COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE CONTINENTAL SHELF OF NORTHWEST EUROPE

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ABSTRACT

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The abundance and species-composition of coccolith assemblages have been described from shelf sediments of northwest Europe. The quantitative abundance of selected coccolith species and total cocccolith numbers have been determined as the number of coccoliths per gram of fine-grained silt (2 to 20 μm).

Eighteen coccolith species occur in the shelf sediments. The assemblages are dominated by Emiliania huxleyi, which frequently forms >90% of the total flora. Coccolithus pelagicus, Syracosphaera pulchra and Gephyrocapsa caribbeanica are the next most abundant species, although they usually form <5% of the assemblages.

Highest numbers of coccoliths (10^9 per gram) occur in sediments from the Celtic Sea and the northern North Sea. 10^8 coccoliths per gram occur in the Irish Sea, western English Channel and central North Sea area. Coccoliths are either scarce (10^6 per gram) or absent from the eastern English Channel and southern North Sea sediments.

The degree of vertical mixing which largely determines the availability of light energy and nutrients for phytoplankton growth is thought to be the most important control on coccolith distribution. Sediments deposited from stratified waters beneath a pronounced thermocline contain high numbers of coccoliths. Sediments deposited from tidally mixed waters contain a sparse nannoflora, limited to six or fewer species. Similar controls on coccolith distribution are also likely to have occurred in the past. The abundance and mode of preservation of coccoliths may therefore provide information on the degree of turbulence in ancient shelf environments.

Detailed studies on sediments from the Solent Estuarine System show that both Recent and reworked (mainly Cretaceous) coccoliths decrease in abundance with decreasing marine influence in the estuaries. The reworked Cretaceous forms are thought to be supplied from the erosion of Chalk cliffs on the Isle of Wight.

Coccoliths are particularly abundant (10^8 per gram) in estuarine sediments from southern Ireland and Cornwall. These estuaries are therefore acting as 'sinks' for marine-derived silt. This work demonstrates the use of coccoliths as indicators of sediment transport directions across the shelf and into adjacent estuaries and coastal embayments.

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CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION.

1.1 Background and main objectives.

Calcareous nannoplankton constitute a heterogeneous group of calcite-secreting forms that include the coccolithophores and certain fossil forms commonly associated with them; discoasterids, schizosphaerellids, and pithonellids.

The coccolithophores are unicellular, biflagellate, golden-brown, haptophyte algae. They are widely distributed throughout the photic and aphotic zones of the world's oceans but are generally rare in polar seas. Together with diatoms and the dinoflagellates they constitute the bulk of the marine phytoplankton. The coccolithophores have the ability to secrete calcite skeletal shields called coccoliths which are extruded to form a cover on the cell surface. This cover of coccoliths is termed collectively the coccosphere. Coccoliths range in size from ca. 1 to 15 μm, whereas the size of a complete coccosphere containing many coccoliths is 5 to 50 μm. The term nannoplankton as defined by Lohmann (1909) for the very small forms , 60 μm or less, that passed through phytoplankton nets , therefore includes both the coccolithophores and their skeletal elements. Other related but morphologically dissimilar groups of organisms traditionally included within the calcareous nannoplankton display a wide range of elaborate structures. These forms have no clear morphological relationship to coccolithophores and occur as calcareous microfossils within the same size fraction, often forming a substantial component of the nannofossil assemblages. The most notable of these forms are the discoasterids.

The fossil coccolithophores and associated

non-coccolith forms have been constituents of fine-grained, pelagic sediments since the early Jurassic. Coccoliths are major contributors to calcareous sediment accumulating on the sea-floor, accounting for some 30% of Recent oozes (Bramlette, 1958), and even more in Tertiary sediments (Bramlette, 1958; Heath, 1969; Berger, 1976).

Coccoliths are sensitive indicators of surface water temperature (McIntyre and Be',1967; McIntyre et al., 1970; Okada and Honjo, 1973) and, to a lesser degree, of surface water nutrient levels (Roth and Berger,1975). Coccolith biocoenoses are altered during sedimentation by the processes of preferential grazing, selective-destruction during ingestion and selective-dissolution at the sediment water interface (Roth et al., 1975). In spite of these processes,however, patterns of accumulation of coccoliths in bottom sediments do reflect environments of production in the overlying waters (Roth and Berger, 1975; Gietzenauer et al.,1976, 1977).

The distribution of calcareous nannoplankton in the major oceans of the world has been well documented (McIntyre and Bé ,1967; McIntyre et al., 1970; Okada, 1970; Okada and Honjo, 1970, 1973). However, their distribution in shelf and neritic sediments has been less well studied, particularly in the Atlantic.

This report provides an ecological and sedimentological investigation of coccolith occurrence in Recent shelf sediments from a temperate latitude. The main aims of the present study are to investigate the changes in coccolith abundance and species distribution in sediments from the continental shelf of northwest Europe. Particular emphasis is placed on the development of counting techniques which can define the quantitative abundance of coccoliths in the sediments.

The shelf of northwest Europe has been studied in detail in three main regions;

1) the Celtic Sea and English Channel,

2) the Irish Sea,

3) the North Sea.

The nannofossil assemblages in each region are delineated and the hydrological factors contributing to the observed variations are discussed. The results of this study are compared with the published data on coccolith occurrence in both plankton and sediment samples from the major oceans of the world. The characteristic features of continental shelf coccolith assemblages and their differences from oceanic assemblages are delineated. Some examples of Mesozoic shelf and marginal sea coccolith assemblages are also discussed.

Coccoliths may form a significant component of the fine fractions of estuarine sediments, particularly where tidal influences are pronounced. The transport and deposition of coccolith assemblages in the Severn Estuary and the Solent Estuarine System are described in some detail. The reworked coccolith assemblages are also documented. The information that these reworked forms provide on local erosion patterns of sediment transport and erosion is discussed.

1.2 Biology and ecology of the coccolithophores.

Most haptophytes are characterised by a haptonema which lies between two smooth, whip-like flagella (Parke and Adams,1960) (Fig.1.1). Internally, the coccolithophores contain a single, sub-spherical nucleus and two golden-brown chromatophores (Weber-van Bosse, 1901). The photosynthetic pigments in the cell are chlorophyll-a and carotenoids (Sherwood, 1974). The cell is enclosed by a membrane, which, in turn, has an outer mucilaginous covering. External to the cell membrane are the coccoliths.

Many haptophytes show an alternation of two distinct stages in their life history (a dimorphic life cycle) (Tappan, 1980). The motile cell alternates during the life

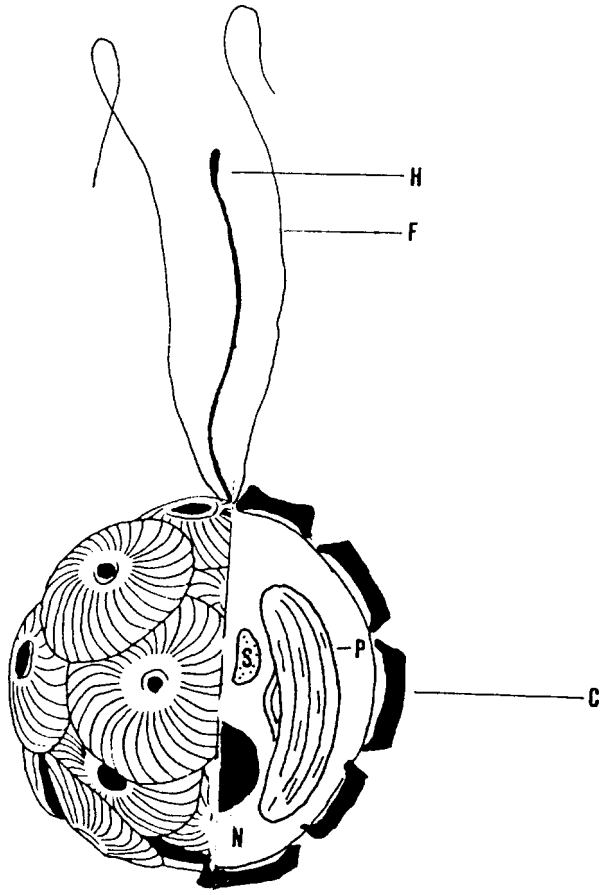


Figure 1.1
Generalised diagram of a coccolithophore motile cell showing exterior at left, and section at right. (Modified after Tappan,1980).
C- coccolith F- flagellum H- haptonema
P- plastids N- nucleus S- storage body of leucosin

history with a non-motile stage which may be a pelagic cyst, a packet of cells or a branching filament (Tappan, 1980). Most coccolithophores are thought to be free swimmers during one stage of their life-cycle, using the pair of flagella for propulsion. However, during the non-motile stage, the haptonema is believed to anchor the species to the substrate. Either the motile or the non-motile stage, or both, may be covered by organic scales, visible only with the electron microscope, or by calcified plates, or by both scales and plates (Tappan,1980). The ability of the coccolithophores to secrete calcareous plates or coccoliths on the organic scales differentiates them from the other members of the Haptophycea, and all other algae.

Studies by Black (1972) show that the plant has a flexible skeleton during the free swimming stage, and a rigid skeleton resulting from membrane calcification during the encysted phase of the life cycle. The greatly varied appearance and even different habit of separate stages in the life cycle has led to their description as distinct living species and genera, which adds to the complication in the recognition of fossil species.

Coccolithophores are predominantly photoautotrophic deriving the necessary energy for the synthesis of organic compounds directly from sunlight. However, some cases of ingestion of 'foreign' organic material have also been reported. Motile cells of Coccolithus pelagicus, for example, have been observed to ingest bacteria and smaller algae (Tappan,1980). This method of nutrition is the exception and is always subordinate to photosynthesis (Black,1965).

Gaarder (1971) has shown that reproduction in coccolithophores may take place in two ways :

1. longitudinal fission of the cell with subsequent regeneration of a similar skeleton,
2. by repeated division of the parent cell with its

skeleton releasing daughter cells.

Coccolithophores, being predominantly autotrophic plankton, are largely restricted to the photic zone of the water column (0 to 200m depth), where sunlight can penetrate. They are found distributed throughout the photic zone, but tend to be concentrated in the upper part of the zone to a depth of approximately 50m. At greater depth their concentration decreases rapidly. However, they have been reported as deep as 4000m in the Atlantic Ocean. Some species may occur over widely varying depths in the same area e.g., Oolithus fragilis (Lohmann) Okada and McIntyre, while other species are depth-zoned, their vertical distribution remaining constant regardless of the season.

Coccolithophores, together with dinoflagellates, dominate the plankton of the marine tropical regions. They occur in smaller numbers in cooler oceanic waters where diatoms and naked flagellates become more important. Approximately 300 living species have now been described, the richest floras being those in the Atlantic. The most abundant living species is Emiliania huxleyi (Lohmann) Hay and Mohler, a cosmopolitan species, which in cultures has grown at temperatures ranging from 7 to 27°C.

Coccolithophores are widely distributed, ranging from the open-ocean, pelagic environment to near-shore littoral and lagoonal environments. Although characteristically oceanic, a few species prefer brackish waters, and some occur in freshwater. Cricosphaera species have been found in supralittoral pools influenced by wave-splash where salinities varied from 0.4 to 25%. (Tappan, 1980). Cricosphaera has also been found as a psammophyte, living in interstitial waters in the sands of the intertidal area at Roscoff (northwest Brittany), in quantities such that the sand was covered by a brownish coating. In the Dead Sea Coccolithus pelagicus (Wallich) Schiller has been found at salinities as high as 250%. . Some coccolithophores are also found living in fresh water bogs,lakes, and rivers, eg. Hymenomanus, Acanthoica and

Awacanthoica (Tappan,1980).

1.3. Coccolith mineralogy, morphology, and crystal structure.

X-ray diffraction patterns and crystal form have shown that in nature coccoliths are composed of crystalline calcite. However, in a controlled culture in a nitrogen-deficient medium all three polymorphs of calcium carbonate (calcite, aragonite, and vaterite) were secreted by Emiliania huxleyi (Wilbur and Watabe, 1963). On the basis of crystallisation, two main types of coccolith are distinguished in coccolithophores:

1. Holococcoliths.
2. Heterococcoliths.

The basis for this subdivision is the varying degree of crystal growth. Holococcoliths have an unmodified crystal form with retention of their geometrical faces and angles. The hexagonal or rhombohedral crystals merely show an ordered arrangement over the surface of the organic scales upon which they were formed. However, the majority of extant and fossil species are constructed of heterococcoliths which are internally formed and elaborately constructed. The crystal faces and angles are modified, and the form of the coccolith is completely controlled by the cell.

Coccolithus pelagicus produces holococcoliths of unmodified crystals during the motile phase of its life cycle, and heterococcoliths of strongly modified crystals during its non-motile phase. This behaviour is unique; no other coccolithophore is known to produce coccoliths of both types during its life cycle. Both holococcoliths and heterococcoliths are made up of numerous crystals, commonly with a radial construction, although rarely achieving exact radial symmetry. These are termed heliolithae. However, nannofossils constructed of a single or very few crystals may have a radial symmetry,

e.g., the discoasterids. These forms are termed ortholithae.

Inorganic calcite generally has four crystalline forms; rhombohedral, prismatic , tubular, and scalenohedral. The majority of coccoliths contain rhombohedral calcite crystals in a radial arrangement, a few have hexagonal prisms, and some have a combination of the two forms in a single crystal (Tappan, 1980). Calcite crystals in coccoliths are arranged in such a way that a negative, uniaxal, pseudo-figure is seen under crossed polars. This results in each individual coccolith showing a well defined cross. Kamptner (1954) observed that each type of coccolith had a diagnostic interference pattern, and the extinction position of the calcite crystals and the curvature of the extinction lines were important for the recognition of species. The lines of the interference figure may either curve to the left or to the right, as they are traced out from the centre of the coccolith in distal view. The former is termed laevogyre, the latter dextrogyre.

The various types of holococcolith, heterococcolith, and ortholithae nannofossils described below are shown diagrammetically in Fig. 1.2.

HOLOCOCCOLITHS.

Crystalloliths are plate-like or saucer-like coccoliths bordered by a marginal row of crystals, one rhombohedra wide, and two rhombohedra high, e.g., the motile phase of Coccolithus pelagicus.

Calyptroliths are coccoliths formed from assemblages of hexagonal prisms and basal pinacoids. These are arranged in a perfect lattice, with the c-axis of the crystal perpendicular to the cell surface, e.g., Calyptrosphaera oblonga Lohmann.

Zygoliths are coccoliths possessing an elliptical

ring with a slightly arched or strongly arched crossbar, e.g., Zygosphaera divergens Halldal and Markali.

HETEROCOCCOLITHS.

Placoliths are coccoliths with two shields or plates connected by a cylindrical column, resembling a collar stud, e.g., Coccolithus pelagicus (non-motile phase).

Lapadoliths, in contrast to proximally open calyptroliths, are basket-like coccoliths with their opening distal in orientation to the cell, e.g., Scyphosphaera apsteinii Lohmann.

Criboliths are shallow-rimmed coccoliths with many central perforations, e.g., Pontosphaera discorpora Schiller.

Caneoliths are coccoliths in a basket-like arrangement with a central area, or bottom, of lamellae, and petaloid upper and lower rims, e.g., Syracosphaera pulchra Lohmann.

Crytoliths are basket-like coccoliths with a projecting central structure, which may be very elongate and spindle-like, e.g., Rhabdosphaera clavigera Murray and Blackmann.

Helicoliths are coccoliths with a marginal flange which begins as a series of short, radial, parallel elements that increase in height around the periphery of an oval disc, and overlaps the early part of the flange to form a spiral construction, e.g., Helicosphaera carteri (Wallich) Kamptner.

Scapholiths are elongated diamond-shaped coccoliths with a central area of parallel laths and a shallow rim, e.g., Calciosolenia sinuosa Schlauder.

Cricoliths are coccoliths comprising a simple elliptical ring, e.g., Hymenomanus .

Discoliths are coccoliths resembling crytoliths with a raised rim of small rhombs surrounding a disc formed by rhombohedra that are concentrated at the centre where they pile up in a short mound or spirally twisted spike, e.g., Ahmuellerella phaseolus Black and Barnes.

ORTHOLITHAE :-

Asteroliths are star or rosette forms with concave faces. The rays are single crystals with their C-axes perpendicular to the plane of the disc, e.g., the discoasterids.

Pentaliths are nannofossils formed of five pieces each consisting of a single crystal orientated 72°apart, e.g., Braarudospahaera bigelowii (Gran and Braarud) Deflandre.

