RECENT TEMPERATE CARBONATE DEPOSITS ON THE CONTINENTAL SHELF NORTH AND WEST OF SCOTLAND: DISTRIBUTION, SEDIMENTOLOGY AND RESERVES

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ABSTRACT

Widespread shelly carbonate sands and gravels have been revealed by a reconnaissance of the seabed north and west of Scotland using IGS samples and geophysical data supplemented by material from further shipboard work. The carbonates cover large areas of the platform around Orkney and Shetland, and are generally less than 1m thick, although possibly reaching 30m in sandwaves and sandbanks around Orkney. Further west the deposits are rarely over 1m thick, smaller, and more isolated, except on the large platform west of the Outer Hebrides. Coastal carbonates occur as extensive beaches and machairs, and in bays and channels close inshore.

Petrographic analysis, radiocarbon dating and bedforms show that most of the material is post-glacial and a product of the modern sedimentary regime. Theoretical considerations of shelly carbonate sediment transport and bedform formation support this, indicating that such bioclastic debris is extremely mobile.

The basic requirements for the formation of these temperate carbonates are relatively strong currents and low terrigenous input. These are inter-related and linked to the major controlling factors, bathymetry and exposure to open sea. Thus carbonate sediments often occur on bathymetric highs: platforms, shoals and knolls, where rocky substrates are often exposed, where there are high rates of both growth and removal of carbonate-secreting organisms, and where the debris is not diluted by non-carbonate.

Estimates of the reserves of each deposit and the total mass of superficial carbonate indicate average accumulation and production rates on the shelf of at least 24 $g/m^2/yr$. Around Orkney local accumulation rates may reach 580 $g/m^2/yr$ and production rates 97 $g/m^2/yr$. An order of magnitude less than for tropical carbonates, these rates are very similar to those of ancient temperate carbonates and thus the Scottish sediments are important modern analogues.

The material has considerable potential for commercial extraction, particularly in the Orkney area.

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Chapter One

INTRODUCTION

I ORIGIN AND OBJECTIVES OF THE PROJECT

During routine survey work to the west and north of Scotland, the Institute of Geological Sciences (IGS)* noted apparently modern sediments rich in bioclastic carbonate. Temperate carbonates were still poorly known on the United Kingdom Continental Shelf (UKCS) and in view of this, and their potential as a resource, the IGS awarded the University of Strathclyde a research contract to investigate them. The project, using IGS data, would seek to explain the origin and distribution of carbonate sediments on the Scottish Continental Shelf (SCS).

The IGS is engaged in a comprehensive examination of the geology of the United Kingdom Continental Shelf (UKCS). The Marine Geology Unit, based in Edinburgh, is assigned to mapping the solid geology and superficial sediments (Quaternary-Recent) of the seabed over what is essentially the Scottish part of the Shelf. This is fundamental reconnaissance work, involving the collection and analysis of enormous amounts of data to produce regional maps (see pp. 8 - 9). In-house limitations of manpower are such that desirable specialist research projects arising from the work cannot always be undertaken by IGS staff. It was in this light that the contract was conceived.

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*For brevity, lengthy names used frequently will be quoted as acronymns following their first full designation. A check list is given in Appendix 1.

II DEFINITIONS

(1) Area of investigation

This lies to the north and west of the Scottish mainland, its limits (Fig. 1) being determined by data coverage, the locations of the most promising areas for carbonate, and the time available. It covers the whole of the inner shelf west of Argyllshire north of 56°N, through the Sea of Hebrides and the Minch and across the shelf as far as Shetland. The southern part also extends westwards from Mull to the continental slope between 56°N and 57°N. West of Orkney it also reaches the continental slope between 59° and 60°N. Its eastern limit extends from 58°N in the Moray Firth to 61°N on the eastern side of the Shetlands.

(2) Nomenclature

In this thesis:

(i) a "carbonate sediment" is defined as sediment containing 75% or more of calcium carbonate by weight;

(ii) a "carbonate-rich sediment" contains 50% to 75% calcium carbonate ($CaCO_3$) by weight;

(iii) a "high-carbonate sediment" contains 50%-100% $CaCO_3$ by weight;

(iv) a "carbonate deposit" is an area of superficial sediment mapped as containing 75% or more $CaCO_3$ by weight (Fig. 2);

(v) an "area of carbonate-rich sediment" is an area of superficial sediment mapped as containing 50%-75% calcium carbonate by weight. This may be either as a distinct patch within an area of carbonate-poor sediment containing <50% $CaCO_3$, or a distinct zone surrounding a carbonate deposit,or a large tract adjoining both carbonate sediments and carbonate-poor sediments (Fig. 2);

(vi) "megaripples" are bedforms recognised from their external morphologies as having wavelengths of 0.6-30m. They are equivalent to the "large scale ripples" of Reineck & Singh (1980);

(vii) "sandwaves" are bedforms with wavelengths greater than 30m, being equivalent to Reineck & Singh's "giant scale ripples";

(viii) the term "beach" includes landward dunes and machair as well as the actual shoreface;

(ix) Mud, sand, and gravel are terms reflecting sediment grain size in the sense of Folk (1968).

III PREVIOUS RESEARCH

(1) Earlier knowledge of Scottish Recent carbonate sediments

Marine carbonate sands and gravels along the coasts of Scotland have been exploited for many centuries. Commonly referred to as "shell sands", these are bioclastic skeletal carbonates and occur on many beaches of the west coast of the mainland, the Hebridean Islands, Orkney and Shetland. They have been used locally for making lime cement and improving the quality of agricultural land (eg. Farrow 1974, Mather et al., 1974, Leask 1928, 1933).

Hydrographic surveys have been made since the sixteenth century, largely under the direction of the British Admiralty (Robinson 1958). The surveys delineated with some considerable detail the bathymetry and types of sea bottom and this was presented on Admiralty Charts and specialist productions such as Close's Fishermen's Charts.

(2) Recent development of Marine Geology and Sedimentology

Introduction of the echosounder in the earlier part of this century generated much new research on shelf sediments. As the first continuously recording marine geophysical device, the echosounder opened up the study of the detailed morphology of the seabed (eg. van Veen 1935) and created wide interest in modern shelf sedimentation by relating the morphology to physical conditions and sediment type (eg. Cartwright & Stride 1958, Stride 1963, Miller 1964, Off 1963, Houbolt 1968, McCave 1971a, Swift et al. 1973).The greater understanding of shelf processes which has resulted can now be applied to specific aspects of modern and ancient shallow marine sediments. Such detailed work has begun in the shelf seas around Britain (eg. Channon and Hamilton 1976, Caston 1981, McCave & Langhorne 1982, McCave 1979), but relatively little has concerned the shelf to the north and west of Scotland. A good overall preview by Belderson et. al. (1971) identifies general associations between seabed types and current patterns. Kenyon and Stride (1970) discuss the area and Ferentinos (1976) investigated sedimentation patterns south of Barra Head. Binns et al. (1974a and 1974b) discussed the superficial sediments of the Sea of Hebrides in connection with their IGS work and Bishop (1977) and Bishop and Jones (1979) similarly covered the Minch, Evans et al. (1980) the Malin Sea, Deegan et al. (1973) the Firth of Clyde, and Chesher & Lawson (in press), the Moray Firth.

(3) Development of research on marine temperate carbonates

Carbonate sediments have long been a focus of interest and we now have a good understanding of their processes of formation in many environments, particularly warm waters (Bathurst 1975, Milliman 1974). Geologists have until recently tended to think of carbonate deposition in terms of warm water only, but it is now clear that carbonate sedimentation can also take place on a large scale in the colder waters (less than 20°C) of the world

(Raymond & Hutchins 1932, Keary 1967, Lees & Buller 1972, Lees 1975, Bjorlykke et al., 1978, Hoskin & Nelson 1969). As a result several ancient carbonate formations have been interpreted as temperate deposits, such as in the Tertiary of New Zealand (Nelson 1978) and in the Lower Permian of Tasmania (Rao 1981a, b, Clarke & Farmer 1982).

During the last two decades detailed work has been undertaken on recent carbonate sediments in specific areas of the temperate seas such as the Rockall Plateau, west of Scotland (Wilson 1979a,Scoffin et al. 1980), the Connemara coast (Lees et al. 1969, Bosence 1973, 1978, Gunatilaka 1975, 1977, Piessens & Lees 1972) and Galway (Bosence 1979), western Eire, the northwest continental shelf of France (Boillot 1964, 1965, Guilcher 1964), Mauritania (Koopman et al. 1979, Piessens & Chabot 1977), and South Australia (Conolly & Von de Borch 1967, Wass et al. 1970, Burne & Colwell 1982).

On the SCS, Pendlebury and Dobson (1976) provided some of the first analyses of the distribution, nature and origin of carbonate sediments in the Malin Sea area. Cucci (1979) investigated in detail the carbonate sediments around the southern part of the Inner Hebrides. His work is a valuable contribution to our knowledge of recent carbonates on the western SCS, and he includes a useful review of ancient and modern temperature carbonates throughout the world. Farrow et al. (1978) and Farrow et al. (1979) also researched carbonates off the west coast of Scotland by sediment sampling and work with underwater television, and Brown (1979) discussed the biological, ecological, and sedimentological aspects of the generation of bioclastic debris in broadly the same area. Bowes and Smith's (1969) preliminary examination of sediments around the Sounds of Mull and Iona, had encompassed many which were carbonate-rich. Bishop (1977) made an assessment of the carbonate contents of the sediments in the Minch. Wilson (1979a,b,c) published the results of work on the outer parts of the north and west SCS by the Institute of Oceanographical Sciences (IOS). A research group based at the University of Aberdeen surveyed the beaches of the Highlands and Islands(summarised in Mather and Ritchie 1977 & Table 1), and included analyses of carbonate contents of sands.

(4) Justification for the project

Information on Recent temperate carbonates in the world's seas, including those around Scotland, is amassing rapidly. However, much of it is detailed, localised work investigating carbonate generation over comparatively small areas under conditions which may not be typical for much of the shelf. On the UKCS for example, there has been much less regional, broad scale consideration of the distribution and nature of the recent carbonate sediments. This is, however, needed to (a) improve our understanding of the role and significance of our local carbonates in the overall context of modern temperate shelf sedimentation, and (b) assess the resource potential of Scottish marine carbonates.

IV DATA ACQUISITION AND RESEARCH STRATEGY

(1) Work by the Institute of Geological Sciences

IGS offshore survey work, discussed in detail by McQuillan and Ardus (1977), generally proceeds using:

(i) Geophysical coverage of an area, generally on a 5-10 km line spacing, using gravimeter, magnetometer, airgun, sparker, boomer, pinger, echosounder and sidescan sonar. Of these, the latter five tools are the most relevant to assessing superficial sediments.

(ii) Seabed sampling, whenever possible, to obtain grab samples, sediment gravity cores and vibrocores, and rockhead gravity cores and drillcores. Additional observational work may be carried out by sub-aqua divers, and by using underwater TV cameras, still cameras, the manned submersible Pisces, and the unmanned submersible Consub 1.

(iii) Routine particle size analyses (PSA), carbonate content analysis and palaeontological analysis.

(iv) Construction of 1:100,000 scale maps from the above data.

(v) Publication of 1:250,000 scale maps, and a report.

By the time the project began, a Sea of Hebrides Report had been completed (Binns et al. 1974b), reports on the Malin Sea (Evans et al. 1980) and the Moray Firth (Chesher & Lawson in prep.) were in preparation, and a project on the Minches (Bishop 1977) nearly completed.

By that time the main IGS effort had been switched to the North Sea, but the earlier sampling programme had included areas to the west, north and northeast of Scotland. With the exception of Shetland much of the project area had been covered in some detail, if somewhat unsystematically. Its data base was then manual, raw data being plotted and extracted by hand on 1:100,000 maps. As the research on the project developed, the IGS data base was continually improved and updated, but this unfortunately was too late for much of the earlier work which had perforce to rely on manual, time-consuming, data-sifting.

This thesis is essentially based on IGS data available when the research contract ended. A great deal more has been acquired and worked up during 1980-82 by the Institute.

(2) Research Cruises

During the three-year research period, I participated in seven periods of work offshore (Appendix 2) to gain additional data and practical experience. Some were legs of the IGS survey programme, others were collaborative arrangements with the Universities of Glasgow and Edinburgh, and the Department of Agriculture and Fisheries for Scotland (DAFS).

(3) Laboratory work

A large part of the work carried out at the University of

Strathclyde consisted of particle size analysis (PSA) additional to that done by IGS, and determining the proportions of bioclastic constituents. (Appendices 9 & 10).

(4) General Method

The project has entailed the screening and utilisation of a large volume of raw data. Over 2500 stations had been sampled by December 1979, together with many thousands of kilometres of geophysical coverage. Samples were selected for detailed work on the basis of their shipboard descriptions and any PSA data available from IGS. Later on, the IGS made comprehensive analysis of most of the unprocessed samples.

The data were first plotted on 1:250,000 working maps or, in the case of some more detailed information (eg. Orkney), on 1:100,000 maps. The final scale for fair maps was 1:1,000,000. After zones of interest were delineated, all geophysical data and core data etc. were assembled to gain a maximum insight into the distribution, morphology, thickness etc. of the sediments. When the occasion arose extra shipboard work was carried out at particular locations (eg. Sandy Riddle, pp.121-126). In general, of course, the research had to be conducted on the basis of data already available.

(5) Thesis layout

In Chapter 2, background information is given on the geology and physical regime of the SCS, so setting the scene. The carbonate deposits are then systematically outlined in as much detail as is available (Chapter 3). The descriptive sections (II-VI) are factual accounts with a very limited amount of interpretation (eg. carbonate thicknesses, sediment derivation, transport directions etc.). Section VII assimilates all the petrographic data from the previous sections and makes shelf-wide comparisons and deductions on their environmental and sedimentological significance.

Chapter 4 is the main interpretational part. An insight is gained into *(i)* the hydrodynamic behaviour of shell sand and *(ii)* the effect of tidal and wave currents acting in unison on the seabed. This is then applied to the carbonate deposits, further elucidating their sedimentological behaviour (section III). In section IV the carbonate's age and history is discussed along with the problems and significance of radiocarbon dates so far acquired. Finally section V classifies the types of carbonate deposit and outlines their mode of formation.

Their geological significance is considered in Chapter 5 in terms of carbonate production and accumulation rate and the preservation potential of the sediments. Chapter 6 investigates the deposits' economic significance; calcium carbonate is an important resource.

A comprehensive summary of the main conclusions of this work is given in Chapter 7.

Chapter Two

GENERAL SETTING

I INTRODUCTION

The area investigated lies offshore of the Scottish Highlands and Islands, and extends to the continental edge some 200 km distant. The Scottish coastline is intricate and variable; generally rocky but diverse, with beaches and shorelines exposed to the open sea, and sheltered channels and fjords. It is comparatively remote and lightly populated with only some localised heavy industry. Commercial activity offshore is mainly fishing and merchant shipping passing north and south.

II TERTIARY-QUATERNARY HISTORY OF THE SCOTTISH SHELF

The overall configuration of the SCS was established at least as early as the beginning of the Tertiary (∿ 65 m.y. BP). Major factors affecting its subsequent palaeogeography have been eustatic changes in sea level, tectonic subsidence along grabens (notably in the North Sea), marginal uplift, and Pleistocene glaciations.

Since the early Palaeocene the shoreline, initially located roughly at the top of the continental slope, has retreated across the shelf. A major setback took place in the Miocene when uplift forced the sea back near the shelf edge again (Anderton et al. 1979). Following that period, the shoreline probably retreated to approximately its present position, until the onset of Pleistocene glaciation (∿ 1.8 m.y. BP). Entrapment of water during phases of expanding ice caps then produced massive eustatic falls in sea level, exposing wide areas of the shelf.

During the periods of subaerial exposure, the shelf was deeply eroded. Rivers from the Highlands crossed it, cutting major valleys, some of which are still recognisable from the bathymetry of the outer shelf (Bishop and Jones 1979).

The detailed history of the pre-Devensian glaciations is poorly understood, because the stratigraphic record is very limited yet complex (Anderton et al. 1979). The last glaciation took place during the late Devensian period, between approximately 22,000 and 12,000 yr. BP. Although at an earlier period an ice-sheet covered much of the continental shelf as far out as St. Kilda (Sutherland et al. 1982) it was more restricted in the Devensian and ablating rapidly by 14,500 yr. BP. Sea level dropped as far as 100 or 150 m below present O.D. (Sissons, 1967, Anderton et al. 1979). Estimating the positions of the shoreline, and hence water depths, since then is difficult because they were determined by two interacting factors, each somewhat uncertain in magnitude: eustatic sea level rise (due to melting ice caps) and land-level rise (due to isostatic rebound). However, the isostatic effects on the shelf away from the mainland are thought not to have been great (Sissons 1967), and the best estimate for the shoreline position after the Devensian glaciation (∿12,000 yr. BP) is probably at the present 120 m bathymetric contour (Bishop and Jones 1979). During the following 1-2,000 years sea-level appears to have risen rapidly, slowing down and reaching its present levels between 6700 years and 5500 years ago (Fig. 4, Anderton et al. 1979 and Bishop and Jones 1979).

Coastlines and water depths on the shelf have thus been relatively stable for the last 6700 years. Water depth is probably increasing steadily by up to 1 mm per year at the present time. This seems likely to continue in the near future, though there is always the possibility of a sudden eustatic increase due to rapid melting of polar ice caps (particularly Antarctica); or other causes.

Since the end of the final glaciation (Loch Lomond readvance at about ~10,500 yr. BP) the British climate has ameliorated until it reached it warmest about 7000 years ago. Temperatures, generally 1-2°C higher than now, were maintained until about 2500 yr. BP, when they began to decline (Sissons 1967).

III GENERAL GEOLOGY

(1) Sub-Pleistocene

The pre-Quaternary geology of the UKCS is summarised by the IGS 1:2,500,000 map (Martindale and Chesher 1979, and Fig. 5).

On the western side of the SCS, at its southern end, the shelf consists mainly of Dalradian metasediments with a strong NE-SW structural grain and small Mesozoic basins. To the north, the Sea of Hebrides-Minch Trough marks the site of a larger, north-south Mesozoic-Cainozoic basin. This is flanked on the mainland to the east by Pre-Cambrian metamorphic and sedimentary formations and on the west by the Pre-Cambrian metamorphic basement of the Outer Isles. The Tertiary igneous centres of Mull, Ardnamurchan, Skye and St. Kilda lie within this western area of the SCS.

North of the mainland the Minch diversifies into a wider series of Mesozoic basins and Pre-Cambrian basement ridges extending as far north as Shetland. One large ridge of Pre-Cambrian runs from the west side of Shetland to the north west end of Orkney. This borders the Orkney-Shetland platform, an area largely of outcropping Devonian sedimentary rocks with Permo-Triassic on their eastern flank. This eastern limit of the platform is a north-south fault (an extension of the Great Glen fault zone) which cuts through Shetland and brings up a large area of Caledonian (?Dalradian) metasediments on its east side. Beyond lies the main north-south faulted margin of the North Sea Basin, with a generally full succession of Mesozoic-Cainozoic sediments. To the south is the Moray Firth Basin, an east-west trending graben containing Mesozoic sediments but little Cainozoic.

(2) Superficial (Quaternary) sediments

(a) Glacial (Pleistocene) sediments

In the North Sea Basin, which is still subsiding, the Pleistocene succession is thick (Holmes 1979, Anderton 1979). However, west of Scotland it is mostly thin and patchy, generally preserved only in the bathymetric basins and at the shelf edge (eg. W. of Shetland). Bouldery material frequently observed lying on an otherwise clear, sandy or rocky seabed is probably mostly reworked glacial debris. Thus undisturbed glacial sediments are often absent on the shelf around Shetland, Orkney, north of the mainland, and west of the Outer Hebrides, whereas they are common and up to 150 m thick in the Minch (Bishop and Jones 1979) and the Sea of Hebrides (Binns et al. 1974a and 1974b). Small pockets have also been observed around Shetland. Most of these sediments appear to have been deposited during the final stages of the last (Devensian) glacial period, any earlier sediments have been removed by later glacial erosion.

Iceberg ploughmarks are still detectable on some of the undisturbed Pleistocene sediments, particularly in the deeper water at the edge of the SCS (Lee & Ramster 1981).

(b) Recent (Holocene) Sediments

Holocene sedimentation has been studied extensively in the North Sea (eg. Klien 1976, Eisma et al. 1979, Owens 1981, Lee & Ramster 1981). Sediments are commonly argillaceous quartz-rich sands, locally cleaner and more calcareous in some places.

Belderson et al. (1971) demonstrated that, over the outer continental shelf to the north and west of Britain, the Holocene forms a highly mobile veneer on the seabed, with all the features of tidal and wave-current transport. Many of the sediments are bioclastic sands and gravels (Wilson 1979a, Ferentinos 1976). In places, particularly around Orkney, very large bedforms (ie. sandbanks) have been noted (Chesher & Lawson in prep.; see also pp. 99-131).

On the inner shelf to the west of Scotland, the sedimentary pattern is much more complicated, varying from gravels and boulder beds to silts and muds (Evans et al. 1980, Pendlebury and Dobson 1975, Binns et al. 1974a, Bishop and Jones 1979). Rockhead exposure is common, predominating along the coastlines of much of the western and northern seaboard and islands, and also patchily exposed over much of the shelf where sediments are thin and mobile (Fig. 6).

The terrigenous sediment pattern, very important to the distribution of carbonates, is largely the result of marine reworking of glacial material on a glaciated topography (eg. Ferentinos 1976). The rock basins, lying inshore of but often deeper than much of the shelf, have seabeds which are very sheltered from wave-currents. Many are efficient sinks for fine grained terrigenous material, derived both from surrounding reworked glacial drift and run-off from land (Fig. 7). Thus, much of the outer shelf and the relatively higher parts of the inner shelf are kept clear of fine grained sediment leaving clean sand, gravel, boulders and bare rock (Figs. 6 & 8).

The beaches, at the landward end of the marine sedimentary system, are as variable as the seabed offshore. Often, the coastline is rocky, bouldery and cobbly with the seabed plunging steeply into deep water. By contrast, shallow muddy estuarine tidal flats are commonly at the heads of sealochs and sheltered bays. Sandy beaches are also common along parts of the Scottish coastline where there is a gentle shelving platform offshore. These are sites of net sand deposition, and can form large systems of offshore bars, foreshore beaches, back-beach dunes, palaeo-beaches (including raised beaches) and palaeo-dunes. Where the sediment is calcareous, the vegetated landward expanse of dunes and old beaches forms fertile ground, called 'machair'.

IV PHYSICAL CONDITIONS

(1) Bathymetry

This is summarised in Figure 3. The fjords, sounds and channels of the mainland west coast and Inner Hebrides are related to an intensely variable seafloor topography which, in places, plunges from near sea level into overdeepened rock basins over 200 m deep (Sissons 1967). These were formed during the Pleistocene by ice from the main sheet on the Western Highlands. The basins generally follow the structural grain of the seabed geology, i.e. NE-SW in the south and SE-NW in the north.

Glacial influences on the bathmetry die out westwards across the continental shelf. The outer continental shelf has a more gentle morphology, though there are some large depressions such as the Flannan Deep and the northern and southwestern extensions of the Minch Trough, and upstanding features such as Stanton Banks, Nun Bank and Solan Bank which produce major shoals.

Worldwide, the edge of the continental shelf is often taken as the 200 m bathymetric contour. West of the mainland, however, the 150 m contour effectively defines the top of the slope, while west of Shetland it is the 180 m contour.

The angle of the slope varies from 6^{0} in places (Binns et al. 1974b) to 0.5^{0} in others (Fannin pers. comm.).

Northwards, towards Orkney and Shetland, the slope and outer shelf topography become more complicated. A large steep-sided basin up to 150 m deep occurs northwest of Orkney, linked by a narrow trough to the main slope. The slope approaches close to the northern end of Shetland, lying only 50 km north of Muckle Flugga. The shelf around Shetland was affected by glaciation (Flinn 1978) and has numerous troughs and channels.

The entire shelf off the northern mainland, around Orkney and in the northern Moray Firth, is a platform not more than 90 m deep. Eastwards, it shelves off into the northern North Sea, which reaches depths of over 150 m in the central parts.

(2) Currents

(a) Tidal currents

Tidal patterns on the UKCS have been reviewed by Huntley (1980). The basic elements of surface tidal behaviour on the SCS are summarised in Figure 9. The situation is locally very complicated, particularly close to the coasts and islands. Thus although Figure 9 suggests maximum tidal currents of 250 cm/sec occur, speeds of up to 500 cm/sec are actually known in the Pentland Firth (Fig. 52b). In general tidal currents are strongest on submerged channels and around peninsulas, decreasing seawards onto the open shelf.

Tidal current variations are mainly semi-diurnal and fortnightly, in response to 'neap' and 'spring' conditions, although there are other long term variations. A visual appreciation of the overall variation in strengths between neaps and springs is gained by plotting the two extreme tidal current curves (Fig. 10). Day by day the curve progresses from one extreme to the other.

Such diagrams vary from place to place. They cannot be easily summarised numerically, but their magnitude and temporal variability can be appreciated from the peak spring current strength (PS) and the peak neap current velocity (PN). During the progression from neaps to springs the current velocity will exceed the peak neap value for progressively longer periods. For a full neap-spring cycle, the proportion of time during which they exceed the peak neap strength is represented by the area under the spring curve and above the peak neap line. Similarly the proportion of time during which the currents are below peak neap strength is given by the sum of the areas of those parts of both curves underneath the peak neap line (Fig. 10). The peak neap exceedance time (PNET) varies between about 40% and 60%.

The overall tidal current activity can then be illustrated by quoting the values and directions of PS and PN, and the value of PNET. Sedimentologically, the maximum current strengths are important, and PS illustrates these extreme conditions. However, duration is also an important factor and the use of PN along with PNET may give a better picture of the long term current pattern.

Near-bottom tidal currents are not as well known as those at the surface. van Veen (1938) demonstrated that in a straightforward tidal channel such as the Dover Straits the current strength decreased parabolicaly towards the bottom (Fig. 11). In the open sea, however, this simple behaviour may not always occur, due to the presence of internal tides. These are caused by vertically distinct bodies of water, usually differing in density, behaving independently. In this case there is no predictable decrease of velocity with depth, and no consistent current direction through the water column (Huntley 1980).

Much of the tidal data in this work is based on Admiralty charts, tidal stream atlases and pilots (eg. Hydrographer of the Navy, 1973, 1974a, 1974b, 1975). Unfortunately this is not always sufficiently detailed or accurate.

Tidal current conditions at specific localities will be discussed in Chapter 3. Probable minimum velocities for 1 m above the seabed, given on the Carbonate Deposit Summary Sheets, are calculated from van Veen's (1938) formula of:

$$v = a\sqrt[5.3]{h}$$

where v = velocity h metres above seabed

a = velocity 1 metre above seabed.

This approximation is good enough for present purposes, bearing in mind that other errors may be substantial. Values for surface tidal currents are often not available for the precise location required and have to be extrapolated from elsewhere. Further, it is necessary to assume that there is a single, unidirectional tidal current from surface to seabed, and this may not always be correct.

(b) Wave currents

Wave data have been gathered from several locations on the UKCS (eg. Draper 1967). Although limited, they are used for the empirical analysis of wave behaviour. Wave conditions and bottom current conditions at a given location can also be estimated from the fetch, water depth, wind duration etc. (Darbyshire and Draper 1963, Draper and Squire 1967, Draper and Fricker 1965, Hadley 1964, Draper 1980).

Surface waves will affect the zone of water down to a depth of at least half their wavelength (Anikouchine and Sternberg 1981). Because the maximum wavelength of oceanic stormwaves is about 400m, the whole seabed of the continental shelf can be affected by waves.

Maximum wave heights likely to occur over the SCS are shown in Figure 12. Further indications of wave conditions at a specific location can be inferred from the tables of Darbyshire and Draper (1963). Seabed orbital current velocities are mostly estimated from the frequency curves and maps of Draper (1967) and Draper (1980). These (Fig. 13) give the frequency of occurrence of certain significant peak particle speeds (SPPS) for different water depths, based on surface wave measurements at specific localities. Maximum particle speeds likely to occur during a storm are obtained by introducing a 'particle speed factor' (Fig. 14; Draper 1967).

The wave height map (Fig. 12) shows the attenuation caused by the continental shelf as the oceanic waves across it. Thus the seabed peak particle speed curves for OWS stations Juliett and India (Fig. 13) show almost the full, unattenuated effect of Atlantic storm waves (maximum wave heights of 35 m) whereas the Sevenstones curves show the seabed effect of waves that have travelled across 150 km of shelf and been attenuated to 25 m maximum wave heights. Over the northern and western SCS maximum wave heights are predominantly between 25 m and 35 m. Hence by interpolation, seabed orbital velocities can be estimated for a given water depth. In the more sheltered Inner Hebridean waters, where maximum wave heights are commonly 15-25 m, the curves for Morecambe Bay are more relevant. None of the curves are strictly applicable to the northern North Sea, and interpolation between the Smith's Knoll and Sevenstones curves will only give a very crude approximation, because fetches and prevailing winds are different. Thus the derived velocities will vary with fetch, bathymetry, distance from shelf edge and other factors, but clearly over much of the region the oscillatory currents exceed 50 cm/sec several times per year.

(c) Combined effect of tidal and wave currents

Wave induced bottom currents are essentially oscillatory, although their resultant vector is often undirectional. They can therefore induce substantial sediment transport (Komar 1976a & 1976b. McCave 1971b, Kaneko and Honji 1979, J.R.L. Allen 1979b, Honji et al. 1980, Channon and Hamilton 1971 & 1976) but their importance becomes paramount when the combined effect of wave induced currents and unidirectional tidal currents is considered. Hammond and Collins (1979) have shown that superimposed oscillatory currents dramatically reduce the threshold velocity of a unidirectional current. The longer period oscillatory currents have the greatest effect.

The combined effect of unidirectional and oscillatory currents is important to understanding shelf sediment behaviour. The matter is fully discussed in Chapter 4 (pp. 181-187).

(d) Storm surges

'Abnormal' tidal elevations can be caused by high winds and large pressure anomalies (Huntley, 1980). If these occur during spring tides, the associated tidal currents will be higher than predicted.

(e) Overall water movements

Net water movements show a general clockwise drift around Britain (eg. Craig 1959, Livingston and Bowen 1977, Lee & Ramster 1981). Surface and bottom movements are summarised in Figures 15 & 16).

(3) Water temperatures

Much of the area investigated is directly influenced by the North Atlantic Drift, which is a wind-driven surface current stemming from the oceanic Gulf Stream. Surface temperatures vary from 7^{0}C in the winter to 13^{0}C in the summer (Fig. 17). The eastern and northeastern parts of the area show the lowest temperatures and greatest fluctuations. Sea-bottom temperatures in the winter are only slightly lower than at the surface, but in summer a small thermocline results in the bottom temperatures being up to 5^{0} cooler (Fig. 17).

Prior to the climatic cooling of 1^{0}-2^{0}C 2500 years ago (p. 16), the water temperatures were presumably higher than at present.

(4) Salinities

Surface salinities over much of the area are determined by the balance between predominant Atlantic waters and continental run-off. They are generally between 34.5 and 35.3‰ but can be lower towards the coast. The geographical and seasonal variations are shown in Figure 18. In coastal waters susceptible to high freshwater run-off the vertical variation with depth can be extreme due to the lack of vertical mixing. This effect dies away rapidly seawards and salinities out on the shelf vary only slightly with depth.

(5) Photic Zone

The depth to which biologically useful sunlight penetrates seawater exerts a critical control on the marine ecology and biological productivity. A useful guide is the 'compensation depth', i.e. the depth at which plant photosynthesis equals respiration.

For the bulk of the marine plants this is the depth reached by 1% of the sun's radiation falling on the water surface (Anikouchine and Sternberg 1981).

The outer shelf, with predominantly clear Atlantic oceanic water, has compensation depths as deep as 80-100 m. Shorewards the depth decreases to as little as 10-20 m. Because sediment agitation and mixing is heavily influenced by the weather and tides, compensation depths over the SCS will vary considerably in time and space.

Chapter Three

THE CARBONATE DEPOSITS : DISTRIBUTION AND CHARACTERISTICS

I INTRODUCTION

(1) Methodology

The main facts concerning the carbonate deposits and associated sediments on the SCS will now be presented. The data for each deposit are summarised on a Carbonate Deposit Summary Sheet (CDSS). Semi-quantitative descriptions of the physical conditions and sizes of the deposit are given, together with a petrographical summaries. The bottom current velocities are second order approximations calculated by extrapolating from published data (see pp. 22-24).

(2) Total $CaCO_3$

The surface sediment carbonate distribution on the SCS is summarised in Figure 19 and Enclosure 1. Carbonate content in individual sediment samples was measured using acid digestion techniques, giving the proportion of $CaCO_3$ by weight.

The sizes of the deposits and their total $CaCO_3$ contents are crudely estimated, yielding an appreciation of the overall magnitude of carbonate deposition. Their boundaries are ill-defined and the thicknesses poorly known, but order-of-magnitude estimates can be made. For example, in many areas where carbonate sediments are noted, side-scan sonar, echo-sounder, pinger, boomer, cores, and direct visual observation (eg. television) can be used to infer that the sediment thickness is mostly less than 1m, sometimes absent (leaving bare rock exposed) but generally at least several centimetres. A reasonable estimate for the average carbonate thickness would be 0.1m. Such estimates, though crude, nevertheless shed light on the nature of carbonate deposition on the SCS. Only where sediment thicknesses exceed 1m and geophysical profiling is carried out, may the degree of accuracy be improved. However, without good core data it is not possible to be sure that these thicker accumulations are entirely carbonate sediment.

To illustrate the usefulness and limitations of these estimates the most likely maximum and minimum average values will be cited for the volumetric calculations. Conversion from volume of sediment to weight of carbonate is carried out using bulk densities determined in the laboratory (Fig. 20).

(3) Petrographical properties

Numerical values for petrographical properties (composition, roundness etc.) on the CDSS are quoted as computed 'means', in one case based on the samples from within the deposit, and in the second case, on other samples (normally carbonate-rich) from the area around the deposit. Although the density and number of the sample stations used is normally exceedingly variable, and these 'means' are therefore not statistically rigorous, the values are extremely important for regional evaluation of the carbonates. Grain characteristics were assessed visually using the scales listed in Table 2. The detail and ranges of the scales are designed specifically for shelly sediments, easily recognisable differences being recorded without introducing spurious "accuracies". Where a visual observation (eg. roundness) is quoted as a range, the mean value is used. The use of coarse scales ensures that the visual estimates are reliable. Consequently, their average values can be taken to one decimal place when comparing different groups. Tenths of a unit are of course not significant in relation to the original scale, but the difference between averages of, say, 3.1 and 3.7 for roundness can be significant, when dealing with "averages" of two groups.

(4) Components

The principal carbonate components, debris from barnacles, bivalves, echinoids, gastropods, serpulids, bryozoa and foraminifera (for examples see Figs. 21-24, 145-151, and Appendix 6), were identified according to Milliman's (1974) criteria. Point counting was carried out on a grid, following splitting and slit sieving of the sand fraction (0.0625 mm- 2 mm), so that volumetric (and weight) proportions could be derived (Lees et al. 1969). Gravel sized (>2 mm) fragments were hand picked and weighed. Percentages quoted normally represent the proportions of components in the recognisable carbonate fraction (Appendix 10). No detailed taxonomic identifications were made. This aspect is very thoroughly covered by work at the IOS (Wilson 1975, 1976, 1979a,b,c, 1982).

(5) Maturity

(a) Definition and use

The maturity of a sediment is a measure of how nearly it approaches an ideal stable state (Whitten & Brooks 1972). For temperate carbonates the ideal state may be as a micritic mud (eg. Fitzgerald et al. 1979).

or solution. It is more useful therefore to regard the maturity of, for example, a shelly sediment as the amount by which it deviates from a fresh, poorly sorted gravel consisting of very angular, unpolished, unstained, unbored grains. Most grain characteristics reflect to some degree the extent of particle breakdown and can be useful, if crude, maturity indicators. Deductions might then be made on the sedimentological history of skeletal carbonate grains since the original organisms died. Major factors determining this history will be (*i*) time (i.e. age) and (*ii*) degree of current working (exposure to currents, current strengths, interaction with other particles, periods of burial, etc). Nevertheless, the relationship between grain breakdown and sedimentological history is more complex than for lithic grains because, besides mechanical action (Chave 1964, Driscoll 1967, Trewin & Welsh 1972) Cucci 1979), chemical action (Alexandersson 1975, 1979, Lewy 1981) and biological action (Milliman 1974, Farrow and Clokie 1979) are also very important in shell breakdown. There is also considerable variation between different organisms in the durability of their debris to these processes (Chave 1964, Farrow and Clokie 1979).

(b) PSA and Sorting

In general the particle size analysis (PSA) of a sediment (Folk 1968), particularly its mud content, gives an indication of the contemporary degree of current activity at the sampling site. For carbonate particles, however, the relationship may be more complex, Thus a coarse sediment may indicate transport or sorting (including winnowing) by strong currents, or simply lack of strong currents which would otherwise help to break down the particles. Generally however, the greater the degree of current activity (in strength and time) the more the particles will be broken down and the finer the sediment becomes. Sorting should also reflect maturity, but it is difficult to assess visually.

(c) Roundness

This should be a good maturity indicator but caution is needed in interpreting it because well rounded shell fragments in a mature sediment can be broken down into angular pieces (eg. see Pilkey et al. 1967).

(d) Surface polish

On occasions, polish can be useful, but it may be confused with the natural shine on fresh shell debris (particularly bivalves). This is frequently lost soon after death (eg. Farrow and Clokie 1979), leaving a dull matt surface.

(e) Staining

In some of the sediments many carbonate grains show brown ferruginous or black manganiferous staining. The causes are not clear (Owens 1981) but the intensity of staining might be expected to increase with time and therefore reflect maturity.

(f) Borings

Shell debris on the seabed is frequently subjected to boring by small sponges and algae (Milliman 1974). This takes place preferentially where the debris is least disturbed - i.e. where current activity is low but sufficient to prevent mud accumulating. Farrow and Clokie(1979) noted that extensive boring was most common among the larger fragments. This could result from their being more static than smaller grains, and are consequently (*i*) more favoured by boring organisms and (*ii*) less prone to mechanical distintegration.

(g) Composition

The components (p. 32) of the sediment may give an indication of maturity, with more durable constituents being more prevalent in more mature sediments.

(h) Maturity Index

The Maturity Index (M) is an experimental tool, devised in an attempt to indicate the overall maturity of the carbonates and carbonate-rich sediments. It is calculated from the grain characteristics as

$$M = \frac{5-GS}{2} + So + R + \frac{P}{2} + St + B$$

where GS is the numerical value for grain size

So is the numerical value for sorting

R is the numerical value for roundness

P is the numerical value for polish

St is the numerical value for staining

B is the numerical value for boring
(See Table 2 for the above scales)

The theoretical range of the scale for M is from 2.5 to 21, increasing with maturity.

Grain size and polish are arbitrarily halved in the formula because when it was devised they were seen as being likely to be the least reliable.

The significance and inter-relationships of the various petrographic properties, and their use to assess carbonate sediment maturity are fully discussed in the light of the results obtained (pp. 149-172).

II INNER HEBRIDES

(1) Gulf of Corryvreckan (CDSS No. 1)

(a) Geography and dynamics

The Gulf of Corryvreckan (Fig. 25) is a deep, narrow, tidally scoured rocky channel linking the northern end of the Sound of Jura to the Firth of Lorne. It is very exposed to storm waves from the west. The strongest tidal current (425 cm/sec at surface) is produced by the west-going stream (Fig. 25a).

(b) Extent, bedforms and thickness

The carbonate deposit is poorly delineated because only one good sample has been obtained from it. Side-scan sonar, sparker and pinger records show that the carbonate sediment forms patches in hollows on the rocky platform outside the western entrance to the main channel (Figs. 26 & 27). The platform plunges westwards into the muddy basin of the Firth of Lorne. Small sandwaves (probably <2m high) occur in places, extending along the platform parallel to the Jura coastline. Samples however, show much lower carbonate contents in this direction, suggesting that the patchy Gulf deposit is limited within a 3-4 km radius of the entrance.

Between the patches are substantial areas of bare or barely covered rock. Some patches are over 2m thick and a most likely average thickness of 0.5 m is inferred.

CARBONATE DEPOSIT SUMMARY SHEET NO. 1

NAME Gulf of Corryvreckan

LOCATION Channel between Jura and Scarba
POSITION (approx); LAT. 56° 10'N LONG. 5° 48' W
WATER DEPTH(m) 120+ AVE. SAMPLE DEPTH(m) 150
BATHYMETRY Deep narrow channel
DISTANCE FROM LAND(km) 0-2 DISTANCE FROM SHELF EDGE(km) 200
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			210	425	
1m above seabed	120	m water depth	85	170	?
		m water depth			
WAVE:		exceedance	50%	1%	0.1%
Nr. seabed	120	m water depth	0	15	25
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 10 x 10^6 ? Patchy

	Max.	Min.	Likely
CaCO3 CONTENT(%)	85	85	85
THICKNESS(m)	2	.1	.5
TOTAL VOLUME(m3)	20x 10^6	1 x 10^6	5 x 10^6
TOTAL WEIGHT(g)	14.7 x 10^{12}	.7 x 10^{12}	3.7 x 10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	245	12.2	61

NOTES Very limited data. 1 sample. Patchy, 2m high sandwaves on geophysics. Rocky.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	14	68	T	3	3	9	T	0
AVE.% FOR SURROUNDING AREA	-	-	-	-	-	-	-	-

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	65%	35%	N	4½	2.0	3.0	3.0	2.0	1.0	9.75
AVE. FOR SURROUNDING AREA	-	-	-	-	-	-	-	-	-	-

NOTES Based on one sample only

N means < 1%

See Table 2 for textural scales.

(c) Petrography

The carbonate sediment is a fairly clean, coarse sand and gravel. Its dominant constituents (Fig. 28a) are bivalve fragments (68%) and, to a much lesser degree barnacles (14%). Bryozoans (9%) form a greater proportion than normal for the Inner Hebrides.

This composition reflects the considerable water depth. But for the strong tidal currents, the area would harbour muddy terrigenous sediments, storm wave currents being comparatively minor at such depths so far from the shelf edge. This concurs with the low Maturity Index (9.75) and local derivation of the debris.

(d) Overview

The presence of asymmetric sandwaves confirms that the sediment is mobile. Unfortunately their orientation is unknown. Current velocities decrease rapidly 2-3km west of the entrance where the tidal stream emerges into the deep open basin of the Firth of Lorne. Hence net deposition is to be expected.

