonate sedimentation on Grand Bank of Newfoundland. Bull. Geol. Soc. Am., vol. 88. p. 1357-1367.

Sneed, E. D., and Folk, R. L. 1958. Pebbles in the lower Colorado River, Texas: A study in particle morphogenesis. J. Geol., vol. 66. p. 114-150.

Spencer, A. M. 1971a. Late Pre-Cambrian glaciation in Scotland. Memoirs of the Geological Soc. of London No. 6. 98p.

Spencer, A. M. 1971b. Late Pre-cambrian glaciation in the North Atlantic region. In: A. E. Wright and F. Mosley (eds.) Ice Ages : Ancient and Modern. Geol. J. Liverpool. Special Issue No. 6. p. 214-240.

Sprigg, R. C. 1952. The geology of the south-east province, South Australia, with special reference to Quaternary coast-line migrations and modern beach developments. Geol. Survey of South Australia Bull. No. 29. 120p.

Stearn, C. W.; Scoffin, T. P., and Martindale, W. 1977. Calcium carbonate budget of a fringing reef on the west coast of Barbados. Bull. Mar. Sci., vol. 27. p. 479-510.

Stride, A. H. 1972. Sediment transport around the British Isles. In: D. J. P.Swift, D.B. Duanne, O. H. Pilkey (eds.) Shelf sediment transport: process and pattern. Dowden, Hutchinson & Ross Inc. Stroudsburg, Pa. p. 373-375.

Summerhayes, C. P. 1969. Recent sedimentation around northernmost New Zealand. New Zealand Jour. of Geology and Geophysics., vol.12. p. 172-207.

Synge, F. M., and Stephens, N. 1966. Late and post-glacial shorelines and ice limits in Argyll and northeast Ulster. Trans. Inst. Br. Geogr., vol. 39. p.101-125.

Telford, W. M.; Geldart, L. P.; Sheriff, R. E., and Keys, D. A. 1976. Applied Geophysics. Cambridge U. Press. 860p.

Tyler, S. A. 1934. A study of sediments from the North Carolina and Florida coasts. J. Sedim. Petrol., vol. 4. p. 3-11.

Uchupi, E. 1961. Submarine geology of the Santa-Rosa-Cortes ridge. J. Sedim. Petrol., vol. 31. p. 534-545.

Vanney, J. R. 1965. Étude sedimentologique du Mor Bras, Bretagne. Marine Geology, vol. 3. p. 195-222.

Wass, R. E.; Conolly, R., and McIntyre, R. J. 1970. Bryozoan carbonate sand continuous along southern Australia. Marine Geology,vol.9.p.63-73.

West coast of Scotland Pilot. 1974. 11th ed. Hydrographic Dept. (U.K.) Taunton. 323p.

Weyl, P. K. 1961. The carbonate saturometer. J. Geol., vol. 69. p.32-44.

Wray, J. L. 1977. Calcareous algae; developments in Paleontology and Stratigraphy 4. Elsevier, Amsterdam. 185p.

Wright, J. B. (ed.) 1978. Oceanography; sediments: units 11 and 12. The Open University. The Open University Press, Milton Keynes.

Yonge, C. M. 1949. The sea shore. Collins, Glasgow. 350p.