Ceratoliths are large horseshoe-shaped crystals. Each ceratolith acts as a single crystal of calcite, but in different genera the optical axis is distinctly orientated, e.g., Ceratolithus cristatus Kamptner.

Prismatoliths are spherical shells composed of a mosaic of interlocking crystal units, e.g., Thoracosphaera. The crystals are constructed of polygonal prisms that may be solid or axially perforate. The genus Thoracosphaera, now classified as a dinophyte and not a coccolithophore (Tangen et al.,1982), has been traditionally included in nannofossil studies.

1.4 Function of coccoliths.

The function of coccoliths, or their significance to the living cell,has yet to be determined. The following is a list of theories that have been proposed regarding coccolith function.

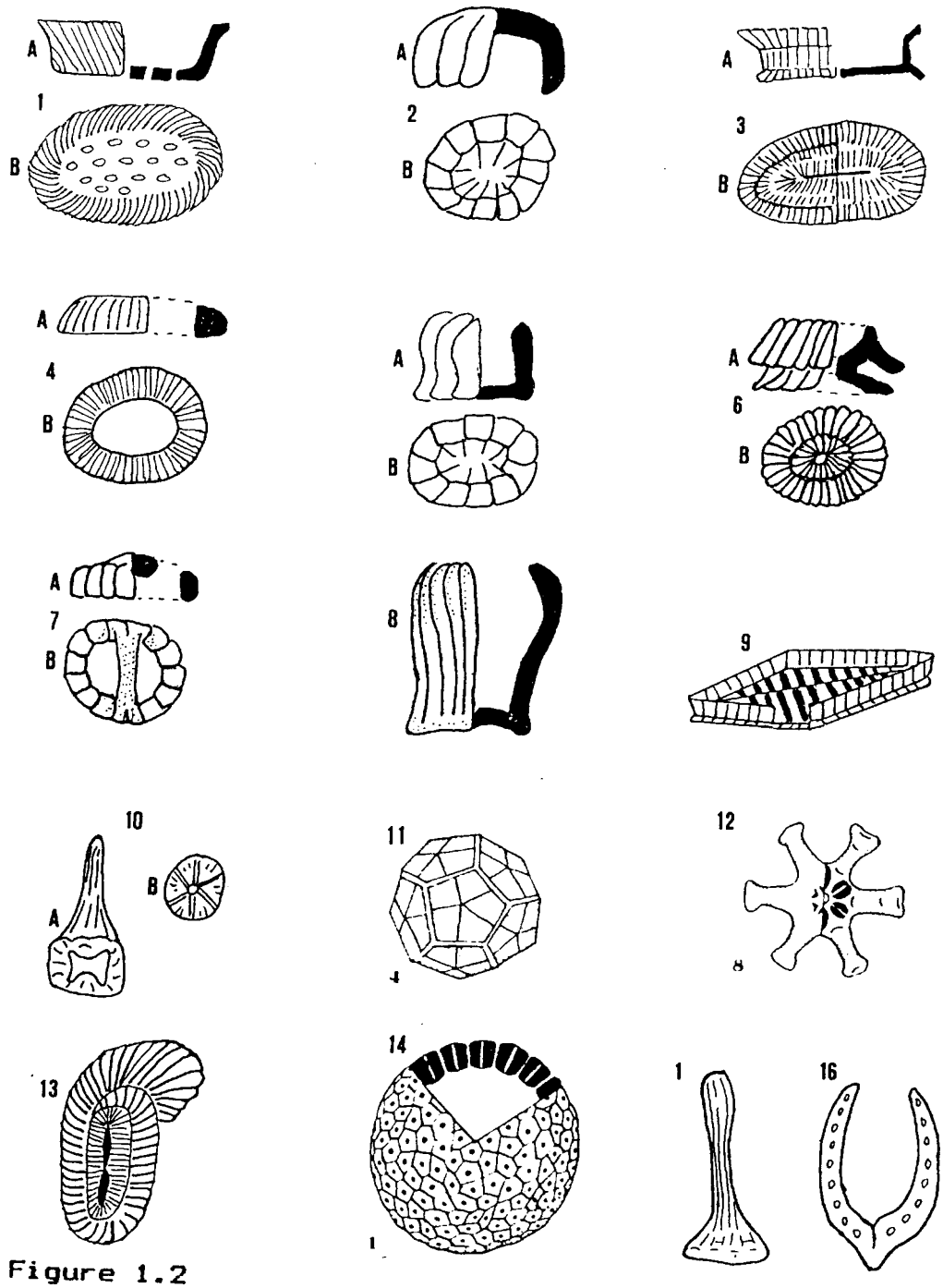


Figure 1.2
Shapes of calcareous nannofossils, shown diagrammatically in plan and edge or profile views; edge views show exterior at left and section at right. (Modified after Tappan, 1980).
1. Cribolith, A) edge B) distal view. 2. Calyptrolith, A) edge B) proximal view. 3. Caneolith, A) edge B) distal view 4. Cricolith, A) edge B) distal view. 5. Discolith, A) edge B) distal view. 6. Placolith, A) edge B) distal view. 7. Zygolith, A) edge B) distal view. 8. Lopadolith, side view. 9. Scapholith, oblique view. 10. Sphenolith, A) side, B) distal view. 11. Pentaliths, complete cell. 12. Asterolith, plan view. 13. Helicolith, distal view. 14. Prismatoliths, complete cell. 15. Rhabdolith, side view. 16. Ceratolith, plan view.

1. They act as shields from excessive sunlight,
2. they concentrate light towards the cell centre,
3. they help the cell to overcome flotation, problems,
4. they act as metabolic barriers,
5. they act as defensive shields.

1.5 History of nannoplankton research.

The first reference to calcareous nannoplankton is attributed to the German biologist C.G. Ehrenburg. In 1836 he reported the occurrence of some minute elliptical granular platelets of 'agaric-mineral' in the Chalk from the island of Rugen. He also figured the first discoasterids and called them 'crystalldrusen', considering that both these and coccoliths to be of organic origin. T.H. Huxley (in Dayman,1858) first recorded the presence of Ehrenberg's crystalloids in deep-sea sediments collected by H.M.S. Cyclops while she was surveying for the first transatlantic telegraph cable. Huxleyi coined the name 'Coccoliths' for these structures because their shape reminded him of cells of the green algae Protococconus, but he also regarded them to be of organic origin.

In the early 1860 s both G.C. Wallich, and H.C. Sorby came to the conclusion that coccoliths were parts of spherical objects to which the former gave the name coccosphere. Wallich at first compared the coccospheres to juvenile stages of foraminifera. However, Sorby continued to consider them as separate organisms because of their distinctive optical properties under polarised light. The fact that coccoliths are the skeletal parts of minute calcareous algae was established by the work of Murray and Renard (1891) and by Murray and Blackmann (1898).

The first systematic work on the calcareous nannoplankton began with the studies of the German

biologist Hans Lohmann. In 1902 he first observed the flagella and placed the coccolithophores with the Chrysomonad algae. Joseph Schiller (1930) in L. Robenhorst's classic work on the Kryptogarten-flora, produced a comprehensive account on all known species of extant coccolithophores. The period 1930 to 1950 was dominated by two nannoplankton workers, Erwin Kamptner and Georges Deflandre. These two workers established a taxonomic classification.

During the mid-1950 s nannofossil studies were greatly enhanced by the introduction of the transmission electron microscope. Braarud et al. (1952) and Deflandre and Fert (1952,1954) were the first to publish photographs of nannofossils using this technique. Further advances in the study of nannofossils were made during the late 1960s by the introduction of scanning electron microscopy (S.E.M.).

Nannofossil assemblages have now been described from sediments from many areas of the world. Biostratigraphic zonation, at first based on land-outcrop sections, has been elaborated and redefined during the past decade on the basis of oceanic sections provided by the Deep Sea Drilling Project (D.S.D.P.). Present research on the distribution of extant coccolithophores is mainly concentrated in the deep-sea pelagic environments where the nannoplankton are most abundant. There have been fewer studies in continental shelf areas, particulary in sediment samples, where the coccolithophore populations are generally thought to be of less importance.

Most studies which have included shallow-water environments refer to the Pacific Ocean. In 1975 Okada and Honjo recorded the coccolithophore distribution in the marginal seas along the western Pacific Ocean and in the Red Sea. Many neritic species in the Red Sea, Yellow Sea, Timor Sea and East and South China seas were found to have irregularly-shaped coccoliths. Additional studies in the East and South China seas have also been carried out by

Chinese workers (Wang and Samtleban, 1983; Chen and Sheih, 1982; and Chen, 1980).

Nannofossil assemblages further south in the Pacific have been described by Burns (1975) from shelf sediments in the western Tasman Sea (36° to 38°S latitude). Another shallow water environment where detailed studies of the nannoflora have been documented is the Great Barrier Reef-Coral Sea Region (Conley,1979; Folk,1972; and Heckel,1973). Lagoonal sediments may also contain abundant calcareous nannofossils. Steylitz (1972) briefly noted the occurrence of Emiliania huxleyi in the fine fractions of recent carbonate sediments from the Bimini Lagoon in the Bahamas. More detailed reports on the coccolithophore flora in a lagoon in Belize (Southern British Honduras) have been compiled by Scholle and Kling (1972) and by Kling (1975).

Studies on coccolithophores in northern coastal waters have been mainly concerned with plankton studies in the Norwegian fjords and adjacent waters (Braarud, 1945; Birkens and Braarud, 1952; Braaarud et al., 1953). However, studies on coccolith distribution in the surface sediments have been largely ignored. Murray et al., (1983) and Murray (1985) are two works which have noted the occurrence of coccoliths in the Celtic Sea and North Sea respectively.

1.6 Stratigraphical value of nannofossils.

Calcareous nannofossils are of great value in stratigraphical correlations because of the following characteristics:

1. they are generally very abundant in marine sediments,
2. they have a wide geographical distribution,
3. rapid evolutionary changes in the group permit a narrow subdivision of the geological column.

Throughout the water column there is a constant descent of dead nannofossil tests, which are eventually deposited to form sea-floor sediments. Their numerical abundance in even the smallest of samples may be enormous; Hay et al. (1967) recorded that oceanic oozes may contain 10^{12} individuals per cubic centimetre. Because coccolithophores are planktonic algae, they have a relatively rapid dispersal over a wide area, and are therefore useful as tools for inter-regional correlation.

Rapid evolutionary changes occurred in nannofossil taxa during the Mesozoic and Cainozoic (Haq, 1971; 1973). In spite of minor fluctuations, species diversity gradually increased throughout the Lower and Middle Jurassic. The first significant diversification occurred during the early part of the late Jurassic (Oxfordian). A second marked increase occurred in the Aptian and Albian, resulting in large numbers of species (> 130) in the latest Cretaceous (Maastrichtian). At the end of the Maastrichtian came the well-documented extinctions of marine organisms. The calcareous nannoplankton suffered great losses with only 4 species surviving into the early Danian. These species, presumably, must have comprised the total genetic reservoir for the Tertiary development.

During the early Tertiary new taxa evolved slowly at first, rising up to a total of 20 species by the end of the Danian, and up to 60 species in the Upper Palaeocene. Rapid evolution occurred during the early Eocene (120 species). This increase was partly due to to the appearance of the discoasters in the late Palaeocene, and their rapid diversity in the middle Eocene. Nannofossil diversity then declined steadily until the end of the Lower Miocene, when just over 30 known species occurred. A second less dramatic radiation of taxa occurred during the Middle Miocene, resulting in a total of over 50 species. Subsequently, a trend of decreasing diversity continued until the Pleistocene. The present-day extant coccolithophore flora is still less diverse than that of the Cretaceous.

CHAPTER 2

MICROFOSSIL TECHNIQUES

CHAPTER 2

MICROFOSSIL TECHNIQUES

2.1 Sample collection.

Samples collected specifically for the study of calcareous nannofossils may be very small; a few grams will usually suffice.

Both estuarine and marine sediments were extensively sampled from the shelf regions of northwest Europe. The majority of the estuarine sediments were collected by taking a surface scrape of the intertidal flats exposed at low water. These sediments were sampled only to a depth of approximately 1 cm beneath the surface. Some shallow-water gravity cores were also taken in selected estuaries (see Chapter 6). The deeper water marine sediments were taken from bottom samples, previously collected by surveys (mainly by the British Navy) and by various collection methods, including shipek grab, dredge and anchor. Additional shallow-water marine sediments were collected by divers. For further details on the source of these samples refer to the sample-collection sections in Chapters 3 to 6.

Samples collected in the field were subjected to a rapid initial study at their location by means of a small, portable optical microscope (see Pl.1, Fig.2). Smear slides were made by scraping a small amount of the sample onto a glass slide and a cover slip was mounted using distilled water. The study of such slides in the field reveals the presence or absence of calcareous nannofossils within minutes of the initial recovery of the sediment. This technique proved useful in the sampling survey of the loughs and estuaries of Ireland.

There are no established rules for determining those sediments which will contain the best preserved nannofossil flora. The grain-size of the sediments obviously must include the size range of calcareous nannofossils (1 to 25 μm). Hay (1977) has listed the following points that may be made concerning nannofossil abundance and preservation:

1. Clay often seems to assist in the preservation of the fine structure of the nannofossils. The clay particles probably serve to isolate the individual nannofossils from solutions in the sediment that may cause secondary calcification or etching of the specimens.

2. Well-preserved planktonic foraminifera and well-preserved calcareous nannofossils often occur together. An abundance of planktonic foraminifera usually indicates an abundance of calcareous nannofossils.

3. Fine-grained sediments of the silt and clay range are generally richest in calcareous nannofossils. Silty-sandstones are also often surprisingly rich in calcareous nannofossils.

Muddy-gravels have also been found to contain a suitable supply of nannofossils. However, a larger initial sample-size is required to ensure there is sufficient silt-sized fraction for experimental studies.

Any sampling programme investigating estuarine environments is dependent to a large extent on the height of the tides. Particular problems occur at high water when there is a general absence of exposed tidal flat sediment. During such times new techniques were devised in an attempt to collect a sample that would record the coccoliths present in that particular area. As a result of these studies, two other potential sources of coccoliths have been identified in intertidal/ supratidal areas:

PLATE 1

Fieldwork in progress: Southern Ireland.

Fig.1 Microscopic analysis of a mud sample from Courtmacsherry Bay.

Fig.2 'Algal-scum' concentrate in a high water channel (Kenmore River). Such deposits were sampled when high tides prevented sampling of the intertidal flats.



1



2

1. Fine-sediment trapped in rock pools by algae living on the rock surface.

2. 'Algal-scum' deposits frequently found concentrated in high tidal channels (see Pl.1,Fig.2.).

The most extensive deposits in the rock pools are found at the intertidal/supratidal boundary. Such areas are not subjected to the diurnal scouring of the tides and additional sediment is probably supplied by supratidal spray from the sea. Although such deposits are not particularly rich in coccoliths they will provide valuble information when no other samples are available for study.

2.2 Sample Preparation.

2.2.1 Initial laboratory investigations.

All samples were first dried for a few days in a drying cupboard (temperature ~ 80°C). This ensured that all the interstitial waters present within the sediment were driven off. Preliminary permanent mounts in the form of smear slides of selected samples were made for study with the optical microscope . These were made by scraping a small amount of the sample onto a glass slide and mixing with distilled water. The slide was dried on a hot plate and a cover-slip mounted using Canada Balsam. This method is quick, simple, and useful for rapid observation of the coccoliths. However, it does not separate the sample into any particle-size fractions , with the result that the ratio of detritus to calcareous nannofossils is generally quite high, with the latter often obscured. This method is also unsuitable for quantitative coccolith studies.

For detailed examination of the nannofossils using the optical microscope and the electron microscope, as much detritus as possible must be removed from the sample. The nannofossils should also be concentrated, cleaned but

not etched. To obtain a higher concentration of the nannofossils, size-segregation techniques should be employed. Coccoliths are generally found within the 2 to 20 μm fraction, but before this fraction was obtained, the organic matter present within the samples was first removed.

2.2.2 Oxidation of organic matter.

2.2.2.1 Introduction.

When organic matter occurs in high concentrations in sediments it must be removed from the sample as it often binds the microfossils to detritus. Of the wide range of sediment-types sampled, extraction of nannofossils was most difficult from fine-grained estuarine sediments, as these generally have a high organic matter content (often in excess of 5%).

Estuarine sediments are particularly rich in diatoms, the pennate forms of which are able to glide over the substrate by production of a stream of mucus between the frustule and the sediment. This mucus secretion binds the silt and clay particles, so accelerating their deposition. Holland *et al.* (1974) have shown that the addition of mucus-secreting diatoms to agitated flasks of sediments increases the rate of deposition and gives the resulting sediment greater stability.