(2) Passage of Tiree (CDSS No. 2)

(a) Geography and dynamics

This wide passage lies southeast of the islands of Tiree and Coll, and northwest of Mull (Fig. 29). The bathymetry is very variable (Fig. 29a), much being rocky platform which rises in places to make

CARBONATE DEPOSIT SUMMARY SHEET NO. 2

NAME Passage of Tiree

LOCATION South of Coll and Tiree
POSITION (approx); LAT. 56^{o} 40' N LONG. 6^{o} 20'W
WATER DEPTH(m) 40-180 AVE. SAMPLE DEPTH(m) 58
BATHYMETRY Wide channel with shoals, cut by a deep basin
DISTANCE FROM LAND(km) 3-5 DISTANCE FROM SHELF EDGE(km) 160
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNF.T
Surface	(southend)-(northend)	20-30	35-55	35%-61%
1m above	55 m water depth	9-14	16-26	
seabed	100 m water depth	8-13	15-25	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	55 m water depth	5-5	50-45	75 -60
	100 m water depth	0-2	20-30	30 -45

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 200×10^{6}

	Max.	Min.	Likely
CaCO3 CONTENT(%)	95	75	85
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	200×10^{6}	2×10^{6}	20×10^{6}
TOTAL WEIGHT(g)	155×10^{12}	1.38×10^{12}	18.6×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	131	1.14	12.1

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	45	29	4	6	7	6	2	3
AVE.% FOR SURROUNDING AREA	30	44	4	4	3	10	4	2

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	30%	67%	3%	3.8	1.0	3.2	2.5	2.9	1.8	10.75
AVE. FOR SURROUNDING AREA	15%	69%	8%	3.2	1.3	1.0	1.0	2.6	2.0	9.6

NOTES

See Table 2 for textural scales.

shoals. The Passage is divided into northern and southern sections by a deep, narrow, glacially scoured basin. This runs from close inshore at Coll, cutting southwestwards across the Passage.

Current conditions are shown in Fig. 29b. The tidal current velocities are generally moderate, reaching 75 cm/sec only at a few localities (eg. around the Treshnish Isles). They are generally stronger at the narrower northern end of the Passage than at the south. The Passage is extremely exposed to storm waves from the southwest.

(b) Extent, bedforms and thickness

The deposit is clearly defined at the north part, extending from west of Ardnamurchan Point down the centre of the Passage. The deep basin separates it from Coll. The southern part of the deposit lies on the relatively shallow platform bordering the south coast of Tiree. Its distribution here is less clear due to a dearth of sample data.

The generally rocky seabed has been proved by geophysics and coring. On it lies a discontinuous veneer of mobile carbonate sediment which is thicker (up to several metres) in the hollows. In basins muddy (glacial?) sediments occur in some of the more substantial hollows or small basins. Some sandwaves lie about 6 km west of Ardnamurchan Point.

Owing to the patchy nature of the deposit its average thickness overall is difficult to estimate. 0.1 m is taken as most likely.

Dives were made by the IGS in Pisces in water depths of 50-70m, at and beyond the very northern limit of the deposit (Fig. 29a). Rocky pavements were encountered, strewn with gravel and boulders interpreted as winnowed glacial debris (Eden et al. 1971). Some of the larger hollows ($\sim$ 100 m across) contained coarse shell sand and gravel forming symmetrical megaripples with amplitudes of 0.2-0.3m and wavelengths of 1.5m. Orientation of their crests varied from NW-SE to NE-SW, depending on that of the associated features such as gullies, steep slopes, and cliff edges.

(c) Petrography

The carbonate sediments are generally coarse sands and gravels, often with a 1-2% mud (<63 m fraction) content. In the bathymetric depressions and basins they merge into very muddy, dominantly terrigenous sands.

The carbonates are rich in barnacles (45%) while bivalves (29%) are the other major component (Fig. 28b). The ratio of bivalves: barnacles increases as the sediment becomes more muddy and less calcareous (CDSS 2). The Maturity Index is moderate (10.70) reflecting the considerable amount of oscillatory current activity to which it has been subjected. The Maturity Index is higher than that of the local, high-carbonate sediments.

(3) Hawes Bank (CDSS No. 3)

(a) Geography and dynamics

This major shoal lies 10 km to the north of Coll, on the eastern flank of the Sea of Hebrides-Minch Trough. Surface tidal currents across it are apparently not strong (Fig. 29). The Bank is extremely exposed to westerly and southwesterly seas and it also faces a considerable fetch to the north. Storm-wave currents are therefore dominant over tidal currents.

(b) Extent, bedforms and thickness

The Bank is a very rocky feature with carbonates lying on its southeastern flank and in gullies on the northern slope. The sediment cover at the southeast is uniform and megaripples, or possibly small sandwaves, can be seen on some side-scan sonar records.

Thicknesses are unclear, but not likely to exceed 1 m. One gravity core showed the deposit to be very thin (<10 cm) in places and lying on rock. A likely average is 0.1 m.

Pisces dives made on the northern slope of Hawes Bank (Eden et al. 1971 and Fig.29a) located rock gullies containing coarse shell sand with megaripples. These had amplitudes of 0.5m and wavelengths of 1m, but their orientations were not recorded.

CARBONATE DEPOSIT SUMMARY SHEET NO.3

NAME Hawes Bank

LOCATION Northeast of Coll
POSITION (approx); LAT. 56° 42'N LONG. 6° 45'W
WATER DEPTH(m) 40-60m AVE. SAMPLE DEPTH(m) 58m
BATHYMETRY Large shoal
DISTANCE FROM LAND(km) 10-15 DISTANCE FROM SHELF EDGE(km) 140
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		20	40	?
1m above seabed	40 m water depth	10	20	
	60 m water depth	9	18	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	40 m water depth	10	70	100
	60 m water depth	4	50	75

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 39×10^6

	Max.	Min.	Likely
CaC03 CONTENT(%)	87	78	83
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	$39\text{x}10^6$	$.39\text{x}10^6$	$3.9\text{x}10^6$
TOTAL WEIGHT(g)	$29.3\text{x}10^{12}$	$.28\text{x}10^{12}$	$2.8\text{x}10^{12}$
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	125	1.18	12.1

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	41	23	4	4	22	2	1	1
AVE.% FOR SURROUNDING AREA	19	47	2	10	14	4	1	3

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	15%	85%	N	3.8	1.5	5.0	4.0	4.0	1.0	14.1
AVE. FOR SURROUNDING AREA	31%	64%	1%	3.3	1.2	3.6	2.8	2.2	1.0	10.25

NOTES

N means <1%

See Table 2 for textural scales.

(c) Petrography

Barnacle debris predominates (41%) over that of bivalves (23%) (Fig. 28c). Gastropods and serpulids are notable minor constituents. Sediments in the less calcareous sediments surrounding the deposit, however, are bivalve dominated, with barnacles as the second major component.

The average Maturity Index (14.1) is extremely high for the carbonate sediments and very high for the surrounding carbonate-rich sediments. Fragments show very high degrees of roundness, polish and staining, but very low amounts of boring.

(d) Overview

These characteristics are thought to reflect a high degree of particle movement in oscillatory currents which ultimately transported the carbonate debris, from their place of origin on and around the rocky bank, to its lee side on the east.

(4) Sound of Eigg (CDSS No. 4)

(a) Geography and dynamics

This is a rocky channel between the islands of Eigg and Muck, swept by fairly strong tides (Fig. 30b). Muck provides some shelter from southwesterly storm-waves (Fig. 30b), but the Sound is still liable to be influenced by waves from the south, west and the

CARBONATE DEPOSIT SUMMARY SHEET NO. 4

NAME Sound of Eigg

LOCATION Between the islands of Eigg and Muck
POSITION (approx); LAT. 56° 50'N LONG. 6° 10' W
WATER DEPTH(m) 20-50 **AVE. SAMPLE DEPTH(m)** 21
BATHYMETRY Shelf between Eigg and Muck
DISTANCE FROM LAND(km) 0-2½ **DISTANCE FROM SHELF EDGE(km)** 170
CURRENTS (cm/sec)

TIDAL:			**PN**	**PS**	**PNET**
Surface			75	150	-
1m above	20	m water depth	43	85	
seabed	50	m water depth	36	72	
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	20	m water depth	20	90	120 (where exposed)
	50	m water depth	8	60	80

NOTES

Parts of channel much more sheltered from waves.
Probably considerable wave refraction into the channel.

VOLUMETRICS
AREA OF DEPOSIT(m2)

	Max.	**Min.**	**Likely**
CaCO3 CONTENT(%)	92	87	90
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	9×10^6	0.09×10^6	$.9 \times 10^6$
TOTAL WEIGHT(g)	6×10^{12}	$.067 \times 10^{12}$	$.68 \times 10^{12}$
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	128	1.25	12.6

NOTES

PETROGRAPHY

Composition	**Barn**	**Biv**	**Ech**	**Gast**	**Serp**	**Bry**	**C.Alg**	**Foram**
AVE.% FOR DEPOSIT	43	32	3	6	6	2	6	1
AVE.% FOR SURROUNDING AREA	34	42	4	8	3	3	1	3

Texture	**Grv**	**Sand**	**Mud**	**GnSz**	**Sort**	**Rnd**	**Pol**	**Stain**	**Bor**	**M**
AVE. FOR DEPOSIT	31 %	64 %	5 %	3.5	1.0	3.0	2.0	3.0	1.0	9.75
AVE. FOR SURROUNDING AREA	24 %	63 %	12 %	3.2	1.2	2.3	2.1	1.9	1.2	8.45

NOTES

See Table 2 for textural scales

southwest by diffraction. A rocky shelf extends all round the islands, but with deep mud-filled basins a few kilometres away on its northwest and southwest sides (Fig. 30a & 7).

(b) Extent, bedforms and thickness

A small carbonate deposit lies in the channel. Gravity cores suggest that it is very thin but there are no geophysical data. Small sand waves were reported during an IGS sub-aqua dive off the Muck coast. The most likely average thickness is 0.1 m.

(c) Petrography

There is considerable petrographical variation from sample to sample and this (particularly the variation in mud content) indicates changeable physical conditions over space and, probably, time. The higher mud contents often occur at the greater depths (Appendix 9), illustrating the progressive weakening of wave and tidal currents in the deeper water inshore areas. Basinal areas thus act as traps for fine grained sediment.

The carbonates are derived predominantly from barnacles (43%) and bivalves (32%), with barnacles being most abundant (Fig. 28d). Calcareous alga debris (6%) is also present in significant proportions besides gastropod and serpulid material.

The Maturity Index (9.75) is low.

The carbonate-rich sediments adjoining the deposit have similar petrophysical properties except that they are muddy, and bivalve debris predominates over barnacle. The Maturity Index for these sediments is very low.

(d) Overview

The carbonate is probably derived locally from the rocky platforms around Eigg and Muck and carried into the Sound by strong wave and tidal currents. Storm-waves entering from both ends of the channel (probably simultaneously in the case of diffracted southwesterly swells) probably concentrate the sediment on the southwest side ofthe channel. The most sheltered spot is close inshore to Muck, where divers identified *Lithothamnium* debris.

(5) Sligachan-Scalpay (CDSS No. 5)

Carbonate sediments have been sampled off the northeast side of the island of Scalpay and at the entrance to Loch Sligachan. Although the nearby Sound of Raasay and Inner Sound are large deep mud-filled glacial basins, the carbonates lie on rocky ground. They are taken to be local, inshore deposits restricted to the narrow coastal platform. Their distribution is unclear, but a vibrocore taken at the mouth of Loch Sligachan proved a thickness of at least 3m (Fig.31).

Other such deposits occur along the Scottish coast (pp. 56-62) but they are often missed by the IGS because their survey vessels do not normally come so close inshore.

CARBONATE DEPOSIT SUMMARY SHEET NO. 5

NAME Sligachan-Scalpay

LOCATION NE side of Scalpay and entrance to Loch Sligachan (E. Skye)
POSITION (approx); LAT. 57° 20'N LONG. 6° 00' W
WATER DEPTH(m) 10-30 AVE. SAMPLE DEPTH(m)
BATHYMETRY Rocky coastal platform
DISTANCE FROM LAND(km) 0.1 DISTANCE FROM SHELF EDGE(km)
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		?37	75	-
1m above	m water depth	-	42	
seabed	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	30 m water depth	?75+	?30+	?40+
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2)

	Max.	Min.	Likely
CaCO3 CONTENT(%)	92	79	86
THICKNESS(m)	3+	.1	1
TOTAL VOLUME(m3)			
TOTAL WEIGHT(g)			
ACCUMULATION RATE (g/m2/yr over 6000 yrs)			

NOTES

Vibrocore revealed at least 3m carbonate
Insufficient data to delineate deposit

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT								
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

No petrographical data.

(6) Rubha Nan Clach (CDSS No. 6)

(a) Geography and dynamics

This deposit lies on the rocky, coastal platform running parallel to the southwest coast of Skye. It is subject to fairly low longshore tidal currents running SE and NW, and severe storm wave currents from the southwest (Fig. 32).

(b) Extent, bedforms and thicknesses

The thickness of the carbonate deposit lying on this platform is uncertain, there being no geophysical or core data for it. It is likely to be only a thin patchy cover of 0.1 m on average.

(c) Petrography

The deposit is dominantly barnacle debris (48%), with high proportions of bivalve and serpulid material (Fig. 28e). The Maturity Index (9.0) is low.

In the less calcareous sediments of the surrounding area bivalve contents increase and barnacles and serpulids decrease. The average Maturity Index (8.1) is lower.

(d) Overview

Wave and tidal currents, although roughly at right angles to

CARBONATE DEPOSIT SUMMARY SHEET NO. 6

NAME Rubha nan Clach

LOCATION West coast of Skye
POSITION (approx); LAT. 57°-16'N LONG. 6°-30'W
WATER DEPTH(m) 20-40 AVE. SAMPLE DEPTH(m) 50
BATHYMETRY Coastal platform
DISTANCE FROM LAND(km) 0.2 DISTANCE FROM SHELF EDGE(km) 160
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface					
1m above	30	m water depth	?75	50	-
seabed		m water depth	14+	28+	-
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	30	m water depth	70	90	120
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 26×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	76	85
THICKNESS(m)	1	0.01	0.1
TOTAL VOLUME(m3)	26×10^6	$.26 \times 10^6$	2.6×10^6
TOTAL WEIGHT(g)	20×10^{12}	.18	1.93
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	129	1.16	12.4

NOTES
Strongest wave currents & tidal currents roughly at right angles to each other.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	48	23	4	6	12	3	1	2
AVE.% FOR SURROUNDING AREA	40	35	5	4	4	6	1	3

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	21%	78%	1%	4.0	1.0	3.0	1.0	2.0	2.0	9.0
AVE. FOR SURROUNDING AREA	39%	58%	2%	3.1	1.5	2.2	1.7	1.3	1.3	8.1

NOTES

See Table 2 for textural scales.

each other, probably often combine to produce longshore drift towards the northeast. Sediment may be accumulating where this transport path is interrupted at the entrance to Loch Bracadale by tidal currents running NE-SW more nearly parallel to the major wave-currents (Fig. 32b).

(7) Shiant (CDSS Nos. 7&8)

(a) Geography and dynamics

This deposit is associated with the large rocky shoals surrounding the Shiant Islands, between the northern tip of Skye and the Outer Isles (Fig. 33a). The current pattern is shown in Figure 33b.

(b) Extent, bedforms and thickness

The deposit lies in the Minch, an area covered in detail by Bishop (1977) who originally worked up the IGS data. The raw material was not available for this study.

IGS sparker lines and some limited side-scan show that, although significant patches of bare rock occur in places, there is a fair sediment cover. Cores suggest that this is generally quite thin. At the southern end carbonate sand with 75% $CaCO_3$ was encountered, lying on at least 0.8 m of sand with 50% $CaCO_3$. South of the Shiant Islands, another core showed 0.1 m of sand lying on terrigenous mud, and several others indicated a very thin cover (<.1 m) overlying rock. At the very northern limit IGS Pisces dives revealed rockhead exposures, bouldery drift, muddy, shelly sands and some gravelly sand ribbons which were up to 0.5m thick (Eden et al 1973).

In the northeastern part poor quality sparker profiles show that the superficial deposits thicken to a maximum of 4 0 m. They form a sandbank-like feature, possibly with sandwaves on it. However, coverage and quality of the records do not allow adequate investigation of it. The body could be largely morainic, like that found by Pisces to the northeast. On the other hand, the Quaternary is reported to be less than 10 m in this area (Bishop 1977). With such high carbonate contents in the surface sediment of the area (>90%), it is possible that the bank represents an appreciable accumulation of carbonate. For this reason its volumetrics are treated separately (CDSS No. 8).

(c) Petrography

Bishop (1977) describes the calcareous material as comprising bivalve, echinoderm and gastropod fragments, but there is no mention of barnacle debris. This is probably a recognition problem, but it may also signify a smaller proportion of barnacles than in most deposits of Inner Hebrides. This would relate to the lower proportion of rock:sediment cover than elsewhere, the lack of very shallow rocky seabed, and the lower degree of wave current activity.

(d) Overview

Carbonate sediment is accumulating on a large bathymetric high near the Shiant Isles, where terrigenous sediment supply is low.

CARBONATE DEPOSIT SUMMARY SHEET NO. 7

NAME Shiant

LOCATION Between Skye and North Harris
POSITION (approx); LAT. 57° 50'N LONG. 6° 20' W
WATER DEPTH(m) 0-100 AVE. SAMPLE DEPTH(m) 84
BATHYMETRY Large shoal with deep trough to NW and shelf SE towards Skye.
DISTANCE FROM LAND(km) 2.15 DISTANCE FROM SHELF EDGE(km) 230 to N
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET	
Surface			150		Locally
1m above seabed	50 m water depth		72		
	m water depth				
WAVE:	exceedance	50%	1%	.1%	
Nr. seabed	50 m water depth	2	40	60	
	m water depth				

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 508 x 10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	94	75	84
THICKNESS(m)	1	.01	.5
TOTAL VOLUME(m3)	508 x 10^6	5.08 x 10^6	50.8 x 10^6
TOTAL WEIGHT(g)	394 x 10^{12}	3.50 x 10^{12}	37.8 x 10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	129	1.15	17.4

NOTES

Possible sandbank in the area -see CDSS No,8 for "Southwest Shiant Sandbank".

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	?	✓	✓	✓				
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	26%	70%	4%	3	1.5					
AVE. FOR SURROUNDING AREA										

NOTES Data mainly from Bishop and Jones (1979)

See Table 2 for textural scales.

CARBONATE DEPOSIT SUMMARY SHEET NO. 8

NAME Southeast Shiant Sandbank

LOCATION SE of the Shiant Isles and NW of Eilean Troddey
POSITION (approx); LAT. 57° 48 N LONG. 6° 15W
WATER DEPTH(m) 30-70 AVE. SAMPLE DEPTH(m)
BATHYMETRY Ill-defined bank formed by superficial sediment.
DISTANCE FROM LAND(km) 12 DISTANCE FROM SHELF EDGE(km) 230 to N
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		-	150	-
1m above seabed	30 m water depth		79	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	30 m water depth	10	50	75
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 7.8×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	94	85	92
THICKNESS(m)	40	1	10
TOTAL VOLUME(m3)	312×10^6	7.8×10^6	78×10^6
TOTAL WEIGHT(g)	242×10^{12}	5.8×10^{12}	59.9×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	5171	124	1280

NOTES

$CaCO_3$ content inferred from nearby samples. Geophysics does not define size and shape of bank properly. Internal composition of the feature is very uncertain.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE. % FOR DEPOSIT								
AVE. % FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

See "Shiant" CDSS No. 7

Carbonate production, on the other hand, is high because of the existence of extensive areas of current-swept rocky seabed.

(8) Other coastal deposits

Underwater accumulations of carbonate sediment are known to occur at several locations along the Scottish west coast. Unfortunately inshore areas, within 1-2 km of the coastline were often not sampled by IGS. Small patches of pure shell sand can often be seen in the nearshore sublittoral zone off rocky coasts (eg. Rhu Coigach, Point of Stoer).

(a) Mull

Patches of shell sand occur on the rocky platform along the west coast of Mull (Bowes and Smith 1969), most extensively in the Sound of Iona off the Ross of Mull (Fig. 34 and CDSS No. 9). This deposit has been studied in detail by Cucci (1979) and Farrow et al. (1978).

The Sound of Iona has fairly strong surface tidal currents and is prone to a southwesterly fetch of 124 km which can generate strong oscillatory bottom currents in the shallow water. It also experiences considerable diffraction effects from the larger, more westerly storm waves. To the north the fetch is small and waves from this direction have little effect because of the damping action of shoals at the northern end.

The deposit is up to 2 m thick over parts of the central shoals where small sandwaves are developed, and it probably has an average

CARBONATE DEPOSIT SUMMARY SHEET NO.9

NAME Sound of Iona

LOCATION Off the Ross of Mull
POSITION (approx); LAT. 56° 20' LONG. 6° 25' W
WATER DEPTH(m) 1-12 m AVE. SAMPLE DEPTH(m)
BATHYMETRY Tidal Channel
DISTANCE FROM LAND(km) DISTANCE FROM SHELF EDGE(km)
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		$\sim$100		
1m above	m water depth			
seabed	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	m water depth			
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 20 x 10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	80
THICKNESS(m)	1	.1	.5
TOTAL VOLUME(m3)	20 x 10^6	2 x 10^6	10 x 10^6
TOTAL WEIGHT(g)	15.5 x 10^{12}	1.4 x 10^{12}	7.1 x 10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	129	11.6	59

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	77	12	3	N		N	1	N
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

From Cucci (1979)

N means <1%

thickness of 0.5m. It lies over glacial drift which appears to have produced a substrate, morphology and hydraulic regime which strongly influenced the biogenic sedimentation. Thus, whereas shell sand is accumulating under the influence of the tidal and wave currents, colonies of calcareous algae are growing and contributing to the sediment at the north end where protected from wave action. The shell sand is dominated by barnacle and bivalve fragments except in the northern end where in places the *Phymatolithon calcareum* (often mistaken for *Lithothamnium*) debris (~30%) predominates.

Cucci concludes that the Iona sediments are mostly Recent and not relict, having been accumulating since the last glaciation. His rates of production and accumulation are therefore based on a period of 10,000 years. These are likely to be under-estimates if the present shorelines and water depths were not established until about 6,000 years ago (see p. 15).

(b) Skye

"Lithothamnium calcareum" sands are recorded from several bays on the west coast of Skye (Anderson and Dunham 1966). One colony grows in Loch Eishort on a submerged spit between a small island and the mainland (Fig. 34). Another occurs in Loch Dunvegan in a similar environment, between the Lampey Islands and the mainland. Several of the loch Dunvegan beaches are rich in calcareous algal debris (Haldane 1939). This is also found in an IGS sample from the entrance to the loch (Appendix 10, M270). Other occurrences are reported from Loch Bracadale.

(c) Plockton - Kyle of Lochalsh

"Lithothamnium" -rich carbonate sediments have been investigated by a company in this area off the mainland of Wester Ross (Fig. 34). The algae appear to be growing and their debris accumulating in the tidal channels between rocks and islets. The sediments contain 5%-50% algal debris, the rest being mixed shell fragments. An area of 0.4×10^6 m^2 was investigated and patches of sediment up to 100 m^2 in size were noted. However the extent of the deposit was not properly assessed, nor was thickness, though considered likely to be "many feet".

(d) Loch Broom

Bowes and Smith (1969) found shell sand in the approaches to Loch Broom (Fig. 34) lying on the rocky shelf which runs from the Summer Isles to Greenstone Point, Bishop (1977) also recognised a small area of carbonate off Rubha Re and Handa Island. They pointed out that exposure to the open sea probably provided suitable conditions for comminution, sorting, and accumulation. Smaller muddy patches of shell sand were located further inshore, one patch off Gruinard Island containing *"Lithothamnium"* debris (Fig. 34). Wilson (1979a)mentions the presence of *Lithothamnium* at the Summer Isles (also Moidart, further south on the mainland).

(e) Significance of calgareous algae

Virtually all the locations mentioned above are sites where calcareous algae are present. This may be significant in two ways: (a) the species of calcareous algae on the SCS show a strong preference for habitats close inshore, (b) the presence of calcareous algae may render the sediment more striking in human terms, causing danger of overemphasis. Quite probably there are many other small inshore deposits of shell sand which are not listed here.

(9) Carbonate-rich (50-75% $CaCO_3$) sediments

(a) Introduction

Some of the deposits in the Inner Hebrides area have very distinct boundaries with very sudden drop-offs in carbonate content to less than 50% (eg. Hawes Bank). Others are surrounded by large areas where the $CaCO_3$ content is 50-75% $CaCO_3$. There are also some sharply discrete bodies of carbonate-rich sediment.

(b) Blackstones Bank to N tip of Rhum

These border the Passage of Tiree and Sound of Eigg deposits (pp.39&45). Blackstones Bank (Fig. 35) is a rocky shoal 25-50m deep exposed to severe wave action. Several Pisces dives by the IGS (Eden et al. 1971 and Eden et al. 1973) revealed thin patches of shell sand lying on lithic gravels and rock. Superimposed megaripples with heights of 0.2m and wavelengths of 2m were noted striking NW-SE. The carbonate-rich sediment (62% $CaCO_3$) is dominantly bivalve debris, and has a very high Maturity Index (12.75) due to high degrees of sorting, roundness, polish and staining. This is attributed to prolonged current agitation aided by the abrasive effect of the substantial proportion of lithic fragments (38%).

Apart from Blackstones Bank, the carbonate-rich sediments in the rest of this area were summarised with the carbonate deposits which they surround (pp. 39 - 48). They have a substantial lithic sand or gravel content and are often very muddy.

(c) Shiant Isles

This surrounds the Shiant carbonate deposit (Fig. 35). The southern part comprises clean sands and gravels, but northeastwards they become extremely muddy (Fig. 7).

(d) Colonsay

On the west side of the island, at the very limit of the study area, carbonate-rich sediments appear to be forming on the wave-swept rocky platform.

(e) Iona Spit

West of the Ross of Mull (Fig. 35) is a rocky bank, subject to severe storm waves and moderate tidal currents (75 cm/sec). Rock is exposed in places. Small sandwaves or megaripples indicating mobile sediment are also visible on the sonar records. The sediment is mainly barnacle debris, with subordinate bivalve and echinoid fragments (Table 3). The high Maturity Index (11.25) results from high degrees of roundness, polish and staining which reflect the currents of the area.

(f) Headlands: An Ceanich, N Rhum and Rhu Coigach

Carbonate-rich sediments also occur off these headlands (Fig. 35). The seabed is rocky, relatively shallow and subject to particularly strong tidal currents.

(g) Sea of Hebrides - Minch Trough

The carbonate-rich sediment in this area (Fig. 35) is interesting because it is very muddy, lies in deep water and is associated with no obvious positive bathymetric feature. The mud itself is highly calcareous (30-66% $CaCO_2$).

The anomaly lies beyond the base of a steep slope descending from the Skye-Rhum platform where carbonates and carbonate-rich sediments are abundant. IGS Pisces dives on this and similar slopes revealed shelly debris which appeared to have spilled down them. Possibly calcareous debris has been funnelled down into deep water in this way. On the other hand it could conceivably have been produced by unusually high infaunal productivity, although this seems less likely.

(10) Beaches

The distribution of beaches containing high-carbonate (50-100% $CaCO_3$) sediment is shown in Fig. 35. Three on Colonsay face due west into the Atlantic and lie adjacent to the rocky carbonate-rich area offshore (p. 61). On Mull one faces the

Sound of Iona, and two others face west and northwest towards the rocky platform harbouring the carbonates and carbonate-rich sediments in the Passage of Tiree. On Tiree itself all sixteen beaches have high carbonate contents. The island is surrounded by a rocky platform, with carbonates and carbonate-rich sediment lying to the west and south (p.39&60). Almost the entire coastline is susceptible to oceanic stormwaves from the northwest, west and southwest and there is also a considerable fetch to the north and south (Fig. 29b).

On Coll the high-carbonate beaches generally face northwards towards the Hawes Bank deposit (p. 43). They are liable to ocean storm waves from the west-northwest as well as local storm waves from the north. There is a complete absence of sandy beaches on the south side of Coll except at the southwestern end. This is due to a steep-sided deep glacial basin lying immediately offshore, which prevents the onshore transport of sands, calcareous or otherwise.

All three western-most beaches on Ardnamurchan have high-carbonate sands. These face northwards and westwards towards the Passage of Tiree and Sound of Eigg where there are carbonates and associated carbonate-rich sediments. This part of the coast is very prone to storm waves from the northwest, west and southwest (Fig. 29).

The beach on the north side of Muck (Fig. 35) faces directly onto the Sound of Eigg carbonate deposit.

On Skye, 'Coral Beach' in Loch Dunvegan (Fig. 34) is associated with the calcareous algal colony which is growing in the vicinity (p. 58).

The two beaches on Greenstone Point (Fig. 35) face northwestwards towards the rocky platform running across the approaches to Loch Broom. This is known to have carbonates lying on it (p. 59).

(11) Summation

Carbonate sediments (>75% $CaCO_3$) and carbonate-rich sediments (50-75% $CaCO_3$) are common around the Inner Hebrides. Their distribution and characteristics are variable, reflecting the complex interplay of the extremely changeable physical conditions which produced and modified them.

Locations of beaches with high-carbonate sediments (50-100% $CaCO_3$) correspond closely with those of the offshore carbonates and carbonate-rich sediments.

Average petrographical properties are shown in Table 4. Barnacle and bivalve debris predominate (Fig. 36a), generally ranging from 20-60%. Echinoid, gastropod, serpulid and bryozoan fragments each normally amount to 1-10%. Higher proportions of barnacles are present in carbonate sediments compared with carbonate-rich sediments. Calcareous algae occur rarely, and foraminifera are generally minor. Maturity Indices are moderate to very high in the carbonate deposits and lower in the surrounding less calcareous sediments. Higher proportions of barnacles occur in the deposits compared with the other sediments around them.

Despite the complexity of the processes involved a broad understanding of the sedimentology of the deposits can be gained. These will be discussed more fully in Chapters 4 and 5.

III HEBRIDEAN SHELF

(1) Stanton Banks (CDSS No. 10)

(a) Geography and dynamics

These banks are extensive rocky shoals, far out on the shelf west of Colonsay. They form the southern limits of outcropping Lewisian metamorphics (Fig. 5). Surface tidal currents are fairly low, but bottom currents may be quite strong over this bathymetric high (Fig. 37b). The Banks are exposed to ocean storm-waves from between north and southwest, and there is also a substantial fetch to the northeast, east and southeast (Fig. 37b). Being only 60 km from the shelf edge, wave attenuation is low and maximum wave heights are 30 m (Fig. 12). As a result the bottom currents are dominated by stormwaves.

(b) Extent, bedforms and thickness

The carbonate deposit lies across the top of the bank much of which is at depths of around 90 m, thought to be a significant erosion level (Eden et al. 1971). Local rocky peaks reach up to depths of 32 m (Fig. 38). An apron of carbonate-rich sediment spreads out down the eastern flank of the Banks.
Two IGS Pisces dives (Eden et al. 1971) revealed a heavily glaciated rocky feature with numerous gullies and hollows. These contained coarse shell sand and were fringed by aprons of cobbles and boulders (Fig. 39). Rock surfaces were heavily encrusted by calcareous

CARBONATE DEPOSIT SUMMARY SHEET NO.10

NAME Stanton Banks

LOCATION On the outer shelf west of Colonsay & Blackstones Bank
POSITION (approx); LAT. 56° 10'N LONG. 7° 52'W
WATER DEPTH(m) 32-140 AVE. SAMPLE DEPTH(m) 137
BATHYMETRY Large deep-water shoal
DISTANCE FROM LAND(km) 100 DISTANCE FROM SHELF EDGE(km) 60
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		30	50	38%
1m above seabed	40 m water depth	15	25	
	130 m water depth	12	20	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	40 m water depth	15	90	110
	130 m water depth	0	25	40

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 172×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	93	83	88
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	172×10^6	1.72×10^6	17.2×10^6
TOTAL WEIGHT(g)	133×10^{12}	1.25×10^{12}	12.9×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	129	1.2	12.5

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	4	33	5	6	36	14	0	2
AVE.% FOR SURROUNDING AREA	10	50	5	2	21	9	0	2

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	9%	91%	0%	4.0	1.5	4.3	3.0	3.0	2.0	12.8
AVE. FOR SURROUNDING AREA	1%	95%	4%	3.5	1.0	4.0	3.0	2.0	1.0	10.25

NOTES

Surrounding area - 1 sample only
See Table 2 for textural scales

organisms.

In the gullies symmetrical ripples were observed on the shell sand with heights of 0.1-0.15m and wavelengths of 0.75m, and crestlines striking at right angles to the gully directions. On more open ground 'starved' symmetrical ripples of shell sand overlay lithic gravels and cobbles (Fig. 40). They had heights 0.2-0.3 m, wavelengths of about 1 m and NE-SW strikes. The carbonate sediment is very thin, probably averaging about 0.1 m in thickness (CDSS No. 10).

(c) Petrography

The carbonate contains abundant serpulid (36%) and bivalve (33%) fragments, but is low in barnacle debris. Bryozoa are also very common (Fig. 41a). The Maturity Index (12.80) is very high. In comparison the surrounding less calcareous sediment has less serpulid material, and has a lower Maturity Index (10.75).

Much of the deposit is probably derived from organisms growing on the rocky outcrop of the bank. The Pisces dives noted the extreme clarity of the water, helping to account for the abundance of encrusting organisms at such considerable depths. The Maturity Index reflects the high degree of wave-current activity to which the sediment has been subjected. A significant difference from Blackstones Bank, to the east, is the absence of lithic sand and gravel. This was also noted by Eden et al (1971).

(d) Overview

The carbonate is probably accumulating on the eastern side of the bank, where currents decrease in rapidly deepening water. Some dispersion of calcareous debris out over the apron of carbonate rich sediment may occur, but the considerably lower Maturity Index suggests this is probably not on a large scale.

(2) Barra Head (CDSS No. 11)

(a) Geography and dynamics

The Barra Head deposit fringes the smaller islands at the southern tip of the Outer Hebrides, south of Barra Island (Fig. 37a). The ground is a rocky shoal, gently shelving on the west but dropping sharply along this eastern edge into the deepest part of the Sea of Hebrides-Minch Trough. The shoal is exposed to moderate tidal currents and extremely strong wave-currents, particularly on its west (Fig. 37b). A textural analysis of sediment on the west side of Barra Head (Ferentinos 1976) indicated that bathymetric highs were erosional, and lows depositional.

(b) Extent, bedforms and thickness

The deposit is probably a continuation of that on the West Hebridean Platform (pp. 72-76) but is treated separately because more is known about it.

CARBONATE DEPOSIT SUMMARY SHEET NO. 11

NAME Barra Head

LOCATION South of the Island of Barra
POSITION (approx); LAT. 56° 47'N LONG. 7° 38'W
WATER DEPTH(m) 40-100 **AVE. SAMPLE DEPTH(m)** 70
BATHYMETRY Shoal around the southern end of the Outer Hebrides
DISTANCE FROM LAND(km) 0-20 **DISTANCE FROM SHELF EDGE(km)** 80
CURRENTS (cm/sec)

TIDAL:		**PN**	**PS**	**PNET**
Surface		40	70	57%
1m above seabed	60 m water depth	18	32	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	60 m water depth	8	50	75
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 390×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	96	83	90
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	390×10^6	3.9×10^6	39×10^6
TOTAL WEIGHT(g)	305×10^{12}	2.8×10^{12}	30.0×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	131	1.21	12.8

NOTES

There may be large patches (eg. 3×10^6 m^2) which are over 0.1 m thick.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	15	34	4	5	9	25	2	6
AVE.% FOR SURROUNDING AREA	10	50	4	4	6	12	2	11

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	7%	92%	1%	3.0	1.8	3.6	3.6	0.9	0.2	9.09
AVE. FOR SURROUNDING AREA	11%	76%	13%	3.0	1.3	2.3	2.3	1.3	1.5	7.75

NOTES

See Table 2 for textural scales.

Pinger and side-scan records show large areas of bare rock (Lewisian) over much of the west and centre of the shoal, with extensive patches of sediment over 1 km across (Figs.42&43). Gravity core data confirm that rockhead is generally close to the surface.

Towards the eastern flank a more uniform cover of sediment coincides with a rapid drop-off in carbonate content and increase in mud. The transition is clearly seen on the side-scan records. Beyond the northeastern limit of the deposit a 25 m thick sandbank-like feature lies on a local seabed high. Sample data in the vicinity of this, but not actually on it, suggest the carbonate content is low.

Pisces dives, immediately beyond the eastern boundary of the deposit (Eden et al. 1971, Eden et al. 1973) proved shelly muddy lithic sands draped over, and burying, glaciated rock surfaces.

The average thickness of the deposit is taken as 0.1 m, although there are probably quite large areas (eg. 3 x 10^6 m^2) where it is at least 1 m.

(c) Petrography

The sediment mainly comprises bivalves (34%) and bryozoan (25%) debris, with substantial contributions from barnacles and serpulids (Fig. 41b). It is well rounded, well polished and moderately sorted, giving only a low Maturity Index. The lack of staining, compared with many other Hebridean deposits, is notable. Surrounding less calcareous sediments on the eastern side are muddy and yield a very low Maturity Index (7.75). They contain more bivalve material and a substantial foraminiferal fraction.

(d) Overview

Production and accumulation of the biogenic debris is thought to be taking place both *in situ* and on the platform to the west. Eastward migration to the Barra Head area is likely, although northward, longshore transport on the western flank may also occur (p. 75).

(3) West Hebridean Platform (CDSS No. 12)

(a) Geography and dynamics

The platform is a large glaciated area extending up to 50 km westwards from the Outer Hebrides (Fig. 44a). It is subject to extremely vigorous wave currents set up by ocean stormwaves from all directions between south, west and north (Fig. 44b). Tidal currents are only moderate.

(b) Extent, bedforms and thicknesses

The area has not been properly surveyed. However, localised detailed observations (underwater TV, echosounder, grab sampling) have indicated its general nature.

Sampling off South Uist and Barra (largely ineffective) along with

CARBONATE DEPOSIT SUMMARY SHEET NO. 12

NAME West Hebridean Platform

LOCATION West of the Outer Hebrides
POSITION (approx); LAT. 57° 30'N LONG. 7° 30'W
WATER DEPTH(m) 20-100 AVE. SAMPLE DEPTH(m) 30-80
BATHYMETRY Shelving, hummocky platform
DISTANCE FROM LAND(km) 0-50 DISTANCE FROM SHELF EDGE(km) 60-80
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		10-25	20-45	46%
1m above	40 m water depth	12	22	
seabed	80 m water depth	5	10	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	40 m water depth	10	75	100
	80 m water depth	5		50

NOTES

VOLUMETRICS

AREA OF DEPOSIT(m2) Limits not known. ? $5,000 \times 10^6$

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	91	80	87
THICKNESS(m)	5	.01	.1
TOTAL VOLUME(m3)		50×10^6	
TOTAL WEIGHT(g)		34×10^{12}	
ACCUMULATION RATE (g/m2/yr over 6000 yrs)		1.15	

NOTES

Minimum case only calculated due to high degree of uncertainty.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR W OF SND OF HARRIS	13	25	13	11	23	12	1	N
AVE.% FOR REST OF AREA	6	39	10	8	13	19	1	2

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR W OF SND OF HARRIS	25%	75%	0%	3.7	1.4	4	3.2	0.8	0.8	9.3
AVE. FOR REST OF AREA	36%	64%	0%	3.7	1.0	4.3	2.7	2.3	2.3	9.9

NOTES

See Table 2 for textural scales.

echosounder profiles shows a hummocky topography with large areas of bare rock, boulder-fields and small thin patches of shell sand. A dead fragment of the ahermotypic colonial coral *Lophelia pertusa* was collected in one sample (SC 18).

Further north, off the Sound of Harris, South Harris and North Uist, echosounder profiles show large pockets of sediment with sandwaves so that thicknesses possibly reach 5 m or more. Observations and photographs by divers working in this area also confirm thick, coarse, highly mobile shell shellsand in places. A hierarchy of steep irregular ripples and megaripples can be seen (Pickin pers. comm.).

The seabed here also has a hummocky, rocky topography, commonly with a thick bouldery cover. Most rock and larger-boulder surfaces are heavily encrusted with bryozoa, barnacles and serpulids. The smaller boulders are much less so, possibly because they are moved around by the most vigorous wave currents (pp. 217-218). Further north still, off the north coast of Lewis, the seabed is comparatively flat and made up of lithic gravel and cobbles with only thin patches of shell sand.

It is difficult to define the limits of the deposit, but the following observations are useful:

(*i*) Sampling and profiling around St. Kilda (60 km to the west) revealed no sandy sediment, let alone carbonate. The sea floor was rocky and bouldery.

(*ii*) While flying from Stornaway to a location in the Northern Rockall Trough (Fig. 44a), I was able to recognise, even in water depths of over 60 m, large patches of rock and white sediment (almost certainly shell sand), showing through the clear Atlantic waters in bright sunlight.

The whole of the 100 m platform (excluding the Flannan Deep) therefore probably has a similar character to the more specific areas described here.

(c) Petrography

The sediments taken from west of the Sound of Harris are very pure shell sands and gravels dominated by bivalves (35%) and serpulids (23%), but with substantial proportions of gastropod, echinoid and bryozoan fragments (Fig. 41c). The Maturity Index is low. (9.3), the grains having high roundness and high polish, almost certainly reflecting continual agitation by oscillatory currents.

(d) Overview

A strong onshore transport path probably leads to the beaches from the platform which is an enormous area of carbonate production. With coastal tidal currents, and stormwaves predominantly from the southwest, there is probably a northwards longshore component. However the Sound of Harris (p. 74) is a major east-west tidal

channel which may block this, causing the more substantial accumulations of carbonate noted in this area.
Longshore transport along the Lewis coast has been suggested by Bishop 1977) and is discussed further below.

(4) Butt of Lewis (CDSS No. 13)

(a) Geography and dynamics

The deposit in this area lies on the rocky uneven shelving platform beyond the northern tip of Lewis. It marks the northern limit of the West Hebridean Platform (Fig. 45a). Tidal currents are strong (a characteristic of offshore headlands) and subject to oceanic storm swells from between the southwest and northeast. The platform is also susceptible to local stormwaves from the east and southeast.

(b) Extent, bedforms and thickness

There is little geophysical data or core data suitable for properly assessing the thickness of the carbonate sediment. Grab sampling and echosounding suggest that the seabed is rocky and hummocky with patches of sediment, possibly several metres thick but no distinctive bedforms have been recognised. An average of 0.1 m is assumed. In the marginal zone, the carbonate-rich sediments are more widespread and uniform and probably average at least 1 m thick.