The organic matter in the samples was removed by treatment with 20% v/v sodium hypochlorite (NaOCl). This process was chosen because it gives rapid removal of organic matter without removing or complexing the carbonate microfossils, sesquioxide coatings or silica (Anderson, 1963). It is based largely on the method described by Jackson (1956). However, a pH of 9.5 was used.

2.2.2.2 Hypohalous acid system.

Sodium hypobromite was used by Troell (1931) and more recently by Bourget and Tanner (1953) to remove organic matter from soils. The use of sodium hypochlorite (chlorox) to oxidize organic matter from shells was carried out by Cassidy and Mankin (1960). The advantages of the use of salts of hypohalous acids for this purpose includes ease of use and apparent freedom from such undesirable effects of hydrogen peroxide as exfoliation of mica (Drosdoff and Miles, 1938) and formation of calcium oxalate (Martin, 1954). An advantage of the hypochlorous acid technique is that its oxidation potential is the highest of the hypohalous acids. Anderson (1963) compared the effects of this treatment with two other methods:

1. Hydrogen peroxide preceded by destruction of carbonates at a pH of 5.
2. Hydrogen peroxide alone.

These results showed that the sodium hypochorite treatment appears to be about equally effective for most samples as method 1, and far more effective than method 2.

2.2.2.3 Procedure of method.

Approximately 20 ml aliquots of 20% v/v NaOCl solution freshly adjusted to a pH of 9.5 by addition of dilute HCl (v/v 20%) were added to a few grams of sample in a centrifuge tube. The tube was placed in a boiling water bath for 20 minutes and then centrifuged for 5 to 10 minutes at 2,000 r.p.m. The solution was decanted and the treatment was repeated . After the final treatment the samples were washed first with 5% w/v sodium carbonate and then with distilled water.

The effect of six consecutive sodium hypochlorite treatments on a saltmarsh sediment are shown in Figure 2.1. It appears from these results that there is little additional oxidation after three treatments. The organic

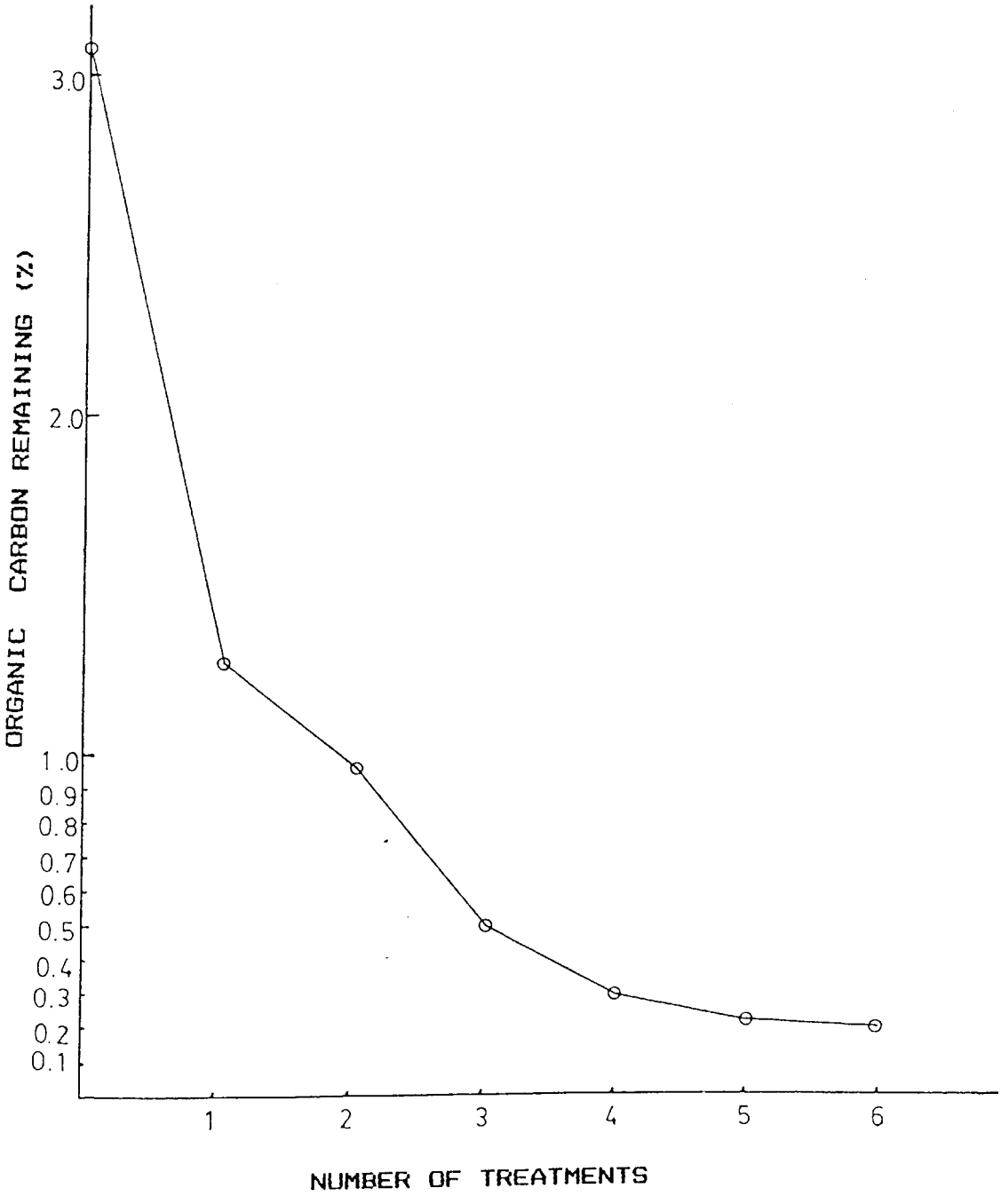


Fig. 2.1
Effects of consecutive sodium hypochlorite treatments on organic matter content of a saltmarsh sediment.

matter contents of the saltmarsh sediment were determined on an infra-red gas analyser. The NaOCl treament was limited to twenty minutes because the hypochlorite decomposes rapidly at high temperature. Repeated treatments are expected to be more effective than prolonged treatments of samples.

Three treatments were carried out on the organic-rich estuarine sediments. Either one or two treatments were carried out on the fine-grained marine sediments, but coarse-grained marine sands and gravels were generally omitted from the oxidation treament.

2.3 Particle-size separation techniques.

Gravity-settling techniques have been used by many authors to separate particles of varying size and density, especially for size analysis of clays. Similar methods have been adopted as a method for nannofossil preparation (Gardet, 1955; pp. 482-483; Bramlette and Sullivan, 1961; p.131). This method involves taking a pipetted sample after different settling times to obtain suspensions containing different sized particles. An alternative method is the use of elutriation, first described by Noel (1965) and Hay (1977). The apparatus essentially comprises a long glass tube. The sample is introduced at the top and during settling is segregated into different size fractions, with the coarser sediment reaching the bottom first. Coccoliths have settling velocities in the order of 1 m per 10 to 20 hours, the smaller forms settling even more slowly. This sort of apparatus can provide a very sharply defined size fraction, if convection currents within the tube are avoided. The disadvantages of elutriation and to a certain extent the gravity technique in general include:

1. The length of time required for fractionation of the sample.

2. The fractionation may be too complete to permit

a preparation of a representative slide for investigation.

Elutriation techniques are useful when a concentration of a few species which might be otherwise too rare to study is needed.

Another technique which may be used to fractionate samples is to filter the samples through a millipore filter. It is advisabe to first strain the sample through a 400 mesh sieve to remove the particles greater than 30 µm. Strained suspensions may be placed in a syringe with a millipore filter cartridge containing the appropiate filter. The coccoliths may be washed off the filter, or the filter may be dissolved , or the coccoliths may be observed directly on the filter. In this study gravity techniques were used to separate particles > 20 µm. This was achieved by allowing a suspension of the sample to settle out through a 5 cm water depth, and pouring off the supernatant liquid after a time interval of 2 minutes 20 seconds (Jackson,1956). The process was repeated until the supernatant liquid remained clear, ie. until all particles > 20 µm had been fractionated off.

The short centrifuge method was adopted to separate the nannofossil fraction (2 to 20 µm) from the < 2 µm fraction. This technique, first described by Edwards (1963), has also been used and/or modified by Hay (1965), Noel (1965), Piennar (1966) and by Medd (1971).

Piennar (1966) published experimental results from fractionation methods, using different speeds and times for centrifuging the samples containing the nannofossils. He first centrifuged the samples at 300 rev/min for 15 seconds to eliminate the coarse fraction. The resulting concentrate was then split into 5 sub-samples, each one centrifuged at different rates and for different times.He tried 5 methods as indicated below:

Method 1. 15 seconds at 300 rev/min.

Method 2. 30 seconds at 850 rev/min.
Method 3. 60 seconds at 850 rev/min.
Method 4. 30 seconds at 1000 rev/min.
Method 5. 120 seconds at 1500-2000 rev/min.

Statistical counts were made by Piennar on each sample to determine the ratio of nannofossils to detritus and detailed studies revealed a total of 43 species. The highest concentration of nannofossils resulted from method 4, while species diversity was low. Methods 2 and 3 resulted in a slightly lower concentration of nannofossils, but with higher species diversity (31 species).

All five methods proposed by Piennar were investigated in this study. The main aim of this investigation was to determine the efficiency of nannofossil recovery relative to the experimental conditions of the five methods. Piennar, although recording the coccolith assemblages in the resultant sediment, did not give similar details of the contents of the resultant supernatant liquid, which was discarded . A smear-slide of the suspended sediment in the resultant supernatant liquid obtained from each method was prapared . Optical analysis of these suspensions revealed that all had a significant quantity of particles > 2 µm. The suspended particles included many coccoliths, paticularly Emiliania huxleyi (diameter, 2 to 4µm). Coccoliths were most common in the supernatant liquid from method 1 and were least common from method 5. These results show that using any one of the five described methods, many small coccoliths are still retained in suspension rather than in the sediment at the bottom of the test-tube. If such methods were employed a bias towards collection of the larger-sized coccolith species would occur. Subsequent species-composition counts would therefore not be representative of the initial sample population.

Further experimentation showed that each sample must be centrifuged for 120 seconds at 2,200 rev/min to ensure

maximum recovery of the nannofossil assemblages. After centrifuging, the supernatant liquid was decanted . The particle-size of the suspended sediment in the supernant liquid using this technique is ~ 1 μm or less. A 5 cm settling depth was used in all test-tubes in this study.

Between centrifuging, the samples were treated in an ultrasonic cleaner for periods of up to 1 minute to clean the nannofossils of adhering clay particles. Several cycles of ultrasonic cleaning and cetrifuging will serve to remove almost all the clay from the sample. However, it should be noted that too much ultrasonic cleaning can damage nannofossils. Clark (1973) reported that a three minute treatment at 50 to 60 w produced optimum disaggregation for his particular samples and ultrasonerator. He also discovered that about 2.6g of sonic pressure was the maximum that nannofossils could endure before destruction.

Most of the clay will have been removed from the sample when the supernatant liquid remains clear after a cycle of ultrasonic cleaning and centrifugation. When this point is reached the supernatant liquid was decanted and the test-tubes containing the coccolith concentrate were then dried overnight in a drying cupboard. When dry, the coccolith concentrates were gently powdered and stored in small labelled plastic bags.

If nannofossils are to be preserved from etching during sample preparation, careful attention must be paid to the pH of all solutions used. Hay (1977) has stated that a pH of 8.5 should be used as a minimum value during sample preparation.

Sodium hexametaphosphate ($(NaPO_3)_6$, Calgon), used as a dispersal agent of clays is not recommended for the concentration of calcareous nannofossils, as a precipitate of calcium orthophosphate ($Ca_3(PO_4)_6$ forms during the preparation and this may coat the nannofossils. Additionally, a solution containing calgon has a pH less

than 8 and may etch nannofossils during the sample preparation. Triple distilled water was used throughout sample preparation, but care must be taken as uptake of CO_2 from the atmosphere may lower the pH of the solution.

2.4 Optical microscope techniques.

Two types of slide are commonly used for optical microscopy:

1. permanent mounts,
2. viscous mounts.

Many materials are available for permanent mounting, all having different refractive indices. Optimum resolution of the nannofossils is achieved by using a mounting medium with a refractive index between the two extremes of calcite (1.4846-1.6585). The contrast that is lost by having the indices of refraction close together may be recovered through phase contrast microscopy. Canada Balsam (n= 1.537) was used as the mounting medium.

Permanent mounts were made from the coccolith concentrates for study with the light microscope. A dilute solution was prepared from the previously dried coccolith residue and distilled water. A few drops of the solution were pipetted onto a glass slide which was dried on a warm hot-plate. A cover slip was mounted using Canada Balsam.

Bramlette and Sullivan (1961) suggested treating coccolith samples with hydrofluoric acid to eliminate clay and replace the calcite in the nannofossils with fluorite (n=1.43), thus giving the nannofossils greater relief when using optical microscopy. When this method is adopted , however, it must be realized that fluoritised specimens are isotropic and cannot be studied in polarised light. Also loss of structural detail may render scanning electron microscopy of little value.

Viscous mounts have been used by many workers

(Bramlette and Sullivan, 1966; Stradner and Papp, 1961; and Edwards, 1963). When this method is adopted , the prepared sample is mounted in silicone oil, either between two glass slides, or between a glass slide and a cover slip. Viscous mounts are useful in light microscopy studies because they allow the orientation of the specimens to be varied. For high magnification optical studies (x 1,600) an oil-immersive (x100) lens was used. This lens was focused through a thin film of silicone oil which had been placed on the top surface of the cover slip. However, Canada Balsam was found to be unsuitable as a mounting medium for high magnification studies. This medium frequently did not have a uniform thickness throughout the area of the glass slide and bubbles were a common problem . In the areas of increased thickness of the mounting medium coccolith specimens could not be accurately focused using the x100 objective.

In later studies, silicone oil was used as the mounting medium instead of Canada Balsam and these problems were eliminated.The R.I. of silicone oil increases only slightly with increasing viscosity varying between 1.403-1.404 (at 25°C) (Anderson, 1960). Other useful properties of silicone oils in this application are their chemical inertness, water-repellant propeties, and stability of viscosity over wide temperature/time ranges.

2.5 Electron Microscope Techniques

Transmission Electron Microscopy (T.E.M.) using carbon replicas has now generally been superseded by Scanning Electron Microscopy (S.E.M.). Preparation of the samples for the latter is easier, faster, and often gives superior results as S.E.M. offers a means of directly examining calcareous nannofossils (Black, 1965). Although occasionally the S.E.M. image is not as crisp as that obtained by T.E.M. using a carbon replica, all of the structural details of the nannofossils can be observed if resolution is optimal. This means that the scanning electron microscope must be kept in pristine condition,

and the column and filament housing should be cleaned regularly. For optimum resolution a high accelerating voltage (25kV) was used for all photographic work. However, lower voltages (15-20 kv) may be used for scanning across the sample.

To prepare a sample for S.E.M. a few drops of the solution containing the nannofossils are carefully delivered from a micro-pippette onto a round aluminium stub. It is essential that an even spread of the sample is distributed over the stub, so that the nannofossils do not become obscured by other particles. The solution was allowed to dry and then the surface of the stub was coated by a thin layer of gold, a few microns thick, using a Belzen sputtering device. The stubs were sputtered 3 times for a period of one minute. This is sufficent time to render the surface of the specimen conductive and will not obscure any structural detail of the nannofossils. All samples were run on an ISI 60A Scanning Electron Microscope.

2.6. Counting Techniques.

2.6.1 Introduction.

In most studies on calcareous nannofossils their abundance in sediments has only been stated in general terms, if mentioned at all. Indeed, Bramlett (1958, p.123) has reported that accurate determination of percentages of coccoliths in rock samples is impractical owing to the difficulties in the separation of the constituent parts.

For any count of coccoliths to be of value, one must express numerical abundance in terms of a known mass or volume of sediment. Previous workers have expressed microfossil abundance in terms of numbers per cubic centimetre (Gumbel, 1873; Downie 1956; Black, 1965 ; Hattin & Darko, 1971). This method cannot be adapted for recent

sediments however, because of the impracticality of cutting 1 cm cubes from unlithified sediments. In this study a method has been devised based on expressing the abundance in terms of numbers of coccoliths per gram of fine silt (2 to 20 μm).

This method has the advantage that direct comparisons between different types of sediments can be easily made, and that any adjustment due to sediment compaction may be ignored. The technique employed was a modification of that used by Hattin (1971).