CARBONATE DEPOSIT SUMMARY SHEET NO.13

NAME Butt of Lewis

LOCATION N of northern tip of Outer Hebrides
POSITION (approx); LAT. 58° 33' N LONG. 6° 08'W
WATER DEPTH(m) 40-100 AVE. SAMPLE DEPTH(m) 64
BATHYMETRY Shelving platform
DISTANCE FROM LAND(km) 2-15 DISTANCE FROM SHELF EDGE(km) 80
CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface		25	45	39%
1m above seabed	60 m water depth	12	21	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	60 m water depth	8	50	75
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 66×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	90	80	87
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	$66x10^6$	$.66x10^6$	$6.6x10^6$
TOTAL WEIGHT(g)	$50.1x10^{12}$	$.47x10^{12}$	$4.8x10^{12}$
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	128	1.19	12.1

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	10	41	7	7	8	21	0	5
AVE.% FOR SURROUNDING AREA	8	58	6	5	3	15	0	6

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	6%	94%	N	2.9	1.8	3.5	3.6	1.0	0.2	9.35
AVE. FOR SURROUNDING AREA	3%	96%	N	2.4	2.1	2.5	3.5	2.1	0.1	9.85

NOTES

N means <1%

See Table 2 for textural scales.

(c) Petrography

The sand is rich in bivalve (41%) and bryozoan (21%) fragments, and barnacle, echinoid, gastropod, serpulid and foraminiferal debris are all present in substantial proportions (Fig. 41d). The composition of the surrounding carbonate-rich sediment is similar. Both have low Maturity Indices (9.35 and 9.85 respectively) the bioclasts being totally unbored and only slightly stained. They are also fine-grained, moderately well sorted and moderately rounded, differing significantly from many of the other offshore carbonate sediments on the northern and western SCS. However they are quite similar to many of the carbonate beach deposits, which are considered to lie at the end of marine transport paths (pp. 81 and 218).

(d) Overview

Bishop and Jones (1979) suggested that the tail of calcareous sediment extending down the east coast of Lewis to Broad Bay lies at the end of a longshore transport path which passes around the Butt of Lewis from the West Hebridean Platform. They present tidal current patterns supporting this idea. It is also clear that the dominant ocean wave pattern will enhance this because stormwaves from the southwest and west influence the west side and those from the north and northeast reach the east side (Fig. 45b). However the present work has shown that the carbonate contents on the east side are not as high as Bishop and Jones suggested (60-70% rather than 75-90%), and that some of this carbonate will have been

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derived from local production sites associated with the Butt of Lewis deposit. Although the carbonates in this deposit have a slightly lower Maturity Index, they are only marginally coarser and less well sorted, indicating that some of the sediment may not be being produced in the immediate vicinity. Most probably it reaches the Butt from the platform to the west and southwest, some moving further round to the east coast.

(5) Other deposits

(a) Sound of Taransay

Carbonate sediments are reported from this [illegible] nel on the west coast of the Outer Hebrides, a tidally swept channel lying between the islands of Taransay and Harris (Lees pers. comm.; Fig.44a).

(b) Barra

Traigh Mor, is an east-facing bay at the north end of Barra (Fig. 46 and Farrow 1974, & Farrow et al. 1978). The sediments are intertidal, dominantly *Cardium* shell banks. Farrow interprets them as transgressive features but the problem is complicated by an adjacent Atlantic-facing beach system which feeds carbonate debris eastwards into the bay (see also p. 81).

(c) Mingulay

A very different form of carbonate deposit has been recorded on a ridge 13.5 km west of Mingulay (Fig. 46) where an IGS Pisces dive found a considerable growth of dead and living *Lophelia prolifera* (Eden et al. 1971).

(6) Carbonate-rich Areas

(a) Stanton Banks and Barra Head

Carbonate-rich sediments bordering the deposits of Stanton Banks and Barra Head have been discussed previously (p. 68 and p. 72).

(b) Hebridean Slope

Carbonate-rich sediment lies at the top of the continental slope itself (Fig. 46), in water depths of over 100 m. Maximum wave currents probably exceed 50 cm/sec and along-slope and upslope tidal and oceanic currents can be up to 100 cm/sec (p. 95 - Northern Slope).

The sediment is rich in bivalves (37%), bryozoa (19%) and the free-living calcareous worm *Ditrupa* (22%) (Table 3 and Wilson 1979a and 1982). Echinoid fragments and foraminifera also make a significant contribution. The sediment has a moderate Maturity Index (11.00) due to moderate roundness, sorting and boring. Such a combination is unusual and might suggest that the sediment is at least, in part, quite old (say, pre-6000 yrs. BP). This would be consistent with the fact that the seabed at these depths has never been subaerially exposed or affected by ice, leaving carbonate accumulation uninterupted for a much longer period than on the shelf. ^{14}C dating experiments support this (Wilson 1982).

(7) Beaches

The beaches of the Outer Hebrides (Figs. 46&47) are renowned for their vast calcareous dunes and machairs (Ritchie 1971 and Ritchie and Mather 1970).

Fifteen out of thirty of the west-facing beaches have high-carbonate sediment (>50% $CaCO_3$). They are seen as the landward depositional sites of much of the West Hebridean Platform production. There is some controversy as to whether sediment is still accumulating on them or being eroded from them (Richie pers. comm., see also p. 249 for further discussion).

East-facing sandy beaches are few because immediately offshore the seabed plunges across the Minch Fault into very deep water. Their sediments are high-carbonate. That at Traigh Mhor faces into the Sound of Barra where, as seen (p. 79), there is a transgressive shellbank. The beaches on the northeast coast of Lewis face the carbonate-rich sediments of Broad Bay and the Butt of Lewis (p. 76).

Extremely large volumes of carbonate are locked up in the beaches and machair and these are assessed later (p. 253).

(8) Summation

Carbonate sediments forming on the Hebridean Shelf are being generated by organisms (particularly encrusting types) growing on the wave-swept Lewisian rock platforms of the Outer Hebrides and Stanton Banks. The dominant components are fragments of bivalves but serpulid, bryozoan and barnacle debris are normally also major constituents (Table 4, & Fig. 36b).

Some of the carbonate generated on the West Hebridean platform may accumulate locally in small patches. Much probably migrates westwards and northwards to depositional sites around Barra Head, the Butt of Lewis, outside the Sound of Harris, and on large beach systems along the Outer Hebrides. That generated on Stanton Banks is accumulating largely along their sheltered eastern flank, with some being dispersed into the surrounding terrigenous sediment.

The results presented here are compatible with those of Wilson (1979a) who carried out much sampling and biological analysis over this part of the outer SCS.

IV NORTHERN SHELF

(1) Cape Wrath (CDSS No. 14)

(a) Geography and Dynamics

This band of carbonate sediment lies off the north and west coasts of the most northwestern headland of the Scottish mainland (Fig. 48a). The seabed is rocky and swept by strong and complex tidal currents (Fig. 48b).

Strong eddies occur around the headland, so that along the north coast a west-going eddy occurs close inshore during the main east-going stream. Similarly there is a north going eddy along the west coast when the main south-going stream is flowing further offshore.

The district is subjected to storm swells from between the west and northeast. The southern part of the deposit experiences frequent local storm-waves from the southwest, and the northern part, local storm waves from the east (Fig. 48b).

(b) Extent, bedforms and thicknesses

An echosounder line (Fig.49) around the Cape shows a zone of large sandwaves and sandbanks corresponding with the location of the deposit. A few of these are asymmetrical, some facing east and some west. Their heights range from 3 to 30m. Much of the seabed around Cape Wrath is very rocky and sample data are limited, but it seems probable that the

CARBONATE DEPOSIT SUMMARY SHEET NO14

NAME Cape Wrath

LOCATION SW and NE of the NW top of the Scottish mainland
POSITION (approx); LAT. 58° 38'N LONG. 5° 01'W
WATER DEPTH(m) 40-75 AVE. SAMPLE DEPTH(m) 70
BATHYMETRY Shelving platform
DISTANCE FROM LAND(km) 5 DISTANCE FROM SHELF EDGE(km) 130
CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface		75	150	55%
1m above seabed	60 m water depth	35	69	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	60 m water depth	8	50	75
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 138×10^{6}

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	88	75	86
THICKNESS(m)	3	.1	1
TOTAL VOLUME(m3)	414×10^{6}	13.8×10^{6}	138×10^{6}
TOTAL WEIGHT(g)	311×10^{12}	9.5×10^{12}	102.7×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	375.6	11.5	123.2

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	27	40	5	5	9	7	1	6
AVE.% FOR SURROUNDING AREA	11	53	7	14	10	8	2	7

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	$\bar{M}$
AVE. FOR DEPOSIT	15%	85%	N	3.8	1.3	3.7	2.7	1.7	0.7	9.35
AVE. FOR SURROUNDING AREA	19%	81%	N	3.6	1.4	3.8	2.7	1.9	1.1	10.25

NOTES

N means <1%

See Table 2 for textural scales.

deposit is separated into two parts: a southwest section and a northeast section. An average carbonate thickness of 1.0 m is assumed.

(c) Petrography

The dominant components are from bivalves (40%) and barnacles (27%) but echinoids, gastropods, serpulids and bryozoa all make significant contributions (Fig. 50a). The surrounding carbonate-rich sediment has less barnacle and more gastropod and bivalve debris. The Maturity Index of the carbonate sediment (9.35) is considerably Lower than for the less calcareous sediment in the surrounding area (10.25). This suggests dispersion from the former into the latter.

(d) Overview

Sediment transport is probably northwards off the west coast, then eastwards and possibly westwards to some extent. Supporting evidence comes from the distribution of carbonate in the beach sediments, with very low concentrations in Sandwood Bay and yet large accumulations at Faraid Head (p. 96).

(2) Nun Bank (CDSS No. 15)

(a) Geography and dynamics

North of Cape Wrath, a deposit lies on the southern end of Nun Bank, around Nun Rock and to the southeast side (Fig.51a). Although relatively smooth and mainly sediment covered, the bank is rocky and uneven at the south, where Lewisian is exposed. Tidal currents are

CARBONATE DEPOSIT SUMMARY SHEET NO.15

NAME Nun Bank

LOCATION Nun Rock - due N of Cape Wrath
POSITION (approx); LAT. 58° 53'N LONG. 4° 58'W
WATER DEPTH(m) 25-80 AVE. SAMPLE DEPTH(m) 70
BATHYMETRY Prominent shoal rising above sea level at Nun Rock
DISTANCE FROM LAND(km) 25 DISTANCE FROM SHELF EDGE(km) 110
CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface		40	75	?
1m above seabed	70 m water depth	18	34	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	70 m water depth	8	50	70
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 90×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	94	75	84
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	90×10^6	$.9\times10^6$	9×10^6
TOTAL WEIGHT(g)	69.8×10^{12}	$.619\times10^{12}$	6.7×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	129	1.15	12.4

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	13	34	10	4	16	17	0	5
AVE.% FOR SURROUNDING AREA	7	45	10	3	15	12	0	8

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	15%	84%	0%	3.9	1.6	3.9	2.9	0.4	0	2.90
AVE. FOR SURROUNDING AREA	11%	89%	0%	3.7	1.2	3.6	2.6	1.2	0.9	8.85

NOTES

See Table 2 for textural scales.

moderate and the area is exposed to ocean storm waves from between southwest and northeast. There is also a fair fetch for local storm waves from between the southwest and south and the northeast and east (Fig. 51b).

(b) Extent, bedforms and thicknesses

Little geophysical data is available for the deposit. Sampling and echosounder profiles suggest generally only a thin cover of sediment across a rocky seabed, with an average thickness of 0.1 m.

(c) Petrography

The average Maturity Index is moderate (10.85) even though the bioclasts are fairly well sorted and moderately rounded. The surrounding carbonate-rich sediment has a higher Maturity Index (12.75) because of more pronounced staining and boring. Bivalve debris (34%) predominates and fragments of barnacles, echinoids, serpulids and bryozoa are present (Fig. 50b). However the proportions of these constituents vary quite markedly over quite short distances (pp.154-158). Compared with the surrounding area of carbonate-rich sediment the deposit has less bivalve debris and more barnacle and bryozoan material.

(d) Overview

The site is one primarily of production with only local, transient pockets of carbonate which is dispersing eastwards over the shelf.

(3) Solan Bank (CDSS No. 16)

(a) Geography and dynamics

Lying on Solan Bank these carbonate sediments extend along the ridge towards the Sule Skerry Bank (Fig. 51a). Solan Bank is in an extremely exposed position and subject to very similar conditions to those at Nun Bank (p. 85). It is thus prone to ocean stormwaves from all directions between southwest, northwest and northeast and there are even substantial wave fetches in all other directions (Fig. 51b).

(b) Extent, bedforms and thicknesses

Small areas of Lewisian rock are exposed on the highest parts of the bank but the sediment cover is more complete away from there. Without geophysical or core information, thickness is unclear. It is likely to be small, with an average of about 0.1 m.

(c) Petrography

The sediment has a high content of bivalve (40%), serpulid (16%) and bryozoan (17%) material, but is low in barnacle debris (Fig. 50c). This is accounted for by the generally deep water and scarcity of rocky surfaces. The deposit has a moderate Maturity Index (10.85) with high degrees of sorting, roundness and polish, a high grain size value, and low degrees of staining and boring. Less calcareous sediments in the surrounding area have a very high Maturity Index (12.75) owing to their much greater degrees of staining and boring.

CARBONATE DEPOSIT SUMMARY SHEET NO. 16

NAME Solan Bank

LOCATION Due N of Cape Wrath and Nun Bank
POSITION (approx); LAT. 59° 05'N LONG. 4° 50'W
WATER DEPTH(m) 80-40 AVE. SAMPLE DEPTH(m) 78
BATHYMETRY Shoal
DISTANCE FROM LAND(km) 50 DISTANCE FROM SHELF EDGE(km) 85
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			40	75	?
1m above	70	m water depth	18	34	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	70	m water depth	8	50	70
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 216 x 10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	81	75	78
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	216×10^6	2.16×10^6	21.6×10^6
TOTAL WEIGHT(g)	155×10^{12}	1.4×10^{12}	15.4×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	120	1.15	11.9

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	6	40	9	8	16	17	0	2
AVE.% FOR SURROUNDING AREA	3	32	5	3	0	12	0	2

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	5%	95%	0%	4.2	2.3	4.5	3.3	.7	1.3	10.85
AVE. FOR SURROUNDING AREA	19%	81%	0%	3.5	1.0	2.5	1.0	4.0	4.0	12.75

NOTES

See Table 2 for textural scales.

(d) Overview

Carbonate is forming on the bank but some dispersion is probably taking place from the deposit to the surrounding area.

(4) Fair Isle Channel

(a) Geography and dynamics

The Fair Isle Channel is a huge tract of open shelf lying between Orkney and Shetland (Fig. 52a). Much of it is a gently undulating platform of outcropping Devonian sandstone. On the west it is bounded by a prominent ridge of Lewisian gneiss, with a steep western side (Figs.5&6). To the east (north and west of Fair Isle) there is a bathymetric low corresponding with outcropping Permo-Triassic formations.

The channel is swept by moderate tidal currents which locally become fairly strong (Fig. 52b). It is prone to ocean stormwaves from all directions between southwest, northwest and northeast, North Sea stormwaves from the east and southeast. The latter are the less frequent and, even assuming maximum wave heights of 20 m, their seabed effect will be minimal because of the considerable water depths (>60 m) over much of the platform (see also pp.191-200).

(b) Extent, bedforms and thicknesses

Geophysical coverage, core data and photographic evidence for the area are good. The ridge on the western side is a dramatic

CARBONATE DEPOSIT SUMMARY SHEET NO. 17

NAME Fair Isle Channel

LOCATION Between Orkney & Shetland, S of 60^o and N of 59^o, excluding N and E margins at Orkney

POSITION (approx); LAT. 59^o 30'N LONG. 2^o 30'W

WATER DEPTH(m) 60-110 AVE. SAMPLE DEPTH(m) 84

BATHYMETRY Mostly platform about 80m. Deeper to E around F.Isle & large depression SSW of Shetland.

DISTANCE FROM LAND(km) 0-50 DISTANCE FROM SHELF EDGE(km) 50-120

CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		45	80	41%
1m above seabed	60m water depth	21	37	
	110m water depth	19	33	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	60m water depth	5	50	.75
	110m water depth	1	30	.40

NOTES

VOLUMETRICS

AREA OF DEPOSIT(m2) 6855×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	84
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	6855×10^6	68.55×10^6	685.5×10^6
TOTAL WEIGHT(g)	5319×10^{12}	47.2×10^{12}	510×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	131	1.14	12.4

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	6	34	9	5	14	26	0	5

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	21%	79%	0%	3.9	1.3	3.4	2.3	0.8	0.5	7.70

NOTES

See Table 2 for textural scales.

rocky feature scored with gullies and hollows containing carbonate sediment (Figs. 6,53&54). As the ridge drops down onto the generally flatter platform on its east, the sediment becomes more widespread though still thin and patchy. Side-scan sonar and photographs reveal parallel symmetrical megaripples with wavelengths of 1-2m and heights of up to 0.2m (Figs. 55&56). These often lie on rocky ground, bouldery or exposed rockhead. The rocky surfaces are heavily encrusted with serpulids and bryozoa, notably the branching *Flustra* (Figs. 56&57), indicating that they are clear of any substantial sediment cover for long periods. The bedforms on the western side of the platform are orientated N-S, but further to the southeast they are commonly NE-SW.

The sediment cover becomes more continuous southeastwards, with less rock-head exposure being detectable. Sandwaves up to 7m high can be seen on the side-scan, with sandribbons streaming away southeastwards from these. Extensive vibrocoring and gravity coring have taken place on this platform which proved the carbonate sediment to be generally less than 0.5 thick and lying on rockhead. However occasional patches of 1.5 m thickness or greater were encountered. Around Fair Isle tidal currents are particularly strong and the seabed is more rocky. The carbonate contents are lower because most of the sediment is a winnowed coarse lithic gravel.

To the south, on the edge of the Orkney-Shetland platform at the margin of the bathymetric depression around Fair Isle, there is a thicker accumulation of superficial sediment (Fig. 143). Sparker profiles and side-scan records show large sandwaves, some with heights of 15 m or more, on the lips of scarps produced by the underlying rockhead (Fig. 58). Their crests strike NE-SW. It is unclear how much of them is carbonate sediment, as there may be underlying glacial moraine. However, the distinctive asymmetrical profiles suggest a mobile sediment cover of at least 15m thickness in places. It is quite possible that this is all carbonate in view of the huge area of carbonate-producing platform to the west. The average thickness is therefore likely to be at least 2m. Because of this, the carbonate volumetrics of the area are treated separately from the rest of the platform (CDSS No. 18 - Fair Isle Sandwave Field).

(c) Petrography

The carbonate sediment in the Fair Isle Channel is generally coarse sand and gravel mainly composed of bivalve (34%), bryozoan (26%) and serpulid (14%) fragments (Fig. 50d). It is characterised by the highest known level of bryozoan material in any carbonates on the SCS. Barnacle , echinoid, gastropod and foraminiferal debris are present in fairly equal proportions. The sediment has a very low Maturity Index (7.70) and has a very high grain size value, suggesting that it is not continually being worked over by currents. Unfortunately there are no comparative petrographical data from the sandwave field where sediment is clearly very mobile. The relationship with carbonates, around Orkney to the south, is discussed later (pp. 111).

CARBONATE DEPOSIT SUMMARY SHEET NO.18

NAME Fair Isle Sandwave Field

LOCATION West of Fair Isle
POSITION (approx); LAT. 59° 30'N LONG. 2° 00'W
WATER DEPTH(m) 80-100 AVE. SAMPLE DEPTH(m)
BATHYMETRY Edge of the Fair Isle Platform
DISTANCE FROM LAND(km) 10 DISTANCE FROM SHELF EDGE(km) 100
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			70	1 25	38%
1m above	60	m water depth	32	58	
seabed	110	m water depth	29	51	
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	60	m water depth	5	50	25
	110	m water depth	1	30	40

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 75×10^{6}

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	84
THICKNESS(m)	5	1	2
TOTAL VOLUME(m3)	375×10^{6}	75×10^{6}	150×10^{6}
TOTAL WEIGHT(g)	291×10^{12}	51.6×10^{12}	112×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	646	114	248

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT								
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

No specific data - see CDSS No. 17

(d) Overview

The Fair Isle Channel deposit is an area of massive carbonate production, with the greatest amount in the west. A general eastward movement of sediment appears to be taking place in response to the moderate tidal currents and dominant storm-swells from the west. The current velocities decrease suddenly at the western edge of the platform, accounting for the extensive carbonate accumulation there. Sediment mobility and transport in the area are investigated in detail in Chapter 4 (pp. 190-198).

(5) Carbonate-rich areas (50-75% $CaCo_3$)

(a) Cape Wrath-Nun Bank-Solan Bank

As seen, there are extensive carbonate-rich areas around the Cape Wrath and Nun Bank/Solan Bank deposits (pp. 87, 88 & Fig. 59).

(b) Northern Slope

Carbonate-rich sediments also lie along the topmost part of the continental slope (the Northern Slope) below depths of about 100m (Fig. 59). Near-bottom wave currents will reach at least 50cm/sec, but also substantial along-slope and upslope tidal and oceanic currents of over 100 cm/sec at the surface and 50 cm/sec near the seabed have been recorded (commercial data).

The sediments probably form a thin, fairly uniform cover on the seabed. They have a characteristic composition (Table 3) like those on the Hebridean Slope (p. 80). Bivalve debris is normally the main constituent but the free-living calcareous worm *Ditrupa* is also present in proportions varying from 0-67% of the carbonate material. Bryozoan fragments are common and echinoids, gastropods, serpulids and foraminifera are all significant contributors. Barnacles are generally minor components.

(6) Beaches

(a) Cape Wrath area

A high-carbonate beach and dune system occurs at Faraid Head near Durness, on the north coast of the mainland (Fig. 59). Massive amounts of carbonate are locked up in these deposits (about 16×10^{12}g). Faraid Head faces northwest directly onto the northern part of the Cape Wrath deposit (p. 83) and it is thought that the carbonate was derived from this same area.

On the other hand the very large beach and dune system at Sandwood Bay (west coast, south of Cape Wrath, Fig. 59), although facing northwest onto the southern part of the Cape Wrath deposit, is very low in carbonate. The bay receives volumes of terrigenous sand from boulder clay reworked by the Strath Shinery river, but apparently only a small contribution of skeletal carbonate from offshore. This strengthens the hypothesis (p. 85) that, offshore, the calcareous debris is migrating northeastwards rather than southwestwards.

(b) Fair Isle Channel

High carbonate beaches on northern Orkney and southern Shetland face the Fair Isle Channel deposit (Figs. 59 & 98). These are discussed later (pp. 129 & 147).

(7) Summation

Widespread production of biogenic carbonate is taking place on the waveswept, tide-swept banks and platforms of the Northern Scottish Shelf. The sediments are all well-washed skeletal sands and gravels with almost no fine-grained sediments (i.e. mud).

Their petrography is summarised in Table 4 and Fig. 36c. Barnacles are notably scarcer and bryozoa more plentiful than in many of the Hebridean deposits. The shelf-edge carbonate-rich sediments are characterised by abundant *Ditrupa* debris. Maturity Indices vary from very low to moderate, with the amount of boring and staining of the shell debris consistently very low.

Dispersion of carbonate may be occurring eastwards and westwards from the Cape Wrath deposit, and accumulation has certainly occurred on the coast at Durness. It is difficult, however, to ascertain whether this latter process is still continuing. Net dispersion rather than accumulation may also be taking place around Solan and Nun Banks.

Massive carbonate production features in the Fair Isle Channel, with sites of accumulation on the eastern flank of the platform. Some of this sediment may be migrating south and east as far as Orkney and beyond (see below).

V ORKNEY AND MORAY FIRTH

(1) North Orkney (CDSS Nos. 19 & 20)

(a) Geography and Dynamics

The deposit is confined within about 15 km of the northern shores of the Orkney Islands (Fig. 52a). A direct continuation of the Fair Isle Channel deposit, it is treated separately because carbonate sedimentation in the islands' vicinity is more varied than on the open shelf. The seabed is mostly gently undulating and shelves steadily northwards and westward into deeper water (up to 80m) interrupted by several large shoals.

Tidal currents are moderate to strong (150cm/sec) and highly variable (Fig. 52b). In shallow water over the shoals, along coasts and around headlands they can become very strong (300cm/sec). The area is very exposed to storm-waves from between west and north and experiences the comparatively moderate shorter period storm-waves from the North Sea to the northeast and east.

(b) Extent, bedforms and thicknesses

Good geophysical coverage (particularly side-scan sonar) is available to assess the seabed morphology and the distribution and thickness of the sediments in some detail. The data are available as two sets: one set shot in the spring of 1974, the other in July 1977 (Appendix 2). The quality of the sidescan is generally good enough to delineate the main boundaries between

CARBONATE DEPOSIT SUMMARY SHEET NO. 19

NAME North Orkney

LOCATION 15 km border along NE and N sides of Orkney
POSITION (approx); LAT. 59° 25' N LONG. 2° 40' W
WATER DEPTH(m) (o-)30-80 AVE. SAMPLE DEPTH(m) 48
BATHYMETRY Broad shelf gently deepening northwards, with major shoals
DISTANCE FROM LAND(km) 0-15 DISTANCE FROM SHELF EDGE(km) 90
CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface		100	150	37%
1m above seabed	30m water depth	46	80	
	60m water depth	53	69	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	30m water depth	17	85	120
	60m water depth	5	45	75

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 1140×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	99	90	95
THICKNESS(m)	2	.01	1
TOTAL VOLUME(m3)	2280×10^6	11.4×10^6	1140×10^6
TOTAL WEIGHT(g)	1824×10^{12}	8.66×10^{12}	995×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	266	1.26	129

NOTES

Numerous sandbanks
This excludes North Ronaldsay north bank (see CDSS No. 20)

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	27	43	5	6	13	6	0	1
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	25%	75%	0%	3.9	1.1	5.1	3.0	1.8	1.4	11.85
AVE. FOR SURROUNDING AREA										

NOTES

Excludes North Ronaldsay north bank.

See Table 2 for textural scales.

sediment and rock. Comparison of the two data sets reveals major differences in the sediment distribution. As a result separate maps were produced independently, from each survey (see also p. 109 and Figs. 60 & 61).

Both surveys show that the outer, seaward part of the area (60-80m deep) is flat with a widespread cover of sediment. There are small, 1-2m high isolated sandwaves striking NNW-SSE and facing eastwards, and fields of megaripples striking NNE-SSW (Fig. 61). In the approaches to North Sound in water depths of 50-60 m a complex pattern of bedforms is visible, reflecting the variable current conditions around the bay. Small sandwaves, megaripples and linear sand patches are however quite difficult to distinguish from each other.

Larger sandwaves and smaller asymmetrical sandbanks have also been mapped. Cuthe Bank (Fig. 71), lying west of Sanday and north of the Lashy Sound, has a 'scarp' facing northwest and a relief of up to 20m. It is unclear how much is due to superficial cover of sediment, nor indeed how much is carbonate sand. The Bank in fact lies at the very boundary of the carbonate deposit. Another strongly asymmetrical feature is recognisable 6 km east of North Hill on Papa Westray (Fig. 71), lying on rockhead sloping northeastwards and facing northeast in water depths of 40-50m. It is 11m high and bears megaripples striking NE-SW. Its lateral extent is not definable, but the profile is sandwave-like in which case it may well consist entirely of mobile carbonate sand.

Nearer the coasts exposed rock becomes common, but in the North Sound there is generally uniform sediment cover. Bearing in mind the large features described, the sediment thickness in the district of North Sound may average over 1 m.

A broad ridge runs northeast from Papa Westray which, in July 1977, was mantled in sediment covered with megaripples orientated NNE-SSW (Fig. 61). During the spring 1974 survey, however, it consisted of exposed rock (Fig. 60). On the northwest flank of this, to the north of Westray, is another bank, shown by sparker profiles to consist of 35 m of superficial deposits (Fig. 62). Megaripples can be seen at the northeast end, but most of its surface is smooth and devoid of substantial bedforms. It is possible that the feature is a mound of moraine with only a relatively thin cover of carbonate sediment.

A large rocky platform surrounds the northeastern islands of Sanday and North Ronaldsay. In Spring 1974 a much larger area of rock was exposed than during July 1977 (Figs. 60&61), illustrating again the extreme mobility of the carbonate material.

With such variations in thickness in time and space, it is difficult to estimate the volumes present. They are clearly large and the average thickness is likely to be at least 1m. This, however, excludes one major sandbank situated 5 km northwest of North Ronaldsay, towards the limit of the rocky platform (CDSS No. 20 - North Ronaldsay north bank). Both surveys show the bank to be ovoid in plan, but in 1974 it was totally surrounded by bare rock (Fig. 60), whereas in 1977 it was distinctly narrower and connected with the sandfield in the west

CARBONATE DEPOSIT SUMMARY SHEET NO. 20

NAME North Ronaldsay - north bank

LOCATION NW of North Ronaldsay, Orkney
POSITION (approx); LAT. 59° 25'N LONG. 2° 27'W
WATER DEPTH(m) 27-50 AVE. SAMPLE DEPTH(m) 48
BATHYMETRY Sandbank with large sandwaves
DISTANCE FROM LAND(km) 5-10 DISTANCE FROM SHELF EDGE(km) 100
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface		100	150	37%
1m above	30 m water depth	53	80	
seabed	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	30 m water depth	17	85	170
	m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 27.1×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	99	98	99
THICKNESS(m)	23	1	5
TOTAL VOLUME(m3)	191×10^6	26.4×10^6	110×10^6
TOTAL WEIGHT(g)	157.8×10^{12}	21.1×10^{12}	88.0×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	940	130	541

NOTES

Lies within the North Orkney area (CDSS No. 19)

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	24	37	2	4	29	3	0	0
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	32%	68%	0%	4.0	1.0	5.3	4.0	2.3	1.3	12.40
AVE. FOR SURROUNDING AREA										

NOTES

See Table 2 for textural scales.

by a tongue of sediment (Fig. 61). The 1974 sparker profiles show the bank to be over 20 m thick. Sandwaves are visible on all the profiles, their heights commonly being up to 15m, and wavelengths about 200m (Figs. 63&64). They all strike NW-SE and most face southwest except at the southeast end where they face northeast. A substantial thickness of carbonate sediment is contained within this feature, the whole of which may well consist of carbonate sand. However it could have a core of moraine, or even reworked terrigenous sand produced during and immediately after the initial, rapid transgressive period. Taking this into account, the average thickness adopted for the sandbank is 5m (CDSS No. 20).

(c) Petrography

The carbonates of North Orkney contain abundant bivalves (43%), barnacles (27%) and serpulids (13%), the first being dominant (Fig. 65a). Those on the North Ronaldsay north bank are much richer in serpulid debris (29%) than the surrounding carbonates (Fig.65a,b). This may be due to the greater resistance of serpulid material to biological and mechanical breakdown. However, it may simply reflect the proximity to a large area of current-swept rock platform where there is high serpulid productivity.

Northwest of the bank there is also a large area of shell gravel made up of living and dead *Modiolus* shells, the latter rapidly degrading (Farrow et al. in prep., Appendix 7). This probably makes an important contribution to the sediment on the bank.

The Maturity Indices are high for both the bank (12.40) and the rest of the area (11.85), due mainly to the bioclasts' high roundness and polish. Combined with the low values for boring these are consistent with a large amount of particle movement by the strong currents of the area.

(d) Overview

The North Orkney area is one of vigorous carbonate production, movement and accumulation, involving large volumes of sediment. Comparison of the 1974 and 1977 distributions demonstrates the high mobility of the sediment. Probably the variation is seasonal, the nearshore seabed being clearer of sediment in the spring after the winter storms than during the summer. Sediment movement within the approaches to the North Sound may be localised, but further north on the open shelf beforms indicate eastward transport. However, most of the sandwaves on North Ronaldsay north bank indicate westward transport, a factor which is probably very relevant to the existence of this major site of accumulation (see also p. 199).

(2) East Orkney (CDSS No. 21)

(a) Geography and Dynamics

This deposit lies on the shelving seabed flanking the eastern side of the Orkneys (Fig. 52a). Its boundaries are arbitrarily defined as it directly adjoins the Fair Isle Channel and North

CARBONATE DEPOSIT SUMMARY SHEET NO.21

NAME East Orkney

LOCATION East side of the Orkney Islands
POSITION (approx); LAT. 59° 00'N LONG. 2° 30'E
WATER DEPTH(m) 30-90 AVE. SAMPLE DEPTH(m) 57
BATHYMETRY Shelving platform (steep nearshore, than less so further offshore)
DISTANCE FROM LAND(km) 0-30 DISTANCE FROM SHELF EDGE(km) 200 (north)
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			98-55	145-90	41%
1m above	30	m water depth	52	76	
seabed	90	m water depth	23	38	
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	30	m water depth	8-20	30-90	45-125
	90	m water depth	0	5-30	10-45

NOTES

Figures quoted for 30 m refer to the stronger, nearshore currents
Figures quoted for 90 m refer to the weaker, offshore currents

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VOLUMETRICS
AREA OF DEPOSIT(m2) 1480x10^6 at >1m thick 700 x 10^6 at > 1m thick

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	98	75	88
THICKNESS(m)	1+5	.1+1	.5+2
TOTAL VOLUME(m3)	(1480+3500)x10^6	(148+700)x10^6	(740+1400)x10^6
TOTAL WEIGHT(g)	3984 x 10^{12}	583 x 10^{12}	1609x10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	305	45	123

NOTES

Figures using the second (larger) set of thicknesses refer to the sandwave field on the platform slope.

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	16	51	4	2	4	16	0	7
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	9%	91%	N	2.8	1.6	2.7	2.7	2.3	1.0	10.05
AVE. FOR SURROUNDING AREA										

NOTES

N means <1%

See Table 2 for textural scales.

Orkney deposits in the north, the sounds and channels between the Islands in the west, and the edge of the surveyed area in the east. Its only 'natural' sedimentological boundary is to the southwest, where the carbonate content decreases seawards and falls below 75% $CaCO_3$ some 5-30 km offshore.

A shallow platform of Devonian rocks borders the eastern side of Orkney. Within a few kilometres of the coast the seabed drops steeply down to a generally flat area which shelves gently from 60m to 90 m eastwards. The steep edge of the platform marks the edge of the Permo-Trias outcrop.

This large area experiences a wide variety of current conditions (Fig. 52b). Nearshore, in shallow water, the tidal currents are strong (150cm/sec) and stormwaves from between north and southeast must exert an important influence. Further offshore the tidal currents are weak to moderate (in the north). Although in the deeper water longer period waves from the north will still have a significant effect, the shorter period waves from the south will have a fairly minor influence.

(b) Extent, bedforms and thicknesses

Good geophysical and core information for the area gives a clear picture of the sediment cover. The inner platform is very rocky, but at its edge there are wide sediment-filled gullies and crevices controlled by fault and fracture patterns (Figs. 66 & 67). The gullies lead southeastwards on to the slope which is mostly covered with sediment. This shows extensive fields of sandwaves which are southeasterly facing and striking NE-SW (Appendix 7, fig. 4, p.522). Some of the larger sandwaves reach heights of 18m (Figs. 68 & 69) and overlie the outcrops of major reflectors in the bedrock. The latter have clearly influenced the morphology of the rock surface. The association of sandwaves with major bathymetric features (eg. the slope) and smaller features (eg. bedrock morphology) indicate a strong topographic control on the origin and distribution of sandwaves (see also pp. 203-204).

The sandwave field is recognisable at many locations along the platform slope off East Orkney. Vibrocoring within the field off Mainland Orkney proved thicknesses of at least 3 m (Allen et al. 1979, Appendix 6). IGS Consub investigations near the top of the slope east of Stronsay revealed starved lunate sandwaves 30 m across, at least 0.5m high, with wavelengths of 50 m and aligned NE-SW (Allen et al. 1979, Appendix 6). Bedrock was exposed in places which was often free of epifauna and therefore probably subject to frequent burial. Vibrocoring to the northeast proved at least 1.5 m of carbonate sediment, but some cores taken along the trend of the platform slope have encountered only a few centimetres on rock. Clearly the thickness is extremely variable. The sandwave-strewn slope can be traced all the way from South Ronaldsay to the Fair Isle Sandwave Field (p.92-93), which is really a northern extension of it (Fig. 52a). An average thickness of 2 m of carbonate sediment seems likely.

Further offshore, on the flatter open seabed, there are small sandwaves generally orientated E-W and facing south. Sidescan records also show megaripples running either parallel or slightly oblique (20°) to the strike of the sandwave crests.

West and northwest of North Ronaldsay, the inshore platform is broader. In July 1977 much of the area was covered by sediment (Fig. 61) with southward-streaming sand patches. In spring 1974, however, much more bare rock was exposed (Fig. 60). Due east of North Ronaldsay lies a sandbank covered with a dense sandwave system (North Ronaldsay- east bank). Although geophysical coverage is poor on this, it does appear to be a substantial accumulation of superficial sediment, much of it probably mobile carbonate. For this reason its volumetrics are assessed separately from the rest of the East Orkney deposit (CDSS No. 22).

(c) Petrography

The carbonate sediments consist largely of fragments of bivalves (51%), barnacles (16%) and branching bryozoa (16%) (Fig. 65c). Foraminifera become major constituents in some of the deeper water sediments.

Barnacle content, however, ranges from 1 to 50%, and bryozoa from 1 to 36%, their variation being converse. Thus, while bryozoan debris becomes more abundant in deeper water, barnacle fragments increase towards the shallows. They are in equal proportions in water depths of about 60m (Fig. 70). Towards the base of the platform slope, and on the deeper open shelf to th east, bryozoa therefore predominate over barnacles; while on the shallow platform and much of the sandwave field on the slope, barnacles predominate. Presumably

CARBONATE DEPOSIT SUMMARY SHEET NO.22

NAME North Ronaldsay - east bank

LOCATION East of N. Ronaldsay, Orkney
POSITION (approx); LAT. 59° 21'E LONG. 2° 17'W
WATER DEPTH(m) 50-35 AVE. SAMPLE DEPTH(m) -
BATHYMETRY Sandbank with sandwaves
DISTANCE FROM LAND(km) 6 DISTANCE FROM SHELF EDGE(km) 180 (north)
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			98	145	41%
1m above seabed	35	m water depth	50	72	
		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	35	m water depth	8-20	30-90	45-125
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 11.6×10^{6}

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	98	90	95
THICKNESS(m)	15	1	3
TOTAL VOLUME(m3)	80×10^{6}	11.6×10^{6}	34.8×10^{6}
TOTAL WEIGHT(g)	64×10^{12}	8.8×10^{12}	27.0×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	920	126	388

NOTES

Volumes estimated from area depth curves

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT								
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

See CDSS No. 21 (East Orkney)

the shallower mobile sediments lack bryozoan debris because current activity and sediment movement are too great for growth, whereas the proximity of the current-swept rock ensures high contributions of barnacle debris. Moreover, bryozoa produced on the platform will break down into smaller fragments more easily than barnacles and thus be size-sorted and carried further into deeper water offshore. There, the weaker currents and more stable substrate should also provide good conditions for bryozoan growth, at the same time being unfavourable to barnacles especially with a lack of exposed rock.

The lack of serpulid fragments is striking, making a stark contrast with the North Orkney and Fair Isle Channel deposits. Even where barnacles are present (normally indicating good conditions for encrusting organisms), the proportion of serpulids does not increase. Presumably they are susceptible to specific hydrographic properties which vary between the North Sea water which dominates East Orkney and the Atlantic water which dominates North Orkney (eg. see Figs. 17 & 18).

The textural characteristics of the carbonate are also variable and difficult to assess. Their average Maturity Index is moderate (10.05), most of the sediments having a low degree of boring, with a majority of the particles being totally unbored. In contrast however, some of the deeper water sediments have a moderate degree of boring. They are also finer than those on the platform or in the sandwave field.

(d) Overview

The East Orkney carbonate deposit is extensive and found in two contrasting environments. Vigorous production and transport of biogenic material is apparently taking place around the coasts of the Islands. This is carried over the eastern edge of the platform and deposited as the current velocities rapidly decrease. Some of it may reach the deeper, flatter sea floor to the east, where movement is much slower and less frequent, probably only occurring during the most extreme of the northerly (south-going) storms (see also pp. 204).

(3) Orkney Sounds (CDSS Nos. 23,24,25)

(a) Geography and Dynamics

The channels and bays of Orkney (Fig. 71) are numerous and varied with wide open firths, narrow deep channels and sheltered shallow bays. A full synthesis of the area is presented by Farrow et al. (in prep.; Appendix 7). Substantial accumulations are present and will be assessed as far as possible here.

Tidal currents in the sounds are often very strong (up to 250 cm/sec), particularly where a narrow channel connects the open sea with a wide inner expanse of water. Where the sounds are wider the currents are weak. Many of the inner sounds are sheltered from any significant wave activity, but those facing stormwaves coming in from the open sea must experience quite strong oscillatory currents at the seabed in relatively shallow water.

CARBONATE DEPOSIT SUMMARY SHEET NO. 23

NAME Orkney Sounds

LOCATION Orkney Island-Mainly around Wide Firth, Gairsay Sound, Shapinsay Sound, Stronsay Firth, Eday Sound.

POSITION (approx); LAT. 59° 04' N LONG. 2° 57' W

WATER DEPTH(m) 0-50 AVE. SAMPLE DEPTH(m) 13

BATHYMETRY Sounds, channels and bays

DISTANCE FROM LAND(km) 0-5 DISTANCE FROM SHELF EDGE(km) -

CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface			50-250	
1m above seabed	50 m water depth		24-120	
	20 m water depth		28-142	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	50 m water depth			
	20 m water depth	- - - 0 to 100 - - -		

NOTES

Wave currents very variable depending on exposure to open sea etc. No applicable reference tables.

VOLUMETRICS

AREA OF DEPOSIT(m2) $70+ \times 10^6$

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	98	75	85
THICKNESS(m)	2	.1	.5
TOTAL VOLUME(m3)	140×10^6	7×10^6	35×10^6
TOTAL WEIGHT(g)	112×10^{12}	4.8×10^{12}	27.2×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	267	11.4	65

NOTES

No good indications of thickness or areal extent

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR OTHER SOUNDS	18	60	5	2	6	3	4	1
AVE.% FOR NORTH SOUND (<50% $CaCO_3$)	5	66	3	2	5	9	0	7

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR OTHER SOUNDS	31%	69%	0%	4.0	1.3	4.5	2.7	1.3	1.7	10.65
AVE. FOR NORTH SOUND (<50% $CaCO_3$)	2%	98%	0%	2.7	1.7	2.5	3.0	1.7	0	8.55

NOTES

See Table 2 for textural scales.

(b) Extent, bedforms and thickness

Carbonates appear to be fairly extensive in the Shapinsay Sound - Wide Firth - Gairsay Sound area (Fig. 71). Having a major calcareous algal component, they are best described as maerl (Milliman 1974, pp. 213-215). The algae probably grow in or near the current-swept channels of the String, the north Wide Firth and Gairsay Sound (Fig. 71). Away from these channels, in the open bays, the sediments contain terrigenous mud.