2.6.2 Method.

0.05 grams of powdered coccolith concentrate (obtained as described in section 2.3) was weighed into a 100ml plastic jar. 50 ml of triple distilled water was then added to the jar. The sample was then suspended by treatment with an ultrasonic generator until completely dispersed.

Each disaggregated sample was then processed for coccolith counting according to the following procedure:

1. A 0.005 ml aliquot was withdrawn from a point near the mid-height of the jar, using a micro-pipette having 0.001 ml graduations.
2. The aliquot was carefully released onto a clean microscope slide, placed on a warm drying plate and allowed to dry.
3. A cover slip was mounted on the slide, as previously described.
4. The slide was labelled.

2.6.3 Counting procedure.

The mounted samples were examined with a binocular Zeiss, petrographic microscope, fitted with a mechanical stage. The photographic mode of the microscope was used

as this produces a rectangular field of view. Coccoliths were counted in the following manner;

1. The slide was moved in a horizontal traverse from the upper right to the upper left of the coccolith concentrate, counting any coccoliths that passed through the field of view. Any coccolith at least 3/4 intact was counted as as one , whereas any coccolith that was 1/4 to 3/4 complete was counted as half.

2. At the end of a traverse a particle was selected that lay on the lower edge of the field of view. The slide was then moved until the particle lay on the upper edge. Counting is then continued along the new traverse in a direction opposite to that of the last traverse.

3. Step 2 is repeated until the entire area of the coccolith concentrate on the slide has been examined.

2.6.4 Calculation

In all calculations the number of coccoliths per slide was first multiplied by 10^4 because the counted subsample represented only 0.005 ml of the original 50ml suspension. To convert the number of coccoliths to numbers per gram of fine-grained silt (coccolith concentrate) the abundance must be multiplied by 20, as the subsample represented only 0.05 grams.

2.6.5. Discussion of the technique.

During laboratory preparation great care must be taken to prevent contamination of samples from external sources such as airborn dust etc. All working surfaces were cleaned regularly. During the initial phases of the investigation various combinations of aliquot samples and volume suspensions were used. The quantities found to be most suitable were 50 ml volume suspension and 0.005 ml aliquots.

Counting difficulties are sometimes experienced when the coccoliths are mixed with other particles, or when only fragments of specimens are recorded. It is particularly important that the suspension used is completely dispersed and homogeneously mixed. When this occurs the coccoliths generally will be recorded as discrete particles (see Pl. 2). Counting was always carried out using polarised light. It would be impractical and very time consuming to count every coccolith in the field of view. Therefore it was decided to devise a method where fewer coccoliths were counted, but where the total absolute abundance of coccoliths could still be determined.

In the initial counting procedure only a marker species was recorded. Coccolithus pelagicus was chosen to be the index or marker species. This species has a large coccolith (12 to 16 µm in diameter), is easily identifiable with the light microscope, and is generally present when modern coccoliths occur in a sample. Because of the large size of the marker species, counting may then be carried out at the relatively low magnification of x 400. This allows a greater area of the slide to be covered during every traverse. Each count takes approximately 20 to 30 minutes to complete.

The total abundance of coccoliths in the sample then has to be determined from a separate species-composition count. The total number of coccoliths in the sample is determined from the ratio 100/ % abundance of C.pelagicus in the sample multiplied by the quantitative abundance of the species in the sample.

For example:

Number of C.pelagicus in sample A = 135×10^5/g
% abundance of C.pelagicus in the sample = 5%
total number of coccoliths in sample A = $100/5 \times 135 \times 10^5$
= 2700×10^5

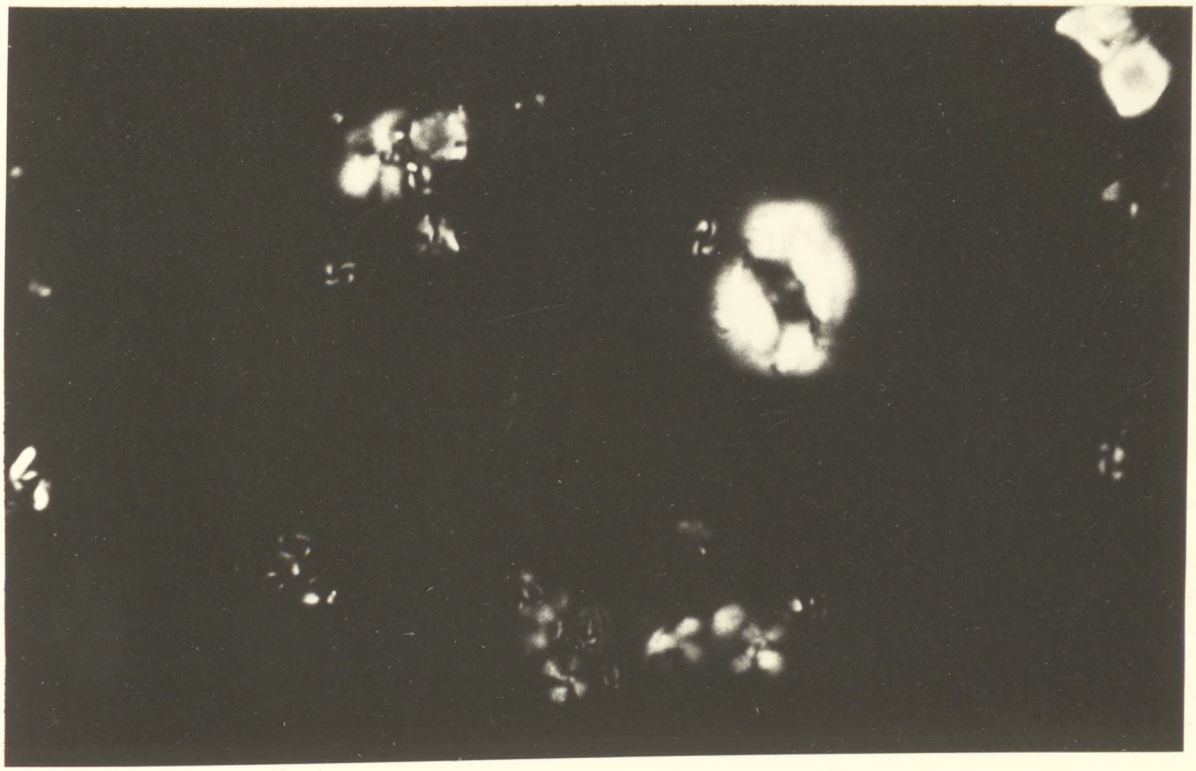
PLATE 2

Photomicrographs of coccolith concentrate from sample BM 51.

The coccoliths generally lie as discrete particles and are not obscured by detritus. Note the large size difference of the individual coccoliths , ranging from ~ 14 um to ~ 2um. Magnification x1,6000.







In the counting procedure outlined in this study there are several factors that may affect the precision of the analysis. These may include variations in the homogeneity of the dispersed coccoliths and variations in the size of the aliquot sample. In order to indicate the importance of such factors replicate calculations were carried out on selected samples. The statistical results are listed below.

Table 2.1
Statistical data for C.pelagicus abundance values.

	Range	Mean	±95% confidence interval	
Sample BM11	203-239	221.25	± 9.41	(n=8)
Solent 20	46-58	55.63	± 3.20	(n=8)

The calculated values for the abundance of C.pelagicus where at least 50 specimens are recorded in each aliquot sample have an accuracy of ± 6% . An additional limit to the accuracy of the calculated values of the total number of coccoliths in the samples are random flucuations in the % abundance of C. pelagicus in the counts and in the subsequent ratio values 100/% C.pelagicus. Variations in the determination of the ratio values are listed below.

Table 2.2 Statistical data describing variations in the ratio of total coccoliths divided by the relative abundance of C.pelagicus.

Sample BM 11	
Number of observations	8
% of C.pelagicus range:	5.0- 6.3 %
ratios of 100/ % of C.pelagicus	16.7-20.0
mean ratio	18.49
standard deviation	1.60

95% confidence interval 18.49 + 1.11

Replicate analyses of the total coccolith/C.pelagicus ratio of sample BM 11 gave an accuracy of ± 6% . Calculated values for the total number of coccoliths, where at least 50 specimens of C.pelagicus are recorded in each aliquot sample, therefore have a accuracy of ± 12 % . Values based on lower numbers of C.pelagicus will be expected to have less accuracy.

The percentage abundance of the coccolith species was determined by counting at least 300 coccoliths per sample (whenever possible). Reference to probability tables compiled for geological use (Shaw, 1964) indicated that with a 300 count there is a 99% chance of finding a species at the 1 to 2 % level.

Most of the coccolith species recorded in the samples were easily identifiable with the optical microscope . The small placolith-type coccoliths (2 to 5 µm in diameter) of Emiliania huxleyi and the genus Gephyrocapsa, however, are difficult to separate. In fact Roth and Berger (1975, p.88) stated " Emiliania huxleyi can only be identified in the SEM with certainty. Strongly dissolved rims are difficult to distinguish from rims of Gephyrocapsa."

In the percentage counts using the light microscope all small placolith specimens (2 to 5 µm) without a bridge are attributed to the species Emiliania huxleyi. Such a procedure may result in an over-estimation of the relative abundance of E.huxleyi in the total, as gephyrocapsids with their bridges broken off, will be attributed to E. huxleyi. To check any error in these percentages scanning electron microscopy was used on selected samples to allow precise identification of the Gephyrocapsa species in the sample. The results are listed below.

Table 2.3.
Percentage abundance of Emiliania huxleyi and Gephrocapsa species in selected samples as determined by optical and scanning electron microscopy.

Sample	BM1		BM4		BM5		JM29	
	E.h	G.spp.	E.h	G.spp.	E.h	G.spp	E.h	G.spp.
O.	83.5	0.5	90.5	0.5	93.5	0.5	93.5	-
S.	84.0	1.0	89.5	0.5	93.0	0.5	93.5	0.5

E.h = Emiliania huxleyi O. = optical microscope
G.spp. = Gephyrocapsa spp. S. = S.E.M.

From these data it can be seen that there is very little difference between the two methods. No large over estimation in the relative abundance of E.huxleyi in the assemblages occurs when counting is carried out using the optical microscope. Additionally, almost all gephyrocapsids observed using SEM have their bridges intact.

In selected samples (mainly from the Celtic Sea and western English Channel) where E.huxleyi is particularly abundant, a second count is carried out. In these cases at least 200 specimens of the subordinate species are counted, excluding E.huxleyi. To simplify the counting procedure and to eliminate the need for counting the small placoliths (2 to 5μm in diameter) gephyrocapsids are also omitted from these second counts.

After the second count all abundances are then normalised so that all species including the dominant and subordinate species make up 100% of the assemblage. For example,

First count of 300 specimens or more yields:

E.huxleyi
Gephyrocapsa } 90%

Subordinate species } 10%

The second count of 200 specimens of the subordinate species gives the relative abundance of each of the subordinate species in the population. Then the proportion of each species in the secound count multiplied by 10% represents the proportion of that species in the total assemblage. This counting method will record more species per sample and will not obscure species which may be important ecological indicators.

The percentage coccolith component in the fine fractions of the sediments is also determined. These percentage values represent the number of coccoliths encountered in a count of 300 or more discrete particles. Counting was always carried out using the optical microscope using polarised light. Duplicated counts of the same sample (n=3) showed that the determined coccolith percentages had a precision of ± 5% .

2.7 Species diversity of the assemblages.

Many indices are available for measuring species diversity. The simplest expression of diversity is to determine the species-composition in an assemblage, the more the number of species (s) the greater the diversity of the assemblage. However, this value is almost wholly dependant on the total number of individuals (N) and is not suitable as a diversity index. An important index useful to define diversity is species dominance (D). The species dominance (D) is given as the percentage of the most dominant species in the sample (P max);

$$D = P_{max}.$$

Dominance is the simplest of the indices that make use of species proportions to define diversity. the Shannon-Wiener Function and Simpson's Index are two parameters that are used to relate the depositional environment with microfossil assemblages (Berger and Parker, 1970; Buzas, 1979).

Berger and Parker have rewritten the Simpson Index as

$$P = 1 - \sum pi^2$$

while the Shannon-Wiener Function is

$$H = - \sum pi \ln pi$$

where P is Simpson's Index, S is the number of species, pi is the proportion of the ith species defined as pi = ni/N where ni is the number of individuals of the ith species and N is the total number of individuals, and H is the Shannon-Wiener Function. H and P depend upon the distributional proportion of the species. The greater the number of species, and the more uniform the distribution of the species , the larger the indices will be . Species dominance, Simpson's Index and the Shannon Function are all calculated for selected coccolith assemblages in this study.

CHAPTER 3

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE CELTIC SEA AND THE ENGLISH CHANNEL

CHAPTER 3

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE CELTIC SEA AND THE ENGLISH CHANNEL.

3.1 Introduction.

3.1.1 Background and objectives.

The changes in the coccolith assemblages across the shelf of the Celtic Sea and English Channel have not previously been systematically assessed. Murray et al. (1983) described the occurrence of coccoliths in both plankton and sediment samples from the Western Approaches to the Channel, however, apart from the number of coccolith species present in the samples, no other quantitative data was presented. Further east , in the central and eastern English Channel, there is no record of the occurrence of coccoliths in the Recent sediments. The objective of this study is to define the species composition, quantitative abundance and other characteristics of the coccolith assemblages in the Recent sediments of the Celtic Sea and English Channel and to compare the results with the published data. The relation between the coccolith assemblages in the sediments and the overlying hydrographic regimes of the area is discussed. Transport paths of coccoliths across the continental shelf are delineated.

3.1.2 The geographical area.

The Celtic Sea forms a shallow embayment of the eastern North Atlantic bordered by the Celtic lands of Southern Ireland, southwest Wales, Cornwall and Brittany

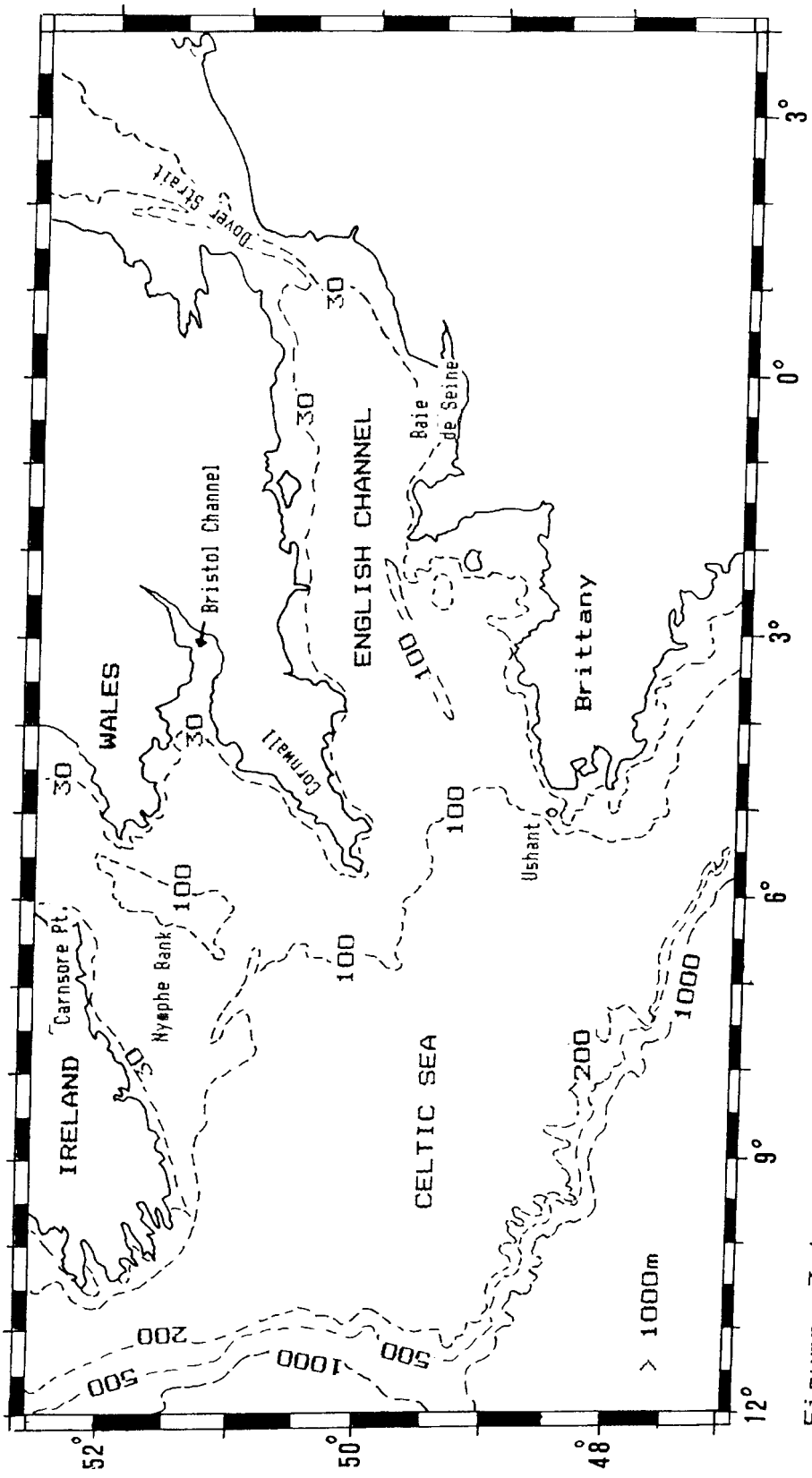


Figure 3.1.
Map of the Celtic Sea and English Channel showing water-depth contours (isobaths) (in metres) and place names used in text