Carbonates also occur in the northeast Stronsay Firth, south Eday Sound and Spurness Sound. The sediments vary from a shell sand to maerl and *Modiolus* gravel (living and dead shells). Calcareous algae were sampled from the Spurness Sound and the entrance to Eday Sound.

Thicknesses in the above areas are difficult to estimate. Gravity cores failed to penetrate the coarse material sufficiently, and pinger profiling was equally unsuccessful except where the sediment was fine and muddy. In places megaripples and small sandwaves are visible on the side-scan sonar records. An average thickness of 0.5m has been used in the volumetric calculations.

In the Stronsay Firth the vertical profiles of two substantial sandbanks, the Baas of Linton and Dowie Sand (Fig. 71) show 25 m of relief. In the absence of sparker lines through the banks this is taken to be the maximum possible thickness of sediment. Volumetric assessments of the two banks are made separately (CDSS

Nos. 24 and 25). Sandwaves with heights of up to 6 m and wavelengths of 200 m populate the tops of both the sandbanks. An average thickness of 3 m has been used in the volumetric calculations.

(c) Petrography

There are several different petrographic types in the Orkney sounds and they have not been fully investigated in this project (but see also Farrow et al. in prep.; Appendix 7). Bivalve fragments predominate (Fig. 65d), in some localities identifiable as mostly *Modiolus* debris. Large areas of *Modiolus* gravel (living and dead shells) were found in parts of the Stronsay Firth. Barnacle debris is abundant in sediments where the coastline faces the open sea (eg. Baas of Linton, Fig.65e). Debris of calcareous algae is found in the vicinity of tide-swept channels sheltered from significant wave activity.

The carbonates have a moderate Maturity Index (10.65). Their high roundness values indicate the intense current activity.

(d) Overview

Local carbonate production and accumulation is taking place in the sounds of Orkney. Much is probably retained between the islands. It is uncertain whether there is a significant net sediment transport direction between the sounds and the open platforms on the outer peripheries of the archipelago.

CARBONATE DEPOSIT SUMMARY SHEET NO. 24

NAME Baas of Linton

LOCATION Stronsay Firth

POSITION (approx); LAT. 59° 04' N LONG. 2° 47' W

WATER DEPTH(m) 10-33 AVE. SAMPLE DEPTH(m) 8

BATHYMETRY Sandbank with sandwaves

DISTANCE FROM LAND(km) 1 DISTANCE FROM SHELF EDGE(km) -

CURRENTS (cm/sec)

		PN	PS	PNET
TIDAL:				
Surface			200	
1m above seabed	33 m water depth		100	
	10 m water depth		130	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	33 m water depth	-	- ?up to 45 -	-
	10 m water depth	-	- ?up to 110 -	-

NOTES

VOLUMETRICS

AREA OF DEPOSIT(m2) 4.0×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	99	90	96
THICKNESS(m)	25	1	3
TOTAL VOLUME(m3)	38.0×10^6	4×10^6	11.8×10^6
TOTAL WEIGHT(g)	30.4×10^{12}	2.72×10^{12}	9.25
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	1267	113	385

NOTES

Carbonate variation estimated from one sample
Volumes derived from area:depth plot

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	34	47	5	2	6	2	2	1
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	3%	97%	0	4	2	5	4	3	1	13.50
AVE. FOR SURROUNDING AREA										

NOTES

1 sample only (OR 79)

See Table 2 for textural scales.

CARBONATE DEPOSIT SUMMARY SHEET NO.25

NAME Dowie Sand

LOCATION Stronsay Firth (S of Stronsay), Orkney
POSITION (approx); LAT. 59° 07' W LONG. 2 ° 40'W
WATER DEPTH(m) 10-35 AVE. SAMPLE DEPTH(m) -
BATHYMETRY Elongate sandbank with sandwaves
DISTANCE FROM LAND(km) DISTANCE FROM SHELF EDGE(km)
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface			200	
1m above	35 m water depth		100	
seabed	10 m water depth		130	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	35 m water depth	- - - ? Up to 45 - -		
	10 m water depth	- - - ? Up to 110 - -		

NOTES

VOLUMETRICS

AREA OF DEPOSIT(m2) 7.2×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	85
THICKNESS(m)	25	1	3
TOTAL VOLUME(m3)	41.10×10^6	7.2×10^6	15.2
TOTAL WEIGHT(g)	31.8×10^{12}	4.9×10^{12}	11.3×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	736	115	262

NOTES

Carbonate variation estimated from one sample
Volumes derived from area: depth plot

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT								
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE.% FOR DEPOSIT										
AVE.% FOR SURROUNDING AREA										

NOTES

No specific data - see CDSS Nos 23 & 24

(4) West Pentland Firth (CDSS No. 26)

(a) Geography and Dynamics

A carbonate deposit lies on fairly flat seabed at the western entrance to the main channel between Orkney and the Scottish Mainland (Fig. 52a).

Tidal currents in the Firth proper are extremely strong, reaching 500 cm/sec (Fig. 52b and p. 121). As the Firth widens west of Dunnet Head the currents decelerate rapidly, but are still moderate. The area is also prone to ocean storm waves from the west and northwest.

(b) Extent, bedforms and thickness

Little geophysical information is available over the deposit and coring has been inconclusive. The Admiralty charts frequently mark "rock" and "stones" in the area, suggesting thin sediment cover. However, an echosounder profile shows extensive development of sandwaves and small sandbanks in the Firth from Dunnet Head to Brims Ness, further west (Fig. 72 see also p. 208). The features are asymmetrical in the east and face west, while towards the west they become symmetrical and then more rounded and degraded in appearance. The sandwaves are up to 10 m high and the sandbanks 30 m.

Immediately west of Dunnet Head there is also a 20 m -high

CARBONATE DEPOSIT SUMMARY SHEET NO.26

NAME West Pentland Firth

LOCATION North of Dunnet Head, Caithness
POSITION (approx); LAT. 58° 45' N LONG. 3° 30' W
WATER DEPTH(m) 60-80 AVE. SAMPLE DEPTH(m) 71
BATHYMETRY Broad Channel between Orkney and mainland.
DISTANCE FROM LAND(km) 5 DISTANCE FROM SHELF EDGE(km) 160 west
CURRENTS (cm/sec)

			PN	PS	PNET
TIDAL:					
Surface			90	165	40%
1m above	80	m water depth	39	72	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	80	m water depth	4	35	50
		m water depth			

NOTES

See also Table

VOLUMETRICS
AREA OF DEPOSIT(m2) 234×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	87	77	84
THICKNESS(m)	5	.1	1
TOTAL VOLUME(m3)	1170×10^6	23.4×10^6	234×10^6
TOTAL WEIGHT(g)	870.5×10^{12}	16.3×10^{12}	172×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	620	11.6	123

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	28	44	4	6	8	7	0	3
AVE.% FOR SURROUNDING AREA	23	39	3	5	7	21	0	3

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	18%	82%	0	3.7	1.2	3.9	3.4	2.8	1.0	11.25
AVE. FOR SURROUNDING AREA	10%	90%	0	2.5	1.0	2.0	4.0	0	0	6.25

NOTES

"Surrounding area" - one sample only

See Table 2 for textural scales.

sandbank. This position, off a headland, is common for a sandbank (Pingree and Maddock, 1979, also p. 208). The Admiralty record the sediment as "shell sand" and the bank may therefore be a substantial carbonate accumulation.

The average thickness for the whole West Pentland Firth Deposit is taken to be 1 m.

(c) Petrography

Consisting mainly of pieces of barnacles (28%) and bivalves (44%), the deposit also has fair proportions of gastropods, echinoids, serpulids, polyzoa and foraminifera (Fig. 65 f). The Maturity Index is high (11.25), reflecting fairly high degrees of roundness, polish and staining due to considerable working by the strong currents.

Peripherally, the carbonate-rich sediment to the northwest is much richer in bryozoan debris (21%) and has an extremely low Maturity Index (6.25).

(d) Overview

The deposit is situated where current velocities are either decelerating or accelerating from east to west or west to east respectively, depending on the flow direction at the time. The Pentland Firth behaves like a huge fast-flowing river, but alternating in direction. This flow, interacting with the powerful storm swell from the west, may form a local zone of bedload convergence, while net 'leakage' to the east occurs. This is discussed later (pp.206-211).

(5) Sandy Riddle (CDSS No. 27)

(a) Geography and Dynamics

The long narrow shoal, Sandy Riddle, extends southeastwards from the Pentland Skerries, a small group of islands at the eastern entrance to the Pentland Firth (Fig. 52a).

Tidal currents at the northern end of the shoal are extreme. In the main channel, on the southwest side of the Skerries, they can attain velocities of 525 cm/sec! Although not as high, the currents in the channels are still very strong for several kilometres on either side of the bank (Fig. 52b). Over Sandy Riddle itself a complex pattern of eddies operates during the south-going tidal stream.

Wave currents are very variable. Those generated by storm waves from the southeast must be strong in the shallow water over the bank but can have little effect in the deep water (>70m) of the channels. The larger of the storm waves from the north, however, must produce fair oscillatory bottom currents north of Sandy Riddle, as well as strong currents on the bank itself (see also p. 207). During these periods the channel on the south side is comparatively sheltered.

CARBONATE DEPOSIT SUMMARY SHEET NO. 27

NAME Sandy Riddle

LOCATION Eastern entrance to the Pentland Firth
POSITION (approx); LAT. 58° - 38'N LONG. 2° - 50' W
WATER DEPTH(m) 10-70 AVE. SAMPLE DEPTH(m) 51
BATHYMETRY Long narrow, sandbank with sandwaves
DISTANCE FROM LAND(km) 10 DISTANCE FROM SHELF EDGE(km) 210
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface (channel 50m-sandbank 20m)		100-310	150-525	33%
1m above seabed	20 m water depth	57	85	
	50 m water depth	148	243	
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	20 m water depth	15	50	75
	50 m water depth	0	15	25

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 29.8 x 10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	97	89	74
THICKNESS(m)	60	1	5
TOTAL VOLUME(m3)	414×10^6	29.8×10^6	134×10^6
TOTAL WEIGHT(g)	328×10^{12}	22.4×10^{12}	104×10^6
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	1834	125	581

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	37	32	3	5	12	10	0	1
AVE.% FOR SURROUNDING AREA	22	29	3	5	21	14	0	10

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	34%	66%	0%	3.9	1.8	4.3	3.9	2.4	.4	11.40
AVE. FOR SURROUNDING AREA	40%	60%	0%	3.4	2.3	3.1	3.0	2.3	.8	10.65

NOTES

See Table 2 for textural scales.

(b) Extent, bedforms and thickness

Underwater television and side scan sonar show that on the southwest side of Sandy Riddle the sea floor is rocky and bouldery (Fig. 73). On the northeast it is more cobbly and gravelly, with some muddy sand. The rock surfaces are heavily encrusted with serpulids, and grazing echinoderms are common.

Extensive profiling with side-scan sonar and pinger has revealed the morphology of the bank in some detail (Figs. 74-79). It is 10 km long, 1-2 km wide, and has a maximum relief of 60 m. The profile becomes lower and less distinct towards the southeast and the north end of the bank is piled against the rocky bathymetric high of the Pentland Skerries.

Large sandwaves on the northeast side have their crests orientated N-S and have their steeper sides facing the west except at the north end. Their heights reach 10 m and wavelengths are 80-200 m. Megaripples on their backs run parallel or slightly oblique (up to 20^{o}) to their crests.

The steep southwest face of the bank appears to be fairly smooth on the profiles, but underwater television reveals large megaripples probably about 0.5 m high (Fig. 80).

IGS sparker profiles cross the southern part of the bank and show it to be made entirely of superficial sediment (Fig. 81). Rockhead rises at the north end, adjacent to the Skerries, but the bulk of the shoal is inferred to be superficial sediment.

How much of the bank is actually carbonate is uncertain but, in view of the extent and dimensions of the sandwaves, an average thickness of 5 m seems likely. There could be a core of moraine or other glacial sediment inside the bank but the enormous quantities of mobile carbonate known in the district suggest there is a reasonable possibility that the whole bank is made of carbonate.

(c) Petrography

The composition of the material along the sandbank is worth close consideration because, in such a "high energy" mobile environment, very little of the debris can be autochthonous. Indeed some of it may have been transported rapidly over considerable distances by the strong currents for many kilometres to the north and west.

For the Orkney and Moray Firth district, the sediment is uncommonly high in barnacle fragments (37%, Fig. 65g). This may be due to high barnacle productivity on the rocky seabed nearby, and/or the high durability of barnacle debris (versus bivalve debris in particular). In the latter case, the greater the proportion of durable fragments, the more mature it would appear to be. It is likely that durability is relevant because, although Chave (1964) found that initially barnacles break down quickly into segments, Cucci (1979) pointed out that after this stage they were very durable.

Bryozoan debris increases southwards along the bank (Fig. 82a). This may result from current sorting, because bryozoa readily break down into easily transportable debris which will not be retained in the coarser material at the north end. On the other hand there may be more bryozoa in the south because this part of the bank receives substantial contributions from the deeper water carbonates where more are growing.

A comparable but inverse distribution is shown by the serpulid debris, the proportion of which decreases southeastwards (Fig.82b). This may be due to current sorting, large and durable serpulid fragments being therefore deposited with the coarser fraction at the northern end; or it may be due to high production on the current-swept rocky areas.

At the north end the coarsest material on the sandbank contains a significant proportion of well rounded granules and pebbles of Devonian flagstone. These decrease in quantity southeastwards (Fig. 82c).

The sediment on Sandy Riddle has a high Maturity Index (11.40) owing to its high polish and roundness, and moderate staining. Grain size is large, decreasing from coarse sand and gravel in the northwest to mainly sand in the southeast (Fig. 82d).

(d) Overview

Sandy Riddle appears to be, or have been, an important site for the accumulation of extremely pure carbonate sediment. The bank is possibly now in a state of equilibrium with sediment merely passing over it without adding to its volume. Material is probably received from considerable distances, particularly to the west and north.

The overall sedimentological regime for the Orkney/Pentland Firth area as a whole is discussed later (pp. 130 & 206-211).

(6) Moray Firth (CDSS No. 28)

(a) Geography and Dynamics

Extending southwards from Sandy Riddle, this deposit lies on the coastal platform off Caithness (Fig. 52a). Tidal currents are generally light and probably stronger along the coast, exceeding 50 cm/sec. Wave currents produced by northerly and northeasterly stormwaves are moderate, but those generated from the east and southeast are significant only in shallow water (Fig. 52b).

(b) Extent, bedforms and thickness

The carbonate content decreases steadily southeastwards, away from the Pentland Firth area (Fig. 19). South of Wick the deposit becomes a narrow, 5 km-wide strip immediately off the Caithness coast (Fig. 52a).

Coring indicates that the deposit is commonly less than 1 m

CARBONATE DEPOSIT SUMMARY SHEET NO.28

NAME Moray Firth

LOCATION East of Caithness
POSITION (approx); LAT. 58° 30'N LONG. 2° 50'W
WATER DEPTH(m) 30-70 AVE. SAMPLE DEPTH(m) 70
BATHYMETRY Gentle shelving seabed
DISTANCE FROM LAND(km) 0-20 DISTANCE FROM SHELF EDGE(km) 400 north
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface			40	50	-
1m above seabed	50	m water depth	19	23	
		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	50	m water depth	0	15+	25+
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 700×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	98	77	86
THICKNESS(m)	3	.1	.5
TOTAL VOLUME(m3)	2100×10^6	70×10^6	350×10^6
TOTAL WEIGHT(g)	1680×10^{12}	48.7×10^{12}	260×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	400	11.6	62

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	19	44	6	2	5	16	0	8
AVE.% FOR SURROUNDING AREA	21	36	6	4	4	15	0	13

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	12%	88%	N	3.3	1.0	3.0	2.6	1.4	1.8	9.35
AVE. FOR SURROUNDING AREA	10%	89%	1%	3.0	1.0	2.0	1.0	2.5	4.0	11.0

NOTES

N means <1%

See Table 2 for textural scales.

thick and lying on rockhead, boulder clay (eg. MF 485, Appendix 6), or quartz-rich sand. Occasionally it reaches at least 1.5 m. Poor quality side-scan records show a fairly uniform sediment cover except where the seafloor is near the coast. A most likely average thickness is therefore about 0.5 m.

(c) Petrography

The sediment is predominantly bivalve debris (44%) with a substantial barnacle (19%) and bryozoan (16%) fraction (Fig. 65h). Echinoid, serpulid and foraminiferal fragments are common but gastropods are generally rare. The Maturity Index is low (9.35) with low degrees of staining and boring.

The carbonate-rich sediments to the east contain terrigenous mud, are finer, and have a high foraminiferal content. Their Maturity Index (11.0) is high, owing primarily to heavy boring. Along with a lateral decrease in carbonate content these petrographical changes correspond with increasing distance from the Orkney/Pentland Firth area where, as seen, massive production and accumulation of carbonate are taking place.

(d) Overview

Carbonates are accumulating on the seabed south of the Sandy Riddle deposit. At the north end the eastern boundary does not correspond with any bathymetric feature or marked change in current regime. Considerable amounts may be produced locally on the platform (as the bryozoan debris suggests) but there are almost certainly significant contributions from the Pentland Firth and Sandy Riddle as well. Longshore drift probably plays an important part in supplying the narrow strip of carbonate in the southern part of the area.

(7) Other deposits

Aerial photographs show accumulations of sediment on the west sides of the Islands of Stroma and Swona in the Pentland Firth (Fig. 71). Almost certainly there is carbonate sediment accumulating in the lee of the islands where major eddies are well documented.

(8) Carbonate-rich areas (50-75% $CaCO_3$)

Gravelly and muddy carbonate-rich sediments occur within the Orkney archipelago in association with the carbonate deposits previously described (pp.112-117). They also occur as a strip on the southeast border of the Moray Firth deposit where the carbonates grade into the fine terrigenous muddy sands of the North Sea (p. 126).

(9) Beaches

High-carbonate beaches (i.e. >50% $CaCO_3$) are numerous on the Orkneys (Mather et al. 1974). They line the northwest, north and east coasts, and face onto the North Orkney and East Orkney carbonate deposits (Fig. 59).

On the Scottish mainland, all the beaches from John O'Groats southwards to Wick all have high carbonate contents and face the Sandy Riddle and Moray Firth deposits. Along the north coast, opposite the West Pentland Firth deposit, the beach sediments are mostly terrigenous although there are local patches with high carbonate contents (eg. west Murkle Bay near Thurso, Fig. 59).

(10) Summation

Massive production, accumulation and transport of carbonate is taking place in the Orkney area. Accumulations are numerous and the bedforms are often spectacular. The favourable conditions are produced by large areas of fairly shallow rocky platform, high coastline: area ratio, strong tidal currents and moderate wave-currents.

Actual distances over which debris is transported are uncertain. With such high local production, the material carried in must become heavily diluted by the local elements. Hence the local epifauna is bound to be a major part of the assemblage. Another complication is the frequent difficulty of distinguishing variations in composition due to sorting from those due to proximity to certain types of biogenic production sites.

In such a vigorously dynamic situation it is only to be expected that old debris will be continually mixed with new, making the final petrography (summarised in Figs. 36d & 36e) difficult to determine and interpret. This may explain why the Maturity Index is less useful in this district. ^{14}C dating experiments illustrate the problem (pp. 224-233).

Sediment transport is generally eastwards and southwards. This is discussed later(pp.206-211).

VI SHETLAND

(1) West Shetland (CDSS Nos. 29 & 30)

(a) Geography and Dynamics

The West Shetland carbonate deposit lies on part of the platform with a varied bathymetry(Fig.83) presumably resulting from glaciation. Thus there are shallow shoals and, close inshore, deeper basins such as St. Magnus Bay and The Deep.

The area is affected by weak to moderate tidal currents (25-75 cm/sec, Fig. 84) but, being close to the shelf edge, is exposed to extreme storm-waves coming from all directions between southwest and north.

(b) Extent, bedforms and thickness

The sediments extend from the Fair Isle Channel carbonates near Foula to the Shetland-Out Skerries deposits at Muckle Flugga in the north. Their eastern margin reaches the Shetland coast in places, but in the northwest is separated by a carbonate-rich coastal zone with a lithic gravel component. Westwards the carbonate content of the sediment decreases rapidly beyond the outer edge of the platform.

Coring and geophysical surveying show that rock is very close to the surface over much of the area and is in many places exposed. Most cores revealed only a few centimetres (<0.1m) of carbonate

CARBONATE DEPOSIT SUMMARY SHEET NO.29

NAME West Shetland

LOCATION West of Shetland, north of 60^{o} N, excluding Foula
POSITION (approx); LAT. 60^{o} 30'N LONG. 1^{o} 40'W
WATER DEPTH(m) 0-100 AVE. SAMPLE DEPTH(m) 91
BATHYMETRY Undulating platform
DISTANCE FROM LAND(km) 0-10 DISTANCE FROM SHELF EDGE(km) 20-40
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface				75	
1m above	50	m water depth		36	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	50	m water depth	5	50	75
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 2000×10^{6}

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	96	75	84
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	2000×10^{6}	20×10^{6}	200×10^{6}
TOTAL WEIGHT(g)	1552×10^{12}	13.8×10^{12}	148×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	131	1.14	124

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	8	44	9	3	19	9	0	8
AVE.% FOR SURROUNDING AREA	6	47	10	3	13	8	0	12

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	24%	76%	N	3.8	1.3	3.6	1.8	2.4	2.6	11.40
AVE. FOR SURROUNDING AREA	16%	84%	N	3.2	1.3	2.8	2.1	1.8	2.1	9.95

NOTES

N means <1%
See Table 2 for textural scales.

sediment lying on rock or, occasionally, boulder clay. Towards the north in some places the carbonate was greater than 0.5 m thick. A most likely average of 0.1 m is used in the volumetric calculations.

IGS Consub dives on the eastern side of St. Magnus Bay found exposed rock surfaces with a wide variety of degrees and types of encrustation (Figs. 85-87). Even at depths of 128 m some rock surfaces were still heavily encrusted with barnacles.

Patches of shell gravel were encountered in the vicinity at depths of 100 m. They comprised dead, but often whole, valves of *Modiolus* and *Glycymeris* (Fig. 88). The bioclasts were discoloured or heavily stained, and probably heavily bored. The sediment had the appearance of an older relict version of the presently growing *Modiolus* beds encountered around Orkney (pp.114,115). It may have formed during the post-glacial transgression before the deepening water killed off the fauna.

The only part of the deposit where the carbonate is clearly thicker is around the island of Foula (CDSS No. 30). Tidal currents there (>100 cm/sec) are considerably stronger than elsewhere. To the northeast between Foula and Mainland (Shetland) is a large expanse of current-swept rocky seabed. On the north side of Foula, a boomer profile records a sandwave field lying on a bathymetric high (Fig. 89). The sandwaves have heights up to 2.5 m and wavelengths of 200m. Their precise

CARBONATE DEPOSIT SUMMARY SHEET NO. 30

NAME Foula

LOCATION West of Shetland
POSITION (approx); LAT. 60° 10'N LONG. 2° 8' W
WATER DEPTH(m) 40-90 AVE. SAMPLE DEPTH(m)
BATHYMETRY Rocky Shoals surrounding the Island
DISTANCE FROM LAND(km) 0-10 DISTANCE FROM SHELF EDGE(km) 50
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface				100+	
1m above	40	m water depth		50	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	40	m water depth	5	50	75
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 95×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	85
THICKNESS(m)	2	.1	1
TOTAL VOLUME(m3)	190×10^6	9.5×10^6	95
TOTAL WEIGHT(g)	147×10^{12}	6.5×10^{12}	70.7×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	259	11.4	124

NOTES

Area Very Poorly Defined

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT								
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT										
AVE. FOR SURROUNDING AREA										

NOTES

No specific data
See West Shetland (CDSS No. 29)

orientations are unknown,but on the profile the steep faces point in a northerly direction. A Consub dive off the east of the island in 40 m of water encountered a dramatic carbonate megaripple field (Fig. 90-93). The megaripples were subparallel and slightly lobate, with wavelengths about 1 m and heights up to 0.3 m. They had pronounced avalanche faces sloping eastwards and crests aligned NNW-SSE. A set of smaller ripples was present in the troughs, orientated virtually at right angles. These had heights of about 0.01 m and wavelengths of 0.05-0.1 m. This is a common association in shallow-water tidal sediments, the small ripples being produced during a different stage of tidal flow when the megaripples have ceased to be active (eg. Reineck and Singh, 1980, p. 42).

Using the above evidence, a likely average thickness of the sediments around Foula is about 1 m (CDSS No. 30).

(c) Petrography

On average the carbonate sediments consist predominantly of bivalves (44%), followed by serpulid debris (19%). Barnacles, bryozoa and foraminifera can be important constituents Fig. 94). There are also wide variations in the contents of serpulids (2-36%), bryozoa (2-22%) and foraminifera (1-30%). The latter is clearly depth related (Fig. 95), the foraminifera accumulating in deep or basinal areas where currents are weaker. The large variation of bryozoan and barnacle content probably illustrates how differences in the microenvironment affect the local fauna and so influence the composition of the sediment derived from it. For instance Consub observations indicated that the types of encrusting organisms changed considerably within small distances and small changes of water depth.

The carbonate sediments have a high Maturity Index (11.4). This compares with the lower Maturity Index (9.95) of the surrounding carbonate-rich sediment, resulting from higher degrees of roundness, staining and boring.

(d) Overview

The deposit lies on a wave-dominated well-washed platform, where carbonate production is high and the resulting sediment probably transitory in places. One site of accumulation apparently flanks Foula where tidal currents have concentrated the sediment. Sandwaves lying off Foula face northwards, suggesting transport in that direction. Elsewhere the transport directions and destinations of the carbonate are not clear. Possibly it is moving northeastwards to the north side of Muckle Flugga, where it may either spill out over the continental slope or return southwards on the east side of Shetland (see p. 148).

(2) Northeast Shetland (CDSS No. 30)

(a) Geography and Dynamics

A carbonate deposit spreads out eastwards of Unst and Yell

CARBONATE DEPOSIT SUMMARY SHEET NO. 31

NAME Northeast Shetland

LOCATION Pobie Bank - east of Unst (N. Pobie Bank)
POSITION (approx); LAT. 60° 40'N LONG. 0° 31' W
WATER DEPTH(m) 100-130 AVE. SAMPLE DEPTH(m) -
BATHYMETRY Deep water, broad shoal.
DISTANCE FROM LAND(km) 0-50 DISTANCE FROM SHELF EDGE(km) 50
CURRENTS (cm/sec)

TIDAL:			PN	PS	PNET
Surface				40	
1m above	100	m water depth		17	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	100	m water depth	0		?50
		m water depth			

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) 1750×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	85
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	1750×10^6	17.5×10^6	175×10^6
TOTAL WEIGHT(g)	1358×10^{12}	12.0×10^{12}	13.0×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	131	1.14	12.4

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	Low	Dominant	✓	✓	✓	✓		✓
AVE.% FOR SURROUNDING AREA								

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT		✓	N	3½	2	4	?	2½	?	High
AVE. FOR SURROUNDING AREA										

NOTES

From ship-board descriptions
N means <1%
See Table 2 for textural scales.

(Fig. 83). It lies on the north end of a large shoal, Pobie Bank, and is linked to a coastal strip on the west by the lip of a prominent 'valley'. The 'valley' runs northwards to the continental slope.

Tidal currents are generally weak (<40 cm/sec, Fig. 84), but the shoal is exposed to storm-waves from between northwest and northeast. Extreme storms must produce moderate bottom oscillatory currents. More frequent southerly storm-waves from the North Sea will have only small effects at such depths.

(b) Extent, bedforms and thickness

Side-scan sonar mapping shows that the entire area of the deposit consists of featureless patches of sand, gravel and rock. Coring encountered a cover of shelly gravel, usually 0-0.3 m thick lying on rock, lithic gravels or boulder clay. At one location, 9 km west of Unst (60/-01-247), at least 2.5m of carbonate sediment were cored; so thicker pockets do exist. Nevertheless, in view of the extensive areas of thin cover, a most likely average thickness of 0.1 m is adopted.

(c) Petrography

Unavailability of the samples from this area means that the petrography of the deposit has not been fully evaluated. Shipboard descriptions indicate that the sediments are generally rich in bivalve debris. Serpulid, echinoid, bryozoan and foraminiferal fragments are common, whereas barnacles are apparently minor constituents. The sediments are clean fine to coarse sands and gravels, moderately well rounded and slightly to heavily stained. They must therefore have a high Maturity Index, resulting from frequent agitation by storm-wave currents.

(d) Overview

The sediments are well-washed slowly accumulating gravelly deposits. The low tidal velocities probably permit production and local deposition on the shoals. Some of the carbonate may be reaching the east coast of Shetland by longshore drift (p. 148).

(3) Shetland-Out Skerries (CDSS No. 32)

(a) Geography and Dynamics

These carbonates lie on the southern part of Pobie Bank (Fig. 83) and extend southwestwards along a ridge as far as the coastal platform flanking the southeast side of Mainland (Shetland).

Surface tidal currents are fairly weak (<40 cm/sec), but oscillatory currents can be strong because the area is exposed to heavy storms from the north. Storms from the east and south set up somewhat lower velocity wave currents (Fig. 84).

CARBONATE DEPOSIT SUMMARY SHEET NO. 32

NAME Shetland - Out Skerries

LOCATION Mainly west of Whalsey (S. Pobie Bank)
POSITION (approx); LAT. 60° 25'N LONG. 0° 25' W
WATER DEPTH(m) 40-120 AVE. SAMPLE DEPTH(m) 64
BATHYMETRY
DISTANCE FROM LAND(km) 0-30 DISTANCE FROM SHELF EDGE(km) 80 north
CURRENTS (cm/sec)

			PN	PS	PNET
TIDAL:					
Surface				40	
1m above	100	m water depth		17	
seabed		m water depth			
WAVE:		exceedance	50%	1%	.1%
Nr. seabed	100	m water depth	0	—	?40
		m water depth			

NOTES

Probably stronger tidal and wave currents close inshore

VOLUMETRICS
AREA OF DEPOSIT(m2) 867×10^6

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	95	75	85
THICKNESS(m)	1	.01	.1
TOTAL VOLUME(m3)	867×10^6	8.67×10^6	86.7×10^6
TOTAL WEIGHT(g)	673×10^{12}	5.96×10^{12}	64.5×10^{12}
ACCUMULATION RATE (g/m2/yr over 6000 yrs)	13.1	1.14	12.4

NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	11	46	12	4	14	6	0	7
AVE.% FOR SURROUNDING AREA	13	54	7	5	4	3	0	14

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	15%	85%	N	3.8	1.3	3.4	2.1	2.4	2.1	10.85
AVE. FOR SURROUNDING AREA	15%	81%	4%	3.0	1.3	2.9	2.3	1.5	2.0	9.85

NOTES

Data for western (coastal) part of deposit only.
N means <1%

See Table 2 for textural scales.

(b) Extent, bedforms and thickness

Side scan sonar reveals large areas of rock with patches of sand and gravel which very rarely carry obvious bedforms. These are poorly defined megaripples with crests orientated NE-SW and linear sand patches which stream away southwards (Fig. 96). Coring revealed very thin (0.3m) sediment lying on rock, lithic gravel or boulder clay. Investigations with Consub west of Helli Ness (Fig. 84) revealed a very thin scatter of gravelly carbonate lying on a cobbly seafloor (Fig. 97). Fragments of the branching coral *Lophelia* were also visible. A likely average thickness is 0.1 m.

(c) Petrography

Sample availability once again restricted the petrographic work, and only the western part of the deposit was properly assessed. This is dominated by bivalve debris (46%), but is also rich in barnacle, gastropod and echinoid fragments (Fig. 94b). The Maturity Index (10.85) is moderate.

Sediments from the adjacent carbonate-rich zone, which lies in shallower water close inshore are quite different. Though still dominantly bivalve debris, they are much finer and rich in foraminifera besides barnacles. They have a low Maturity Index (9.85). This is contrary to the picture West of Shetland (p.136). Efficient particle size sorting must operate in this coastal region.

(d) Overview

On the outer part of the deposit the carbonates are similar to those of Northeast Shetland (pp.137-140). Both are being generated and deposited on a wave-washed bank. Indeed on Pobie Bank they are only separated by a well washed 3-5 km wide zone of mainly lithic gravel low in carbonate.

Nearshore the sediment becomes less calcareous, finer and greatly enriched in foraminifera.

The sediments have a significant mud content. This reflects the sporadic nature of the storm-induced bottom currents, which leaves quiet periods for fine grained sediment to settle. Conditions are thus different from those in Northeast Shetland (p. 137) which, being so close to the shelf edge, is more exposed. Sediments there are well washed. The carbonate content of the mud ranges from 30-60%, indicating a major biogenic contribution and confirming that carbonate production, accumulation and degradation are all occurring virtually *in situ*.

(4) Yell Sound

(a) Geography and Dynamics

Yell Sound is a major channel running through the Shetland Islands, between Mainland and Yell (Fig. 83). Extremely strong tidal currents (up to 350 cm/sec) run in it. The northern part is exposed to ocean storm waves from the north and its eastern part to North Sea storm waves from the east (Fig. 84).

CARBONATE DEPOSIT SUMMARY SHEET NO.33

NAME Yell Sound

LOCATION Between Yell and Mainland (Shetland)
POSITION (approx); LAT. 60° 35'N LONG. 1° 15'W
WATER DEPTH(m) 40-80 AVE. SAMPLE DEPTH(m) 74
BATHYMETRY Deep Channel
DISTANCE FROM LAND(km) 0-2 DISTANCE FROM SHELF EDGE(km) -
CURRENTS (cm/sec)

TIDAL:		PN	PS	PNET
Surface			100-350	
1m above seabed	70 m water depth		45-157	
	m water depth			
WAVE:	exceedance	50%	1%	.1%
Nr. seabed	70 m water depth	- -	at N. end - - ?	45 +
	70 m water depth	- -	at E. end - - ?	10 +

NOTES

VOLUMETRICS
AREA OF DEPOSIT(m2) Patchy - extent not known

	Max.	Min.	Likely
$CaCO_3$ CONTENT(%)	90	79	87

THICKNESS(m)
TOTAL VOLUME(m3) Not determined
TOTAL WEIGHT(g)
ACCUMULATION RATE
(g/m2/yr over 6000 yrs)
NOTES

PETROGRAPHY

Composition	Barn	Biv	Ech	Gast	Serp	Bry	C.Alg	Foram
AVE.% FOR DEPOSIT	5	59	13	1	11	5	0	5
AVE.% FOR SURROUNDING AREA	5	53	15	3	5	10	0	10

Texture	Grv	Sand	Mud	GnSz	Sort	Rnd	Pol	Stain	Bor	M
AVE. FOR DEPOSIT	14%	86%	N	3.5	1.0	2.7	1.3	1.6	3.3	9.20
AVE. FOR SURROUNDING AREA	7%	92%	1%	3.3	1.3	2.1	2.0	1.5	2.3	9.00

NOTES

N means <1%

See p. for textural scales.

(b) Extent, bedforms and thickness

Apart from limited routine sampling the Sound has not been properly surveyed. Cores penetrated up to 0.8 m of carbonate sediment but in places it was very thin (<0.1 m) or absent. Some of the seafloor is clean and rocky; elsewhere its sediment cover is quite muddy. Sand waves and sandbanks of carbonate sediment may be expected in the channel, but there is no direct evidence.

In view of all the uncertainties, no attempt has been made to assess the volume of carbonate. They might be substantial (see p. 148).

(c) Petrography

The sediments are mainly bivalve fragments (59%), echinoids and serpulids being the other major components (Fig. 94c). The Maturity Index (9.20) is low.

The nearby carbonate-rich sediments (50-75% $CaCO_3$) are finer and contain fewer serpulids and more bryozoa and foraminifera. They are probably derived from areas with slacker currents.

(d) Overview

Carbonate sediments occur in Yell Sound under a strong tidal current regime, and influenced by storm waves at the entrances to the channel. Their extent and environment cannot at present be fully evaluated.

(5) Other Deposits

(a) Balta Sound and The Yei

An important coastal carbonate-producing environment is indicated by the beach and spit sediments at Balta and Huney. These are small islands immediately off the east coast of Unst, separated from it by the tidally-swept channels Balta Sound and the Yei (Figs. 98 & 99).

The beaches and spits consist of carbonate sediments. It seems likely that there are further accummulations in the channels as the situation is analogous to that of the Sound of Iona (p. 56 and 147).

(6) Carbonate-rich areas (50-75% $CaCO_3$)

Around Shetland the marginal areas of carbonate-rich sediment are fairly narrow because the $CaCO_3$ content falls off abruptly seawards (Fig. 98).

One area, however, is actually within the West Shetland Deposit. Significantly, it lies in The Deep, a pronounced basin on the southwest side of Mainland (Fig. 98).

(7) Beaches

(a) East Shetland

The beaches along the east coast of the southern peninsula of Shetland have mostly high-carbonate (>50% $CaCO_3$) sands and face the Shetland-Out Skerries deposit (Fig. 98). Further north sandy beaches are rare, but a large carbonate beach complex occurs around Balta Sound, off Unst (see above). This is probably fed by intense local production in and around the Sound (see also pp. 146).

(b) West Shetland

The west coast of the southern peninsula faces onto the West Shetland and Fair Isle Channel deposits and substantial carbonate beach and dune systems have built up along it. Particularly interesting is the large tombolo which links St. Ninian's Isle to Mainland (Fig. 100). This is made of carbonate sand, some of which may have been derived from the offshore deposits. However there are many physical similarities with the configuration of other island/channel systems, for example the Sound of Iona and Balta Sound (see p. 146).

(8) Summation

On Pobie Bank, east of Shetland, carbonate production and accumulation are, in general occurring *in situ*. Some of the material may be slowly supplying the nearshore parts of the eastern deposits and, ultimately, the beaches on the east Shetland coast.

West of the islands there is much production of carbonate. In the vicinity of Foula accumulation is occurring but to the north of here the situation is obscure. There may be *in situ* accumulation. On the other hand if sediment is being removed by the predominant storm waves from the southwest combined with tidal currents (producing northeastward drift) then it is not clear where it is going.

Apart from high carbonate beaches at the south, there are none on the west side of Shetland. In fact, along the northwest side the coastal zone spanning the entrance to Yell Sound is low in carbonate, being largely lithic gravel. Perhaps calcareous debris is being swept into Yell Sound by tidal currents and storm waves from the north. If this is true the deposits in the Sound might be quite large.

Material further offshore may be drifting northwards, in which case some may get carried over the edge of the slope north of the Shetlands. A map of $CaCO_3$ content on the slope might then reveal a fan of carbonate sediment spreading out down the slope. Unfortunately the present work stops short of the main slope (Fig.98) but there is a suggestion of this. Simultaneously some sediment at the north end is probably being carried south as longshore drift along the east coast zone under the influence of storm waves from the north.

VII ANALYSIS OF PETROGRAPHY

(1) Introduction

Inspection of raw data from each deposit (Appendix 10) often reveals a considerable variation from sample to sample. This is due to both experimental and natural causes. Over much of the area, particularly off the west coast, it is not possible to correlate the petrography of individual samples with their local environment. However, comparison of petrographic 'averages' from each deposit (Table 4) reveals significant variations and trends which can be related to the different general environments of the deposits and as a result display regional geographical variation.

Averages of each petrographic property for the deposits have been ranked in order of magnitude and listed beside summarised descriptions of their physical environments (eg. Table 5). In this way variation patterns and possible relationships become readily apparent. Where appropriate they have been tested by correlation coefficients and factor analysis.

Only over the Northern Shelf, where the sampling distribution is most even, and the local physical conditions less variable, has it been possible to attempt mapping the compositional variation, sample by sample (pp.154-158).

(2) Composition : variation between deposits

(a) Barnacles

A clear correlation exists between the proximity to the coast and the proportion of barnacle debris (Table 5 & Fig. 101). Thus the highest average values occur in the coastal deposits of the Inner Hebrides (>40%) where there is a high coastline: seabed area ratio. The coastal deposits of Orkney, Caithness and Sutherland on the other hand have only moderate contents (20-40%), while those on the exposed offshore platforms have lower still (4-20%). The decline parallels the lower coastline:seabed ratios and must reflect the two main factors influencing barnacle debris production, viz. (*i*) the amount of rocky substrate available for encrustation, (*ii*) water depth. The effect of latter is confirmed by the correlation coefficient of -0.5598, P=0.002 (p.164 and Fig. 114). Hence, although barnacles can grow at considerable depths (eg.>100 m in St. Magnus Bay, west Shetland, p. 134), the production of their debris is greatest in intertidal and shallow waters (0-30 m). This is so not only because the environment is highly favourable to barnacle growth (maximal light/turbulence/aeration, etc.), but because the heavy wave turbulence in shallow water zones facing the open sea leads to rapid removal of barnacles from encrusted surfaces (Farrow et al. 1978).

Although the coastal sandbanks around Orkney are rich in barnacle debris (24-37%) there is no overwhelming evidence of significant enrichment by transport and sorting. Thus surrounding sediments thought to be 'upstream' are often equally rich in barnacle debris (Table 6). The high contents are considered to be primarily a reflection of the importance of the proximal shallow coastal platform as a carbonate source.

In other words, barnacle contents are therefore excellent indicators of proximity to, and the extent of, rocky coastal zones.

(b) Bivalves

Bivalve debris invariably makes up the largest or second largest proportion in the carbonate sediments. Average proportions, which range from 23% to 63%, do not show good correlations with their environments (Table 8 , Fig. 102). This must be because bivalves as a group are virtually ubiquitous, their various genera being adapted to different environmental niches: rocky substrates, terrigenous sediment substrate, shelly sediment substrate, tidal current dominated, wave current dominated and so on. Furthermore, infaunal bivalves are probably very important contributors to stable carbonate deposits (Wilson 1982). Investigation of the spatial proportions of the debris of lower taxa ought to yield more interesting results.

Nevertheless the deposits at the extremes of the ranked bivalve content (Table 8) do show some correspondence with their physical environments. Those containing very high bivalve proportions (47-68%) are invariably associated with tide-dominated sounds; those with low proportions (23-32%) are associated with coastal wave-dominated areas.

Bivalve content must therefore be treated with caution as an environmental indicator, although in some cases it can be useful.

(c) Echinoids

Average echinoid contents of the deposits reach a maximum of 13%, individual samples ranging from 0% to (rarely) 30%. Despite this small range the ranked table shows clear correspondences between (*i*) open ocean and open sea conditions and higher echinoid contents, and (*ii*) sheltered inshore zones with lower contents (Table 9, also Fig.103). Echinoid debris becomes most abundant away from the strongest tidal currents, but where there is a strong direct influence from the Atlantic Ocean. It could therefore be used as an environmental indicator.