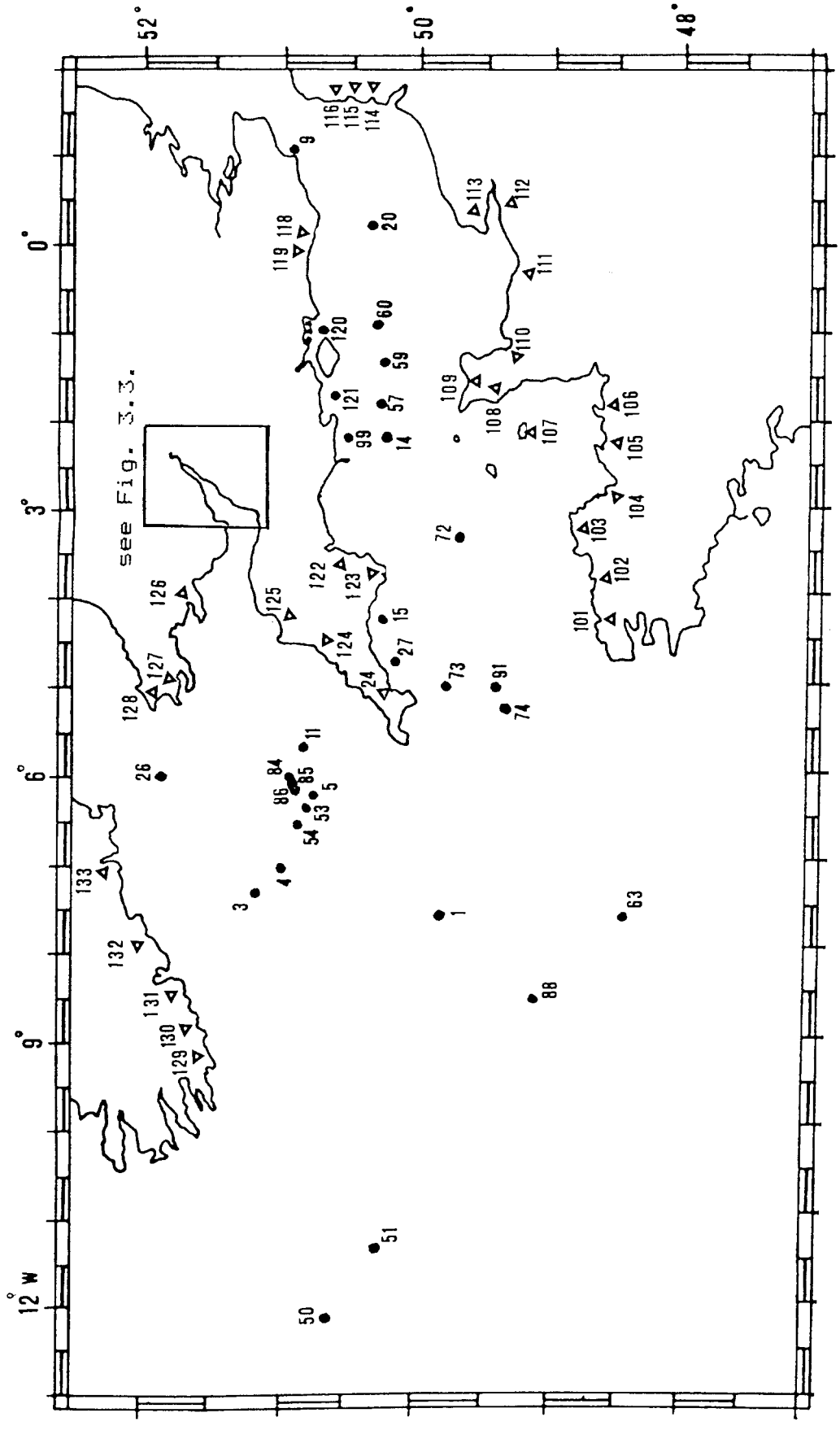


Figure 3.2.
Location of sample points.

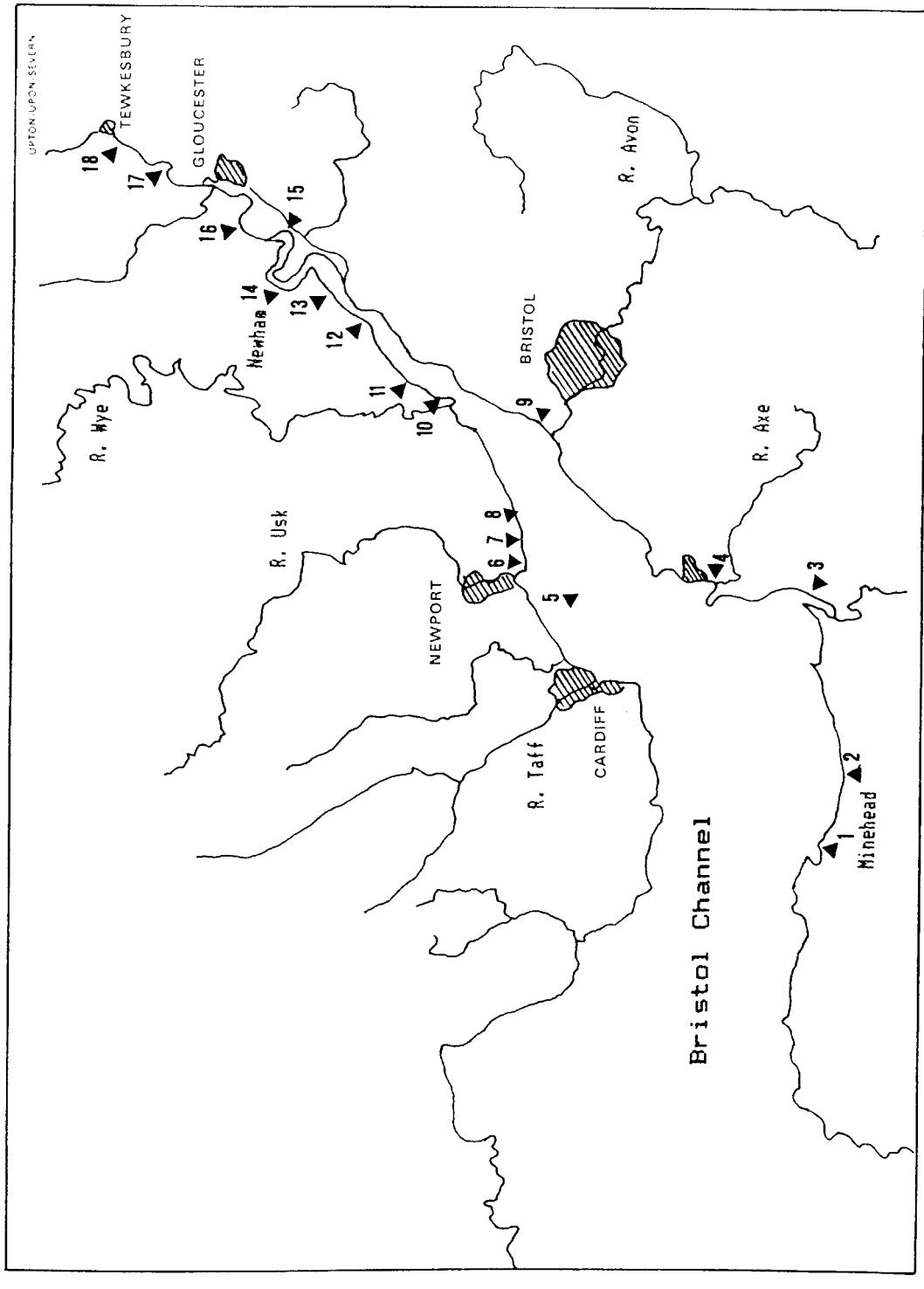


Figure 3.3.
Location of sample sites in the Bristol Channel and the Severn Estuary.

(Cooper, 1967). It may be arbitrarily separated from the Irish Sea by a line drawn from St. Davids Head (Dyfed) to Carnsore Point (southeast Ireland), and from the western entrance to the English Channel by a line drawn from Lands End to Ushant (northwest France). The western limit of the Celtic Sea is generally taken as the break of slope at the 200 m contour of water-depth. The Dover Strait is regarded as the eastern limit of the English Channel. The Bristol Channel and the Severn Estuary are also included in this study.

3.1.3 Morphology and topography.

The Celtic Sea and English Channel are remarkably flat-bottomed, except for the linear banks and the outcrop of the Haig Fras Granite (Hamilton, 1979). A sharp break in bathymetry occurs in the west, at the continental margin. The continental shelf is one of the widest in north western Europe and extends some 900 km eastwards along the English Channel at a gradient of about 1:5500.

The English Channel is characterised by large areas of solid-rock outcrop on the sea floor, particularly in the central area. The western English Channel is floored with a basal pebble layer, deposited during the Flandrian transgression. Above this basal layer and reworked into the upper part, is a thin layer of biogenic sand and gravel (Boillot, 1964, 1965). The Celtic Sea is also floored by a coarse basal deposit, but this is more extensively overlain by muddy sediments and few areas of exposed rock occur. In the Celtic Sea extensive glacial and post-glacial sediments occur, which may be up to 100 m thick. These superficial sediments form a wedge which thickens, and is of progressively younger age towards the west.

3.1.4 Climate of the area.

The Celtic Sea is subject to a temperate climate with cool summers and mild winters (Cooper, 1967).

Westerly winds predominate , while rainfall and the frequency of gales decrease from west to east . Gales are most common in the winter and are responsible for the greatest rates of net transport. Evaporation is generally highest in the winter because of the increased wind speeds.

3.1.5 Temperature of the surface waters.

In winter the water column is well-mixed from the surface to the bottom and the surface contours of water temperature for February are also representative of the whole water column (Fig. 3.4). The coldest winter temperatures range from about 10.5°C in the deeper parts of the Celtic Sea to about 6.5°C at the eastern margin of the Channel (Pingree,1980). Summer temperatures reach their maximum of 17°to 18°C in August, near the end of the heating cycle. In the west , a warm water tongue (16° C isotherm) protrudes into the English Channel and northern Celtic Sea . This represents the full development of stratified conditions in the region of weak tidal mixing (Fig.3.5).

3.1.6. Salinity.

Figure 3.6 shows the distribution of surface salinity in the Celtic Sea and English Channel for February, March, and April; the period when the waters are of highest salinity. Highest values (~35.5%.) occur in waters at the southwestern margin of the Celtic Sea. Lowest salinity values in the Celtic Sea (~34.75%.) are found at its northern margin, near the entrance to St. George's Channel. The main axis of the high salinity tongue of water (>35.0%) extends down the central region of the English Channel. The English side of the Channel is more saline than the corresponding French side, where runoff from the rivers Seine and Somme reduces the salinity below 34%. .

The period August to October is generally when the waters are freshest (see Fig.3.7). During this period

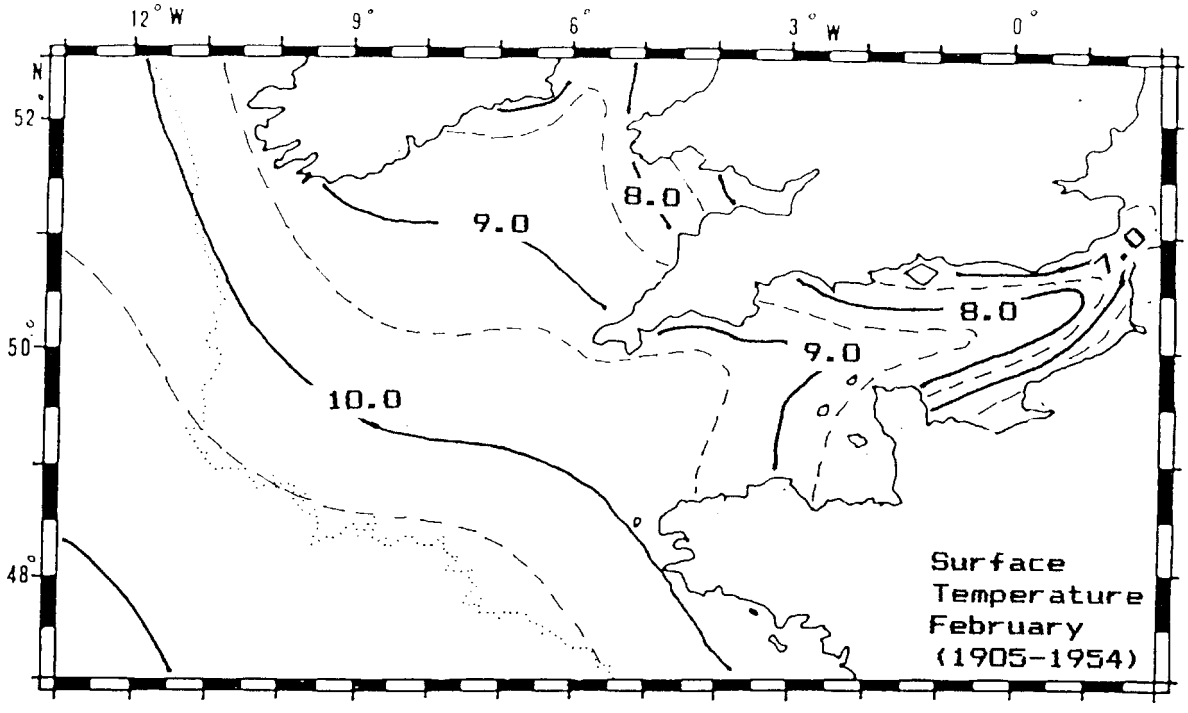


Figure 3.4.
Mean distribution of sea surface temperature °(C) for February (after Pingree, 1980).

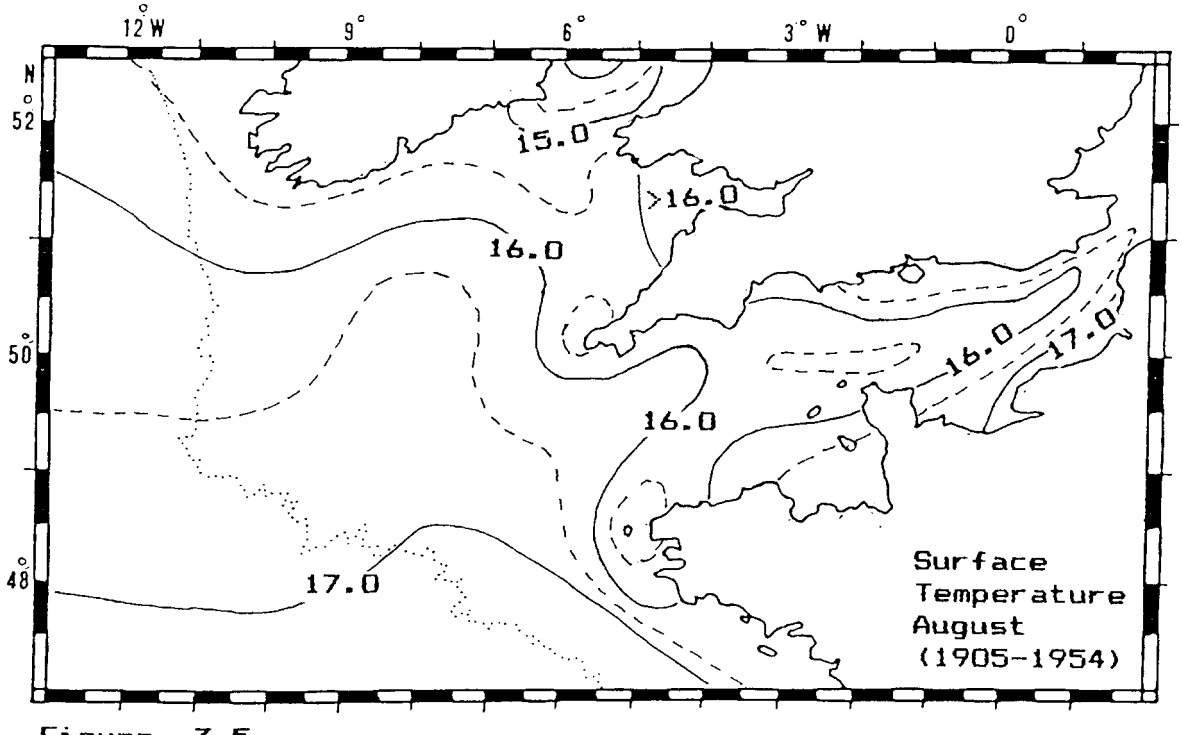


Figure 3.5.
Mean distribution of sea surface temperature °(C) for August (after Pingree, 1980).

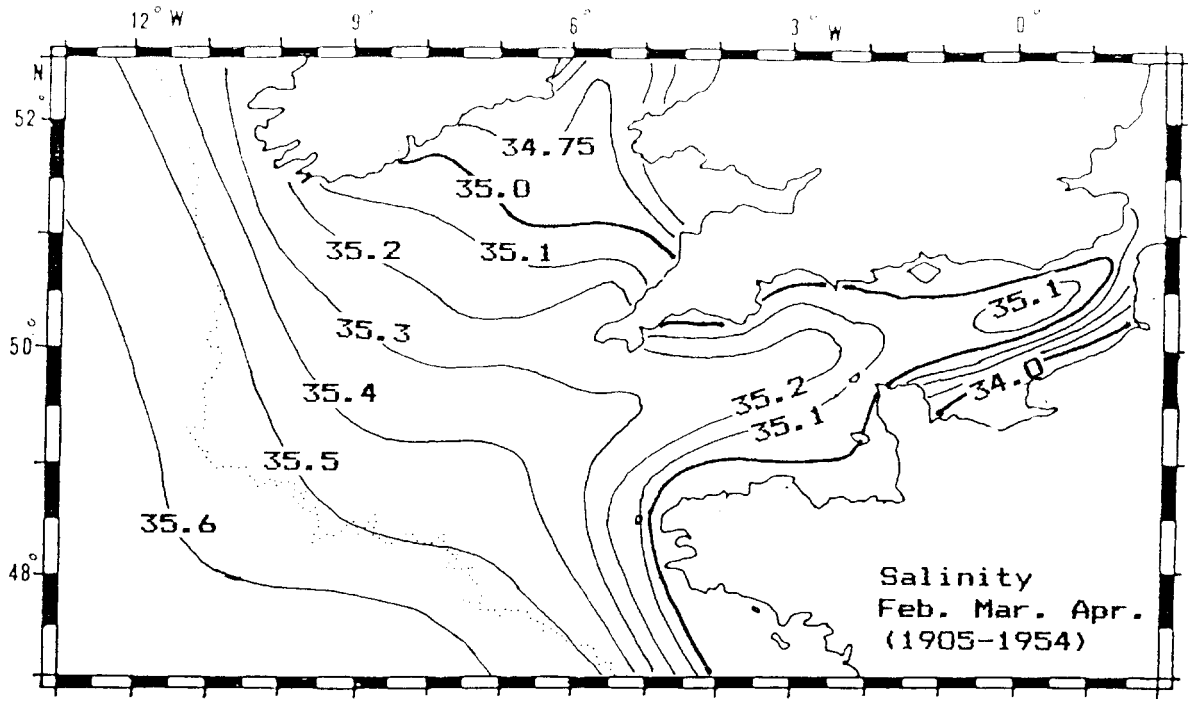


Figure 3.6.
Mean distribution of sea surface salinity (‰) for the February, March, April period (after Pingree, 1980).

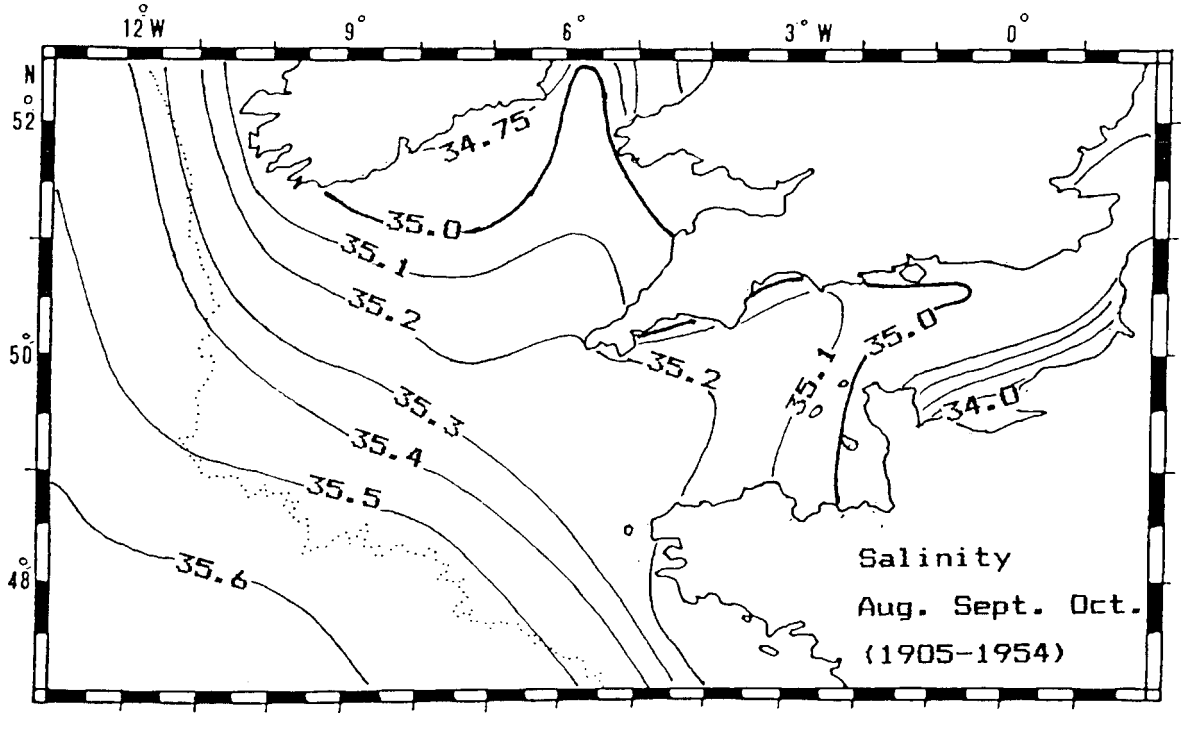


Figure 3.7.
Mean distribution of sea surface salinty (‰) for the August, September, October period (after Pingree, 1980).

high salinities >35.2 ‰. occur in the western English Channel and in the southern Celtic Sea. Salinities less than 35.0 ‰. occur in the surface waters of the northern Celtic Sea and in the eastern English Channel.

3.1.7 Tides.

The tidal wave approaches from the southwest, a direction normal to the greatest slope of the shelf edge (Pingree, 1980). The tidal range varies from about 11m in the Gulf of St. Malo to about 1m west of the Isle of Wight (Pingree, 1980). The amplitude of the surface tidal streams at spring tides ranges from about 0.5 knots (0.3 m/s) near Nymphe Bank in the north Celtic Sea to 3 knots (1.3 m/s) in the Central English Channel (Sager and Sammler, 1964, 1968). Values of up to 9 knots. (4.6 m/s) are reached off headlands such as Cap de la Hague. Tidal streams generally rotate in a clockwise direction in the Celtic Sea and western entrance to the English Channel. Further east in the Channel they are anticlockwise, but become more nearly rectilinear as the Channel narrows (Pingree, 1980).

3.1.8. Development of the seasonal thermocline.

A seasonal thermocline occurs in the Celtic Sea and western English Channel (Pingree, 1975). The thermocline first starts to develop near Nymphe bank in the Celtic Sea during early spring. It then spreads quickly across the Celtic Sea , penetrating the English Channel less than a month later (Pingree, 1975). Off Brittany and North Cornwall its development is relatively delayed because of increased tidal mixing in these regions. Where surface tidal streams exceed 2 kts. (1m/s), no pronouced thermocline occurs and consequently, conditions around Ushant, Lands End and in the central English Channel remain well-mixed throughout the summer (Matthews, 1911; Dietrich, 1950).

The thermocline begins to break down in the English

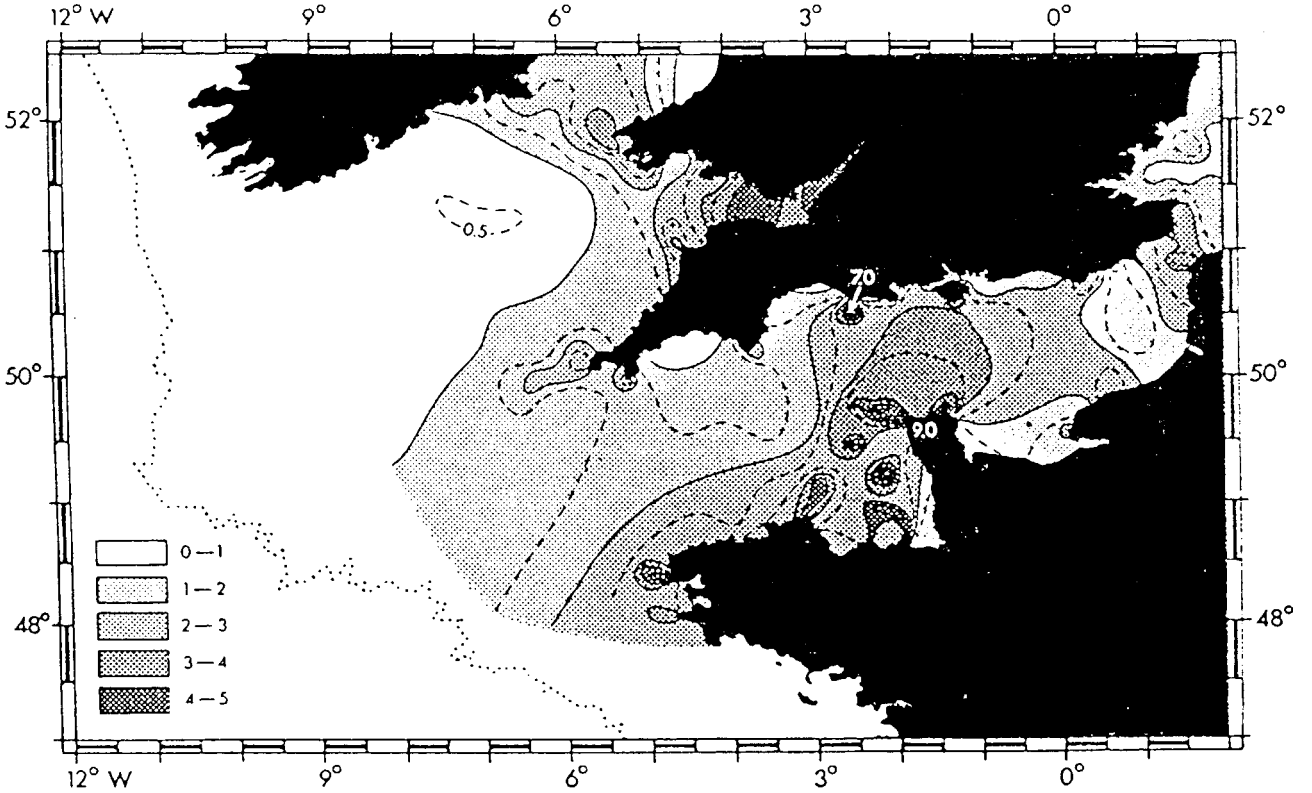


Figure 3.8
Distribution of tidal stream amplitudes at spring tides in knots (surface values).
(After Pingree,1980).

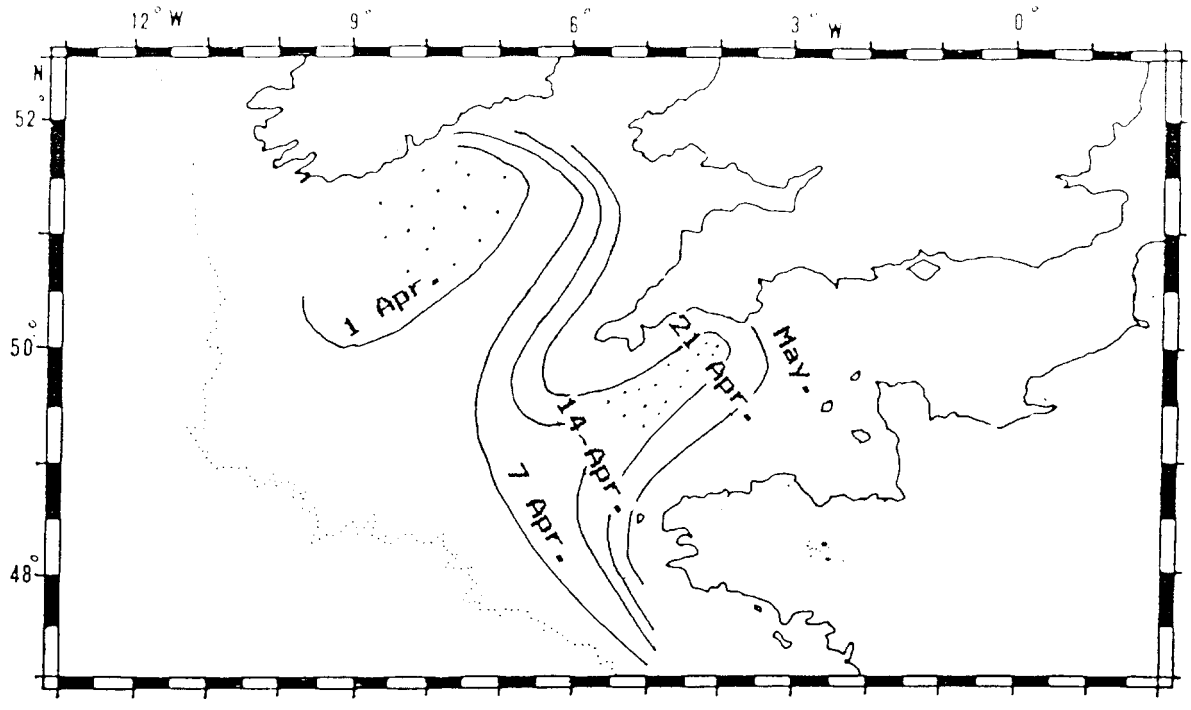


Figure 3.9.
The distribution of thermocline development as outlined by weekly contours in the Celtic Sea and western English Channnel (after Pingree, 1975).

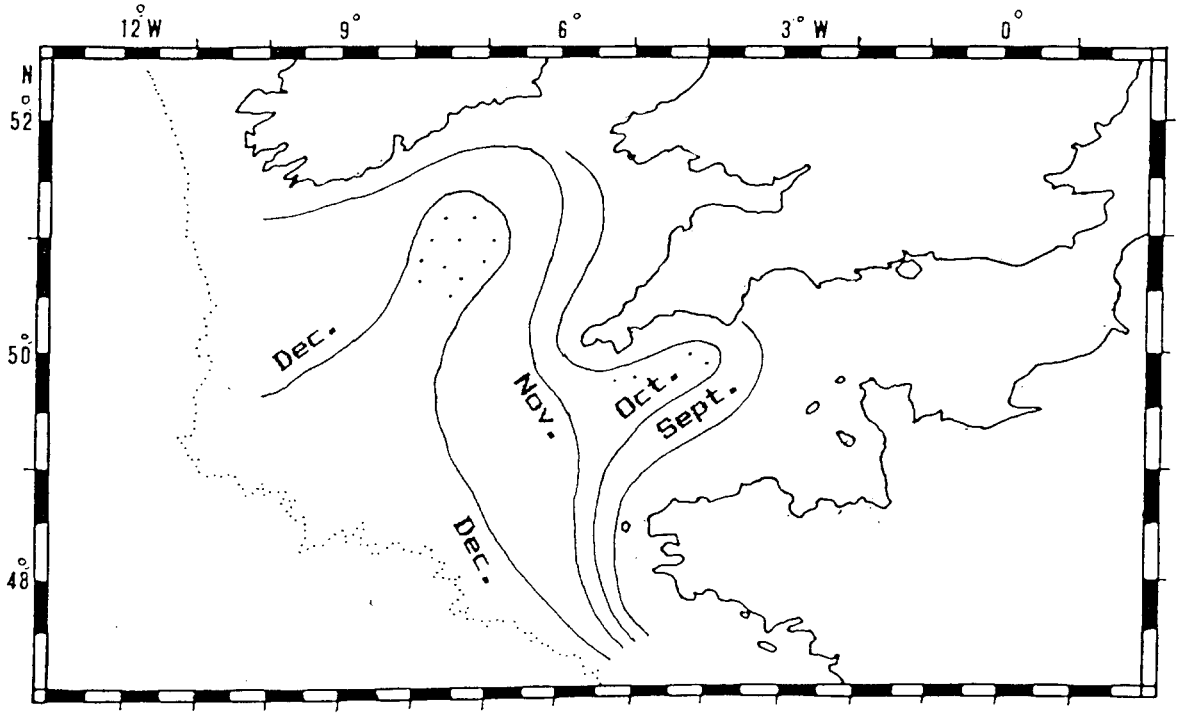


Figure 3.10.
Erosion of the thermocline across the English Channel and Celtic Sea (after Pingree, 1975).