(d) Gastropods

Average gastropod contents range from 1% to 11% (Table 10). When ranked, they show no clear relationship with the depositional environment and thus cannot be used as an indicator.

(e) Serpulids

The average proportions of serpulids range from 3% to 36%. Ranking shows (*i*) a positive relationship with offshore influence generally, and Atlantic waters in particular, and (*ii*) a negative relationship with coastal influences generally and North Sea waters in particular. The opposing effects of the Atlantic and North Sea are illustrated by the marked difference in average serpulid content between the North Orkney (13%) and East Orkney (4%) deposits, both of which are associated with rocky tide-swept platforms (Table 11, Fig. 104).

The serpulid contents thus give indications of the balance between offshore and Atlantic conditions and coastal and North Sea influences.

(f) Bryozoa

Average bryozoan contents in the deposits range from 2% to 26%. When ranked in order of magnitude (Table 12) they show a crude positive relationship with deeper open shelf conditions, and a negative one with nearshore conditions (Fig. 105).

Thus they can be used to indicate water depth and/or proximity to coastlines.

(g) Calcareous Algae

Calcareous algae are generally absent, but their debris amounts to up to 10% in some of the samples. A few of the deposits investigated average 1-2%, and all these are coastal. The debris is probably mostly derived from present-day coastal channels and bays, but rarely may be from older channels and bays obliterated by rising sea level.

Hence the presence of calcareous algal debris can be used broadly as a coastal indicator. Proportions exceeding 2% may safely be taken as further indication of proximity to tide-swept sheltered channels or bays.

(h) Foraminifera

Average foraminiferal contents range from 0-8%. They are scarce in deposits heavily influenced by currents (particularly tidal currents), but are more abundant on the open shelves (Table 13, Fig. 106). This inferred relationship with current activity is supported by the correlation coefficient of -0.5815 ($P=0.001$) for % foraminifera versus grain size (p. 167 and Fig. 127).

Thus foraminifera can be used for the recognition of offshore open-shelf conditions (high frequencies) and nearshore current-swept conditions (low frequencies).

(3) Composition: variation on Northern Shelf and around Orkney

(a) Introduction

As previously outlined (p. 149) this region has received some special attention because, although the $CaCO_3$ contents are often less than 50%, a reasonable spread of compositional data has been assembled for the sediments between the Butt of Lewis and Orkney. Furthermore, the relatively more uniform bathymetry and physical conditions might produce less local variation in sediment type, so an attempt was made to produce contour maps of the component percentages. These were constructed by using a computer contouring programme based on an algorithm by Crane (1972). The results must of course be treated with some caution, because of locally abrupt changes in contouring values and sample density.

(b) Barnacles

The strong coastal influence on barnacle content is well exemplified in Fig. 107. Barnacles also tend to be more abundant in the more pure carbonates than in the surrounding less calcareous sediments (e.g. the lobes extending northwest over Solan Bank and southeast over Sandy Riddle).

(c) Bivalves

Fig. 108 illustrates (*i*) the generally high proportions of bivalve debris in the East Orkney and Moray Firth carbonate deposits, and (*ii*) the extremely high porportions (mainly infaunal lamellibranchs) in the calcareous part of the low-carbonate sediments (e.g. N. Minch and north of Sutherland).

(d) Echinoids

Higher proportions of echinoid debris tend to occur in the sediments with lower carbonate contents (Fig. 109). These in turn are found mostly where the tidal currents are weaker, viz. open shelf or basins such as the north Minch.

(e) Gastropods

Although higher proportions occur in some of the carbonate deposits (Fig. 110; e.g. Solan Bank, Cape Wrath, Sandy Riddle) on the whole gastropod debris seems to be randomly distributed and not obviously related to any particular factor.

(f) Serpulids

Concentrations of serpulids occur on the northwest side of the Nun Bank/Solan Bank feature, on the northwest side of the Cape Wrath platform, and on the west side of Shetland. This illustrates the strong preference for direct exposure to the Atlantic oceanic environment (Fig. 111).

(g) Bryozoa

Concentrations occur in two distinct environments (Fig. 112): *(i)* exposed rocky wave-swept areas (e.g. Nun Bank, Solan Bank, Fair Isle Channel), and *(ii)* more sheltered or deeper waters (e.g. North Minch, outer shelf of East Orkney and Moray Firth). The types of bryozoa in these environments are probably different but unfortunately were not distinguished in this work. In the exposed areas they are chiefly encrusting and flexible-branching types able to withstand considerable current activity; and in the more sheltered waters they are delicate branching types which would be easily damaged if the currents were strong.

(h) Calcareous Algae

The proportions of these have not been plotted because, within the area of the map, they are significant proportions only in some of the Orkney Sounds (pp.112-117).

(i) Foraminifera

Foraminiferal debris becomes more abundant on the outer open-shelf towards both the Atlantic and the North Sea (Fig. 113). In coastal areas and over shoals, where there is significant current activity, it is scarce. This distribution relates to the fine grain size and low bulk density of the material (Maiklem 1968).

(j) Conclusions

Contouring reveals the general variation in composition over the Northern Shelf and illustrates the principles underlying it as deduced from the carbonate deposits only (pp.150-154). However the results must be treated cautiously because (*i*) variations in sample density can produce spurious highs and lows, and *(ii)* spatial and temporal variations in physical conditions and sediment type make interpretation difficult.

(4) Composition: variation patterns between deposits (>75% $CaCO_3$) and surrounding sediments (<75% $CaCO_3$)

Nearly all the carbonate deposits in the Inner Hebrides, Hebridean Shelf and Northern Shelf contain distinctly lower proportions of bivalve debris (within the carbonate fraction) than the surrounding more terrigenous sediments. This illustrates the greater importance in the latter of free-living infaunal bivalves compared with encrusting, substrate-dependent barnacles, calcareous worms and bryozoa which make up a greater proportion of the calcareous fraction in the more pure carbonates. Foraminiferal contents, too, are generally higher in the less calcareous sediments, as before reflecting the small grain size and weaker currents (p. 154).

The above pattern is not found, however, on Solan Bank, east of Shetland (Shetland-Out Skerries), or in the Orkney-Moray Firth area. Here, besides barnacle debris, bivalves are more abundant in the carbonate deposits, while bryozoan and foraminiferal fragments are prevalent in the lower-carbonate sediments.

This indicates that bivalves make a major contribution to these deposits.

(5) Textural variation between deposits

(a) Introduction

As discussed (pp32-35), the textural parameters (grain characteristics) of a carbonate sediment may reflect its sedimentological history. In this light, an experimental Maturity Index (M) was devised in an attempt to summarise the textural conditions of such a sediment in terms of its sedimentary history (p. 35). The results suggest that the maturity of the Scottish carbonates varies widely and that a crude relationship often exists between individual characteristics of the grains and their sedimentological environments. It is not easy to measure this relationship because several parameters, some unquantified, are needed to define the environment. Therefore characteristics of each deposit are tabulated in order of magnitude, and general trends and relationships deduced by inspection.

(b) Grain Size

Average grain sizes (Table 14) range widely from 4.5 to 2.8 units (see Table 2). The higher values tend to characterise deposits from areas either extremely exposed to the open ocean, or continually subjected to strong tidal currents. Smaller grain size values relate with more inshore situations such as platforms and shelves. Interestingly the four lowest come from the Moray Firth, East Orkney, Barra Head and the Butt of Lewis. These are all east-facing areas, in whole or part, and thus sheltered from the direct effects of strong Atlantic storm-wave currents. They are also at the 'downstream' ends of large expanses of carbonate and may well be the distal ends of carbonate transport paths.

(c) Sorting

Average values for sorting (Table 15) range from 1.0 to 2.3 units but no consistent pattern emerges. This may be partly due to severe problems in visually estimating sorting, and partly to the complexities of hydraulic sorting of shelly material, which is strongly related to grain shape and bulk density besides grain size (Maiklem 1968, Channon and Hamilton 1975; also pp.175–179).

(d) Roundness

The higher roundnesses (Table 16) are associated with deposits either exposed to the open ocean and therefore subject to severe wave currents or to severe tidal currents, or both. Roundness, which reflects abrasion (Blatt et al. 1980, pp. 81-84), must be related to the total time during which the grains were moved by the currents. This will depend on (*i*) the frequency of occurrence of the currents at any given location and (*ii*) the total time during which the currents acted on the grains (before removal to, or burial in, a more inert environment). Thus two different depositional settings are likely to yield very high roundness values: (*i*) oceanward banks subject to strong oscillatory currents but little unidirectional movement (resulting in regular agitation but no rapid movement along a transport path), (*ii*) tidal sandbanks along or at the end of transport paths, where sediment becomes recycled (pp. 242-244) and also where wave agitation is common.

These considerations explain the observed hierarchy of roundnesses (Table 16) and why the open platform sediments show lower values than those from the types of bank described above. Thus the platform sediments are presumably in slow transit and not subject to attrition by protracted current activity as occurs in some other places (p. 195).

(e) Polish

Average values for the degree of polish on the carbonate grains (Table 17) range from 1.0 to 4.0 units. Despite doubts about the reliability of polish assessments (p. 34,36), there is a crude relationship with the inferred degrees of exposure to strong currents. Consistent with this is the reasonable correlation between roundness and polish (p. 166).

(f) Stain

Staining averages range from 0.4 to 4.0 units (Table 18). Although no relationship with the physical environment is immediately obvious, it may be significant that the sediment from all three large tidal sandbanks showed higher average values than the sediments nearby (Table 7).

Thus, at least in these cases, the staining may have been caused by aerated and agitated water at the seabed. This should produce oxidising conditions necessary for precipitation of (iron) oxides on the skeletal debris, a process known as halmyrolysis (Owens 1981, Swift and Boehmer 1972).

(g) Borings

There is no obvious relationship between the degree of boring of the skeletal debris and physical environment, although it seems likely that the seabed microenvironment will have a major impact on the nature and behaviour of boring organisms (Table 19; see also p.34,35).

(h) Maturity Index

Offshore ocean-dominated banks and strongly tidal coastal sandbanks and sand sheets have the highest Maturity Indices (Table 20; see pp. 35-36 for derivation of M). There is a clear relationship between Maturity Index and the degree of current activity undergone by the sediment. As will be seen (p. 168), analysis of the relationships between the various petrographic properties supports this. Thus the Maturity Index is taken to be a function of the magnitude, frequency and duration of current activity. While the Maturity Index will not simply increase with age, age will be one of the factors affecting it.

(6) Textural differences between deposits (>75% $CaCO_3$) and surrounding sediments (<75% $CaCO_3$).

The two characteristics which show consistent differences between carbonate deposits and other sediments are those most clearly associated with current activity. Thus (*i*) grain size of the carbonate deposit is higher than for that of the surrounding material, and (*ii*) all except two of the carbonate deposits show higher degrees of roundness (Table 21). This exemplifies the closer linkage of the carbonate deposits with high degrees of current activity than those of other shelf-sediments.

Other characteristics vary less consistently. Polish in the carbonate deposit is often greater than in more terrigenous sediment, but this is not always so. In the Inner Hebrides, Stanton Banks and the Orkney and Shetland area, staining is more intense in the deposits than in the surrounding sediments, whereas on the rest of the Hebridean Shelf, Northern Shelf and Moray Firth the reverse is true. Differences in degrees of boring and sorting are inconsistent over the whole area.

The cumulative effect of these features is to produce two categories of deposit: (*i*) those with Maturity Indices less than in the surrounding sediment, and those with Maturity Indices which are greater (Table 21). The manipulation carried out here on such crude textural data is of course very tentative. But it may be significant that those deposits with Maturity Indices lower than in the surrounding sediments appear to be those lying close to production sites, where the carbonate debris is being fed into transport paths which show decreases in $CaCO_3$ content in the sediments downstream as the carbonate is dispersed. Conversely, many apparent sites of deposition and accumulation (eg. tidal sandbanks) have high Maturity Indices.

(7) Inter-relationships between individual petrographic characteristics

(a) Introduction

Scatter diagrams have been constructed and correlation coefficients computed (Till, 1974 and Nie et al. 1970) for average sample depth, proportions of constituents and textural characters (Table 22).

The significant correlations are discussed below. These results provide useful corroboration for many of the deductions made in the previous sections (2-6).

(b) Correlations with water depth

Water depth shows a reasonable correlation of -0.5598 (P=0.002) with barnacle content (Fig. 114), +0.4346 (P=0.017) with bryozoan content (Fig. 115) and -0.4912 (P=0.007) with the proportion of calcareous algae (Fig. 116). These data quantify the broad association inferred between barnacles and shallower near-shore conditions (p.150), calcareous algae with coastal conditions (p.154) and bryozoa with deeper, more offshore, shelf environments (p. 156).

(c) Correlations between components

Because, when dealing with percentages, there is inevitably an in-built negative correlation between the proportion of one component and another, only positive and very strong negative correlations are taken as meaningful.

There is a low correlation of +0.3819 (P=0.033) between foraminiferal and echinoid contents (Fig. 117), and a moderate one of +0.4741 (P=0.010) between foraminifera and bryozoa (Fig. 118). This is logical, as all three components are indicators of open shelf, low current conditions (pp.152-154). There is also a low correlation of +0.4448(p=0.015) between barnacles and calcareous algae, reflecting their association with coastal environments(pp.150 & 154).

The strongest negative correlations are shown by barnacles versus echinoids (-0.5794, P=0.002, Fig. 119), barnacles versus bryozoa (-0.5974 P=0.001, Fig. 120) and bivalves versus gastropods (-0.6517 P=0.000, Fig. 121). The negative correlations involving barnacles are environmentally significant because barnacle debris is a good indicator of shallow coastal conditions (p. 150) and echinoid and bryozoan debris of deeper offshore deposits(p. 152). The good correlation for bivalves versus gastropods is not easy to explain because neither has been recognised as a particularly good environmental indicator.

(d) Correlations between grain characters

High correlations are found between roundness and polish (+0.7960, P=0.000, Fig. 122), and boring and polish (-0.6058, P=0.001, Fig. 123). These probably reflect the partial relationship of the three characters with the degree of current working. Least obvious perhaps is the negative correlation between polish and boring, on the face of it attributable to the frequent motion of the particles rendering them less susceptible to boring but more prone to abrasion. However this conclusion must be treated with caution because the recognition of a grain as "well polished" is difficult if it is also extensively bored. Thus 'operator error' may lead to polish and boring being, to some degree, mutually exclusive.

As expected from these relationships, the Maturity Index proves to be highly correlated with roundness (+0.7057, P=0.000, Fig. 124) and polish (+0.5668, P=0.002, Fig. 125). No relationship with boring is detectable.

Another interesting outcome of this statistical approach is the emergence of a high correlation between staining and the Maturity Index (+0.7353, P=0.000, Fig. 126). This is puzzling because there is no recognisable correlation between staining and the other grain characteristics which make up the Maturity Index. As seen, the processes of staining are poorly understood (p. 161) but the correlation does apparently support the notion that the Maturity Index is a reflection of the sedimentological history of the carbonate. Staining must have some relationship with age (p. 34), but exposure to well oxygenated waters may also be important (p. 162 ; also p. 167 , below).

(e) Correlation between component proportions and grain characteristics

Several interesting relationships are found between the occurrence of certain components and textural characteristics of the carbonates. Thus the percentages of foraminifera are inversely correlated with average grain size (-0.5815, P=0.001, Fig. 127). This is a consequence of the fineness of foraminiferal debris. Barnacles show a positive correlation (+0.5587, P=0.002, Fig. 128) with staining. Wilson (1982) noted that they were often particularly heavily stained compared with other material. Hence the correlation may reflect a chemical preference of iron oxides for barnacle debris. On the other hand it might equally relate to staining in the well oxygenated wave-dominated coastal zones because these are also the places where the production of barnacle debris is highest (p. 150).

Serpulid content correlated with roundness (+0.4866, P=0.008, Fig. 129). This is also reflected in the Maturity Index (Fig. 130) and may result from the high durability of serpulid debris leading to enrichment in more mature sediments. If so, then composition, in particular serpulid content, can also indicate maturity.

Bryozoan contents are inversely correlated with staining

(-0.6501, P=0.000, Fig. 131) and boring (-0.4644, P=0.011, Fig. 132). The former may arise from many bryozoans' preference for seabeds sheltered from vigorous current activity because these are often places where the water is less well oxygenated. Converse to the relationship between barnacles and staining, this further supports the theory that staining is produced by halmyrolysis (p. 162). The negative relation between bryozoa and boring may only indicate the vulnerability of bryozoa to complete disintegration when attacked by boring organisms. Resulting from these and poorer correlations with other grain characteristics, the bryozoan contents are negatively correlated with Maturity Index (-0.5190, P=0.005, Fig. 133).

Foraminifera correlate negatively with roundness (-0.5238, P=0.004, Fig. 134), doubtless owing to their removal by almost any degree of current working. This, and other poorer correlations with other characteristics, combine to give a negative correlation (-0.4311, P=0.018, Fig. 135) for foraminiferal content versus the Maturity Index.

The above observations on bryozoan and foraminiferal content give further support to the concept that composition can be a useful indicator of the maturity (or immaturity) of a bioclastic carbonate sediment.

(f) Factor Analysis

Principal components were computed using a Varimax rotated factor matrix (Nie et al. 1970) a process in which the

correlation coefficients are used to detect underlying relationships between the variables. All the quantified variables were analysed except Maturity Index, which is artificially derived from the grain characteristics.
Of the four main factors derived (Table 23), the first two account for 65% of the variation in petrography of the sediment.

Factor 1 shows a strong negative relationship with barnacle content, calcareous algal content and staining, and moderate to strong positive influences on depth, echinoid content, serpulid content, bryozoan content and, to a lesser extent, foraminiferal content. This factor is therefore closely related to offshore conditions as opposed to nearshore conditions.

Factor 2 is strongly and positively related with grain size, sorting and calcareous worm content, and moderately with stain and polish. On the other hand it shows strong negative relationships with bryozoan and foraminiferal contents and a small negative relationship with echinoid content. This factor thus appears to be closely related to the maturity of the sediment. Indeed all the characteristics used for the Maturity Index are positive in the case of Factor 2, four of them showing moderate to strong relationships (see above). The Maturity Index does indeed seem to be a reasonable measure of carbonate sediment maturity.

(8) Discussion

(a) Summation

(i) The biogenic compositions of the carbonates broadly reflect the environments in which they occur (Table 24). This was also concluded by Boillot (1965), Brown (1979) and Wilson (1982), but it is somewhat contrary to the views of Bosence (1979a, b) and others. It can also indicate the maturity of the sediment. Bryozoan, echinoid and foraminiferal debris are more abundant in the immature sediments; serpulids more so in the mature sediments.

(ii) The textural parameters size, roundness and polish can be used to measure the degree (i.e. magnitude and duration) of current activity which the sediment has undergone. Visual assessment of sorting does not appear to produce any useful data. The degree of iron staining results from a complex process probably involving the carbonate particles' total duration in well oxygenated waters agitated by currents. By contrast, the degree of boring may reflect the time during which grains have remained static and vulnerable to attack by organisms.

(iii) A Maturity Index, calculated on the basis of the textural parameters, does provide information on the maturity of the sediment, which in turn reflects the local sedimentological environment of the deposit.

These findings will be further exemplified in Chapter 4 and integrated with other data on sediment transport patterns.

(b) Implications

(i) Although the carbonate sediments consist of debris which is predominantly allochthonous in the literal sense, their make-up does vary with the local environment. This implies that they are autochthonous on the broader scale. Their frequently close association with obvious sites of carbonate production (commonly rocky areas) supports this interpretation.

The above does not necessarily mean that the death assemblages in these carbonates accurately represent the living fauna and flora of the district. Preferential breakdown of some materials, mixing of debris from different microenvironments, and current sorting of coarse robust material from finer and more delicate material probably must take place as stressed by Bosence (1979a,b). Nevertheless even in strong currents, such as around tidal sandbanks, the imprint of the original assemblage will probably still be recognisable in the final downstream assemblage, however modified.

This leads to the problems of assessing the nature and the extent of carbonate transport, and of identifying which deposits are sites of true accumulation (carbonate input>output). Indeed if the deposits are essentially autochtonous, is there any widespread net carbonate sediment transport?

The Maturity Index (M) and its contributory textural parameters may help to solve these problems.
Deposits with high M's are likely to be on sites of accumulation, either at the ends of transport paths or (where there is a local pattern of sediment recycling) along them. Conversely, deposits showing lower M's should be more proximal to production sites, either accumulating under weaker current conditions or feeding carbonate transport paths.

Further light can be shed by evaluating the differences between the Maturity Indices of the carbonates and those of less calcareous sediments surrounding it. If the latter have higher Maturity Indices, then it is logical to conclude that they are receiving material from the carbonate deposit. If the reverse is true then it is unlikely that there is dispersal from the deposit.

In the following Chapter (4) these principles, with other data and theoretical predictions, will be used to interpret the sedimentology of the carbonates on the SCS.

Chapter Four

SEDIMENTOLOGY

I INTRODUCTION

The previous chapter was mainly concerned with the characteristics of the carbonate sediments. Only brief references were made to the likely local patterns of sedimentation. These local patterns will now be further investigated and integrated with the regional picture of carbonate production, transport and accumulation on the SCS. To achieve this, hydrodynamic considerations and the inferred current activity on the shelf must be married with the known distribution and behaviour of the carbonates, their textural characteristics and associated bedforms.

Some years ago Channon and Hamilton (1976) attempted this for the Southwestern Approaches, but there was then only a poor understanding of the combined effects of oscillatory and unidirectional currents. Subsequently Owens (1979, 1981), in a detailed study of part of the North Sea, used petrographic analysis to describe a dynamic sedimentary environment, showing distinct sediment dispersion patterns. He found that a combination of generally weak tidal currents with geologically frequent and strong oscillatory currents produced patterns reflecting significant topographic control. Fine-grained, dominantly terrigenous anaerobic sediment accumulated in the basinal areas, and coarser, more calcareous aerobic sediments on the highs. These show a typical temperate "foramol" (Lees and Buller 1972) skeletal carbonate fraction. Owens concluded that carbonate productivity was probably greatest on well-washed oxygenated highs (where in any case the terrigenous sedimentation rate was low or zero). There was thus slow, *in situ* accumulation of coarse carbonate and a slow dispersion of finer carbonate into the surrounding sediment. Owen's conclusions most relevant to the present work may be summarised as follows:

(a) The superficial sediments of the North Sea are in dynamic equilibrium with the prevailing modern physical environment, most importantly, the occasional (but geologically frequent) severe storms and their consequences. But they are not necessarily in equilibrium with normal day-to-day conditions.

(b) The most significant carbonate sediment accumulation takes place on bathymetric highs where, owing primarily to the higher currents, terrigenous sedimentation is lowest and biogenic production highest.

These findings can be applied to the north and west SCS. Thus (a) supports the notion that with such severe exposure to storm-waves from the west, seabed oscillatory currents will play an important role in transporting sediment across the shelf, including the deeper offshore parts where tidal currents are less extreme. Wave and tidal current activity are commonly more extreme than in the North Sea (Figs.12&13) and topographic highs are widespread (Fig. 3), some making large platforms. These, by applying (b), would be expected to show large areas of carbonate, which is indeed the case.

II HYDRAULICS OF SKELETAL CARBONATE TRANSPORT

(1) Importance

The temperate carbonates on the SCS are essentially mobile deposits. Varying with place and time, bioclastic debris is either accumulating or dispersing in direct response to the hydraulic regime; and its production is also closely dependent on that regime. This contrasts with many warm water carbonate buildups (e.g. reefs) which are "passive" in that they result from *in-situ* biological productivity and are subject to limited physical reworking.

Scottish carbonates must therefore be treated as integral parts of the whole sedimentation pattern on the SCS, bioclastic and terrigenous.

Two useful distinctions can be made between the carbonate and terrigenous grains:

(a) Carbonates on the shelf at depths <100-120m must be overwhelmingly post-glacial, and mostly postdating the rapid rise of sea-level which ceased about 6000 years ago (p. 15). Any post-mortem textural modifications are therefore responses to the recent environment (pp. 32-36& 170). Hence the carbonates are neither relict nor palimpsest. For the terrigenous debris this is not necessarily true. Little surface sediment on the shelf above storm-wave base (<200m) can be considered relict. Some is undoubtedly reworked glacial sediment and might be palimpsest (see Swift et al. 1971).

However Owens (1981) has shown that for the North Sea, post-glacial reworking, redistribution and chemical activity is so important that even this is unlikely.

(b) Carbonate grains are generally far from spherical. Preponderantly bits of bivalves and barnacles, they are commonly platey, but all manner of other shapes occur - irregular, blocky, nodular, and prismatic etc. (Lees et al. 1969, Maiklem 1968). As a result their hydraulic properties are extremely different from those of quartz and spherical grains, on which most theory and experiment still depend. Conventional grain size analysis cannot therefore be used directly to determine current velocity thresholds, suspension criteria, transport rates or hydraulic sorting (Channon and Hamilton 1976).

From (a) it follows that a study of the textural characteristics of the skeletal carbonates should throw light on their physical environments. This has been confirmed by the present work (pp.170-172). However (b) raises serious obstacles to estimating the amount of sediment transport involved in carbonate production and accumulation.

Before attempting to assess the hydraulic behaviour of carbonate grains on the SCS, it will be advantageous to recall the nature and reliability of the information which must be used. This falls into five categories, summarised below.

(i) Particle size was analysed in terms of:

(A) the proportions of mud-,sand-and gravel-sized material by conventional sieving (PSA:p. 33) and

(B) visual estimates of the range of size from which a number representing the mean could be extracted (p. 31).

(ii) Particle density which, reflecting the amount of void space and influenced by the chemical composition, varies considerably from 2.95 (pure aragonite) to 1.6 (Jell et al. 1965).

(iii) Current velocity which varies rapidly in time and space. Surface tidal currents indeed change hour by hour, week by week etc. (pp.22-24) and over such short distances that estimated velocities are liable to appreciable errors. Additional errors can occur when near-seabed velocities have to be inferred from those at the surface. The lack of measurements of subsurface currents and seabed roughness (see below) thus restricted the work to empirical relationships like those derived by vanVeen (1938). Shear velocity (U_*) cannot be calculated from the Kerman-Prantl equation (Channon and Hamilton 1976) as this requires subsurface current data. An attempt to limit these problems was made by deliberately underestimating the maximum velocities. The frequency of these velocities is also crucially important.

Similar problems were encountered over seabed oscillatory current velocities. Again the maxima were intentionally underestimated. The frequency of occurrence of different current strengths (p.25-26) is here of paramount importance.

(iv) Seabed roughness, which influences threshold and current velocities (Channon & Hamilton 1976). Sediment particle size, bedforms and general seabed morphology will all have an influence. In the absence of subsurface current data which can be used to

quantify this, and in view of its intense variability over the SCS, it has been deemed safer to ignore roughness.

(v) Salinity and temperature which, as discussed previously (pp. 28 & 27), vary considerably in place and time.

Much intricate mathematical information is available for estimating hydraulic thresholds (grain behaviour, velocity profiles, Reynolds Numbers, and nearbed shear stresses etc.) but the nature of the SCS data does not justify deploying all this. So here hydraulic information is assimilated into a basic form, and used empirically in combination with the best possible interpretations (from other data) of carbonate transport in the Fair Isle Channel and elsewhere on the SCS.

(2) Hydraulic equivalence of carbonate grains

The vast differences between the settling velocities of skeletal and solid spherical carbonate grains were highlighted by Maiklem (1968; and Fig. 136). He demonstrated that the settling velocities of plates 2mm-8mm in maximum diameter (and probably greater) are similar to the theoretical velocities of calcite spheres between 0.5 and 1.0 mm. For some platy shapes there was no increase in velocity with increased maximum diameter. Other common shapes (rods and hollow spheres) showed similar differences, but to a lesser degree. Hence a current that produces a well sorted quartz sand with a 0.5-1mm size range might produce a carbonate gravel made up of particles between 2mm and 10 mm in size, Visually this would appear poorly sorted, but hydraulically it it would be well sorted. The problem was recognised by Channon and Hamilton (1976) who tried to solve it by carrying out size analysis in a large sedimentation column (Channon 1971). Their approach may be the best way of making hydraulic sense of carbonate grain size, but the equipment was not available for this present project.

Instead therefore, Maiklem's graph (Fig. 136) has been used to convert grain sizes of platy carbonates into their spherical quartz equivalents. Threshold velocities are then interpreted from the conventional threshold diagrams (see below), many of which are for spherical quartz grains.

(3) Carbonate sediment movement and suspension thresholds

(a) Threshold of movement under unidirectional currents

This threshold has been estimated in two ways:

(i) through experimental comparisons in a flume between shell sand and quartz sand, followed by the appropriate adjustments to the threshold curves for quartz sand to give the correct threshold values for carbonate sand;

(ii) by converting carbonate grain sizes to hydraulically equivalent quartz sizes with Maiklem's graph (Fig. 136) and using these for obtaining threshold velocities from published data on quartz grains.

Threshold comparisons were made in a flume between three sieved size ranges of quartz sand/gravel and shell sand/gravel (58-037-2, see Table 38). It was established that, for sizes up to 4 mm, the carbonates' thresholds were about half those of similar sized quartzes. This is consistent with Maiklem's curves which indicate that, up to a size of 4 mm or so, spherical quartzes have settling velocities about twice those of platy carbonates. However, for larger sizes his graph suggests that the difference increases to three times or more.

The uses and pitfalls of threshold diagrams are thoroughly discussed by Miller et al. (1977). They prefer the usage of dimensionless parameters such as those of Shields (1936) and Yalin (1972) rather than the diagrams of Sundborg(1956) and Hjulström (1935, 1939) which apply only to specific physical conditions. Thus Sundborg's (1956) diagram (Fig. 137) applies strictly to fresh water at 20° C. However for simplicity, and bearing in mind the approximations for current velocity, particle size and hydraulic equivalence, and the objectives of this exercise, it has been adopted for estimating threshold velocities. The major difference between the experimental conditions and those at the SCS seabed is the greater seawater viscosity (due to lower temperatures), which will slightly raise thresholds (e.g. see Belderson et al. 1982, fig. 3.4).

To summarise, carbonate sediment thresholds can be estimated either *(i)* directly through Sundborg's graph, using hydraulically equivalent quartz grain size, or *(ii)* by using the added curve for platy carbonate grains which I have constructed from flume results and Maiklem's (1968) graph.

(b) Oscillatory and combined oscillatory and unidirectional currents

Estimation of threshold velocities under the combined effects of oscillatory (wave induced) currents and 'unidirectional' (tidal) currents has been virtually impossible until recently, owing to the lack of experimental data. Inman and Bowen (1963) had already observed sediment transport under combined wave and unidirectional currents but concluded that the relationships were exceedingly complex. Hence Channon and Hamilton (1976) were obliged to treat tidal and wave currents separately using the threshold diagrams of Manohar (1955) and Inman (1949).

Some of the first experimental results were obtained by Hammond and Collins (1979) who compared thresholds under unidirectional, oscillatory and combined currents of the two (Table 25). They found that for a given particle size *(i)* the threshold velocity under an oscillatory current was higher than under a unidirectional current, and *(ii)* the threshold velocity of a unidirectional current was reduced if an oscillatory current was superimposed, and vice-versa.

Hammond and Collin's results (Table 25) are arranged so that the equivalent unidirectional threshold velocity is known for a series of combinations of different wave and unidirectional threshold velocities. Hence it is surmised here, that given the velocities of an oscillatory current and a superimposed unidirectional current, a single unidirectional velocity can be derived from the Table which, in terms of particle movement capability, would have the same effect as the two aforementioned currents combined. This value can be used directly in a conventional threshold diagram. It will be referred to as the 'combined equivalent unidirectional velocity' or 'CV'.

The experimental work represents a significant advance in our understanding of the problem. But, in order to estimate bottom-current thresholds and transport capabilities, some extrapolation and manipulation of the results is necessary.

(i) Cross-check with Strathclyde flume results. Threshold velocities for unidirectional currents and quartz sand were estimated in a flume at Strathclyde using averaged velocities for water depths of 6-12 cm. These were compared with those of Hammond and Collins which were derived using a current meter 2 cm above the sediment surface. The results are crudely compatible (Tables 25&26).

(ii) Cross-check against Sundborg's diagram. Hammond and Collins' experiments were carried out at low water temperatures, and current strengths were measured at only 2 cm above the sediment surface. Comparison of these threshold current strengths with those of Sundborg for 1 m above the sediment in fresh water at 20^{o}C shows that they are about half the velocities measured at 2 cm. (eg. for 0.36 mm

grains, threshold velocity (Sundborg) = 44cm/sec, threshold velocity (Hammond & Collins) = 22 cm/sec.) This is also compatible with van Veen's (1938) relationship derived for larger fluid thicknesses. Hence the relationship $V_{1.0} = 2x\ V_{.02}$ will be used for converting the velocities of Hammond and Collins ($V_{.02}$) to estimates of the velocities 1m above the seabed ($V_{1.0}$) on the SCS.

(iii) Empirical relationship between CV and its two components. By converting the velocities of Hammond and Collins 2 cm unidirectional current data to velocities for 1 m above the sediment surface, it can be seen that Hammond and Collins' velocities at 2 cm were equivalent to 14 to 54 cm/sec at 1m above seabed. Estimated tidal velocities (TV) on the SCS exceed these values in some places. Furthermore, the oscillatory current velocities (WV) quoted by Hammond and Collins only range from 3 to 24 cm/sec whereas estimated maximum wave velocities on the western SCS are up to 120 cm/sec.

Wherever possible the experiment-based velocities will be used directly, but for estimating CV from higher current velocities a crude empirical relationship had to be derived from the data available. As can be seen from Table 25 , for wave periods of 5 secs,

$$CV_{.02} \stackrel{\frown}{=} TV_{.02} + 0.3WV \qquad \text{-------}(A)$$

and for wave periods of 15 seconds

$$CV_{.02} \stackrel{\frown}{=} TV_{.02} + 0.7WV \qquad \text{-------}(B)$$

(It should be noted that the empirical relationship does not hold for 5-second wave currents only, when TV=0). The prime importance of the wave period is clear. Oceanic storm-waves experienced north and west of Britain show periods of up to 15 seconds and more locally derived storm-waves have periods nearer 5 seconds (Draper 1980).

Now because tidal current velocities at 1 m above the seabed are the basic source in this work (i.e. see CDSS sheets) the empirical equations can be converted, using $V_{1.0} = 2V_{.02}$, so that for 5 sec wave periods:

$$CV_{1.0} = 2\left(\frac{TV_{1.0}}{2} + 0.3WV\right)$$

giving $$CV_{1.0} = TV_{1.0} + 0.6\ WV \qquad (C)$$

and for 15 sec. wave periods:

$$CV_{1.0} = 2\left(\frac{TV_{1.0}}{2} + 0.7WV\right)$$

giving $$CV_{1.0} = TV_{1.0} + 1.4\ WV \qquad (D)$$

It must be stressed again that CV does not represent a real current velocity. The "combined velocity" is merely a provisional device for estimating particle movement from conventional threshold diagrams, given oscillatory and tidal current velocities. This is done simply by calculating $CV_{1.0}$ and applying it to, say, Fig.137 .

Obviously the relationship derived from Hammond and Collins' results can only justifiably be used where the direction of wave oscillation is parallel to the unidirectional current direction. It is not clear what the relationship would be if, say, they were perpendicular to each other. Their experiments also take no account of the direction of wave propagation, which itself can produce sediment drift (Komar 1976a).

Although Hammond and Collins' work therefore needs further clarification and elaboration, their experimental oscillatory current threshold velocities agree with those of Komar and Miller (1973, 1975). Their data are very useful and are used here in order to advance our understanding of carbonate sediment transport on the SCS as far as possible.

(c) Suspension criteria

McCave (1971a)used the work of Bagnold (1966) and others to demonstrate that in the southern North Sea large amounts of sand finer than 0.23 mm diameter are transported in suspension. For suspension, he assumed that

$$\theta = \frac{CV^2}{gD}$$

where θ = non dimensional shear stress

$C = 0.4$ to 0.19

V = settling velocity of sediment grains

D = diameter of sediment grains

g = acceleration due to gravity = 980 cm/sec^2.

To utilise McCave's 'fig. 13' (Fig. 138) the θ: grain diameter graph, with its suspension transport boundary has been converted to $U_{1.0}$: grain diameter (Fig.139) using

$$\theta = \frac{\Gamma o}{(e_s - e_f)\ gD}$$

to calculate Γo (total shear stress) where,

e_s = density of grains (taken here as 2.65 - but this is high for some material eg. barnacles)

e_f = density of fluid (water 1.0 g /cm^3 at 20^oC)

then, friction velocity (U_*) can be calculated using

$$U_* = \sqrt{\frac{ro}{e_f}}$$

Thus McCave's suspension diagram can be replotted on the U_* : grain-diameter diagram and this transposed to that for $U_{1.0}$: diameter (Miller et al. 1977, figs. 3, 6). The final plot, together with the equivalent bedload threshold of carbonate grains, is also shown in Fig. 139. McCave (1971 a) concluded that a critical suspension curve based on C=0.19 was more appropriate than that of Bagnold (1966) based on C=0.40.

Using McCave's curve it is clear that currents of 20-40 cm/sec (1m above the seabed) will transport quartz up to 0.23 mm diameter in suspension. This is equivalent to suspending shelly particles up to 1mm. For carrying larger sizes a sharp increase in current velocity is required. Thus a current of 100 cm/sec will only carry in suspension quartz grains up to 0.28 mm in diameter and shelly carbonate grains up to 2 mm. The massive increase in velocity required for suspending only slightly coarser grains will be referred to here as the 'suspension barrier'. Beyond it the critical suspension curve flattens again so that, for example, a current of 200 cm/sec can suspend quartz grains of 0.5 mm, or carbonates larger than 5 mm.

The suspension barrier effect has some far-reaching consequences on sediment transport and grain size distribution. These will be discussed later (pp.192-193).

(4) Application of predicted conditions to carbonate thresholds and suspension criteria

On the basis of the above relationships, and given specific wave and tidal currents, it is possible to gain some idea of what movement of carbonate sediment may be possible. But on entering the natural environment we are confronted with another severe complication. This is the independent variation of tidal and wave currents over time.

The subject has been discussed for each type of current (pp. 22-24 and 25-26) and, where possible, illustrative values quoted (Carbonate Deposit Summary Sheets) which suggest their frequency of occurrence. However, to produce a long-term $CV_{1.0}$ frequency diagram by combining the frequency:current strength diagrams for waves and tides would be very lengthy and complex and could not be attempted at this stage. Instead, the likely values of $CV_{1.0}$ that a locality might experience can be expressed by six terms:

(a) $\underline{CV_{0.1\%,\ PN}}$. This is computed by first obtaining the 'significant peak particle speed '(SPPS) from the appropriate of Draper's (1967) curves (Fig. 13 & p. 25) for 0.1% exceedance (about 1 day in 3 years). Providing the directions of wave propagation and tidal currents are similar, this velocity is used with that for the peak neap tidal current 1 m above the seabed ($PN_{1.0}$) to derive $CV_{0.1\%,PN}$ from formula (C) or (D) (p. 184). This value can be used to deduce the particle size moved by, on average, one wave in four, when a tidal current equal to or greater than $PN_{1.0}$ is running during an extreme storm occurring about once in three years.

(b) $\underline{CV_{0.1\%\ max,\ PS}}$. The 'maximum particle speed' is first obtained by multiplying the 0.1% SPPS by 2.2, - the 'particle speed factor' for a 20-hour storm (Fig. 14 & p. 25). (In fact Atlantic storms often last for 24 hours (Channon and Hamilton 1976)). This is combined (using formula (C) or (D) p. 184) with the velocity of the peak spring tidal current 1m above the seabed ($PS_{1.0}$) to give $CV_{0.1\%\ max,\ PS}$. This then, enables an estimate to be made of the maximum particle size moved by at least one wave during an extreme (24-hour) storm occurring about once in three years.

(c) $\underline{CV_{1\%,\ PN}}$. This is formulated as in (a) except using a SPPS for 1% exceedance. It gives an estimate of the particle size moved during a severe storm (occurring about 3 days per year) by one wave in four, while a tidal current equal to or greater than $PN_{1.0}$ is running.

(d) $\underline{CV_{1\%\ max,\ PS}}$. This is computed as in (b) except using a maximum particle speed based on a SPPS with 1% exceedance. Thus it estimates the particle size likely to be moved by at least one wave during a severe storm (occurring about 3 days per year).

(e) $\underline{CV_{50\%,PN}}$. A SPPS with 50% exceedance is used and combined with PN as in (a). Thus the particle size can be determined which is moved by one wave in four during at least half the year (ie. 'fairly calm' weather), providing that a tidal current of at least the $PN_{1.0}$ velocity is running.

(f) $\underline{CV_{50\%\ max,\ PS}}$. Derived as in (b) except by using a SPPS with 50% exceedance, this demonstrates the maximum particle size likely to be moved during at least half the year (ie. in 'fairly calm' weather).

Together with a knowledge of PNET (which will indicate the duration for which PN is exceeded) a reasonable picture of the extent of sediment movement on the SCS can be gained.

III CARBONATE SEDIMENT TRANSPORT, BEDFORMS, ACCUMULATION

(1) Preamble

The carbonates will now be discussed in the light of the preceding theoretical and experimental conclusions. The area from the Fair Isle Channel to the Moray Firth is described first because it contains substantial carbonate accumulations, and for this reason has yielded the most detailed and reliable information. With a better understanding of the processes which are occurring there, it will then be easier to interpret the rest of the shelf.

(2) Fair Isle Channel - Orkney - Shetland - Moray Firth

(a) Commentary

A large-scale picture of transport around northern Scotland (Fig. 140) has been presented by Lee & Ramster (1981). This is based primarily on side-scan sonar and deductions from known oceanographic conditions (Johnson et al. 1982). Northeast-going transport is postulated on the west of Shetland; and southeast-going transport through the Fair Isle Channel, which becomes more southerly east of Orkney and continues into the Moray Firth. Minor north-going longshore drift, tidally driven, is suggested east of south Shetland. The Pentland Firth is cited as a location of bedload parting (beginning of transport paths in opposite directions).

The new data amplify and support much of this, but cast some doubt on the extent of west-going transport from the Pentland Firth.

(b) Fair Isle Channel

(i) Sediment mobility : movement thresholds. The carbonate in the Channel is very coarse, containing an average of 20% gravel (pp.91&93& Figs.55&56). The large rounded and apparently symmetrical ripples comprise large proportions of carbonate gravels ranging from 2 to 20 mm in particle diameter. Elsewhere, finer material is evident; and as shown in Fig. 57 a 'sprinkling' of sand (probably up to 0.25-1.0 mm size) has been scattered thinly over the seafloor. Water depths are 80m at this camera site.