Channel in September as the water column starts to cool, but does not disappear completely the Celtic Sea until mid-December. Near Nymphe Bank where tidal mixing is weak , the water column remains stratified for 9 months of the year.

3.1.9 Residual water movement and circulation patterns.

The general flow of water through the Celtic Sea and English Channel and into the North Sea via the Straits of Dover was established by the work of Garstang (1897) and Matthews (1914). Additional support for this was given by using plankton indicators of water movement (Russel, 1935, 1936, 1937). More recently Kautsky (1973) reported on the movement of the radio nucleid Cs-137 released near Cherbourg. The nucleid was transported along the Dutch coast towards the Skagerak, with a mean flow of about 1.9 km/ day. Superimposed on the mean flow in the area are local water circulation patterns. In the Celtic Sea, these are represented by anticlockwise eddies (Matthews, 1914). In the western Channel it is thought that the circulation is clockwise in the winter and anticlockwise in the summer (Lumby, 1935).

3.1.10 Samples.

Sub-samples were taken from bottom samples previously collected by surveys (mainly by the British Navy) and by different collection methods including Shipek grab, dredge and anchor. These samples form part of the Ocean-Bottom collection of the British Museum (Natural History). Surface samples were also collected from a number of estuaries in the area. The samples of the French estuaries were supplied by the University of Caen. A few shallow-water marine samples were also collected by divers along the coasts of Hampshire and Dorset. A list of these samples may be found in Table 3.2 and 3.3. Seventy-nine samples of surface sediments were examined

as described below ;

1) thirty open-water samples from the continental shelf with water depths ranging from 15m to 168 m,

2) two samples from the continental slope (depth 1257 to 1269m),

3) fourty-seven intertidal estuarine sediments.

Table 3.1 Location and water depth of samples from the Celtic Sea and English Channel.

SAMPLE NO.	LATITUDE	LONGITUDE	DEPTH (M)
	° '	° '	
BM 1	49 48 N	07 35 W	132
BM 3	51 09.3 N	07 23.8 W	97
BM 4	51 02.5 N	07 05.1 W	99
BM 5	50 44.1 N	06 16.5 W	95
BM 9	50 57.5 N	01 03.3 E	29
BM 11	50 47.9 N	05 38.7 W	61
BM 14	50 12.1 N	02 10.0 W	55
BM 15	50 18.2 N	04 17.8 W	48
BM 20	50 22.3 N	00 11.8 E	43
ES 24	50 09 N	05 03 W	-
BM 26	51 49.6 N	06 00.7 W	112
BM 27	50 11.8 N	04 43.0 W	55
BM 50	50 35.8 N	12 19.5 W	1269
BM 51	50 13.0 N	11 23.0 W	1257
BM 53	50 46.9 N	06 23.6 W	97
BM 54	50 49.7 N	06 31.5 W	93
BM 57	50 14.7 N	01 47.4 W	NR
BM 59	50 13.3 N	01 16.0 W	55
BM 60	50 17.0 N	00 57.0 W	66
BM 63	48 25 N	07 34 W	166
BM 72	49 39.9 N	03 26.1 W	74
BM 73	49 44.4 N	05 00.8 W	86
BM 74	49 22.3 N	05 15.5 W	91
BM 84	50 52.7 N	06 08.2 W	89
BM 85	50 51.3 N	06 09.1 W	89
BM 86	50 50.0 N	06 09.1 W	90
BM 88	49 03.5 N	08 32.7 W	157
BM 91	49 26.5 N	05 01 W	95
DI 99	57 37 N	02 11 W	-
ES 101	48 34 N	04 36 W	-
ES 102	48 36 N	03 53 W	-
ES 103	48 48 N	03 12 W	-
ES 104	48 32 N	02 42 W	-
ES 105	48 38 N	02 06 W	-
ES 106	48 36 N	01 45 W	-
ES 107	49 10 N	02 09 W	-
ES 108	49 22 N	01 48 W	-
ES 109	49 42 N	01 30 W	-
ES 110	49 22 N	01 10 W	-
ES 111	49 20 N	00 27 W	-
ES 112	49 22 N	00 06 E	-
ES 113	49 30 N	00 06 E	-
ES 114	50 16 N	01 33 E	-
ES 115	50 24 N	01 34 E	-
ES 116	50 32 N	01 35 E	-
ES 117	51 02 N	02 06 E	-
ES 118	50 49 N	00 04 E	-
ES 119	50 40 N	00 16 W	-
DI 120	50 44.2 N	00 59.7 W	12
DI 121	50 43.5 N	01 43.5 W	15
ES 122	50 32.4 N	03 31.8 W	-
ES 123	50 23.5 N	03 34.5 W	-
ES 124	50 35 N	04 50 W	-

Table 3.1. (continued)

SAMPLE NO.	LATITUDE	LONGITUDE	DEPTH (M)
	° '	° '	
ES 125	51 04.9 N	04 10.0 W	-
ES 126	51 38.5 N	04 06.5 W	-
ES 127	51 43 N	05 09 W	-
ES 128	51 53 N	05 10 W	-
ES 129	51 28 N	09 15 W	-
ES 130	51 35 N	08 50 W	-
ES 131	51 35 N	08 35 W	-
ES 132	51 45 N	08 12 W	-
ES 133	52 16 N	07 07 W	-

BM = British Museum sample, ES = estuarine sample, DI = marine sediment collected by divers.

Table 3.2
Location of sample sites in the Bristol Channel and Severn Estuary.

Sample	Location	grid reference
S1	Minehead Hbr.	SS 971 471
S2	Watchet Docks	SS 063 453
S3	Parrett Estuary	ST 288 466
S4	Weston	ST 309 584
S5	Newport Deep	ST 305 785
S6	Uskmouth	ST 374 822
S7	Redwick	ST 416 835
S8	Magor Pill	ST 438 847
S9	Avonmouth	ST 500 790
S10	Severn Bridge	ST 552 905
S11	Pill Ho	ST 568 957
S12	Lydney Hbr.	SO 653 014
S13	Purton	SO 672 047
S14	Newham	SO 693 120
S15	Rodley	SO 757 117
S16	Hartlands Hill	SO 754 153
S17	Norton	SO 848 258
S18	Tewkesbury	SO 888 388

3. 2 RESULTS

3.2.1 Introduction.

The area studied can be divided into two broad physiographical regions :

1) The shelf of the Celtic Sea and western English Channel (including the Bristol Channel and Severn Estuary),

2) The continental slope to the west of the Celtic Sea

Twenty-two species of Recent coccolith are found in the surface sediments from the slope and shelf regions in the area. These are listed in Table 3.3.

3.2.2 Coccolith assemblages from the shelf of the Celtic Sea and English Channel.

Eighteen coccolith species are recorded in sediments from the continental shelf of the Celtic Sea and English Channel. The number of coccolith species found in the sediments decreases eastwards across the shelf towards the English Channel (Fig.3.11). Eight or more species occur throughout the shelf of the Celtic Sea and the western English Channel and in the Bristol Channel. Intermediate diversities (4 to 6 species) typify the sediments around the coast of Wales, the Severn Estuary and in the central Channel. Lowest diversities (three or fewer species) occur in sediments from the eastern Channel. The relative abundances of the more common species are listed in Tables 3.4, 3.5 and 3.6.

Table 3.3.
List of coccoliths recorded from the Celtic Sea and English Channel sediments.

Braarudosphaera bigelowii (Gran and Braarud) Deflandre
Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan
Ceratolithus cristatus Kamptner
Coccolithus pelagicus (Wallich) Schiller
Coronosphaera mediterranea (Lohmann) Gaarder
Discosphaera tubifera (Murray and Blackman) Ostenfeld
Emiliania huxleyi (Lohmann) Hay and Mohler
Gephyrocapsa caribbeanica (Boudreaux and Hay)
Gephyrocapsa ericsonii McIntyre and Be'
Gephyrocapsa oceanica Kamptner
Helicosphaera carteri (Wallich) Kamptner
Rhabdosphaera clavigera Murray and Blackman
Pontosphaera discopora Schiller
Pontosphaera messinae Bartolini
Scapholithus fossilis (Kamptner)
Scyphosphaera apsteinii Lohmann
Syracosphaera histrica Kampter
Syracosphaera nodosa Kamptner
Syracosphaera pulchra Lohmann
Umbellosphaera tenuis (Kamptner) Paasche
Umbilicosphaera hulburtiana Gaarder
Umbilicosphaera sibogae (Weber-van Bosse) Gaarder
Umbilicosphaera sibogae (Weber-van Bosse) Gaarder var. foliosa Okada and McIntyre

The coccolith assemblages are dominated by Emiliania huxleyi. The species is ubiquitous in sediments from the Celtic Sea and western English Channel. In sediments deposited from open-shelf waters it forms 82.5 to 97 % (mean 91.5 %) of the assemblage. Its relative abundance decreases towards land; 81 to 84 % along the Irish coast, 81 to 51 % in sediments from the Bristol Channel and Severn Estuary, 67 to 79% within estuarine sediments from north Cornwall (Fig. 3.14). Even lower abundances occur in the central Channel where it forms 47 to 88% (mean 53.0 %). However , east of the Isle of Wight its distribution is more varied. It is subordinate to Coccolithus pelagicus (Wallich) Schiller in Baie de la Seine, but forms up to 69 % near Dungeness. E.huxleyi is absent in sediments from the French coast along the Strait of Dover.

The quantitative abundance of E.huxleyi follows the distribution of the total abundance of coccoliths in the sediments (see Figs. 3.11 and 3.13). Highest abundances of both values (10^9 coccoliths per gram) occur in the deeper water sediments (> 75m) of the central Celtic Sea . Their abundances drop to 10^8coccoliths per gram in coastal sediments of southern Ireland and in the western English Channel. Lower abundances occur in sediments deposited in the inner Bristol Channel and lower Severn Estuary (10^7per gram). In the upper Severn Estuary, north of Newnham, 10^5 to 10^6coccoliths per gram occur in the tidal sediments. Coccolith abundances continue to decline in an easterly direction throughout the shallow water sediments of the central and eastern English Channel. Sediments deposited at the eastern extremity of the Channel contain only 10^5 coccoliths per gram.

Coccolithus pelagicus and Syracosphaera pulchra Lohmann are the only other ubiquitous species in the sediments of the Celtic Sea , western English Channel, Bristol Channel and lower Severn Estuary. Highest abundances of C.pelagicus (>1000 $\times 10^5$ per gram) are restricted to a small area in the central northern Celtic

Sea (Fig.3.15). South of this area abundances are >500 x 10^5 per gram. Abundances of the species decrease in coastal sediments from the northern Celtic Sea and in the western English Channel (<250 x10^5per gram). C.pelagicus occurs in declining numbers eastwards along the Channel. Abundances range from 100 x 10^5per gram in the western Channel to less than 50 x 10^5in the eastern Channel.

The relative abundance of C.pelagicus in the sediments, however, increases towards the English Channel and Bristol Channel. In the western Celtic Sea sediments it averages 1% ;this rises to over 5 % in the western Channel and over 15% in the Bristol Channel (Fig.3.16). C.pelagicus generally dominates coccolith assemblages in sediments east of the Isle of Wight. Maximum values occur in the eastern Channel where C.pelagicus forms a monospecific Recent flora in the sediments. C.pelagicus is the only ubiquitous species in the sediments of the English Channel.

Syracosphaera pulchra is also most abundant in shelf sediments from the central, northern Celtic Sea (x10^8 per gram). Throughout the rest of the Celtic Sea and in the Western Approaches the species abundance declines to x10^7 coccoliths per gram. Lower abundances are typical of sediments from the central Channel area ($10^5$to 10^6per gram). S.pulchra occurs along the Brittany Coast but is absent from sediments east of the Isle of Wight. The relative abundance of S.pulchra follows the distribution of the species quantitative abundance in the sediments. Highest values occur in the Celtic Sea and Bristol Channel where the species forms up to 7.6 % of the nannoflora. Lower values occur in the western Channel (mean 0.5%).

Gephyrocapsa caribbeanica occurs in most of the samples from the Celtic Sea and western English Channel. Its relative abundance ranges from 0.5 to 6.0 % (mean 2.0 %). No systematic variation of the species is observed in the sediments. The species is very scarce in the central Channel sediments and is absent from those of the eastern

Channel sediments and the Baie de la Seine.

Minor species found in the sediments (2.0 to 0.1 %), include: Helicosphaera carteri (Wallich) Kamptner, Rhabdosphaera clavigera Murray and Blackman, Braarudosphaera bigelowii (Gran and Braarud), Umbilicosphaera sibogae (Weber-van Bosse) Gaarder, Discosphaera tubifera (Murray and Blackmann) Ostenfeld , Syracosphaera nodosa Kamptner and Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan. Variations in the relative abundance of these species are difficult to detect because of their scarcity in the sediments. Some inferences on their distribution, however, may be made with reference to the subordinate species counts listed in Table 3.5.

H.carteri is more abundant in samples from the western English Channel (16 % of the subordinate species assemblage) as compared with about 2 % in the Celtic Sea. It is absent from sediments deposited in the eastern English Channel and in the Baie de la Seine. C.leptoporus declines from 34.0 % in the western Celtic Sea to 1.0 % in the Channel. It is absent from the central and eastern English Channel. R.clavigera is another species which is limited to the Celtic Sea and western Channel. B.bigelowii, however, is widely distributed throughout the Channel and Celtic Sea.

Trace amounts (<0.1%) of Umbilicosphaera hulburtiana Gaarder, Syracosphaera histrica Kamptner , Coronosphaera mediterranea (Lohmann) Gaarder, Pontosphaera discopora Schiller and Scyphosphaera apsteinii Lohmann occasionally occur. C.mediterranea is recorded from sediments along the southwest coast of Ireland and also off the southern coast of Cornwall. U.sibogae is recorded in open-water sediments from the Celtic Sea and at the western entrance to the English Channel. S.nodosa is recorded mainly in the open-water sediments from the northern Celtic Sea. It also occurs at site 27 off the Cornish coast. All these species are absent from sediments in the central and

eastern English Channel and in the Severn Estuary.

3.2.3. Percentage coccoliths and carbonate in the fine fractions.

The coccolith-component in the fine fractions of the sediments generally increases with distance from the coast (Fig. 3.22). Lowest abudances occur in sediments deposited in the eastern and central Channel and in the upper Severn Estuary (<1%). An area of sediment containing between 1 and 10 % coccoliths occurs in the western English Channel and around the coasts of Southern Ireland, Wales and Cornwall. Greater than 10 % coccoliths occur in sediments deposited in the central and northern Celtic Sea. Maximum coccolith values occur nearest the shelf edge in the western Celtic Sea (>20%).

Carbonate values follow a broadly similar distribution to the coccolith abundances (Fig. 3.23). Lowest values occur in coastal regions and in the western Channel (< 25 %). Highest values are found in the deeper water sediments nearest the shelf-break (> 50 %). Similar high carbonate values occur in the eastern Channel, where sediments contain large numbers of reworked coccoliths. East of the Isle of Wight some assemblages contain over 99% reworked Cretaceous and Tertiary forms. In the Celtic Sea reworked coccoliths are scarce (<1.0 %), highest values are found in estuarine sediments from the South Wales (3 to 7%) and in the Severn Estuary (4 to 16%).