The calculated CV values for the range of conditions in the west Fair Isle Channel are listed in Table 27 . By referring to Fig. 139 it is clear that, although during 'normal' weather only fine carbonate sand moves, during the severe storms (3 or 4 times per year), depending on depth, carbonate grains 3-20 mm in diameter are in continual movement. Also, within two or three years, currents occur that can move carbonate particles of well over 100 mm in diameter. Specifically, in 80 m of water (Figs.55-57,&Table 28), the sprinkling of sand is on average mobilised for at least 371 hours per year (Appendix 3 , Table 47) and the megarippled gravel for at least 28 hours (Appendix 3 , Table 46).

Thus it appears that all the carbonate debris lying in the Fair Isle Channel is mobile under modern conditions, the sediments and their bedforms being responses to the present long-term current regime.

(ii) Sediment mobility : suspension. The suspension criteria previously proposed (pp.185-186) will now be applied to the sediments observed at 80 m depth (Figs. 55-57) in the Channel using the data in Tables 27 & 28. The particle sizes in the megaripple sediments range from 2-20 mm. For these to be put into suspension, currents exceeding 100cm/sec are required (Fig. 139). Calculated values for CV at this location are listed in Table 28, whence

$CV_{1\%,\ PN} = 69$ cm/sec

$CV_{1\%\ max,\ PS} = 142$ cm/sec

PNET = 41%

Thus during a storm at 1% exceedence, bottom currents will, every one wave in four, over 40% of the time, be carrying in suspension carbonate sand up to 2 mm in diameter (Table 28). Materials coarser than this will be temporarily lifted by the odd wave which drastically exceeds the significant wave height at the surface. Only during the extreme once-in-three years storm (<0.1% exceedence) will gravel-sized materials become frequently suspended because then

$CV_{0.1\%,\ PN} = 90$ cm/sec

$CV_{0.1\%\ max,\ PS} = 189$ cm/sec

During most storms, therefore, carbonate gravel generally moves as bedload. Sand-sized debris on the other hand, must often be in suspension; and that finer than 1 mm will generally be transported in suspension even during mild weather conditions.

These conclusions suggest that the large gravelly megaripples are formed by bedload transport during storms, or at least the waning stages of the most severe storms (see below). They also explain the apparent lack of fine material in the bedforms and the 'sprinkling' of sand observed on rock surfaces(Fig. 57) during calm summer conditions. The latter must normally travel in suspension, even by comparatively mild currents. The effect of the 'suspension barrier' (pp.185-187) is very evident.

(iii) Sediment mobility - bedforms. The megaripples in the Fair Isle Channel (Figs. 55&56), photographed in mid-summer, appear somewhat stable being heavily bioturbated, and penetrated by the encrusting fauna and flora of the rocks beneath (although the latter could also mean they are very transient). However the threshold and suspension criteria previously calculated (Appendix 3, Tables46 & 47) show that all the sediment is mobilised during the strongest winter storms. Clearly then, the megaripples are related in some way to these conditions.

The overiding importance of oscillatory currents and the symmetrical profiles of the megaripples suggest that the megaripples are, indeed, wave-current ripples. This hypothesis is testable by applying J.R.L. Allen's (1979a) analysis of wave-ripple characteristics and orbital current velocities and diameters. Furthermore, bottom-current conditions deduced by Allen's method can then be compared with those derived from the known surface conditions. These calculations which are set out in Appendix 4, Tables 48&49, yield the following:

	orbital velocity U_{max}	orbital diameter d
calculated from surface conditions	1.1 cm/sec	5.9 m
calculated from bedforms	0.78 cm/sec	2.0 - 50 m

Hence, despite the uncertainties of megaripple geometry and the particle sizes, there is good correspondence between the values estimated by the two independent techniques. This suggests that the megaripples are rolling-grain ripples formed during severe storms which occur at least three or four times per year (Appendix 4, Table 48). During the most extreme storms the ripples are probably destroyed completely, but reform during the waning stages of the same event.

(iv) Net transport. These theoretical predictions concerning sediment mobility in the Channel are clearly compatible with direct observations of the seabed. On a geological time-scale all the carbonate sediment is highly mobile. On a short (yearly) term the large gravelly bedforms are stable. During the extreme storms, three or four times per year, the gravel moves readily as bedload, reinforcing the megaripples. Only during the extreme (one-in-three-year) storms will it be frequently stirred up into

suspension. The bedforms are then probably destroyed. Most other storms must either enhance or modify them. Carbonate grains up to 1mm, on the other hand, are put into suspension during most storms, and by spring tides even in calm weather. Thus the gravelly megaripples may have an average lifetime of 3 years, whereas the thin sand sprinkled on the rock surfaces moves as suspended load throughout the year. The only sporadic movement of this coarse material also helps to explain its low roundness (p. 161) and low maturity.

While the frequency of mobilisation of the carbonates has been estimated with some success, it has proved more difficult to estimate their net transport rates and directions. Tidal currents through the Fair Isle Channel are very similar in both directions, and the direction of the stronger varies from place to place. Also, the North Atlantic Drift must exert a considerable effect as it flows eastwards through the Channel. Another problem is that, although here the overwhelming direction of propagation of the bottom current-generating waves is to the east, previous research has produced no clear evidence that deep water oscillatory currents necessarily transport sediment in that direction (Komar 1976a).

The above findings concerning thresholds, suspension and bedforms (pp.191-195) make one thing clear: the transport rates for carbonate sand must be drastically different from those of carbonate gravel. These will now be examined.

Sand up to 1mm. Fig. 139 shows that most carbonate particles up to this size are carried in suspension when the threshold velocity is exceeded. Mobility calculations for material at the TV2 location (Figs. 55-57) indicate that, on average, this sand will be in motion (mostly suspended) for at least 371 hours per year (Appendix 3, Table 47). As seen, the total duration is dependent on the wave-current exceedance of at least one wave in four operating during certain periods. Having a settling velocity of only 4-5 cm/sec, the sand is likely, for much of the time, to remain suspended during the passage of the "other three waves".

In the east, where tidal currents are stronger, the sand may be in motion for considerably longer periods. The net water drift through the Fair Isle Channel is almost certainly northwest to southeast (Lee & Ramster, 1981). Craig (1959) has attempted to quantify this, suggesting a net surface rate of 6-8 km/day north of Orkney and a near-bottom rate of 5 km/day (Fig. 16). Being the only estimates available, these have been used. However, in view of the predictions concerning near-seabed currents (p. 24) the near-seabed drift rate has been calculated from the surface drift rate using van Veen's (1938) formula. This gives 3 km/day.

If we now assume, very simplisticly, that the sand, when in suspension, has the same net drift rate as the water, then its net transport rate is $3\left(\frac{371}{24}\right)$ or 46 km/yr southeastwards.

Sand 1-2 mm. Table 28 indicates that at the TV2 locality this material is put into suspension by at least one wave in four during conditions occurring at the 1% exceedence level (3½ days/year) for an average of 41% of the time. The settling velocity being 4-8 cm/sec under, say, 15-second period waves, it will probably settle out of suspension before the next big wave arrives. An arbitrary adjustment for this fact has been made by halving the yearly average during which the suspension velocity is "frequently" exceeded.

Accepting that, the sand would be in suspension for (84 x 0.41 x 0.5) hours/year or 17 hours/year.

A 3 km/day net drift rate would move the material, on average, $\left(\frac{17 \times 3}{24}\right)$ km/year, or 2.8 km/year in a SE direction.

Gravel > 2mm. Lying beyond the "suspension barrier" this particle size is rarely put into suspension. The only significant periods are during the one-in-three-years extreme storms (Appendix 3, Table 46). On these occasions one in four waves will lift some gravel and the biggest will lift everything. However, with settling velocities of 6 cm/sec and over, this gravel grade can only be in suspension for a total of a few minutes in three years. If it is, say, 1 min/year, then the transport rate is $\left(\frac{1 \times 3}{60 \times 24}\right)$ km/year or 2.7 x 10^{-3} km/year. This is about 3 m per year, in a SE direction. The net transport (if any) of carbonate gravel must therefore be very slow. In fact it is probably more prone to even the slightest net drift which might be caused by storm waves propagated in an easterly direction combining with the unidirectional east-going currents.

Summary of transport rates

1. Fine carbonate sand (platey grains up to 1 mm) passes eastwards through the Fair Isle Channel within five years.
2. Coarse carbonate sand (1-2 mm) moves through the Channel within 70 years.
3. Carbonate gravels migrate very slowly (if at all), at the most only several metres per year.

(c) North Orkney and N. Ronaldsay north bank

(i) Sediment mobility-thresholds. Very pure carbonate (98%) sediment is widespread in this area (pp.99-105). It has a high grain size value (3.9, = coarse sand) and high gravel content (25%). Tidal currents are not well documented, but they are strong (PN=150 cm/sec), and extreme in some places (300 cm/sec off the northern end of N. Ronaldsay). The combination of stronger currents and shallower waters (Table 29) should make the sediment even more mobile than out in the Fair Isle Channel (Tables 27 & 28, & Appendix 3, Tables 46 & 47). During most weather carbonate material up to coarse sand size is almost certainly moved as bedload and suspended load by peak tidal currents, along with some gravel grade material as bedload. Severe and extreme storms may move even more considerable quantities of gravel in suspension. The high mobility inferred would explain the radical differences in sediment distribution recorded by surveys taken during different seasons in different years (pp.99-101, & Figs. 60 & 61) and also the large areas of bare rock.

(ii) Sediment mobility-bedforms. The high mobility predicted is also compatible with the many large-scale bedforms in the area (Fig. 61). In the deeper more offshore parts these are low (1-2 m high) asymmetrical east-facing sandwaves indicating eastward sediment transport (p. 101). On North Ronaldsay north sandbank, however, there is a large sandwave field indicating westward transport. East-facing sandwaves have only been recorded at its southeast tip. Hence the sandbank is located where the local transport direction is west-going, opposing the predominant east-going path to the north. The bank may be sited in a large scale tidal vortex of the kind often associated with tidal flows round headlands (Pingree and Maddock 1979, Langhorne 1982). In that case the bank would have been generated and sustained by a sediment circulation loop, resulting in net accumulation (Fig. 152Bf). Further, the sediment is considerably more mature than that in the surrounding area (Table 21). This is also consistent with a depositional site where, once captured by the sandbank, the sediment remains trapped in a circulatory system for a considerable time. Banks such as this thus also have the highest carbonate accumulation rates known on the SCS (probably at least 540 g/m^2/yr, p. 103).

All the large-scale bedforms are apparently generated by tidal currents assisted at times by oscillatory currents, which increase the suspended load. Extreme currents generated by storm-waves, however, are probably very destructive, particularly in shallow water such as on the tops of sandwaves. Thus the

North Ronaldsay north sandbank, would be expected to lose sand periodically from its crest. This explains why at the end of the winter in 1974 it was broader, with lower sandwaves (5-7m) than in the summer of 1977 (sandwaves 7-15 m). The destructive effect of storms on sandwaves has been noted by Langhorne (1982) and Johnson et al. (1981).

(iii) Summation.

1. Net eastward transport of sediment occurs along the northern margin of the area, probably at rates somewhat faster than those calculated for the Fair Isle Channel.

2. The sediment distribution shows marked seasonal variations due to the extremely strong wave currents experienced by the area during storms. In winter much of the area is bare rocky platform and the North Ronaldsay north sandbank is broader, possibly lower and featured with smaller sandwaves.

3. Net accumulation occurs around North Ronaldsay north bank in response to a sediment circulation loop lying to the northwest of North Ronaldsay. A net carbonate accumulation rate of at least 540 g/m2/yr is probable (CDSS No. 20).

(d) East Orkney, N. Ronaldsay East Bank, Fair Isle Sandwave Field, Orkney Sounds

(i) Sediment mobility-thresholds. The average grain size here

is 2.8 (see Table 2 for scale), considerably less than on the north side of Orkney and in the Fair Isle Channel. The average gravel content is 9%, but this is not evenly spread. Some samples from areas of sandwaves (Fig. 52a) have gravel contents of 33%, whereas the average is 2% elsewhere.

The currents along the east Orkney coast are complicated and not easily predictable. Tidal currents are moderate, but vary rapidly from place to place, particularly in and around the entrances to the Sounds (p. 112). Offshore they assume a simpler N-S pattern. The strongest wave-currents must be generated by winds between northeast and southwest (Fig. 52b and p. 107). Thus Draper's (1967) frequency graphs (Fig. 13) are not directly applicable, and can only be used as guides to the expected bottom currents. Nevertheless Table 30 shows a rapid drop in current velocities eastwards as water depth increases. This is due mainly to a large decrease in the effect of waves.

For most of the year, only the nearshore platform above 50 m is significantly influenced by wave currents (Table 30). These, in combination with tidal currents, are considered capable of moving as bedload carbonate sand up to 2-10 mm in size and up to 3 mm as suspended load. Below 50 m, under most conditions sand up to 1 mm or so should be moved by peak tidal currents, mainly as suspended load. Stormy conditions, however, are apparently strong enough to put gravel-sized carbonate frequently into suspension; and, in deeper water, to move it as bedload. If correct, these predictions explain the large tracts of bare rocky platform observed on the east coast of Orkney, even during the middle of summer (Fig. 61 & Appendix 7, Fig. 4), compared with the sharp increase in sediment cover below 50 m, notable in places for substantial sandwaves.

Inshore, within the Sounds of Orkney, a complex pattern of dominantly tidal transport occurs, although there are shores exposed to the open sea which also experience strong wave activity. Transport paths are complex but probably fairly local. The Stronsay Firth may receive some sediment from the coastal platform. It contains large sandbanks which are presumably accumulation sites.

(ii) Sediment mobility-transport and bedforms. The North Ronaldsay east bank (p.109) lies on the southeast side of the island. It probably results from a peninsula-generated tidal vortex produced during the flow of the southeast-going stream, exactly analogous to the north bank on the northwest side of North Ronaldsay (pp. 102-104). The smaller size of the former may result from irreversible sediment losses into the sandwave field flanking it on the east.

The sandwave field lies on the slope at the edge of the Orkney platform (p.108) where the currents are commonly strong enough to move carbonate sediment up to 1mm in diameter, much of it in suspension. Sand coarser than 1 mm and gravel should be moved as bedload by the stronger tidal and storm-driven currents, and some in suspension. The conditions appear to satisfy the criteria of McCave (1971a)for the formation of sandwaves, viz. (1) adequate tidal current velocity, (2) low to moderate wave activity, (3) strong elongation of the tidal current ellipse. He points out that megaripples superimposed on sandwaves indicate a combination of bedload and suspension transport.

The sandwave field on the slope is the immediate 'dumping ground' for material swept off the Orkney platform. Much of it is initially in suspension (Fig.141). Depending on the time, weather, water depth and grain size, progressively more drops out of suspension and moves on into deeper water as bedload, at progressively slower rates. At any one locality the strongest currents will occur on the crests of the sandwaves. This explains the marked difference in grain size observed between the sandwaves and the surrounding sediment. This is a typical "down transport path" pattern of J.R.L. Allen (1970, fig .5-10).

There is no doubt that sandwave formation is a result of complex physical inter-relationships, and that at the margins of the sandwave zones conditions become absolutely critical. This has been noted during studies of the southern North Sea (McCave 1971a, Johnson et al. 1981). On the deeper water limits of the East Orkney sandwave fields, their formation appears to have been very dependent on original seabed morphology. All along the slope from South Ronaldsay to Fair Isle (at about 80 m depth) a series of strong bedrock seismic reflectors outcrops on the seabed (pp.107-108).Presumably once forming marked ridges they now bear large sandwaves (Figs. 58, 68, 69). Orientations of the sandwaves are often unclear, but probably most are oblique (NE-SW) to the N-S bedrock features. Prior to the sandwaves, therefore, the bedrock features themselves acted as large 'bedforms', causing strong currents over their upstream slopes. Flow separation at their crests and low currents and vortices in their lees (as in Jopling 1965, for ripples) then provided ideal conditions for sandwave formation when sediment was supplied. The Fair Isle sandwave field (pp.92, 93) is a northward continuation of the same zone. Here it is restricted to deeper water (>70m), because of the much stronger influence of oceanic storm-waves on the Fair Isle Channel floor.

Bedforms, which are distributed over much of the East Orkney area, have orientations and facing directions which consistently indicate southward sediment transport on the east side of Orkney (Appendix 7, Figs. 4&6). Further north and east, however, the carbonates spread eastwards into the North Sea well beyond the area investigated (Fig. 19). This indicates a stronger east and southeast component over this part, resulting from currents coming through the Fair Isle Channel.

The eastern, deeper water limits of the deposit are probably sites of net accumulation of fine grained carbonate sediment. Sediment is apparently swept off the rocky parts of the shelf, migrates aross the sandwave field and reaches deeper water. There, it probably moves, to a limited extent, during peak spring currents, but mostly during severe northerly storms when, a few times per year, it is stirred into suspension. Craig (1959) estimated 'near-bottom' water drift as 3 km/day southwards, but if the van Veen (1938) formula is applied to his estimated surface rate of 6 km/day a drift rate of 2 km per day is derived for 1 m above the seabed. On this basis a sediment transport rate of several kilometres per year is possible in the deeper water.

The average petrography of the East Orkney carbonates (Table 4) indicates that they are not very mature ($M=10.05$). This is probably because once material is swept into deeper water it is not extensively reworked, but augmented by considerable quantities of locally produced infaunal debris (bryozoa, echinoids and foraminfera etc.).

(iii) Summary. The coastal seafloor above 50 m east of Orkney is a wave-and tide-swept rocky platform which is kept clear of sediment. It is also probably a site of high carbonate production by bivalves and encrusting organisms. Sediment reaching the northern part of the platform from the Fair Isle Channel and North Orkney areas is accumulating under a peninsula-generated vortex on North Ronaldsay east bank, at probable average rates of no less than 390 $g/m^2/yr$. All the way from Fair Isle Channel to south Orkney, the carbonate sediment is swept eastwards over the edge of the platform, and progressively dumped as the current velocities decrease with increasing depth. This leads to a lateral transition from suspended load to bedload transport of the coarse sand and gravel, which then forms an extensive sandwave field. Beyond this, in still deeper water, the transport direction of the finer sand offshore becomes southwards.

Carbonate production and accumulation within the Sounds of Orkney are essentially localised. Average accumulation rates on the sandbanks in the Stronsay Firth are at least 250-400 $g/m^2/yr$.

(e) Pentland Firth-Moray Firth

(i) Sediment mobility - thresholds. The carbonates in the West Pentland Firth are coarse, with an average grain size value of 3.7 (see Table 4 for scale) and averaging 18% gravel. To the east, at Sandy Riddle, they coarsen to averages of 3.9 and 34% gravel. Beyond Sandy Riddle, along the northwest margin of the Moray Firth, they become finer, with an average of 3.3 and 12% gravel.

The calculated bottom-current velocities and combined equivalent unidirectional velocities (CV) for the Firth (Table 31) demonstrate why the carbonates lie at the limits of a rocky current-scoured channel. On any day of the year in the Pentland Firth, tidal currents alone are capable of carrying sand-sized carbonate of up to 1mm in suspension and at least 2 mm as bedload. Frequently, almost any size of carbonate debris will be carried as bedload. In the centre of the channel, and elsewhere during spring tides or westerly storms, even the gravel may achieve suspension. The carbonate deposits occur at both ends of the Firth where the currents slacken as they pass out of it.

On Sandy Riddle the sediments are very coarse. At its northernmost and shallowest extremity they contain up to 64% gravel; at its southern end, 8%. Surface current velocities vary rapidly across the bank and, combined with sharp bathymetric variations, make the bottom velocities very variable and difficult to estimate (Table 31 , Fig. 142).

During most weather conditions most of the carbonate sand and gravel must be transported as suspended load by tidal currents in the main channel on the northwest and in the channels on either side of the sandbank (Fig.52a,b). On the bank itself the coarser sand moves as bedload, and the finer material still in suspension. As the currents weaken southwards transport will be more and more as bedload. During severe storms the shallower parts of the bank are subject to fiercely destructive wave-action, large quantities of carbonate sand and gravel being lifted into suspension and redeposited lower on its flanks.

In the Moray Firth, along the east coast of Caithness, tidal currents are weaker, so that during calm weather they produce very little sediment movement. During storms, however, sand-sized material must be moved, mainly in suspension, by combinations of tidal and oscillatory currents. Gravel-sized carbonate will only be moved by the strongest storm-waves from the north.

There is a good correspondence between the current and particle size patterns throughout the area. Thus the coarsest sediment lies at the east end of the Pentland Firth, fining southwards into the Moray Firth (Fig. 82d).

(ii) Sediment mobility - bedforms and transport paths. The sandwaves and small sandbanks at the eastern end of the West Pentland Firth deposit face westwards (p. 118). Further to the west they become symmetrical and then degenerate into rounded features (Fig. 72). The western edge of the sandwave field proper apparently coincides with the edge of the carbonate deposit. This is mapped as a very sharp transition from >75% $CaCO_3$ to <50% $CaCO_3$. Although the recorded tidal currents are very similar in both directions, the sandwaves indicate westerly transport over the eastern part of the deposit. However their increasing symmetry westwards suggests zero net transport (Johnson et al. 1982). The area also contains large sandbanks (p. 118). This site may be a zone of bedload convergence, lying between localised westerly transport from the Pentland Firth, and the easterly transport path along the north coast of Scotland.

The calculated near-bottom velocities in this part of the Firth (Table 31) lie in a range capable of producing both bedload and suspended load transport of the carbonate. The sandwaves are therefore in an environment conforming to McCave's (1971a) criteria (p. 203).

The shoal to the west of Dunnet Head is probably generated by a current vortex produced by the west-going stream passing the Head (p.118).

Sandy Riddle, the large sandbank in the lee of the Pentland Skerries (p. 121), is a typical tidal sandbank. The rate of carbonate accumualtion may be at least 581 g/m^2/year. Along most of its length the sandwaves predominantly face west, but in places are symmetrical. The sandbank itself is generally asymmetrical in cross-section, its steep side facing southwest. But halfway along its length is a zone which is virtually symmetrical (Fig. 79). At the north end the sandwaves face east, suggesting a circulation pattern around it like these for offshore tidal banks (McCave and Langhorne 1982). However, the pattern may be particularly complicated because large eddies occur over the bank southeast of the islands (p. 121).

The orientation of the sandbank, used as a primary indicator (Kenyon et al. 1981), suggests that the net sediment transport direction is southerly. However this may be an oversimplification. Sandwaves east of Orkney indicate southward and southeastward transport, so sediment several kilometres offshore probably drifts onto the northeast flank of the bank. However sediment in transport paths closer into the Orkney shoreline is probably captured by the extreme currents of the Pentland Firth and carried rapidly either westward or southeastward according to the tidal current direction at the time. It is important to note that, with near-bottom currents of 140 cm/sec commonly flowing in the Firth for 2-3 hours at a time, carbonate sand and gravel can be carried in suspension for 15 km or more during one 6-hour tidal flow. Thus sediment entering the

Pentland Firth at the east may, within one day, be deposited at either the east or west end. Indeed it may oscillate backwards and forwards between the two for some time, although the net transport direction is probably eastwards. Close links between the deposits of the West Pentland Firth and Sandy Riddle are suggested by their similar petrographies (Table 4), including high maturities.

The band of much finer sediment streaming southwards along the Caithness coast and onto its beaches (pp.126-129) is following a typical longshore drift transport path driven by waves from the northeast combined with tidal currents running parallel to the coast. Craig (1959) identified a net water drift in the same, southwesterly, direction (Fig. 16). He also recognised another stream leaving the coast in a southeasterly direction, cutting across the outer part of the Moray Firth. At its departure point a tongue of carbonate sediment juts out from the coastal strip (Figs. 19&52a), and this does not appear to be due to bathymetric control. This was noted by Owens (1977) who traced it most of the way across the Firth. The tongue does not appear to be bathymetrically controlled and it is therefore likely that carbonate is being transported away from the eastern end of the Pentland Firth along both the southwesterly and southeasterly paths. Side-scan sonar over this region is unfortunately too poor to resolve the bedforms and their transport directions.

The Moray Firth sediments are apparently less mature than those in the Pentland Firth deposits (p. 128). This must be due to the weaker currents, allowing considerable contribution from infaunal producers, and epifaunal input from the rocky shoreline, without extensive reworking.

(iii) Summation. The transport paths mapped by Johnson et al. (1982) are broadly confirmed. However the Pentland Firth is apparently not a zone of straightforward bedload parting.
The West Pentland Firth is probably a zone of bedload convergence deriving carbonate from both west and east. The eastern entrance of the Firth is a zone of bedload 'splitting' because some sediment must go west and some south.

Continual circulation and tidal oscillation of carbonate is taking place both in the Pentland Firth and on Sandy Riddle. Finer material eventually passes out of the system along a southward transport path which itself splits into two.

Both ends of the Pentland Firth are zones of carbonate accumulation, being of the order of 581g/m^2/yr on Sandy Riddle. This is a net rate because there must be steady 'leakage' southwards from the east end.

Carbonate is very unlikely to migrate far west of the Pentland Firth, as this would be against the general eastward transport set up by a combination of tidal currents and storm waves from the west and northwest.

(3) Inner Hebrides

(a) Commentary

Around the Inner Hebrides transport patterns change locally because of the highly varied physical environments. The only substantial transport paths suggested by Johnson et al. (1982) are (*i*) southwestwards through the Passage of Tiree, (*ii*) northwards from the north end of the Passage (a bed-load parting between Ardnamurchan, Mull and Coll separating it from (*i*)), and (*iii*) northwards on the east side of the Little Minch between Skye and Shiant (Fig. 140).

Northward near-bottom movements through the Little Minch were suggested by Craig (1959), with eastward drift on the north side of Coll and Tiree (Fig. 16). Contrary to Johnson et al. (1982) Craig also suggested some eastward drift in the Passage of Tiree.

(b) Gulf of Corryvreckan

Details of the temporal variations in tidal currents are not available (CDSS No. 1). Estimated CV's for the Gulf are calculated on the assumption that peak neap velocities approximate to half the strength of peak spring currents (Table 32). Bottom wave-currents must be very weak during most weather, but severe storms will help to raise significantly the carbonate grain size which can be carried in suspension. Carbonate sediment will be transported as bedload during all peak tidal currents, and during peak neap currents sand will also be in suspension. During peak spring currents carbonate gravel up to 5 mm or more may even achieve suspension.

The extreme tidal currents in the confined channel run out suddenly into open water which deepens rapidly (pp.37-39). Coarse sand and gravel caught in the tidal stream will be dumped over the edge of the platform. Thereafter the sediment is prone to much less current agitation, so the process is probably ireversible. This could account for the low Maturity Index and the large grain size (Table 4).

(c) Passage of Tiree

Calculated CV's (Table 33) show that during storms from the west the carbonate sand and gravel here will be mobilised, much in suspension. During peak spring currents, even in calm weather, sand up to 1mm may be similarly transported. This deduction is supported by the rocky nature of the seabed and the coarseness of the carbonate, which is trapped in the depressions on the rocky platform (pp.39-42). Fine material is presumably carried onto the beaches of Coll, Tiree, Ardnamurchan and Mull.

The bedload parting suggested by Johnson et al. (1982) is located at the rocky, current-swept, northern end of the Passage of Tiree. Their proposed southwest transport by tidal currents along the Passage is presumably based on observations of sandwaves and sandribbons. This opposes the predominant direction of stormwave propagation. Hence, carbonate sediment will be dumped as the tidal currents slacken southwestwards along the Passage. The large fan of carbonate-rich sediment (50-75% $CaCO_3$) lying to the southwest of the deposit might well represent the tail-end of this path (Fig. 35).

The large parallel symmetrical megaripples reported on the northern flanks of the deposit are very similar to those in the Fair Isle Channel (p. 92). Like the latter, they are probably generated during severe storms and are stable under calmer conditions.

(d) Hawes Bank

Currents of similar strengths to those in the Passage of Tiree probably occur over this bank, although it may be more prone to stormwaves and have weaker tidal currents (Fig. 29b). Wave currents are probably the main factor keeping the higher rocky parts free of sediment, enabling high carbonate production. The carbonate debris is swept into gullies and hollows and down the flanks of the bank (p. 43). As mapped, the deposit lies in the southeastern lee of the shoal, where presumably the weakest wave-currents occur. Its position may also be partially sheltered from the predominant east-going tidal stream. The very high maturity of the carbonate (Table 4) reflects the intense, regular, current working which the sediment has undergone.

(e) Inshore deposits: Sounds of Eigg and Iona, Rubha nan Clach, Sligachan-Scalpay.

As can be seen from the data calculated for the Passage of Tiree (Table 33), wave currents generally exert an overriding control over sediment transport on the coastal platforms (depths <50 m). During storms all grades of carbonate sand and gravel are transported and broken down, and the finer material carried away in suspension. Accumulation occurs where there is some shelter from wave activity and where tidal currents are stronger (eg. in the bays along the east and west side of Skye, pp. 58). Sheltered island-coastal channels like the Sounds of Eigg (pp.45-48) and Iona (p. 56) appear to receive some sediment from external sources, mainly as a result of wave diffraction into the channel (eg. Cucci 1979). Within the channels tidal currents are the overriding control on sediment transport and deposition.

(f) Shiant

Bottom-current conditions here are fairly similar to those in the Passage of Tiree (Table 33). Tidal currents, however, are generally stronger and more dominant, and stormwaves play a lesser role because the Little Minch is sheltered from due westerly storms (Fig. 33b). Nevertheless stormwaves from the north and south must be important.

This predominance of tidal currents accounts for substantial sandbanks in the area (p. 53); and presumably the sandwaves seen by Johnson et al. (1982) to indicate northwesterly transport along the southwest side of Shiant. As seen, the strong currents keep the shallower parts of the seabed as bare rock, while the carbonate sediment accumulating in the deposit is a coarse sand and gravel.

(4) West Hebridean Shelf

(a) Commentary

Transport paths along the outer shelf, parallel to the edge, have been suggested by Johnson et al. (1982), but net directions have not been determined. Westward transport of carbonate from Barra Head has been recognised (Ferentinos 1976), and Bishop (1977) suggested that carbonate sand moves clockwise round the Butt of Lewis (pp. 79 & 82).

(b) Stanton Banks

Here, movement of sediment is strongly wave-controlled (Table 34). Exposed to the full strength of Atlantic waves, the Bank's shallowest parts experience sufficient current activity to move all grades of carbonate sand for at least 50% of the time. Gravel must also be removed as bedload and suspended load during storms, accounting for the large areas of bare rock (p. 66). Over the 90 m platform and its deeper flanks, sediment movement will be more restricted to stormy periods. Conditions and transport at these depths will resemble those in the Fair Isle Channel. This is supported by the presence of similar symmetrical megaripples.

The position and shape of the carbonate deposit (Fig.37a) indicate eastward transport on the flank of the shoal. This is probably a response to wave, tidal and gravitational control. The sediment is fairly coarse sand and gravel, and net transport rates are likely to be slow, as indeed they are for the same materials in the Fair Isle Channel (a few metres per year: p. 197). On the Bank the sediment is also very mature (p. 68), reflecting the amount of current agitation it has experienced. Finer sand is probably dispersed eastwards at a faster rate. Indeed, the limited sample data indicates that the sediment east of here is considerably finer (CDSS No. 10, p. 67).

This apparent eastward sediment drift thus opposes the direction of net water drift (Craig 1959), presumably because wave-current transport dominates.

(c) Barra Head-West Hebridean Platform-Butt of Lewis

The calculated values of CV around the oceanward side of the Outer Hebrides (Table 35) show clearly the dominating influence of wave action on carbonate sedimentation. Tidal currents are more important, however, around Barra Head (pp.69-72), the Butt of Lewis (pp.76-79) and the Sound of Harris (p. 74), where they are stronger. During storms carbonate sand and gravel are carried as suspended and bed load into hollows on the platform, leaving the knolls rocky and bare. Once deposited in the hollows the sediment should be sheltered from excessive reworking. This would account for its apparently low maturity. Over these hummocky parts of the platform, therefore, transport may be very localised. Asymmetrical sandwaves are visible on some of the larger patches of carbonate around Barra Head and the Sound of Harris (p. 74), confirming the greater importance of tidal currents at these locations.

In places, fine grained carbonate sand must frequently be put into suspension by peak tidal currents even during moderate weather. This sediment very probably reaches the western beaches of the Hebrides (p. 81) during constructive wave conditions (Appendix 8) and passes eastwards round Barra Head (Ferentinos 1976 and p. 72) and the Butt of Lewis (Bishop 1977, and pp. 78-79).

(4) Northern Shelf and Shetland

(a) Commentary

Net water drift over this extensive area of open shelf appears to be northeastwards under the influence of the North Atlantic Drift (Craig 1959&Fig.16). Sediment transport in the same direction (Fig.140) has been confirmed by Johnson et al. (1982) and Fannin (pers comm.). Johnson et al. also identified a northward transport path close inshore on the southeast side of Shetland. The picture is less clear off the north of mainland Scotland. Craig (1959) and the Admiralty pilot have suggested eastward water movement, while Johnson et al. (1982) propose westward sediment transport away from the Pentland Firth. It is however suggested here (p. 211) that any westward movement will be restricted to the western end of the Pentland Firth, while net regional transport is eastwards.

(b) Cape Wrath

Around Cape Wrath tidal currents are strong enough to transport sediment even during mild weather (Table 36). For much of the year carbonate sand must be transported as bedload and suspended load. During stormy weather carbonate gravel will also move as bedload and to some extent as suspended load.

In view of this, the location of the two parts of the Cape Wrath deposit, on either side of the point (pp.83-85), is interesting. It suggests deposition caused by peninsula-generated tidal current vortexes (Pingree and Maddock 1979). The tidal current data are not sufficient to support this directly but sandwaves on the northeastern deposit face west, against the inferred direction of water and sediment drift. This suggests a local limited bedload convergence and sediment circulation pattern like that proposed for the North Ronaldsay north bank (p. 199).

Curiously, however, the carbonate is apparently not very mature; indeed it seems to be less mature than in the surrounding less calcareous sediment (p. 85 and Table 21). Possibly the deposits are temporary resting sites for sediment as it move eastwards along the coast and perhaps also westwards (p. 85).

(c) Nun Bank and Solan Bank

Sand on the tops of these shoals will be transported during most peak spring currents, and more so during stormy weather, when most of it will be carried in suspension (Table 36, Fig. 139).

The deposits lie on the eastern flanks of the shoals (p. 85,88 and Fig.. 51), sheltered to some extent from westerly storm-waves and the predominant east-going water drift. The flanks are, however, exposed to strong wave-currents and the amount of net accumulation is uncertain.

The carbonate in these deposits is less mature than in the neighbouring sediments (<75% $CaCO_3$), and this, along with the mapped shapes of the carbonate deposit (Fig. 51), supports the suggestions that carbonate debris is dispersing eastwards from them.

(d) Shetland platform; general

Current conditions and transport rates on the Shetland platform resemble those in the Fair Isle Channel (Table 27 and pp.190-198). The main differences are due to the more variable bathymetry around Shetland. Localised carbonate accumulation in the depressions is therefore more common.

The tidal currents are strongest around Foula, Muckle Flugga and Sumburgh Head (Fig. 84), accounting both for the large areas of bare platform and also sandwave fields of thicker carbonate (eg. around Foula).

The coarsest sediments are found in the West Shetland deposit (24% gravel) and these also have the highest maturities in the Shetland area. This may be attributed to the predominant Atlantic storm waves from the west and north. In contrast, the deposits on the east side (Northeast Shetland and Shetland-Out Skerries) experience Atlantic storms from the north only, and North Sea storm waves from east and south.

The proposed northeasterly transport of sediment along the west side of Shetland (p. 190) confirms the paths mapped by Lee & Ramster (1981). The case for northward transport on the southeast side seems possible in view of the strong inshore tidal currents and the predominating North Sea waves from the southeast (Fig. 84) which would cause longshore drift in that direction.

Nevertheless the picture is probably incomplete, because at the northern end of eastern Shetland, southward longshore movement of sediment is likely to result from the more direct exposure to waves from the north (Fig.84).

The very immature sediment in Yell Sound is probably mostly locally derived, although it is possible that some is swept in from the platform at its north and east ends.

(e) Shetland: Balta Sound and St. Ninian's

Balta Sound is another island/coastal channel environment stimulating prolific carbonate production and accumulation (p. 146). Substantial underwater sandbanks and coastal spits have built up in the lee of the island, where wave diffraction and tidal currents combine to form an intense bedload convergence.

St. Ninian's 'island' on the southwest side is a similar environment at a more advanced stage. Underwater sandbanks and coastal spits have grown and merged to form a dramatic tombolo linking the island with Mainland (Fig. 100).

(f) Summation

Data from the carbonate deposits can be integrated with theoretical predictions of carbonate sediment movement in various environments and localities on the SCS.

This has led to the recognition of carbonate sediment transport patterns which are mostly compatible with those mapped on a larger scale by Johnson et al. (1982). A composite map of carbonate sediment transport paths is shown in Figure 143.

Crucially important are the great differences of transport rate between fine sand, coarse sand and gravel. The disparity is extreme between fine sand and everything coarser because the former is largely transported as suspended load. This has far-reaching consequences on carbonate sediment transport and accumulation, and its petrography.

IV RADIOCARBON DATING

(1) Methodology

Large shell fragments are commonly used for the ^{14}C dating of Quaternary marine sediments. Several attempts have been made to date offshore Scottish Holocene deposits using carbonate debris, and to relate petrographical variations (eg. staining) with the ages of the fragments (Table 37).

A major problem in the dating of skeletal carbonate sands and gravels is the size of sample required, viz. several tens of grams (>30 g in the case of the East Kilbride laboratory). This has meant that only composite samples containing hundreds of different grains could be analysed. The results are therefore difficult to interpret unambiguously, because they are only 'average' radiometric ages.

The dilemma is illustrated in Fig.144. A simple time-decay curve is shown for ^{14}C, which has a half life of approximately 5570 years. The age of any individual biogenic fragment is related to the proportion of ^{14}C remaining in the carbonate. However radioactive decay is exponential, and therefore in a bulk sample containing a spread of ages the younger material has a greater effect on the 'average' radiometric age than the older.

Now any bulk sample which contains an even spread of ages will yield an 'average' radiometric age which is that dividing the area under the decay curve into two. Thus a sample with an even spread of materials between 6000 and '0' years old will give an 'average' radiometric age of approximately 2550 years. On the other hand, a sample containing equal proportions of materials from 0 to 12,000 years old will have an apparent age of only 3950 years. Simplistically, a composite sample comprising a 50/50 mixture of zero-aged and infinitely old carbonate would give an 'average' radiometric age of 5570 years (viz. one ^{14}C half life) (D. Harkness, pers. comm).

To avoid confusion, the figures quoted here will be the straightforward 'apparent' radiometric ages. They incorporate the apparent age of Scottish seawater (400 years). To relate them to land-based radiometric ages, 400 years should be subtracted from them. The 'corrected' values are listed in Table 37 .

(2) Average Radiometric Ages - Discussion

The radiometric ages so far obtained on carbonate debris on the SCS range from 10862 yrs to 558 years *. With the exception of shallow water debris from the west coast giving ages of only a few hundred years, all the ages exceed 2752 years, and most range up to 6370 years (Table 37).

The lack of ages younger than 2700 years from the offshore carbonates may be due to one or more of four different factors. Each of these will be discussed in turn.

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*This does not include a check carried out on 'post-bomb' living material.

(a) Continuous mixing and accumulation. Most of the carbonate sediment being mobile (pp.175-223), new material must continually be mixing in with the old. As seen before (p. 225), as it builds up on the shelf the predicted average age of a well mixed sediment which has been accumulating since sealevel stabilised about 6000 years ago is approximately 2550 years. Hence the sample from the Pentland Firth, which gave 2752 years (Wilson 1979a) may exemplify this. Younger ages are unlikely if carbonate production and mixing has been taking place steadily throughout the last 6000 years.

Three of Cucci's (1979) young ages came from whole valves, so eliminating the mixing problem. The barnacle debris comprising the fourth probably came either from very close to a production site and/or from a depositional environment where very little mixing took place. Both situations are common in the Inner Hebrides, where transport paths are often very local; from bathymetric highs to bathymetric lows (pp. 236).

The scarcity of ages under 2550 years is therefore accounted for. But the hypothesis also implies that, if steady accumulation and mixing has been operating for 6000 years, there should also be no ages significantly older than 2550 years. These have, however, been obtained. Some, from carbonates on the deeper parts of the shelf, may reflect the fact that sediment there has been accumulating for 10-12,000 years or longer. Even so, continuous accumulation for 12,000 years still gives a bulk age of only 3950 years. If the sample (C74 144/1) from the Fair

Isle Channel had been produced by continuous homogeneous mixing with fresh material, it would have had to accumulate for several tens of thousands of years to give a radiometric age of 5406 years. However, such a long period of mixing is ruled out by the history of glaciation in the Channel (Flinn 1978).

The samples so far analysed therefore show a definite bias towards older ages. For some reason they contain more 'older' material than 'younger'.

(b) Higher production rates due to warmer climate. From 7000-2500 years BP, the terrestrial climate of Britain was 1-2°C warmer than now (p. 16). As the British terrestrial climate is closely linked to Atlantic seawater temperatures, it may be presumed that the sea was also warmer. This probably sustained a higher biological productivity, and therefore a higher carbonate accumulation rate than now, leading to a pre-2500 years BP bias in the radiometric ages.

(c) Higher production rates during the post-glacial transgression. Carbonate productivity is generally greatest in the shallower, more coastal parts of the shelf. However all the samples except those from the Inner Hebridean coasts were taken from depths greater than 60m. It can be argued that carbonate production was higher at these locations during the post-glacial transgression (12,000-6,000 years BP). Large areas of shelf, presently below 50m, would have been in much shallower water during this period. For instance, one dated sample containing apparently relict barnacle debris was taken from a location on the western shelf at 130 m water depth (Wilson 1982 and Table 37).

One drawback to the argument is the fact that during the transgression there must have been large amounts of reworked terrigenous glacial material around. An abundance of suspended fines and the lack of rocky and shelly substrates may have hampered carbonate production.

(d) Current sorting. As demonstrated, on the SCS carbonate gravel is transported at comparatively slow rates, while carbonate sand, particularly fine to medium sand, moves very rapidly (eg. in the Fair Isle Channel, p. 196). Thus coarse debris may *(i)* move much more slowly away from production sites than finer material and *(ii)* be far less prone to continuous mixing with new material. In an area like the Fair Isle Channel therefore, where the sediment is very coarse and gravelly, much local variation would be expected in the 'average' radiometric ages of bulk samples. They should range from very old to very young. Furthermore, if there has been higher carbonate productivity in the past (as suggested above in (b) and (c)) then some organisms may have tended to grow larger than at present. Possibly, also, the taxa of larger organisms were more common. (For example post-glacial transgressive lag deposits containing large *Arctica* shells have been noted in cores (Allen et al. 1979:- Appendix 6). A greater abundance of large shells etc. would have led to more gravelly debris than now. This would have been much less mobile than the finer debris produced since and would therefore bias the 'average' ages towards the 'older' side.

Wilson's age determinations were carried out exclusively on carbonate gravel (pers. comm.). Moreover, most of the dates so far obtained (Table 37) have used predominantly gravelly material because it is easier to hand-pick this in sufficient quantities for analysis.

(3) Tests on specific fractions from bulk samples.

Wilson (1982) selected barnacle fragments from a shell gravel and obtained a significantly greater age (11560 years), than that of the bulk sample (8335 years). This demonstrated that the original sample contained material with a wide spread of ages.

A more detailed experiment was carried out as part of the present project. The sample used (58-03/2) was from the sandwave zone east of Copinsay (East Orkney deposit), being a coarse sand and gravel containing 84% $CaCO_3$. Further details of its composition are shown in Table 38. Eight different textural-biological components were separated into subsamples (Figs. 145-151) and the radiometric ages of these determined.

The ages are given in Table 37. They show significant variations, with an overall difference of 1,300 years between the oldest and youngest, and the 'age' of the bulk sample was 3900 years. Thus suggests a wide variation in age of components within the original sample. The sediment must therefore have undergone frequent mixing during its history. It also follows that fragments in the subsamples themselves must have widely varying ages.

As discussed previously (pp.170-172 and 32-37), the preservation, size and physical appearance of any one grain depends on its history of burial and reworking, and this will relate very roughly to its age. The experiment shows that the 'heavily bored' and 'well rounded' bivalve fragments are, <u>on average</u>, older than the 'unbored angular' fragments. This supports the validity of the textural criteria used in the petrographic work (pp. 33-35).

However, the barnacle subsamples, selected using staining and grain wear, do not show significant differences in age. This is probably because staining can be caused by a comparatively short event affecting all grains of different ages to the same degree (eg.halmyrolisis, pp.162,167). The admixture of materials of varying ages in the Copinsay sample therefore probably records the sediment's history of burial and reworking. While buried below the seabed, the material was protected from mechanical abrasion and attack by boring organisms. At times the sediment re-emerged in an 'active' zone where the ageing process continued until buried again.

Table 37 also shows that the ages of the biogenic components differ significantly in the order bivalves>serpulids>gastropods> barnacles.

This could have arisen from different combinations of at least five factors: mechanical and chemical durability, length of transport path, post mortem chemical behaviour (e.g. susceptibility to exchange with sea water) and dominant organisms (related to the ecological history of the area).

It will be noted that the shell from a living bivalve gives an appropriately 'young' age, despite being 'post-bomb' material.

Another attempt to identify young and old material in one sample was made on the rock dredge sample NS 15SD. This contained whole, as well as large fragments of *Arctica islandica* valves. Some were grey and heavily bored; others (normally the whole shells) were unbored, clean, white and fresher looking. Two age determinations were made on separate unbored valves, and two each on two fragments of very heavily bored material. The work was carried out at the Harwell laboratory, where less material is required for the analysis compared with the East Kilbride laboratory. The ages are strikingly different: about 1600 years for the unbored, and 5000-5800 years for the heavily bored material (Table 37). This provides another instance of a wide range of ages in the carbonate at one general location.

Two qualifications need to be made. First, the sample was obtained using a rock dredge which presumably collected material along a line of several hundred metres; and possibly dug tens of centimetres below the surface. Secondly, the material came from an area of shelly terrigenous sand (17% $CaCO_3$). It was not, therefore, necessarily typical of a mobile carbonate deposit.

(4) Future work

Further progress towards understanding post-glacial carbonate sedimentation on the SCS will require a considerable extension of radiocarbon work. The following lines of approach are proposed:

(a) Increased number and geographical spread of bulk-sample age determinations.

(b) Similar experiments to those described above, but with even larger original samples and more rigorously selected grains for subsamples which should be of the minimum size required for analysis. If possible, gravel-sized material, particularly coarse gravel (say, >4mm diameter), should be avoided.

(c) Age determinations on single grains using new ^{14}C techniques now becoming available for exceedingly small samples.

(d) Identification of areas of steady fine-grained carbonate sedimentation where reworking may be minimal (eg. on the eastern limits of the Fair Isle Channel and East Orkney deposits at the edge of the North Sea basin). Age determinations would be carried out on vertical sequences of subsamples from vibrocores. Significant age differences between different horizons may show up.

(e) Detailed dating of material in and around a site of proven present-day carbonate production. Bulk ages would be traced away from the production site along predicted transport paths.

(5) Summation

The use of radiometric dating of the carbonates is severely hampered by the fact that much of the material has been forming and mixing together over the last 6000 years or more.

However the evidence obtained suggests that biological carbonate productivity on the SCS, although considerable at the present time, may have been higher during some period since the last glaciation. If so, then it was probably due to warmer seawater temperatures and wide areas of shallower water offshore.

More work needs to be done in this field because the nature and limited number of radiometric ages so far obtained are clearly inadequate. Thus (a) only a few locations have been sampled, (b) most analyses were on bulk samples of mixed sediment, (c) most of the materials were coarse sands and gravels, more liable to be older lag deposits compared to finer, more mobile sands.

V CLASSIFICATION AND GENESIS OF THE CARBONATE DEPOSITS

(1) Introduction

In elucidating the origin and sedimentology of the carbonates these will now be categorised in terms of environments of production, transport and deposition. There are, of course, no sharp boundaries between the types, so some deposits are listed under more than one category.

(2) Shoals - rocky highs

(a) Description

These are discrete bathymetric highs which shallow to depths of 0-50m and are related to bedrock geology and morphology. Sizes vary from several square kilometres to several hundred square kilometres. They either stand above the general level of flattish shelf (Fig. 152Ab) or are separated from other highs by deep basins (Fig. 152Aa).

The highest parts of shoals are generally bare rock, encrusted with a prolific fauna and flora, particularly calcareous organisms. Within crevices, hollows and gullies on the upper parts, too, pockets of carbonate sediment occur. At depths greater than about 70 m those shoals exposed to westerly stormwaves from the open Atlantic may have storm-generated megaripples on their sediments. The main carbonate deposits lie on the eastern flanks of such shoals sheltered from the strongest and predominant stormwaves..

The sediment is coarse sand and gravel. It is generally rich in debris of encrusting rock-dwelling organisms. Barnacles are particularly abundant in the shallow water nearer the coast (eg. Hawes Bank, Table 5), and serpulids in deeper ocean-dominated situations (eg. Stanton Banks, Table 11). Bryozoa are prevalent (Table 12) and the bivalve content is low compared with other deposits. Maturity Indices are high, due mainly to very high roundness (Table 16). Some fragments are heavily stained (Table 18). In the vicinity of some of the shoals the carbonate in the surrounding sediment is more mature than the deposit (see later).

(b) Genesis

Vigorous current activity generated by waves and tides removes terrigenous mud and sand; both *in situ* glacial debris and modern input from the coast. This would otherwise dilute the carbonate material. The fine-grained terrigenous material is either trapped in the deep basins, which act as very effective sediment sinks, or carried off the shelf into the ocean (or N. Sea) basin. Coarser materials may be distributed across the shelf along sediment transport paths, or move shorewards, or be merely reworked locally. Major redistributions of sediment in this way were probably important during the transgressive period. Nowadays the system is more nearly in equilibrium.

This removal of terrigenous sediment by currents exposes rocky surfaces suitable for encrustation by carbonate-generating organisms. High current activity produces nutritious well oxygenated water favourable to biological producivity. It also accelerates the rate of removal of encrusting carbonate organisms, adding material to the sediment and making way for new growth. This is particularly true of wave action.

The derived carbonate sediment is transported to more sheltered parts of the shoal: hollows, crevices, gullies and the leeward side. On shoals separated by deep basins, carbonate transport paths can only be local. If the sediment is unable to stabilise on the top or flanks of a shoal, its ultimate destination is the basins themselves. On shoals standing proud of an expanse of flattish shelf, carbonate sediment unable to settle permanently will migrate on to the shelf and be dispersed along discrete transport paths.

It is interesting that, in the shoal environment, wave-currents are probably more important than tidal currents.

During the transgressive period, today's deeper shoals lay in shallower water and therefore may have had higher carbonate productivity (see p. 277).

On shoals where there is a net loss of carbonate sediment to the surrounding shelf, the carbonate in the deposits (>75% $CaCO_3$) will be less mature than that in the surrounding sediment (<75% $CaCO_3$).

(c) Deposits in this category

The shoal-type deposits are listed in Table 39. Around the Inner Hebrides there may be small scale versions of these which have not been recognised in this present work.

(3) Oceanward hummocky platforms - rocky knolls and sand-filled hollows

(a) Description

These are large areas (many hundreds of square kilometres) of ocean-dominated platform, generally 40-100m deep, where wave-currents are very strong and tidal currents variable. The bathymetry often reflects a hummocky glaciated surface of metamorphic rocks similar to that seen on land on the Outer Hebrides. The knolls are of bare rock heavily encrusted with carbonate-secreting organisms. The hollows contain carbonates, sometimes several metres thick (Fig.152 Ac). Sandwaves and megaripples are occasionally developed on them. Predominant constituents are fragments of encrusting organisms (barnacles, bryozoans, and particularly serpulids; Tables5, 12,11) and bivalve debris is abundant (Table 8). Proportions of echinoid material are relatively high (Table 9), and in some cases, foraminifera also (Table 13). The carbonate is generally a coarse sand and gravel, moderately rounded, and shows low-moderate Maturity Indices (Table 20).

There are only minor amounts of terrigenous sediment on these hummocky platforms and modern terrigenous input from the land is minimal.

(b) Genesis

High current activity, generated particularly by waves, removes terrigenous material which would otherwise dilute the carbonate. Major redistribution of glacial sediment took place during the transgression, transporting it to the hollows or shorewards or seawards.

As in the case of shoals, high current activity produces nutritious, well oxygenated water favourable to high carbonate productivity. It also increases the rate of removal of encrusting organisms, adding to the sediment and making way for new growth. This derived carbonate is transported into the nearby hollows where it accumulates. In some cases, particularly where tidal currents are stronger, transport across the sand patches is significant and sandwaves develop. Onshore and longshore transport are also possible. In general, wave currents are probably more important than tidal currents, though the latter are quite strong in places.

Viewing the platform as a whole, its deeper parts may produce less carbonate than at times in the past when sea level was lower. However, this may be compensated to some extent by present-day production from nearshore shallows which were previously subaerial.

(c) Deposits in this category

These types of deposit (Table 39) lie on the western, Atlantic-facing sides of the most distant of the Scottish islands, the Outer Hebrides and Shetland. They are ideal sites for carbonate formation with clear, vigorous ocean waters sweeping the seabed, which is free from any major terrigenous input off land.

(4) Platforms - rocky pavements

(a) Description

These are large areas of exposed rock with shallow hollows and crevices, and comparatively gentle bathymetric variation (cf. hummocky platforms, Fig. 152 Ad). The pavements may be bounded by coastlines or basins and their tidal and wave currents can be strong. The carbonate on them forms thin sheets of mobile sediment with sandwaves, sandribbons and megaripples in places. Megaripples in some deeper parts (>70m) are generated by stormwaves. Besides being rich in bivalve debris the carbonate has a variable composition controlled by oceanic, tidal and coastal influences. Inshore platforms are rich in barnacles and those further offshore contain abundant serpulids and bryozoa. Terrigenous sand is generally absent, but terrigenous gravel may be present.

(b) Genesis

Current activity over the glaciated pavements has led to large rocky areas supporting high biological productivity producing carbonate debris, as described for other types of deposit(eg. p.235).

This material travels along local or regional transport paths to accumulate either on the flanks of the platform (pp.244-246) or in coastal platform deposits (e.g. tidal sandbanks, pp.242-244)or on beaches (pp.248-250).

Large areas presently between 50 and 100 m depth during the lower sealevels of the transgressive period, may have supported different but widespread and more rapid carbonate production during the lower seabeds of the transgressive period.

(c) Deposits in this category

Of the two deposits in this category (Table 39), the Fair Isle Channel covers a huge area and is crucial to carbonate sedimentation in the Orkney - Shetland region.

(5) Coastal platforms - narrow, rocky strips

(a) Description

These deposits lie on rocky nearshore pavements, where wave and tidal currents can be intense (Fig. 152Be). Barnacle and bivalve production is predominant. The resulting debris may lie in gullies, crevices or hollows on the pavement, as well as on the adjoining beaches. Most of it is highly mobile, periodically forming extensive sheets across the platform. In particular situations large tidal sandbanks develop (pp.242-244). The sediments are usually rich in bivalves and barnacles and sometimes serpulids (Tables 8, 5 & 11). Their Maturity Indices generally range from moderate to high (Table 20) and their grain sizes from gravel to fine sand (Table 14). Some of the finer sands have significant quantities of foraminifera (Table 13).

(b) Genesis

High current activity has created highly productive sites as described before for the other types. The carbonate debris is transported by wave and tidal currents either onshore, longshore, or offshore, depending on local transport paths. It ultimately accumulates on beaches (p. 249), tidal sandbanks (p. 243) or the platform slope and adjacent shelf (p. 245 and Fig. 141).

In this environment, maximum production rates were probably not achieved until after the stabilisation of sea level.

Prior to then, large areas of these coastal platforms would have been intertidal or above sea level.

(c) Deposits in this category

These are listed in Table 39. They occur close to areas of very high carbonate productivity, and also on more distal coastal strips where much of the material is supplied by longshore drift.

(6) Tidal sandbanks

(a) Description

These sand bodies show characteristic morphologies, being elongate, 1-10 or more kilometres long, asymmetrical in cross-section and covered with well developed sandwaves and megaripples (Kenyon et al. 1981, McCave and Langhorne 1982, Houbolt 1968). There is often evidence of circulating transport paths across and around them.

The sediment generally comprises very pure coarse sand and gravel carbonate. The bivalve content is relatively low, but it is often richer in barnacle and/or serpulid debris than other types of deposit (Tables 5&11). The particles are generally well rounded and polished, and often iron-stained (Tables 16, 17, 18). Maturity Indices are some of the highest found (Table 20) and are taken to indicate genuine maturity.

(b) Genesis

The origin of tidal sandbanks on the world's continental shelves is still speculative (see Kenyon et al. 1981). Some, for example, are clearly connected with pre-existing morphological features; others may form spontaneously when fixed current patterns produce closed sediment-circulation at one location.

The carbonate sandbanks on the SCS probably formed in response to a variety of factors. One prerequisite for them all is a highly mobile cover of carbonate sand and gravel transported from very productive sites. This sediment travels as bedload and, at least partially, as suspended load. There must also be a balance between the degrees of tidal and wave-current activity. Wave-currents can assist tidal current transport, but become destructive if too vigorous (Langhorne 1982).

Most of the sandbanks can be attributed to one or more of the following situations and sets of circumstances:

(i) Where there is net sediment transport in a specific direction, banks can form downstream in the 'shadow' of a positive bathymetric feature. Sandy Riddle, lying in the lee of the Pentland Skerries, is a good example of this (Fig. 74).

(ii) Where pre-existing 'banks' such as glacial moraine also act as a 'nucleus'.

(iii) Beyond peninsulas, where large scale tidal current vortexes are set up, producing sediment circulation (Fig. 152Bf and

Pingree and Maddock, 1979). Several of the Scottish deposits fit this category (eg. North Ronaldsay, p. 102 and p. 199 ; Cape Wrath, p. 219).

(iv) In tidal channels and tidal passages where complex tidal patterns may also induce spontaneous bank formation. There may also be some seabed or coastal morphological control here (Fig. 152Bf).

(c) Deposits in this category

The largest and most spectacular of carbonate sandbanks are all in the Orkney area (Table 39). The reasons for this are thought to be (*i*) abundant supply of sediment, and (*ii*) the degree of protection from the very destructive Atlantic stormwaves coming in from the west.

(7) Platform flank and adjoining shelf (or subsiding basin margin)

(a) Description

One substantial example of this type of deposit was discovered in the area surveyed. This, the Fair Isle - Orkney sandwave field and adjoining North Sea shelf (Figs 141, 152Be), is of major importance.

The current-swept platform around Orkney and in the Fair Isle Channel has a thin widespread cover (~10 cm) of coarse mobile carbonate (pp.90–95 and 99–112). On the slope at the edge of this platform are thicker accumulations (several metres thick) forming a distinct sandwave field (p. 108). Grain sizes vary dramatically, some of the sandwaves consisting of very coarse sand and gravel.

There is, however, a general decrease in coarseness with increase in water depth and distance from the platform. Correspondingly, the proportions of several components change progressively. Bryozoan, echinoid and foraminiferal fragments become more abundant, while barnacle and serpulid debris declines (pp.109 – 111).

Beyond depths of about 90 m there are still megaripples and sandribbons but only very low sandwaves. Further east, into the North Sea basin, the sediment becomes terrigenous and its carbonate content falls below 75%.

(b) Genesis

The obvious prerequisite for the formation of a deposit of this type is a major supply of mobile carbonate from a platform.

Carbonate sand and gravel is carried over the edge of the platform, travelling as bedload and suspended load. As the current velocities decrease down the slope the transport rates fall, and carbonates build up. Where the transition from heavy suspended load to predominantly bedload transport takes place conditions will be good for sandwave formation (p. 203). The finer slow-moving sediment beyond the main slope must be additional infaunal debris, particularly bryozoan, echinoid and foraminiferal debris.

Although the net current flow is off the platform in the Fair Isle - Orkney case this is not an essential factor in the formation of flank accumulations. Even random transport directions on the platform will gradually dump the sediment irreversibly down its flanks (Swift et al., 1971).

(8) Tidal channels, bays and sounds

(a) Description

Deposits in these environments often occur as intra-channel and intra-bay sandbanks. They may be small-scale features with or without megaripples or sandwaves. Elsewhere they can be larger, typical tidal sandbanks (pp.242-244). Shoals often develop in channels between small islands and the coastlines and these sometimes build up above sea level to form tombolos (Fig. 152Bh).

Other deposits are found at the mouths of tidal channels (Fig.152Bg), particularly the larger ones such as the Pentland Firth and Yell Sound. Extensive sandwaves and sandbanks may be developed on these. Deposits can also occur at the entrances to bays.

The petrography of the carbonates varies considerably. Bivalves and barnacle debris often predominate (Tables 8 & 5). Calcareous algae are frequently present if the channel is current-swept and yet protected from excessive wave action. Typically, the sediments are coarse, with variable Maturity Indices.

(b) Genesis

The bulk of their material having been formed in very shallow coastal waters, these deposits must be modern (ie. <6000 years old). In certain cases some of the carbonate may be older, having been carried in from further offshore.

Strong tidal currents are necessary to produce highly productive areas of seabed. Besides bare rock, there can be all manner of gravelly and cobbly bottoms supporting production (eg. *Modiolus* beds, calcareous algal colonies, etc.). Wave-currents also can be important in encouraging carbonate production (eg. of barnacles), as well as transporting sediment and maintaining it at depositional sites. But many inshore deposits occur where there is reasonable shelter from the worst wave action. Clear water and low terrigenous input from the land are other important factors affecting carbonate production and the formation of inshore carbonate deposits.

Bay and channel-mouth deposits develop where sediments, carried through channels by tidal currents, leave the suspension and bed loads, as velocities wane. Often an equilibrium is established between the rates of out-going tidal transport and incoming, wave-driven transport of sediment.

(c) Deposits in this category

Table 39 lists the deposits in this category, which is seen to cover a variety of distinctly different sedimentary regimes. Some subdivisions are indicated, but it must be stressed that this category is more generalised than the others.

(9) Beaches

(a) Description

Many beach sediments contain more than 75% of $CaCO_3$ but, owing to the variable nature of the information available, all those with over 50% are grouped together.

These high carbonate sands often make extensive beach and dune systems (machair). The largest face west towards the Atlantic; but others on the east coasts of Caithness, Orkney and Shetland face east towards the North Sea. Almost without exception, they are adjacent to offshore carbonate deposits and highly productive rocky areas.

The sands are generally more than 1 m thick (Mather and Ritchie 1977). They are often fine-grained, well polished carbonates, the recognisable material being predominantly bivalve and barnacle debris.

Dune systems are stabilised by vegetation, where not too damaged by human activity, but the seaward sides of many appear to be undergoing erosion.

(b) Genesis

Such deposits can be formed by onshore transport from nearshore intertidal and sublittoral production zones (eg. coastal platforms).

Where they are particularly extensive there is probably a contribution from the more offshore platform deposits and production zones; for example Outer Hebrides beaches being supplied by the West Hebridean Platform. These are discussed in relation to the effect of hypothetical wave-energy electricity generating schemes (Appendix 8).

Some doubt exists as to whether the beaches are still receiving carbonate from offshore or whether, as suspected by W. Ritchie (pers. comm.), they are undergoing true erosion. Admittedly, the rate of carbonate production may be less than in the past (p. 233), but in any case natural erosion would be expected in the Scottish islands, where sea level is rising compared with land level. Such eroded material should be redistributed further back in the dune system, rather than completely removed.

The beaches are therefore probably still active parts of carbonate sedimentation on the SCS, representing final accumulation sites at the ends of some of the offshore transport paths.

(10) Summary of criteria for formation of carbonates on the SCS

The two most basic requirements for the formation of these temperate carbonates are:

(i) relatively strong currents,

(ii) low terrigenous input and rocky substrates.

This is very much in accordance with the views of Raymond & Hutchins (1932), Keary (1967), Cucci (1979) and Owens (1981). See also Fig. 155.

Chapter Five

GEOLOGICAL PERSPECTIVE

I CARBONATE BUDGET

(1) Introduction

Knowledge of modern temperate carbonates on the world's shelves is now recognised as important for understanding the geological record (pp. 5-7). But there is still very little quantitative information concerning their sedimentation rates for comparison with those of warm waters. This is perhaps not surprising because, owing to the short time since the sealevel became stable, post-glacial carbonates are bound to be thin. Combined with inherent thickness variations across the shelf, this makes it difficult to estimate the amount of carbonate present.

However, as demonstrated (Chapter 3) it is possible to place limits on the likely thicknesses (and hence volume and mass) of the carbonates and to estimate the areas of carbonate-rich (50-75% $CaCO_3$) sediments, and of the extent of coastline 'high-carbonate' (50-100% $CaCO_3$) systems. For the first time therefore, it is possible to estimate carbonate sedimentation rates on the SCS.

Apart from difficulties in estimating the present quantities of carbonate, there are also problems in determining the time over which it accumulated. Sea level has been relatively stable for 6000 years (p. 15); but prior to that, it was rising, progressively invading the Scottish landmass and submerging large areas of shelf under deepening water. The present outer and deeper parts of the shelf have therefore probably been producing carbonate for at least 10,000 years. On the other hand carbonate production in the shallower areas was probably not fully established until 6000 years BP, and there are suggestions that in the deeper parts of the shelf it is now considerably less than before then (p. 227). Hence the minimum period of accumulation is taken as 6000 years and the maximum as 10,000 years. On balance, the former has been adopted for calculating average accumulation rates because the sedimentary regime is likely to have only reached a state of equilibrium after 6000 BP.

Although the SCS seabed has considerable relief on the small and large scale, only planimetric areas have been used in these simple calculations.

In total, 23% of the shelf surveyed is covered by carbonate sediments (>75% $CaCO_3$) and 45% is covered by high-carbonate sediments (anything >50% $CaCO_3$).

(2) Volumes and sedimentation rates

(a) Carbonate Deposits (<75% $CaCO_3$)

The estimated total mass of carbonate in the main offshore deposits is summarised in Appendix 5 (Table 50,p.475). This lies in the range 919 x 10^{12} to 23811 x 10^{12} and the average sedimentation rate is therefore probably between 4 and 173 g/m^3/yr (Table 40). The most reasonable value is taken as that derived from the "most likely average thicknesses" (see CDSS sheets) and an accumulation period of 6000 years. On this basis the average carbonate sedimentation rate *in situ* has been 37 g/m^2/yr.

(b) Carbonate-rich (50-75% $CaCO_3$) sediments

These have not been studied in detail and, although they have been mapped, their thicknesses are poorly understood. In general they are probably similar in style to the carbonate sediments, forming a mobile cover of less than 1 m thick except locally.

For this reason the range within which the volume of carbonate-rich sediments lies is estimated from their total area combined with *(i)* a minimum average thickness of 0.05m and *(ii)* a maximum of 1m. Assuming the $CaCO_3$ content averages 65% by weight, this gives a range of 34 g/m^2/yr to 105 g/m^2/yr for the *in situ* accumulation rate of carbonate in such a sediment.

(c) High-Carbonate (>50% $CaCO_3$) beaches

The volume of carbonate in these beaches is estimated from the data of Mather and Ritchie (1977) who give the areas of beaches with more than 40% $CaCO_3$. The derived range of masses is 109 x 10^{12}

to 474 x 10^{12}g and of *in situ* carbonate sedimentation rates of 109 $g/m^2/yr$ to 436 g/m^2.

(3) Carbonate Productivity

In addition to estimating *in situ* sedimentation rates, the calculated masses of carbonate can sometimes be used for crudely estimating the local and regional rates of production.

(a) Orkney area

The thick masses of carbonate in the Orkney area (pp. 99-131) are probably best understood where the average sedimentation rate must lie between 18 $g/m^2/yr$ and 312 $g/m^2/yr$. The most likely value is 128 $g/m^2/yr$ (Table 40 and Appendix 5, Table 52). This is higher than the average for the SCS as a whole.

Despite its high mobility, most of the sediment is probably derived from the Orkney area. If so, the average sedimentation and production rates should be roughly equal. Some material is probably carried in from the more outlying parts of the Northern Shelf, eg. the Fair Isle Channel. To allow for this the area may reasonably be increased to 5000 x 10^6 m^2, reducing the inferred production rate to between 14 and 238 $g/m^2/yr$, with a most likely value of 97 $g/m^2/yr$ (Appendix 5, Table 52).

(b) Total carbonate in all high-carbonate sediments ($>50\%$ $CaCO_3$)

High carbonate production is intimately associated with areas low in terrigenous sediment (p. 250). In general, carbonate debris from the production zones tends to move away to areas of dominantly terrigenous sediment. It is unlikely that much carbonate is transported from areas of terrigenous sediment to areas of high-carbonate ($>50\%$ $CaCO_3$). Therefore the high-carbonate sediments must derive almost all their carbonate from within their own areas. The exceptions are areas of "clean" current-swept seabed, such as nearshore and intertidal platforms. These may supply significant amounts of carbonate to beaches and coastal sandbanks. Hence a small allowance is made for the extra productive acreage.

Adding the estimated total masses of carbonate in the offshore deposits ($>75\%$ $CaCO_3$), carbonate-rich sediments (50-75% $CaCO_3$) and high carbonate beaches ($>50\%$ $CaCO_3$) yields a range of average SCS carbonate accumulation rates for sediments with more than $>50\%$ $CaCO_3$) (Table 40 and Appendix 5, Table 53). Accepting this as roughly equal to the range of production rates (see above), we obtain 4 to 135 $g/m^2/yr$ with a most likely value of about 24 $g/m^2/yr$ (Table 41).

Many factors are not taken into account in these crude calculations. The most important are losses of carbonate from current transport, and breakdown of carbonate into mud-sized material. Chemical dissolution may play a part, but there is little evidence of it. If anything, therefore, the production rates derived from average sedimentation rates are underestimates.

(4) Comparison with rates for other shelf carbonates

(a) Sedimentation rates

The average SCS sedimentation rates (Table 40) are very similar to those estimated for the temperate carbonates in the Oligocene of New Zealand (Nelson 1978). The latter are lithified skeletal sediments which strikingly resemble the platform carbonates of the SCS. The results presented here support Nelson's conclusion that, in general, this type of carbonate sedimentation is at least one order of magnitude slower than on warm water shelves.

However, rates on the SCS are locally much greater than the average owing to the sediment's high mobility. For example, on sandbanks they lie somewhere in the range 125 to 1834 $g/m^2/yr$ and on the platform-edge between 114 and 646 $g/m^2/yr$. Thus the rates of carbonate accumulation on the temperate shelf can be as great as in a warm sea if the transportative mechanism is able to supply a smaller depositional area with debris gathered from a wider region.

(b) Productivity

Estimated average productivities on the SCS compare favourably with those derived by Cucci (1979) for the Sound of Iona (Table 41). Around 30 $g/m^2/yr$, they are one or two orders of magnitude slower than the carbonate productivity of a typical coral reef: ∿1500 $g/m^2/yr$ (Stearn et al. 1977).

(5) Summation

Average SCS sedimentation and productivity rates are several tens of $g/m^2/yr$. They are compatible with the very limited data from other temperate shelf carbonates.

While productivity rates are highly significant the sedimentation rates are less easy to interpret. Thus in areas with thin mobile cover of carbonate it is not always clear whether there is any net accumulation, whereas elsewhere, such as on sandbanks and platform edges, more rapid accumulation is clearly taking place. But even sandbanks may have built up rapidly in the past and now be in equilibrium with sediment gains from upstream transport paths equalling losses downstream.

Average carbonate productivity and average sedimentation rates on the SCS are at the most one tenth of those on tropical shelves. Locally, however, the SCS sedimentation rates are much greater, if only for short periods.

Nevertheless, modern temperate carbonates such as these have considerable potential for forming significant bioclastic limestone horizons. This is born out by the existence of extremely similar deposits in the geological record. Both the Pleistocene Red Crags of East Anglia (Dixon 1979) and the Oligocene limestones of New Zealand (Nelson 1978) show remarkable similarity in details of their petrography, geometry, bedforms, relationships with other sediments, and rates of deposition. Not surprisingly, they have been attributed to very similar environments of deposition.

II PRESERVATION POTENTIAL

(1) Discussion

Although temperate shelf carbonates are now becoming recognised as geologically significant, it is important to consider whether the accumulations on the SCS could actually be preserved in the geological record. There is as yet no good evidence that they are undergoing any significant preservation processes. Totally unlithified and mobile, they show no signs of burial by laterally equivalent sediments of other facies.

As seen, closely similar deposits have been preserved in the past. The Pleistocene Red Crag deposits have survived reworking during regressive periods because they lie in a shallow depression on the London Clay surface (Dixon 1979) and have been lithified by groundwater calcification. Submarine diagenesis may have cemented the Oligocene temperate carbonates of New Zealand during shallow burial (Nelson, 1978). This may have occurred due to the removal of magnesium from the pore waters by clay minerals (Russell 1970), enabling calcite precipitation (Garrison et al. 1969). However, sea water temperatures were possibly a few degrees higher than on the present day SCS, and this factor should not be overlooked.

Recent carbonates on the Kings Plateau, off New Zealand, are described by Nelson (1982) as thin, discontinuous and likely to remain so, because most of the material is ultimately redistributed into the surrounding basins. This happens particularly during low sea level, for example in the last glacial period. Carbonate debris on the SCS is similarly transported to the more terrigenous basins (p. 236) forming thin bands seen in some of the muds vibrocored by IGS. They probably represent sudden influxes generated by storms.

Scoffin et al. (1980) suggest that the recent carbonates on Rockall Bank (similar to those off New Zealand) would build up and be preserved if continuous subsidence were to take place. Continuous subsidence in pace with sedimentation rate is a well established mechanism for preserving thick sequences of shelf sediments. But most of the SCS carbonates are intimately associated with upstanding platform areas which show little sign of subsidence. Instead, eustatic rises of sea level have taken place, producing the same effect as subsidence in the short term. When in the future the inevitable fall in sea level occurs, the carbonates will be prone to severe reworking. Another period of glaciation would be devastating. Nevertheless, some preservation potential is envisaged for these present-day carbonates and this will now be discussed.

(a) Shoal carbonates

Shoal deposits are generally thin and often unstable (pp. 236). Many are losing carbonate as fast as they are gaining it. Their preservation potential is low because the only alternative to subsidence is sustained long-term sealevel rise over millions of years. This would have to operate at a rate approximating to that of carbonate sedimentation; and, of course without further glaciations. Some of the deeper shoal deposits might be submerged below the storm wave base (>200 m) and buried beneath encroaching fine grained terrigenous material (Fig. 153A,B).

During drops in sea level, the shallower deposits would be completely reworked. Thorough removal would occur if there were further glaciation. In both of these cases only small pockets of carbonate would be preserved, filling fissures, deep hollows and gullies and, possibly, the interstices of boulder fields and screes. Deeper shoals, however, could remain below sea level during regressive periods, in which case carbonate productivity might even increase. Thus, here carbonate may continue to build up even during considerable sea level changes (Fig. 153B).

(b) Oceanward hummocky platform carbonates

As above in (a), total preservation of these deposits (p.237) would again only occur under conditions (apart from subsidence) of long-term, sustained rises in sea level. They might, however, survive falls in sea level without such severe reworking as, lying in the bottoms of hollows, they would not be easily redistributed by increased current activity. Encroachment by non-marine sediments and vegetation could form a protective cover but they would remain prone to fluvial and glacial erosion. Solution beneath acid-producing soils might occur, but of course groundwater lithification is also highly probable.

(c) Platform and coastal platform carbonates

These extensive carbonates on exposed, open and generally upstanding seabed could, in principle, be preserved below terrigenous material during major rises in sealevel (Fig.153A,B) like those on shoals and hummocky platforms (see (a) and (b) above).

However, during falling sealevels the deposits on the shallower platforms would be liable to complete reworking and redistribution into large regressive beach complexes (Fig. 153B). Subaerial exposure could lead to cementation by groundwater (p. 259). Only very local patches in crevices, steep hollows and gullies would be likely to retain the original depositional fabric. Deeper offshore platforms which were not exposed might increase their productivity as the water shallowed. Therefore carbonate may continue to build up even during widely fluctuating sealevels.

(d) Tidal sandbank carbonates

Tidal banks might sometimes survive in a modified form because their sheer size would make them resistant to total reworking. Those in tidal channels could be susceptible to rapid burial by terrigenous sediment deposited as tidal current velocities decrease when sea level rises (Fig.153 A,B).Banks on the coastal platforms, like other platform deposits, are less likely to be preserved in this way. However, during a rapid fall in sea level they may be resistant to total reworking, so that the inner core remains intact, and the outer part is remoulded to form say, a nearshore bar, or beach system (Fig. 153B).

(e) Platform flank/adjoining shelf (subsiding basin margin). carbonates.

Typified by the margin of the subsiding North Sea basin flanking Orkney and Fair Isle Channel platforms, this situation has the greatest potential for carbonate preservation. Here at the transition from coarse mobile calcareous sediment to finer less mobile calcareous sediment to fine terrigenous sediment, accumulation rates are comparatively high (p. 256). Subsidence on the basin edge will permit continuous rapid carbonate deposition and encourage its preservation (Fig.154). In addition any increase of water depth, whether eustatic or due to subsidence, will result in muddy terrigenous sediment transgressing up the slope, and burying the carbonates. Generally deposited in fairly deep water (p. 245) these platform flank carbonates could only be extensively reworked during major falls in sea level, or glaciation.

(f) Carbonates in tidal channels, bays and sounds

Discounting future glacial action, the preservation potential of these deposits is good. Continued rise in sea level might lead to some being modified, but others would simply be buried under laterally coexistent sediments such as intra-bay muds (Fig. 153A,B).

Regressions would rapidly separate these deposits from their marine environment, possibly resulting in their preservation under a sequence of estuarine, intertidal and non-marine sediments, where ground water cementation could occur (Fig. 153B).

(g) Carbonate beach systems

Beach complexes have some preservation potential, at least in the short term. During transgressions they move landwards, while during regressions they may be augmented by reworked offshore platform carbonates producing extensive beach complexes (Fig. 153B). Ground water lithification, particularly in carbonate dunes, was noted around Scotland (e.g. Faraid Head, Sutherland and Evie, Orkney).

(2) Summary of preservation potential

(i) If present-day carbonate sedimentation is taking place during an interglacial period, most of the SCS deposits, which lie on bathymetric highs and in fairly shallow water (<70m), will eventually be reworked by regressive coastal processes as the next glaciation sets in. Subsequently they will be liable to modification or destruction through various processes, including marine and non-marine proglacial and glacial influences.

(ii) If further glaciation were not to recur during the next few million years, and eustatic sea level stabilises, continues to rise, or fluctuate mildly (say ± 50m about its present level), then thick carbonate sequences could accumulate, particularly on the platform margins. In one million years, for example, an average of 27 m could accumulate over large areas of the SCS, and in the main depositional areas it would be much thicker. Such deposits might therefore be reasonably expected to survive erosion and reworking during a future regression Most probably they would be the thicker sequences, at the platform edges.

(iii) The key to long-term and widespread preservation of temperate shelf carbonates lies in:

1. Tectonic subsidence of accumulation sites or substantial long-term rising sea level in pace with sedimentation rates.

2. Cementation, either after burial below the seabed (eg. New Zealand Oligocene limestone, p. 259) or as a result of groundwater influence (eg. Red Crag deposits, p. 259).

Chapter Six

IMPLICATIONS FOR COMMERCIAL EXPLOITATION

I USAGE OF CALCIUM CARBONATE

(1) Agricultural lime

Shell sand from Scottish beaches and dunes has been widely used on a local scale for agriculture (p.4).

During the 1970's there was a substantial enterprise extracting 'maerl' from offshore Brittany, France (Booth 1975). This was marketed as a lime also with some attributes of a fertiliser. High in calcareous algal content the material was claimed to contain additional beneficial elements including magnesium and a wide range of trace elements. However it seems that in fact it differs little from shell sands or even from dolomitic limestone sources. The only advantage of maerl may have been that the crystallographically poorly ordered carbonate released Ca and Mg more quickly into the soil (IGS 'in-house' studies). Other small scale enterprises, along the lines of the Brittany operation, have been attempted off the south coast of Cornwall (England) and the west coast of Ireland.

(2) Cement

Beach carbonates around Scotland have been used in the past as local sources for making cement.

During the 1950's a cement industry was established in Iceland, using offshore shell sands. These were extracted by suction-dredging at rates of several thousand tonnes per day (Vestdal 1961). Dominantly molluscan debris, they contain about 80% $CaCO_3$ and 20% basalt fragments. They were processed to fulfill specified cement standards, and in 1971 were satisfying about 2/3rds of Iceland's demand (Archer 1971). Bramwell (1977) reported that there was little sign of the reserves being depleted.

Investigations have also been made on the carbonate deposits off Brittany with a view to supplying the cement industry (Le Gorgeu, 1976).

(3) Other

Lime in various forms is used for a variety of other purposes in industry and agriculture, such as smelting, grit in chicken feed, and even roadmetal (Banner 1980).

II COMMERCIAL REQUIREMENTS

(1) General

Calcium carbonate is marketed as a low-cost bulk material, normally extracted from large quarries onshore. The main requirement is proximity to potential markets, in order to keep transport costs down.

For cement, large reserves need to be available in order to justify the capital investment in plant (Vestdal 1961).

For agricultural lime, much smaller low-cost operations can be mounted. Large reserves are therefore not as critical as for cement.

(2) Chemical Composition

(a) For agriculture

Although SCS shell sand might possibly be marketed on the basis of "natural goodness" that limestones do not contain, there are no stringent agricultural requirements on the overall composition of the sediment. A reasonable Mg content is preferred (say >1% MgO) and harmful contaminants (e.g. heavy metals) should of course be minimal.

(b) For cement

The cement industry requirements are more stringent. There are several standards and types of cement, but in general high magnesium contents are undesirable. For example BS. 12.1958 permits a maximum of 4% MgO in the total mix of Portland cement (Berridge 1969).

In Iceland shell debris is separated from non-carbonate contaminants by a flotation (Vestdal 1961), but no particular allowance is made for its chemical composition.

Salt, being effectively removed by washing, does not appear to be a problem.

(3) British/Scottish requirements

Nearly all British lime is obtained by quarrying. There are extensive reserves in England, where the more expensive commodity from offshore Scotland is unlikely to compete at present. However the situation could conceivably change in the future if environmental constraints, already beginning to hamper quarrying, raised the costs above some critical level.

Scottish onshore sources of lime are far more limited. For agriculture, local limestone is often available (Berridge 1969), although not necessarily easily accessible or environmentally suitable for large scale extraction. The Highland area is a large potential market for agricultural lime. Much carries acidic soils and, being classified as 'hill farm', qualifies for government subsidies to aid liming.

For cement, the Highland limestone sources (mainly Dalradian and Durness formations) are not suitable for cement because of their high MgO contents (Berridge 1969). Hence there is only one major cement factory in Scotland and this is in the southeast at Dunbar, where Carboniferous limestones are utilised. Transport costs are therefore high over much of Scotland, and failure to obtain supplies from Dunbar requires fetching of cement from even further, viz. northern England or beyond. Thus there may be some potential for a cement industry in northern Scotland, supplying the industrial conurbations of the Highlands.

III CHEMICAL COMPOSITION OF THE SCS CARBONATES

(1) General

Preliminary generalisations can be made on the chemistry of the main components of the carbonates by using the data of Gunatilaka (1975), Milliman (1974) and Cucci (1979). In particular, the variation in Mg content can be roughly predicted given also the regional component variation of the carbonates.

Carbonates rich in serpulids, echinoids, foraminifera or calcareous algae will have the highest Mg contents (Table 42). With the exception of serpulids, and of calcareous algae from nearshore environments, these are usually present only in small quantities and will not have much effect. However the deposits with higher Mg levels (Table 43) will be the least suitable for cement manufacture. These may actually be the most desirable for agricultural use but the Mg content is not so crucial a factor in that case.

(2) Analyses

Chemical compositions of samples from the Barra Head, Moray Firth and Shetland-Out Skerries deposits are given in Table 44. For comparison, an analysis of a sample of marketed French 'maerl' is also presented.

MgO contents of all the samples are below the maximum levels acceptable for cement manufacture.

(3) $CaCO_3$ content

Sediments with the highest carbonate contents are clearly preferable for exploitation. Although by definition the 'deposits' described here all contain >75% $CaCO_3$, in fact most exceed 85%. The highest values occur on the tidal sandbanks, where they average more than 95%.

(4) Implications of carbonate chemistry on commercial development

All the deposits are suitable for use as agricultural lime. Those containing higher Mg may prove the most marketable, particularly of course material from inshore deposits containing calcareous algae.

Most, if not all except maerl, of the deposits would be suitable for the cement industry as MgO contents are less than 4%. Preferred will be those rich in barnacles, bivalves and bryozoa, and low in serpulids, echinoids and foraminifera. The extensive East Orkney - Moray Firth deposits are noteworthy in these respects.

IV RESERVES

(1) Tonnage

Carbonate reserves are listed on the CDSS sheets and in Table 50, Appendix 5). The largest lie between Shetland and the Moray Firth. Based on the 'most likely' case, these contain 4285 x 10^6 tonnes of $CaCO_3$,amounting to 84% of the total in the deposits identified on the SCS. Those around Orkney probably contain at least 2990 x 10^6 tonnes of $CaCO_3$, making up 59% of the total.

In the west, the deposits are isolated, thin, patchy and much smaller. Their 'most likely' masses range from 2 x 10^6 tonnes (Rubha Nan Clach) to 366 x 10^6 tonnes (West Hebridean Platform). The only other deposit in the region likely to contain reserves exceeding 100 x 10^6 tonnes is that off Cape Wrath (103 x 10^6).

(2) Exhaustibility

If, as surmised in Chapter 4, carbonate production and accumulation is continuing at present and if extraction from a deposit were to be carried out at a rate equal to the accumulation rate, then there would be little risk of seriously depleting it. Hence the 'equilibrium extraction rate' (Table 45). Using this model, 'depletion extraction rates' can also be calculated for reducing the reserves to zero in a given period (Table 45).

Now the equilibrium extraction rate in particular may not be reliable. In some cases it may be overestimated because present production rates are lower than the average for the last 6000 years (p.233). In others it may be underestimated, for example in some tidal sandbanks now in equilibrium, with their rates of sediment gain and loss being equal (see p. 257). If such a bank was diminished and its morphology altered by commercial extraction, sediment losses to downstream transport paths may reduce so that material builds back up on the sandbank at a rate faster than the apparent average for the last 6000 years. This would mean that the sandbank could be exploited faster than the calculated depletion extraction rate without seriously diminishing its reserves.

The examples chosen in Table 45 vary greatly in size. Small deposits such as Hawes Bank (3 x 10^6 tonnes) might sustain extraction rates of at least 1.5 tonnes/day without depletion of their reserves, and 156 tonnes/day for total depletion over 50 years. Medium-sized deposits such as Sandy Riddle and Cape Wrath (about 100 x 10^6 tonnes) have equilibrium extraction rates of 50 tonnes/day and 50-year depletion extraction rates of 5700 tonnes/day. The Orkney carbonates as a whole have estimated equilibrium extraction rates of 1333 tonnes per day and 50-year depletion rates of 161,333 tonnes/day.

V ENVIRONMENTAL CONSEQUENCES

(1) Ecological effects

Some of the deposits lie in areas which are important fishing grounds. Drastic reductions in the normal seabed sediments might cause ecological changes which are detrimental to fish stocks. Where there is high infaunal carbonate production, overdepletion might also seriously affect the carbonate production rates. However, many of the larger deposits could only be seriously reduced by very high extraction rates. Indeed much carbonate could be removed without causing any depletion.

The carbonate sediments are notable for their high day-to-day mobility (Chapter 4). Hence the associated ecosystem must already be adapted to continual disturbance and sudden and drastic changes in sediment distribution. Dredging, geared so that sediment is not completely removed from any location, should therefore not seriously affect the ecology of the area, although this aspect will have to be thoroughly investigated.

(2) Physical effects

As seen, most of the deposits are intimately associated with the local current regime. Morphological modifications (particularly in tidal sandbanks) caused by extraction may generate local changes in the currents until the original forms are built up again. The environmental consequences of this are unlikely to be serious. Catastrophic coastal erosion, for instance, is not very probable as most deposits are some distance offshore.

If, as suggested (p. 250), the high-carbonate beaches are receiving sediment from offshore deposits, care will be needed to avoid over-extraction along onshore transport paths. Any substantial decrease in the sediment supply to a beach could lead to its erosion.

VI VIABILITY

It is not within the scope of this project to investigate the economics of extracting and marketing the offshore Scottish carbonates. Nevertheless it is clear that, should the economic aspects be attractive, a substantial extraction industry could be sustained on the SCS for many decades.

The most promising area for commercial development is around Orkney, including perhaps the Moray Firth and Fair Isle Channel. Exploitation on a small or moderate scale could sustain the production of agricultural lime, and larger scale extraction might support a modest cement industry. Much of the Orkney carbonate is likely to be of suitable quality for both. Furthermore,this part of the SCS is easily accessible from the northeastern extremity of mainland Scotland, which in turn is more accessible to the rest of the country than other parts of the north and west coasts.

One drawback may be the constraints imposed on dredging operations by the severe tides and the winter weather of the district. These factors (particularly the latter) become more critical for greater water depths (Banner 1980). Some of the carbonate is in fact out of reach of many present-day dredgers, which can only operate in depths of up to about 45 m.

Exploitation of the other deposits, which are smaller and less accessible, would incur higher offshore and onshore transport costs. However, of these the larger ones, around Shetland, Cape Wrath and the Outer Hebrides, are most attractive. It seems unlikely that any of the other smaller deposits on the western side of Scotland could be utilised for anything but small-scale local agricultural purposes. Possible exceptions are the inshore deposits rich in calcareous algae which, as discussed previously (p. 266), give them extra marketability.

VII SUMMATION

Of the SCS carbonate deposits those around Orkney, off northeast Scotland, are the most attractive for commercial development from every viewpoint: reserves, renewability, purity, chemical composition and market accessibility.

The others, lying in less accessible areas to the north and west, seem unlikely to be viable commercially except for local small-scale development. All the same, some have considerable carbonate reserves.

Chapter Seven

SUMMARY OF CONCLUSIONS

SUMMARY OF CONCLUSIONS

Approach

The regional reconnaissance reported here of Recent skeletal carbonate deposits on the Scottish Continental Shelf leads to a broad basic model of temperate carbonate shelf sedimentation (Fig. 155). The large-scale approach adopted is complementary to more detailed studies by others of specific aspects of carbonate sedimentation, often over very restricted locations. Hopefully, it enables them to be placed into a more useful geological context.

Distribution, production and accummulation

Systematic quantitative and qualitative surveys (Chapter 3) reveal that sediments with more than 75% $CaCO_3$ cover 23% of the shelf area mapped, and those with 50-100% cover 45%.
They probably contain at least 6714×10^{12} g $CaCO_3$, representing an average accumulation rate of no less than 24 $g/m^2/yr$. Locally, the rate may be as high as 580 $g/m^2/yr$. The average carbonate production rate is also probably about 24 $g/m^2/yr$, but in places (particularly in coastal regions) reaching 97 $g/m^2/yr$. These rates are an order of magnitude less than those in the tropics.

The distribution of offshore carbonate deposits is closely related to particular forms of bathymetric high, viz. various forms of platforms and shoals (Chapter 4). Inshore deposits occur in channels, bays and sounds. The deposits of the Inner Hebridean area are relatively small and isolated owing to the glacial morphology of the seabed. On the extensive platforms of the Outer

Hebrides, Shetland and particularly Orkney, the carbonate deposits are larger and more continuous.

Controls on production

Formation of the deposits is influenced by bathymetry, proximity to coastlines, current activity, rock exposure and terrigenous sediment sinks (Chapter 4). These factors combine to form a highly favourable environment with: low dilution by terrigenous material, high carbonate productivity because of well oxygenated nutritious clear water, and enhanced current activity keeping the substrate clear of debris which would otherwise inhibit further productivity.

Controls on accumulation

The ultimate fate of the carbonate debris varies with the type of deposit (Chapter 4). On the exposed tops of the platforms and shoals, the material is thin and very mobile. Down some of their flanks the transport rates decrease as the currents slacken, leading to thicker accumulations. Fine carbonate frequently goes further, depending on the nature of the seabed. Pulses of coarse material can be washed into the deeper terrigenous basins by storm-generated currents. Where local topography is highly variable (eg. heavily glaciated) the transport paths are short, from shoal to flank, to terrigenous basin. The resulting accumulations are only true carbonates (>75% $CaCO_3$) where the basins are shallow and well washed by currents (eg. intra-platform hollows). On the more extensive platforms and open shelf areas, the debris can enter the larger long-distance transport paths, many of which have been recognised previously by others (Chapters 3 and 4). These suggest a broadly anticlockwise movement of sediment around the Scottish mainland and islands. Along the coastal areas there are in places heavy accumulations, forming sandbanks. Substantial amounts of carbonate also migrate shorewards to build up and maintain sandy beach-systems. Local production of carbonate can also sustain inshore accumulations.

Dynamical sedimentology

Investigations of the hydrodynamics of the platy particles (predominant in skeletal carbonates) and of physical conditions at the SCS seabed show that, at least down to 100m, virtually all the carbonate is mobile on a time scale of several years. In the shallower places strong tidal currents and frequent and strong wave-currents produce a high-energy environment where sediment is highly mobile and the seabed therefore very rocky. In deeper areas the movement of carbonate is controlled far more by storm-wave currents. The greater the water depth, the more severe and infrequent the storms must be to move material of the same size.

Most of the deposits are coarse sands and gravels. This is because the finer carbonate is removed in suspension by comparatively mild currents and deposited elsewhere in quieter waters, within, or on the flanks of muddy terrigenous basins.

Petrography

Although the carbonates are mobile, and therefore strictly allochthonous, their petrographies are related to the environments in which they occur (Chapter 3). Thus biogenic composition is influenced by water depth, proximity to coastlines, tenor of Atlantic Ocean water, tidal and wave-currents, substrate, and the general submarine topography. Grain textures are generally end results of the degree of current activity undergone by the sediment and reflect their cumulative dynamic histories up to the present day. Therefore, bearing in mind that the sediments are continually modified as they pass 'downstream' (eg. by mixing with locally-generated material), texture and composition can be used to derive a meaningful measure of their maturity. The parameters size, roundness and polish are particularly useful in this respect. The Maturity Index (M) is also of considerable use, being derived from the above three characteristics along with degrees of sorting; polish and staining.

Dating

High mobility and continuous mixing, however, make it difficult to determine ages. Over most of the shelf they are undoubtedly 'post-glacial'. ^{14}C analyses (Chapter 4) illustrate the severe difficulties of dating a sediment which has been continually mixed with older material as it was generated. They also suggest that the present production of carbonate over much of the shelf may not be as high as it has sometimes been during the past 10,000 years. This may have been due to the seawater being warmer and/or shallower.

Preservation potential

Long-term preservation, in its present form, of much of this (interglacial?) temperate carbonate seems unlikely. However there are circumstances in which its chances of survival would be enhanced, for example if the present period of glaciation has ended. The deposits most likely to survive will tend to be the thickest, especially those on platform-basin flanks, in shallow hollows and in sandbanks. The observations made on the SCS deposits should nevertheless be applicable to any model of temperate skeletal carbonate shelf sedimentation, including those deposited on a steadily subsiding platform (which may be the most common type in the fossil record).

Recent carbonates on the SCS are indeed very similar to the Cenozoic temperate carbonates of East Anglia (UK) and New Zealand. Both suggest average carbonate production and accumulation rates that are an order of magnitude less than those of tropical carbonates today.

Geological significance

Even so, temperate carbonate sedimentation, as an integral part of clastic shelf sediments, must be geologically important. The present survey of a mere 6000-10,000 years' carbonate accumulation has shown that, if present-day conditions continued for a geologically significant period (say 1 million years), then substantial carbonate formations (>27m thick) could be preserved in the Scottish geological record.

Exploitation

The SCS carbonates are generally very pure $CaCO_3$ and constitute a potential resource of considerable magnitude. Thus the deposits of the Shetland-Orkney-Moray Firth region contain over 4000 million tonnes and, moreover, are easily accessable for transhipment to Scottish markets; and even, perhaps, elsewhere.

As shown in Chapter 6, if the economics of offshore exploitation became commercially attractive these reserves could sustain a lime industry in northern Scotland for a carefully planned period of decades. Exploitation rates could be adjusted to strict environmental requirements such as "no depletion of reserves", "depletion to zero reserves in 10/50/100 years", etc. There would in fact be an option on treating these deposits as a renewable, or a non-renewable resource.

REFERENCES

ALEXANDERSSON, E.T. 1975. Etch Patterns on Calcareous Sediment Grains : Petrographic Evidence of Marine Dissolution of Carbonate Minerals. *Science, 189*, 47-48.

ALEXANDERSSON, E.T. 1979. Marine maceration of skeletal carbonates in the Skagerrak, North Sea. *Sedimentology, 26*, 845-852.

ALLEN, J.R.L. 1970. *Physical Processes of Sedimentation.* Allen and Unwin, London.

ALLEN, J.R.L. 1979a. A model for the interpretation of wave ripple-marks using their wavelength, textural composition and shape. *J. geol. Soc. London, 136*, 713-724.

ALLEN, J.R.L. 1979b. Initiation of transverse bedforms in oscillatory bottom boundary layers. *Sedimentology, 26*, 863-865.

ALLEN, N.H., FANNIN, N.G.T. and FARROW, G.E. 1979. Resin peels of vibrocores used in the study of some shelly sediments on the Scottish Shelf. *Mar. Geol. 33*, M57-M65.

ANDERSON, F.W. and DUNHAM, K.C. 1966. The Geology of Northern Skye. *Mem. Geol. Surv. Scotland.*

ANDERTON, R.A., BRIDGES, P.H., LEEDER, M.R. and SELLWOOD, B.W. 1979. *A Dynamic Stratigraphy of the British Isles.* Allen and Unwin, London.

ANIKOUCHINE, W.A. and STERNBERG, R.W. 1981. *The world ocean, 2nd Edition.* Prentice-Hall, New Jersey.

ARCHER, A.A. 1971. Economics of off-shore exploration and production (solid minerals). *International Seminar on the Development of the Mineral Resources of the Continental Shelf.* Port of Spain, Trinidad and Tobago, April 1971.

BAGNOLD, R.A. 1966. An approach to the sediment transport problem from general physics. *U.S. Geol. Surv. Profess. Papers, 422-I.*

BANNER, F.T. 1980. Seabed Resources, Potential and Actual (excluding Hydrocarbons). In: BANNER, F.T., COLLINS, M.B., and MASSIE, K.S. (eds). *The North-West European Shelf Seas: the Sea Bed and the Sea in Motion II. Physical and Chemical Oceanography, and Physical Resources.* Elsevier, Amsterdam, 547-567.

BATHURST, R.G.C. 1975. *Carbonate Sediments and their Diagenesis, 2nd Edition.* Elsevier, Amsterdam.

BELDERSON, R.H., JOHNSON, M.A. and KENYON, N.H. 1982. Bedforms. In: STRIDE, A.H. (ed). *Offshore Tidal Sands*, Chapman and Hall, London, 27-57.

BELDERSON, R.H., KENYON, N.H. and STRIDE, A.H. 1971. Holocene sediments on the continental shelf west of the British Isles. In: DELANY, F.M. (ed). The Geology of the East Atlantic Continental Margin. *Rep. Inst. geol. Sci. London, 70/14*, 157-170.

BERRIDGE, N.G. 1969. A summary of the mineral resources of the 'Crofter Counties' of Scotland. *Rep. Inst. geol. Sci. London, 69/5.*

BINNS, P.E., HARLAND, R. and HUGHES, M.J. 1974a. Glacial and postglacial sedimentation in the Sea of the Hebrides. *Nature, 248*, 751-754.

BINNS, P.E., McQUILLIN, R. and KENOLTY, N. 1974b. The Geology of the Sea of the Hebrides. *Rep. Inst. geol. Sci. London, 73/14.*

BISHOP, P. 1977. *Glacial and post-glacial sedimentation in the Minches, North West Scotland.* Unpublished Ph.D. thesis, University College London.

BISHOP, P. and JONES, E.J.W. 1979. Patterns of Glacial and Post-Glacial Sedimentation in the Minches, North-West Scotland. In: BANNER, F.T., COLLINS, M.B. and MASSIE, K.S. (eds). *The North-West European Shelf Seas: I. Geology and Sedimentology.* Elsevier, Amsterdam, 89-194.

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, 25*, 227-246.

BLATT, H., MIDDLETON, G., and MURRAY, R. 1980. *Origin of Sedimentary Rocks.* Prentice-Hall, New Jersey.

BOILLOT, G. 1964. Géologie de la Manche Occidentale. *Annales de L'Institut Océanographique, 42* 1-220.

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

BOOTH, E. 1975. Seaweeds in Industry. In: RILEY, J.P. and SKIRROW, G. (eds). *Chemical Oceanography Volume 4, 2nd Edition.* Academic Press, London, 219-268.

BOSENCE, D.W.J. 1973. Recent Serpulid Reefs, Connemara, Eire. *Nature, London, 242*, 40-41.

BOSENCE, D.W.J. 1978. Recent Carbonate sedimentation in Connemara, Western Eire: A Comment. *Estuarine and Coastal Marine Science, 7*, 303-306.

BOSENCE, D.W.J. 1979a. Live and dead faunas from coralline algal gravels, Co. Galway. *Palaeontology, London*, 449-478.

BOSCENCE, D.W.J. 1979b. Trophic analysis of communities and death assemblages. *Lethaia, 12* , 120.

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.*

BRAMWELL, M. (ed). 1977. *Atlas of the Oceans,* Mitchell Bearley, London.

BROWN, B.J. 1979. *Shell transport and community recognition in modern shelf seas.* Unpublished Ph.D thesis, University of Glasgow.

BURNE, R.V. and COLWELL, J.B. 1982. Temperate carbonate sediments of Northern Spencer Gulf, South Australia; a high salinity 'foramol' province. *Sedimentology, 29,* 223-278.

CARTWRIGHT, D.E. and STRIDE, A.H. 1958. Large sand waves near the edge of the continental shelf. *Nature, London, 181,* 41.

CASTON, G.F. 1981. Potential gain and loss of sand by some sand banks in the Soutnern Bight of of the North Sea. *Mar. Geol. 41,* 239-250.

CHANNON, R.D. 1971. The Bristol fall column for coarse sediment grading. *J. sediment. Petrol. 41,* 867-870.

CHANNON, R.D. and HAMILTON, D. 1971. Sea bottom velocity profiles on the continental shelf south-west of England. *Nature. London. 231,* 383-385.

CHANNON, R.D., and HAMILTON, D. 1976. Wave and tidal current sorting of shelf sediments southwest of England. *Sedimentology, 23,* 17-42.

CHAVE, K.E. 1964. Skeletal durability and preservation. In: IMBRIE, J. and NEWELL, N.D. (eds). *Approaches to Palaeoecology.* John Wiley and Sons, New York, 377-387.

CHESHER, J. and LAWSON, D. in press. The geology of the Moray Firth. *Rep. Inst. geol. Sci. London.*

CLARKE, M.J. and FARMER, N. 1982. Late Palaeozoic Cold-Water Carbonate Sedimentation in Tasmania - Discussion. *J. sediment. Petrol. 52,* 682-683.

CONOLLY, J.R., VON DER BORCH, C.C. 1967. Sedimentation and physiography of the sea floor south of Australia. *Sediment. Geol. 1,* 181-200.

CRAIG, R.E. 1959. Hydrography of Scottish Coastal Waters. *Marine Research, 2.* Scottish Home Dept., H.M.S.O.

CRANE, C.M. 1972. Contour plotting for functions specified at nodal points of an irregular mesh based on an arbitrary two parameters co-ordinate system. *Computer Journal, 15,* 382-384.

CROFTS, R. and MATHER, A.S. 1972. *Beaches of Wester Ross.* Report, Dept. of Geography, University of Aberdeen.

CROFTS, R. and RITCHIE, W. 1973. *Beaches of Mainland Argyll.* Dept. of Geography, University of Aberdeen.

CUCCI, M.A. 1979. *Recent Carbonate Sediments of the West Coast of Scotland between Ardnamurchan and Islay.* Unpublished Ph.D. thesis, University of Edinburgh.

DARBYSHIRE, M. and DRAPER, L. 1963. Forecasting wind-generated sea waves. *Engineering (London) 195,* 482-484.

DEEGAN, C.E., KIRBY, R., RAE, I. and FLOYD, P. 1973. The superficial deposits of the Firth of Clyde and its sea lochs. *Rep. Inst. geol. Sci. London, 73/9.*

DIXON, R.G. 1979. Sedimentary facies in the Red Crag. *Proc. Geol. Assoc. London, 90,* 117-132.

DRAPER, L. 1967. Wave activity at the seabed around northwestern Europe. *Mar. Geol. 5,* 133-140.

DRAPER, L. 1980. Wave Climatology of the U.K. Continental Shelf. In: BANNER, F.T., COLLINS, M.B. and MASSIE, K.S. (eds). *The North-West European Shelf Seas: II Physical and Chemical Oceanography, and Physical Resources.* Elsevier, Amsterdam, 353-368.

DRAPER, L. and FRICKER, H.S. 1965. Waves off Land's End. *J. Inst. Navig. 18,* 180-187.

DRAPER, L. and SQUIRE, E.M. 1967. Waves at Ocean Weather Ship Station "India" (59^oN, 19^oW). *R. Inst. Nav. Archit. (London), Trans., 109,* 85-93.

DRISCOLL, E.G. 1967. Experimental field study of shell abrasion. *J. sediment. Petrol. 37,* 1117-1123.

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. London, 71/16.*

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. London, 73/2.*

EISMA, D., JANSEN, J.H.F. and VAN WEERING, T.C.E. 1979. Sea-floor morphology and recent sediment movement in the North Sea. In: OELE, E, SCHÜTTENHELM, R.T.E. and WIGGERS, A.J., The Quaternary History of the North Sea, *Acta Univ. Ups. Symp. Univ. Ups. Annum. Quingentesimum Celebrantis, 2,* 217-231.

EVANS, D., KENOLTY, N., DOBSON, M.R. and WHITTINGTON, R.J. 1980. The geology of the Malin Sea. *Rep. Inst. geol. Sci. London, 79/15.*

FARROW, G.E. 1974. On the Ecology and Sedimentation of *Cardium* Shellsands and Transgressive Shellbanks of Traigh Mhor, Island of Barra, Outer Hebrides. *Trans. R. Soc. Edinburgh, 69,* 203-229.

FARROW, G.E., ALLEN, N.H. and AKPAN, E.B. in prepn. Bioclastic carbonate sedimentation on a high-latitude, tide-dominated shelf: Northwest Orkney Islands, Scotland. Revised manuscript submitted to *J. sediment. Petrol.,* (April 1983).

FARROW, G.E. and CLOKIE, J. 1979. Molluscan grazing of sublittoral algal-bored shells and the production of carbonate mud in the Firth of Clyde, Scotland. *Trans. R. Soc. Edinburgh, 70,* 139-148.

FARROW, G.E., CUCCI, M. and SCOFFIN, T.P. 1978. Calcareous sediments on the nearshore continental shelf of Western Scotland. *Proc. R. Soc. Edinburgh, 76B,* 55-76.

FARROW, G., SCOFFIN, T., BROWN, B., and CUCCI, M. 1979. An underwater television survey of facies variations on the inner Scottish Shelf between Colonsay, Islay and Jura. *Scott. J. Geol. 15,* 13-29.

FERENTINOS, G.K. 1976. Sediment distribution and transport processes on the outer continental shelf of the Hebridean Sea. *Mar. Geol. 20,* 41-56.

FITZGERALD, M.G., PARMENTER, C.M. and MILLIMAN, J.D. 1979. Particulate calcium carbonate in New England shelf waters; result of shell degradation and re-suspension. *Sedimentology,* 26, 853-857.

FLINN, D. 1978. The most recent glaciation of the Orkney-Shetland Channel and adjacent regions. *Scott. J. Geol. 14,* 109-123.

FOLK, R.L. 1968. *Petrology of Sedimentary Rocks.* Hemphill's, Texas.

GARRISON, R.E., LUTERNAUER, J.L., GRILL, E.V., MACDONALD, R.D and MURRAY, J.W. 1969. Early diagentic cementation of Recent sands, Fraser River delta, British Columbia. *Sedimentology, 12,* 27-46.

GUILCHER, A. 1964. Sedimentation sous-marin dans la partie orientale de la Rade de Brest, Bretagne. In: VAN STRAATEN, L.M.J.U. (ed). *Developments in Sedimentology, 1,* 148-156.

GUNATILAKA, H.A. 1975. The chemical composition of some carbonate secreting marine organisms from Connemara. *Proc. R. Irish Acad. 75, Section B,* 543-556.

GUNATILAKA, H.A. 1977. Recent Carbonate Sedimentation in Connemara Western Ireland. *Estuarine and Coastal Marine Science, 5,* 609-629.

HADLEY, M.L. 1964. Wave-induced bottom currents in the Celtic Sea. *Mar. Geol. 2,* 164-167.

HALDANE, D. 1939. Note on the nullipore or coralline sands of Dunvegan, Skye. *Trans. Geol. Soc. Edinburgh, 13,* 442-444.

HAMMOND, T.M. and COLLINS, M.B. 1979. On the threshold of transport of sand-sized sediment under the combined influence of unidirectional and oscillatory flow. *Sedimentology 26,* 795-812.

HJULSTRØM, F. 1935. Studies in the morphological activity of rivers as illustrated by the River Fyris. *Geol. Inst. Univ. Upsala, Bull. 25,* 221-528.

HJULSTRØM, F. 1939. Transportation of detritus by moving water. In: TRASK, P.D. (ed.) Recent Marine Sediments, A Symposium. *Spec. Publ. Soc. econ. Paleontol. Mineral. Tulsa, 4,* 5-31.

HOLMES, R. 1977. Quaternary deposits of the Central North Sea. 5. The Quaternary geology of the UK sector of the North Sea between 56° and 58° N. *Rep. Inst. geol. Sci. 77/14.*

HONJI, H., KANEKO, A. and MATSUNAGA, N. 1980. Flows above oscillatory ripples. *Sedimentology, 27,* 225-229.

HOSKIN, C.M. and NELSON, R.V. 1969. Modern marine carbonate sediment, Alexander Archipelago, Alaska. *J. sediment. Petrol. 39,* 581-590.

HOUBOLT, J.J.H.C. 1968. Recent sediments in the Southern Bight of the North Sea. *Geol. Mijnbouw, 47,* 245-273.

HUNTLEY, D.A. 1980. Tides on the North-West European Continental Shelf. In: BANNER, F.T., COLLINS, M.B. and MASSIE, K.S. (eds.). *The North-West European Shelf Seas: II. Physical and Chemical Oceanography, and Physical Resources.* Elsevier, Amsterdam, 301-351.

HYDROGRAPHER OF THE NAVY 1973. *Admiralty Tidal Stream Atlas, North Coast of Ireland, West Coast of Scotland.* NP 218, Hydrographic Dept. Taunton.

HYDROGRAPHER OF THE NAVY 1974a. *Admiralty Tidal Stream Atlas, Orkney and Shetland Islands.* NP 209, Hydrographic Dept., Taunton.

HYDROGRAPHER OF THE NAVY 1974b. *West Coast of Scotland Pilot, 11th Edition.* Hydrographic Dept. Taunton.

HYDROGRAPHER OF THE NAVY 1975. *North Coast of Scotland Pilot, 1st Edition.* Hydrographic Dept., Taunton.

INMAN, D.L. 1949. Sorting of sediments in the light of fluid mechanics. *J. sediment. Petrol. 19,* 51-70.

INMAN, D.L. and BOWEN, A.J. 1963. Flume experiments on sand transport by waves and currents. *Proc. 8th Conf. Coastal Eng.,* 137-150.

JELL, J.S. MAXWELL, W.G.H. and McKELLAR, R.G. 1965. The significance of the larger foraminifera in the Heron Island Reef sediments. *J. Palaeontol. 39,* 273-279.

JOHNSON, M.A., KENYON, M.H., BELDERSON, R.H. and STRIDE, A.H. 1982. Sand transport. In: STRIDE, A.H. (ed.). *Offshore Tidal Sands,* Chapman and Hall, London, 59-94.

JOHNSON, M.A., STRIDE, A.H., BELDERSON, R.H. and KENYON, N.H. 1981. Predicted sand-wave formation and decay on a large offshore tidal current sand-sheet. In: NIO, S.-D., SCHUTTENHELM, R.T.E. and VAN WEERING, T.J.C.E. (eds.). Holocene Marine Sedimentation in the North Sea Basin, *Spec. Publs. int. Ass. Sediment, 5,* 247-256.

JOPLING, A.V. 1965. Hydraulic factors controlling the shape of laminae in laboratory deltas. *J. sediment. Petrol. 35, 777-791*

KANEKO, A. and HONJI, H. 1979. Initiation of ripple marks under oscillating water. *Sedimentology, 26,* 101-113.

KEARY, R. 1967. Biogenic carbonate in beach sediments of the West Coast of Ireland. *Sci. Proc. R. Dublin Soc. Ser. A., 3,* 75-85.

KENYON, N.H., BELDERSON, R.H., STRIDE, A.H. and JOHNSON, M.A. 1981. Offshore tidal sand-banks as indicators of net sand transport and as potential deposits. In: NIO, S.-D., SCHUTTENHELM, R.T.E. and VAN WEERING, T.J.C.E. (eds.). Holocene Marine Sedimentation in the North Sea Basin, *Spec. Publs. int. Ass. Sediment, 5,* 257-268.

KENYON, N.H. and STRIDE, A.H., 1970. The tide-swept continental shelf sediments between the Shetland Isles and France. *Sedimentology, 14,* 159-173.

KLEIN, G. DE. V. (ed). 1976. *Holocene Tidal Sedimentation.* Dowden, Hutchinson and Ross, Stroudsberg, US.

KOMAR, P.D. 1976a. The transport of cohesionless sediments on continental shelves. In: STANLEY, D.J. and SWIFT, J.P. (eds.). *Marine Sediment Transport and Environmental Management,* John Wiley and Sons, New York, 107-125.

KOMAR, P.D. 1976b. *Beach Processes and Sedimentation.* Prentice-Hall, New Jersey.

KOMAR, P.D. and MILLER, M.D. 1973. The threshold of sediment movement under oscillatory water waves. *J. sediment. Petrol. 43,* 1101-1110.

KOMAR, P.D. and MILLER, M.C. 1975. On the comparison of the threshold of sediment motion under waves and unidirectional currents, with a discussion of the practical evaluation of the threshold. *J. sediment. Petrol. 45,* 362-367.

KOMAR, P.D., NUEDECK, R.H. and KULM, L.D. 1972. Observations and significance of deep water oscillatory ripple marks on the Oregon continental shelf. In: SWIFT, D.J.P., DUANE, D.B. and PILKEY, O.H. (eds). *Shelf Sediment Transport,* Dowden, Hutchinson and Ross, Stroudsbury, U.S.

KOOPMANN, B.J. LEES, A., PIESSENS, P. and SARNTHEIN, M., 1979. Skeletal carbonate sands and wind-derived silty marls off the Saharan coast: Baie du Lévrier, Arguin Platform, Mauritania. *"Meteor" Forsch.-Ergebnisse, Section C, 30,* 15-57.

LANGHORNE, D.N. 1982. A study of the dynamics of a marine sandwave. *Sedimentology, 29,* 571-594.

LE GORGEU, J.P., MAUMENE, J., and RICHER, F., 1976. Prospection de sables calcaires marins pour l'industrie cimentière. In: *VII^{me} Colloque de l'Exploitation des Océans.* Asteo, compte-rendu du Theme III - Impact du développement des ressources océaniques sur l'economie nationale.

LEASK, A. 1928. Shell sand deposits in Orkney. *J. Orkney Agric. Discuss. Soc. 3,* 57.

LEASK, A. 1933. Shell sand deposits in Orkney. *J. Orkney Agric. Discuss. Soc. 8,* 76-77.

LEE, A.J. and RAMSTER, J.W. (eds.). *1981 Atlas of the seas around the British Isles.* Min. Agriculture, Fish. and Food, H.M.S.O.

LEES, A. 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. *Mar. Geol. 19,* 159-198.

LEES, A. and BULLER, A.T. 1972. Modern temperate-water and warm water shelf carbonate sediments contrasted. *Mar. Geol. 13,* M67-M73.

LEES, A., BULLER, A.T. and SCOTT, J. 1969. Marine carbonate sedimentation processes, Connemara, Ireland. *Reading University Geological Reports No. 2.*

LEWY, Z. 1981. Maceration of calcareous skeletons. *Sedimentology, 28,* 893-895.

LIVINGSTONE, H.D. and BOWEN, V.T. 1977. Windscale effluent in the waters and sediments of the Minch. *Nature. London, 269,* 586-588.

McCAVE, I.N. 1971a. Sand waves in the N. Sea off the coast of Holland. *Mar. Geol. 10,* 199-225.

McCAVE, I.N. 1971b. Wave effectiveness at the seabed and its relationship to bedforms and deposition of mud. *J. sediment. Petrol. 41,* 89-96.

McCAVE, I.N. 1979. Tidal currents at the North Hinder lightship, southern North Sea: flow directions and turbulence in relation to maintenance of sandbanks. *Mar. Geol. 31*, 101-114.

McCAVE, I.N. and LANGHORNE, D.N. 1982. Sandwaves and sediment transport around the end of a tidal sand bank. *Sedimentology, 29*, 95-110.

McQUILLAN, R. and ARDUS, D.A. 1977. *Exploring the Geology of Shelf Seas.* Graham and Trotman, London.

MAIKLEM, W.R. 1968. Some hydraulic properties of bioclastic carbonate grains. *Sedimentology 10*, 101-109.

MANOHAR, M. 1955. Mechanics of bottom sediment movement due to wave action. *Tech. Mem. Beach Eros. Bd. U.S. 75.*

MARTINDALE, W. and CHESHER, J.A. 1979. *Sub-Pleistocene Geology of the British Isles and the adjacent Continental Shelf.* IGS 1:2,500,000 map.

MATHER, A. 1970. *The Beaches of Caithness.* Report, Dept. of Geography, University of Aberdeen.

MATHER, A. and CROFTS, R. 1972. *Beaches of West Inverness-shire and North Argyll.* Report, Dept. of Geography, University of Aberdeen.

MATHER, A.S. and RITCHIE, W. 1977. *The Beaches of the Highlands and Islands of Scotland.* The Countryside Commission for Scotland, Perth.

MATHER, A.S. and SMITH, J.S. 1974. *The Beaches of Shetland.* Report, Dept. of Geography, University of Aberdeen.

MATHER, A.S., SMITH, J.S. and RITCHIE, W. 1974. *Beaches of Orkney.* Report, Dept. of Geography, University of Aberdeen.

MATHER, A.S., SMITH, J.S. and RITCHIE, W. 1975. *The beaches of Northern Inner Hebrides.* Report, Dept. of Geography, University of Aberdeen.

MILLER, M.C., McCAVE, I.N. and KOMAR, P.D. 1977. Threshold of sediment motion under unidirectional currents. *Sedimentology, 24*, 507-527.

MILLER, R.L. (ed.) 1964. *Papers in Marine Geology.* MacMillan, New York.

MILLIMAN, J.D. 1974. *Marine Carbonates*, Springer-Verlag, Berlin.

NELSON, C.S. 1978. Temperate shelf carbonate sediments in the Cenozoic of New Zealand. *Sedimentology, 25*, 737-771.

NELSON, C.S., HANCOCK, G.E., CAMP, P.J.J., 1982. Shelf to basin temperate skeletal carbonate sediments, Three Kings Plateau, New Zealand. *J. sediment. Petrol. 52*, 717-732.

NIE, N.H., BENT, D.H. and HULL, C.H. 1970. *Statistical Package for the Social Sciences* McGraw-Hill, New York.

OFF, T. 1963. Rhythmic linear sand bodies caused by tidal currents. *Bull. Am. Assoc. Petrol. Geol. 47*, 324-341.

OWENS, R. 1977. Cruise Report - John Murray 77JM02, Leg 2. *Internal Rep. 77/15*, IGS Continental Shelf Northern Unit.

OWENS, R. 1979. *Holocene sedimentation in the central North Sea.* Unpublished Ph.D. thesis, University of Edinburgh.

OWENS, R. 1981. Holocene sedimentation in the North-western North Sea. In: Holocene Marine Sedimentation in the North Sea Basin. *Spec. Publs. int. Ass. Sediment. 5*, 303-322.

PENDLEBURY, D.C. and DOBSON, M.R. 1975. Sediment and macrofaunal distribution in the eastern Malin Sea as determined by side-scan sonar and sampling. *Scott. J. Geol. 11*, 315-332.

PILKEY, O.H., MORTON, R.W. and LUTERNAUER, J. 1967. The carbonate fraction of beach and dune sands. *Sedimentology, 8*, 311-327.

PINGREE. R.D. and MADDOCK. L. 1979. The tidal physics of headland flows and offshore tidal bank formation. *Mar. Geol. 32*, 269-289.

PIESSENS, P. and CHABOT, A.G. 1977. Bathymetry and sediments of the Arguin Platform, Mauritania, West Africa. *Mém. Inst. Géol. Univ. Louvain, 29*, 369-379.

PIESSENS, P. and LEES, A. 1977. Sédimentation de carbonate biogéniques récents dans la Baie de Clifden (Connemara, Irlande). *Mémo. Inst. Géol. Univ. Louvain, 29*, 357-367.

RAO, C.P. 1981a. Criteria for recognition of cold-water carbonate sedimentation: Berriedale Limestone (Lower Permian), Tasmania, Australia. *J. sediment. Petrol. 51*, 491-506.

RAO, C.P. 1981b. Cementation in cold-water bryozoan sand, Tasmania, Australia. *Mar. Geol. 40*, M23-M33.

RAYMOND, P.E. and HUTCHINS, F. 1932. A calcareous beach at John O'Groats, Scotland. *J. sediment. Petrol. 2*, 63-67.

REINECK, H.-E. and SINGH, I.B. 1980. *Depositional Sedimentary Environments*, 2nd Edition. Springer-Verlag, Berlin.

RHYS, G.H. and ARDUS, D.A. 1981. The geology of the British Isles and the adjacent continental shelf - the offshore post-Hercynian basins. In: KERR, J.W.N., FERGUSSON, A.J. and MACHAN, L.C. (eds.). Geology of the North Atlantic Borderlands, *Canadian Society of Petroleum Geologists, Memoir 7*, 665-682.

RITCHIE, W. 1971. *The Beaches of Barra and the Uists.* Report, Dept. of Geography, University of Aberdeen.

RITCHIE, W. and CROFTS, R. 1974. *The Beaches of Islay, Jura and Colonsay.* Report, Dept. of Geography, University of Aberdeen.

RITCHIE, W. and MATHER, A.S. 1969. *The Beaches of Sutherland.* Report, Dept. of Geography, University of Aberdeen.

RITCHIE, W. and MATHER, A. 1970. *The Beaches of Lewis and Harris.* Report, Dept. of Geography, University of Aberdeen.

ROBINSON, A.H.W. 1958. The charting of the Scottish Coasts. *Scott. Geogr. Mag. 74*, 116-127.

RUSSELL, K.L. 1970. Geochemistry and halmyrolysis of clay minerals, Rio Ameca, Mexico. *Geochim. cosmochim. Acta, 34*, 893-907.

SCOFFIN, T.P., ALEXANDERSSON, E.T., BOWES, G.E., CLOKIE, J.J., FARROW, G.E. and MILLIMAN, J.D. 1980. Recent, temperate, subphotic, carbonate sedimentation: Rockall Bank, northeast Atlantic. *J. sediment. Petrol. 50*, 331-356.

SHIELDS, A. 1936. Application of similarity principles and turbulence research to bed-load movement. *Mitteilungen der Preussischen Versuchsanstalt für Wasserbau und Schiffbau*, Berlin. In: OTT, W.P., and VAN UCHELEN, J.C. (translators), California Inst. Tech., W.M. Keck Lab. of Hydraulics and Water Resources, Rept. No. 167.

SISSONS, J.B. 1967. *The Evolution of Scotland's Scenery.* Oliver and Boyd, Edinburgh.

STEARN, C.W., SCOFFIN, T.P., MARTINDALE, W. 1977. Calcium carbonate budget of a fringing reef on the west coast of Barbados. Part 1 - Zonation and Producitivity. *Bull. mar. Sci. 27*, 479-510.

STRIDE, A.H. 1963. Current-swept sea floors near the southern half of Great Britain. *Q.J. Geol. Soc. London, 119*, 175-199.

SUNDBORG, A. 1956. The River Klarälven; a study in fluvial processes. *Geog. Ann. Stockholm, 38*, 125-316.

SUTHERLAND, D.G., BALLANTYNE, C.K. and WALKER, M.J.C. 1982. A note on the Quaternary deposits and landforms of St. Kilda. *Quaternary Newsletter*, No. 37.

SWIFT, D.J.P., BOEHMER, W.R. 1972. Brown and grey sands on the Virginia shelf: color as a function of grain size. *Bull. geol. Soc. Am. 83*, 877-884.

SWIFT, D.J.P., DUANE, D.B. and McKINNEY, T.F. 1973. Ridge and swale topography of the Middle Atlantic Bight, N. America: secular response to the Holocene hydraulic regime. *Mar. Geol. 15*, 227-247.

SWIFT, D.J.P., STANLEY, D.J. and CURRY, J.R. 1971. Relict sediments on the continental shelves; a reconsideration. *J. Geol. Chicago, 79*, 322-346.

TILL, R. 1974. *Statistical Methods for the Earth Scientist.* Macmillan, London.

TREWIN, N.H. and WELSH, W. 1972. Transport, breakage and sorting of the bivalves *Mactra corallina* on Aberdeen beach, Scotland. *Palaeogr. Palaeoclimatol. Palaeoecol. 12*, 193-204.

VAN VEEN, J. 1935. Sand waves in the Southern North Sea. *Int. Hydrog. Rev. 12*, 21-29.

VAN VEEN, J. 1938. Water movements in the Straits of Dover. *J. Cons. perm. int. Explor. Mer. 13*, 7-38.

VESTDAL, J. 1961. Iceland relies on sea for new cement industry. *Pit and Quarry, 53*, 82-91.

WASS, R.E., CONOLLY, J.R. and MACINTYRE, R.J. 1970. Bryozoan carbonate sand continuous along southern Australia. *Mar. Geol. 9, 63-73.*

WHITTEN, D.G.A. and BROOKS, J.R.V., 1972. *The Penguin Dictionary of Geology.* Penguin Books, Middlesex.

WILSON, J.B. 1975. The distribution of the coral *Caryophyllia Smithii* S.&B. on the Scottish Continental Shelf. *J. mar. biol. Ass. U.K. 55*, 611-625.

WILSON, J.B. 1976. Attachment of the coral *Caryophyllia Smithii* S.&B. to tubes of the polychaete Ditrupa arietina (O.F. Muller) and other substrates. *J. mar. biol. Ass. U.K. 56*, 291-303.

WILSON, J.B. 1979a. Biogenic carbonate sediments on the Scottish continental shelf and on Rockall Bank. *Mar. Geol. 33*, M85-M93.

WILSON, J.B. 1979b. The distribution of the coral *Lophelia pertusa* (L) *L. Prolifera* (Pallas) in the north-east Atlantic. *J. mar. biol. Ass. U.K. 59*, 149-164.

WILSON, J.B. 1979c. 'Patch' development of the deep-water coral *Lophelia pertusa* (L) on Rockall Bank. *J. mar. biol. Ass. U.K. 59*, 165-177.

WILSON, J.B. 1982. Shelly faunas associated with temperate offshore tidal deposits. In: STRIDE, A.H. (ed.). *Offshore Tidal Sands*, Chapman and Hall, London. 126-171.

YALIN, M.S. 1972. *Mechanics of Sediment Transport*. Pergamon Press, New York.