3.2.4. Species diversity of the assemblages.

The distribution of dominance values in the coccolith assemblages is shown in Fig. 3.25. The dominance (D) is high throughout the southern Celtic Sea and western Channel (> 90 %) and also at the eastern margin of the Channel (100%). Lowest dominance values occur in the assemblages deposited in the coastal regions of the Celtic Sea and in the western and central English

Channel. The distribution of the diversity of the coccolith assemblages as measured by the Shannon-Wiener Function (H) and the Simpson Index (P) are shown in Figs. 3.26 and 3.27 respectively. Lowest diversity values of H (<0.5) and P (<0.25) occur in assemblages deposited in the Celtic Sea, western English Channel and at the eastern margin of the Channel. Highest diversities occur in the coastal regions of the northern Celtic Sea and in the central English Channel.

Diversity indices were also calculated for the subordinate species assemblages in selected samples (Figs. 3.28, 3.29 and 3.30). These data may show subtle variations in the indices that are otherwise masked by the very high dominance of E.huxleyi. Indices of the subordinate species assemblages are generally greatest in the southern Celtic Sea and decrease towards the northern Celtic Sea and the English Channel. Dominance values show an opposite trend. Lowest values occur in the deeper waters of the southern Celtic Sea (40 to 50%). Higher values typify sediment in the western Channel (up to 85%).

Table 3.4. Relative abundance and species-composition of coccolith assemblages from the Celtic Sea and English Channel.

Sample	E.hx	C.pl	Sy.p	H.ct	C.lp	G.cr	B.bg	D.tb	Rh.c	U.sb	Sy.n
1	84.0	5.9	6.7	0.3	1.5	0.5	0.6	0.3	0.1	0.1	–
3	85.0	2.4	7.6	P	0.2	3.5	0.7	0.2	0.3	–	P
4	91.0	3.8	3.9	P	0.4	0.5	0.2	0.2	–	–	–
5	93.0	2.2	3.5	P	P	0.5	0.3	0.2	0.3	–	P
9	69.0	31.0	–	–	–	–	–	–	–	–	–
11	90.0	4.8	4.1	0.1	0.2	–	0.6	0.1	0.1	–	–
14	P*	P*	–	–	–	–	–	–	–	–	–
15	91.0	7.2	0.6	0.1	0.1	P	0.7	0.1	0.2	–	–
20	71.0	24.0	–	2.5	–	0.5	1.0	–	–	–	–
24	88.0	5.0	2.0	–	–	4.0	–	–	1.0	–	–
26	82.0	6.4	6.7	0.1	P	4.0	0.5	0.3	–	–	–
27	95.0	3.0	1.1	0.2	P	P	0.4	P	0.2	–	P
53	90.0	3.0	4.0	0.5	0.5	1.0	0.5	–	0.5	–	–
54	91.0	3.3	3.6	0.1	P	1.0	0.4	0.2	0.2	–	0.2
60	76.5	24.5	–	–	–	–	–	–	–	–	–
63	94.5	1.6	0.6	0.3	1.4	1.5	0.1	–	P	–	–
72	97.5	1.7	0.2	0.4	P	–	0.1	P	0.1	–	–
73	94.0	3.2	1.0	0.1	P	1.0	0.4	0.1	0.1	–	–
74	95.5	1.9	1.1	0.7	P	0.5	0.1	0.1	0.1	–	–
84	90.5	1.0	5.5	–	P	1.0	1.0	–	–	–	–
85	91.5	2.1	4.7	0.4	0.3	0.5	0.3	0.1	P	P	0.1
86	92.0	1.0	6.0	–	0.5	P	0.5	–	–	–	–
88	95.0	1.8	0.8	0.5	1.3	0.5	0.1	P	P	–	–
91	95.0	2.2	1.2	0.7	0.1	0.5	0.2	–	–	0.1	–
99	68.0	30.5	–	2.0	–	–	0.5	–	–	–	–
102	92.0	2.5	0.5	0.5	–	3.5	P	–	–	–	–
103	92.0	3.4	0.4	0.2	P	4.0	P	–	–	–	–
104	47.0	48.0	–	–	–	1.0	2.0	–	–	–	–
105	49.5	41.5	–	4.0	–	4.0	1.0	–	–	–	–
106	51.5	45.5	–	1.0	–	2.0	P	–	–	–	–
107	56.5	38.5	2.0	2.0	–	1.0	–	–	–	–	–
108	63.5	24.5	1.0	5.5	–	4.5	1.0	–	–	–	–
109	76.5	16.5	1.5	3.0	–	3.0	–	–	–	–	–
110	88.0	12.0	–	–	–	–	–	–	–	–	–
111	33.5	66.5	–	–	–	–	–	–	–	–	–
112	25.0	75.0	–	–	–	–	P	–	–	–	–
113	43.0	57.0	–	–	–	–	–	–	–	–	–
114	–	100.0	–	–	–	–	–	–	–	–	–
115	–	100.0	–	–	–	–	–	–	–	–	–
116	–	98.0	–	–	–	–	2.0	–	–	–	–
117	–	98.0	–	–	–	–	2.0	–	–	–	–
118	25.5	75.5	–	–	–	–	–	–	–	–	–
119	50.0	50.0	–	–	–	–	–	–	–	–	–
120	22.0	76.0	–	–	–	1.0	1.0	–	–	–	–
121	78.0	18.0	–	2.0	–	2.0	–	–	–	–	–
122	43.0	57.0	–	–	–	–	P	–	–	–	–
123	44.0	53.0	–	3.0	–	–	1.0	–	–	–	–
124	79.0	8.0	6.5	2.0	0.5	11.0	1.0	–	–	–	–
125	69.0	16.0	6.0	1.0	–	6.0	2.0	–	–	–	–
126	75.0	20.5	4.5	–	–	–	–	–	–	–	–
127	82.5	10.5	1.0	1.0	1.0	4.0	P	–	–	–	–
129	84.0	8.3	3.9	0.2	0.8	2.0	0.6	–	0.1	–	0.1
130	81.0	8.5	5.0	0.5	1.0	3.0	1.0	–	–	–	–
131	83.5	8.0	4.0	0.5	1.0	3.0	–	–	–	–	–
132	83.0	8.5	2.0	0.5	2.0	4.0	–	–	–	–	–
133	85.5	8.0	4.5	0.5	0.5	1.0	P	–	–	–	–

E.hx = E.huxleyi, C.pl = C. pelagicus, Sy.p = Syracosphaera pulchra
H.ct = Helicosphaera carteri, C.lp = Calcidiscus leptoporus
G.cr = Gephyrocapsa caribbeanica, B.B = Braarudosphaera bigelowii,
D.tb = Discosphaera tubifera, R.cl = Rhabdosphaera clavigera.
P = < 0.25 % , P* = present but accurate percentage not determined.

Table 3.5 Relative abundance and species-composition of the subordinate nannofossil assemblages from the Celtic Sea and Western English Channel.

Sample	C.pl	Sy.p	H.cl	C.lp	B.bg	D.tb	R.cl	U.sb	Sy.n
1	38.0	43.5	2.0	9.5	4.0	2.0	0.5	0.5	–
3	22.0	69.0	–	2.0	3.0	2.0	2.0	–	P
4	45.0	46.0	0.5	4.0	2.0	2.5	–	–	–
5	34.0	54.0	0.5	0.5	3.5	2.5	3.5	–	1.0
11	48.0	41.0	1.0	2.0	6.0	1.0	1.0	–	–
15	80.0	7.0	1.5	1.0	8.0	1.0	2.5	–	–
26	46.0	48.0	1.0	–	3.0	2.0	–	–	–
27	60.0	22.0	4.0	–	7.5	0.5	4.0	–	0.5
50	3.5	3.0	0.5	93.0	–	–	P	P	–
51	2.0	7.0	P	91.0	–	P	0.5	0.5	–
54	41.0	44.5	1.0	0.5	5.0	2.0	3.0	–	2.0
63	41.0	15.5	8.0	34.5	1.5	–	P	–	–
72	70.0	6.0	15.0	1.0	3.0	2.0	3.0	–	–
73	65.5	19.0	1.5	1.0	8.0	1.0	4.0	–	–
74	48.0	28.0	18.0	1.0	2.0	1.0	2.0	–	–
85	26.1	58.4	4.5	3.5	4.5	1.0	0.5	0.5	1.0
88	40.0	18.5	10.0	26.5	2.0	1.5	1.5	–	–
91	49.0	27.0	16.0	3.0	4.0	–	–	1.0	–
103	85.0	10.0	4.0	1.0	P	–	–	–	–
129	59.5	27.5	1.5	6.0	4.5	–	0.5	–	0.5

U.sb = Umbilicosphaera siboqae, Sy.n = Syracosphaera nodosa.

Table 3.6
Percentage abundance and species-composition of coccolith assemblages in the surface sediments of the Bristol Channel and Severn Estuary.

	E.hx	C.pl	Sy.p	H.ct	C.lp	B.b	G.cr	D.tp	R.cl	Rew
1	69.0	17.0	5.0	1.0	–	1.0	5.0	1.0	1.0	8
2	72.0	15.5	6.5	0.5	–	1.5	3.5	0.5	–	8
3	65.0	23.0	2.0	0.5	–	0.5	–	–	–	9
4	51.0	42.0	3.0	1.0	–	2.0	–	1.0	–	11
5	64.0	27.0	5.0	1.0	–	1.0	–	2.0	–	8
6	59.0	36.0	0.5	3.5	–	0.5	–	0.5	–	10
7	70.5	25.5	1.0	2.0	0.5	1.0	–	0.5	–	9
8	59.5	38.0	–	1.0	0.5	1.0	–	–	–	16
9	66.0	29.0	2.0	–	–	1.0	–	2.0	–	7
10	76.5	22.0	1.0	–	0.5	–	–	–	–	7
11	74.0	21.0	4.0	–	1.0	–	–	–	–	
12	87.0	10.0	3.0	–	–	–	–	–	–	7
13	75.0	21.0	3.0	–	–	1.0	–	–	–	4
14	75.0	20.0	3.0	1.0	–	–	1.0	–	–	4
15	77.0	17.0	4.0	–	–	1.0	–	1.0	–	6
16	77.0	15.0	5.0	2.0	–	1.0	–	–	–	7
17	72.5	19.5	2.5	–	–	–	–	–	–	5
18	–	–	–	–	–	–	–	–	–	–

Rew = % reworked coccoliths of total assemblage.

Table 3.7. Quantitative abundance of coccoliths and carbonate in the fine fractions (2-20μm.) from the Celtic Sea and English Channel.

Sample	No.of E.h $\times10^5$/g	No.of C.p $\times10^5$/g	No.of Sy.p $\times10^5$/g	Total $\times10^5$/g	% Cocc.	% Carb.
1	10,000	719	800	12,400	12	60
3	38,100	1076	3,400	45,000	17	34
4	20,000	824	800	22,000	15	30
5	21,000	489	500	22,000	19	44
9	65	30	–	95	<1	87
11	4,200	222	190	4,600	5	35
14	ND	ND	ND	ND	<1	45
15	1,800	142	10	2,000	3	20
20	180	60	–	250	<1	52
24	ND	ND	ND	ND	<1	ND
26	5,000	387	400	6,000	3	36
27	3,700	117	33	3,900	2	19
53	20,000	666	880	22,000	15	21
54	13 800	502	380	15,000	8	28
60	200	64	–	260	<1	46
63	29,000	496	200	31,000	23	68
72	6,700	118	10	6,900	4	35
73	4,200	142	50	4,400	4	30
74	9,100	196	110	10,000	13	36
84	20,000	218	1,200	22,000	16	39
85	13 500	310	700	15,000	10	39
86	24,000	262	1,600	26,000	16	40
88	28,000	524	230	29,000	20	63
91	5,000	116	60	5,300	5	39
99	110	52	–	170	<1	44
103	1,300	41	7	1,400	<1	16
104	44	44	–	92	<1	23
105	90	75	–	180	<1	32
106	55	50	–	105	<1	50
107	120	78	4	200	<1	31
108	210	86	4	350	<1	35
109	220	46	4	290	<1	35
110	ND	ND	–	ND	<1	36
111	4	7	–	10	<1	57
112	15	22	–	39	<1	47
113	19	26	–	45	<1	45
114	–	2	–	2	<1	41
115	–	26	–	26	<1	61
116	–	6	–	6	<1	59
117	–	7	–	7	<1	57
118	3	10	–	13	<1	57
119	14	14	–	28	<1	61
120	100	56	–	160	<1	18
121	220	50	–	280	<1	14
122	50	61	–	110	<1	10
123	190	240	–	450	<1	16
124	1,800	187	150	2,300	1	21
125	550	129	50	810	1	19
126	460	160	35	780	<1	14
127	230	29	2	280	<1	9
129	4,100	402	110	4,880	5	34
130	2,400	246	140	2,900	5	22
131	3,200	304	150	3,800	4	29
132	2,300	236	60	2,800	4	18
133	2,600	239	134	3,000	4	23

E.h = *Emiliania huxleyi*, C.p = *Coccolithus pelagicus*,
Sy.p = *Syracosphaera pulchra* ND = not determined.

Table 3.8
Abundance of carbonate and coccoliths ($\times 10^4$/g) in the fine fractions (2-20um) of sediments from the Bristol Channel and Severn Estuary.

	No.of *E.huxleyi*	No.of *C.pel*	Total no.	(%) cocc.	Wt.(%) $CaCO_3$
1	nd	nd	nd	nd	nd
2	nd	nd	nd	nd	nd
3	4,000	2,020	6,300	4	20
4	1,900	1,610	3,800	2	19
5	2,900	1,220	4,500	3	14
6	2,000	1,200	3,300	3	19
7	3,500	1,280	4,900	2	15
8	2,300	1,420	3,700	2	15
9	2,300	1,000	3,400	2	14
10	2,200	640	3,500	2	13
11	3,400	960	4,600	2	13
12	5,000	580	5,800	3	13
13	940	260	1,200	1	15
14	1,100	300	1,500	1	8
15	900	200	1,200	1	10
16	250	50	300	<1	6
17	20	5	30	<1	3
18	–	–	–	–	2

nd = not determined.

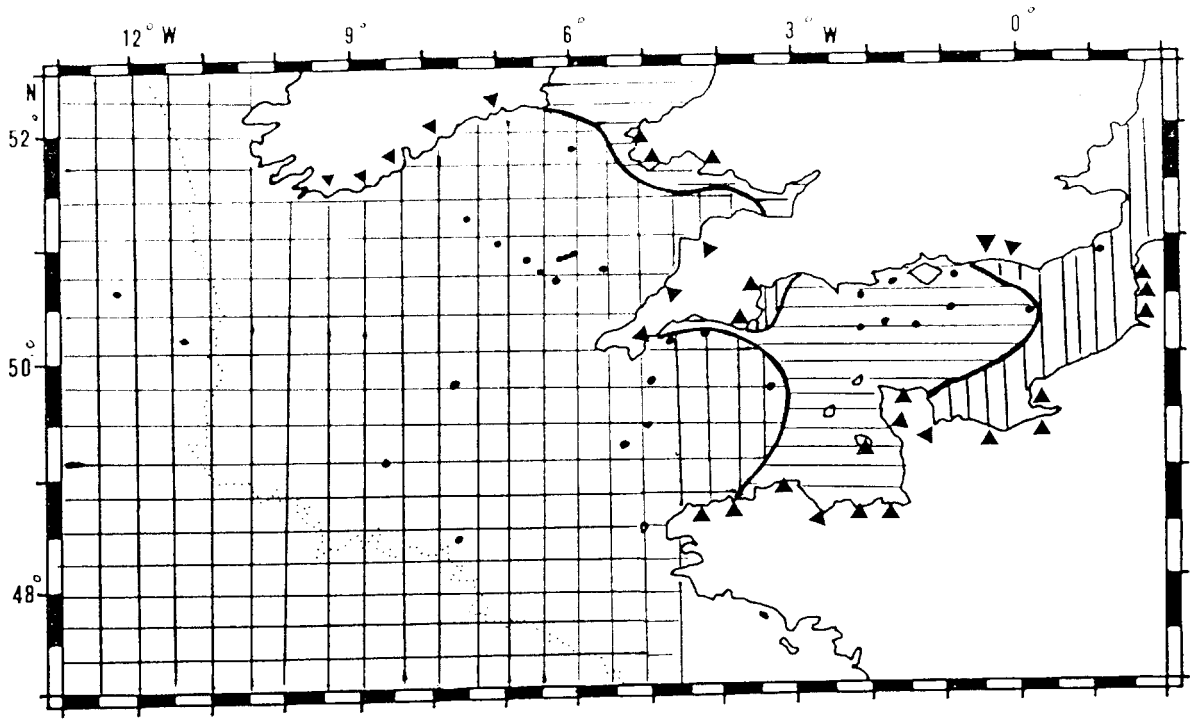


Figure 3.11.
Diversity (S) of coccolith assemblages in the surface sediments.

8 or more species
4 to 6 species
3 or fewer species

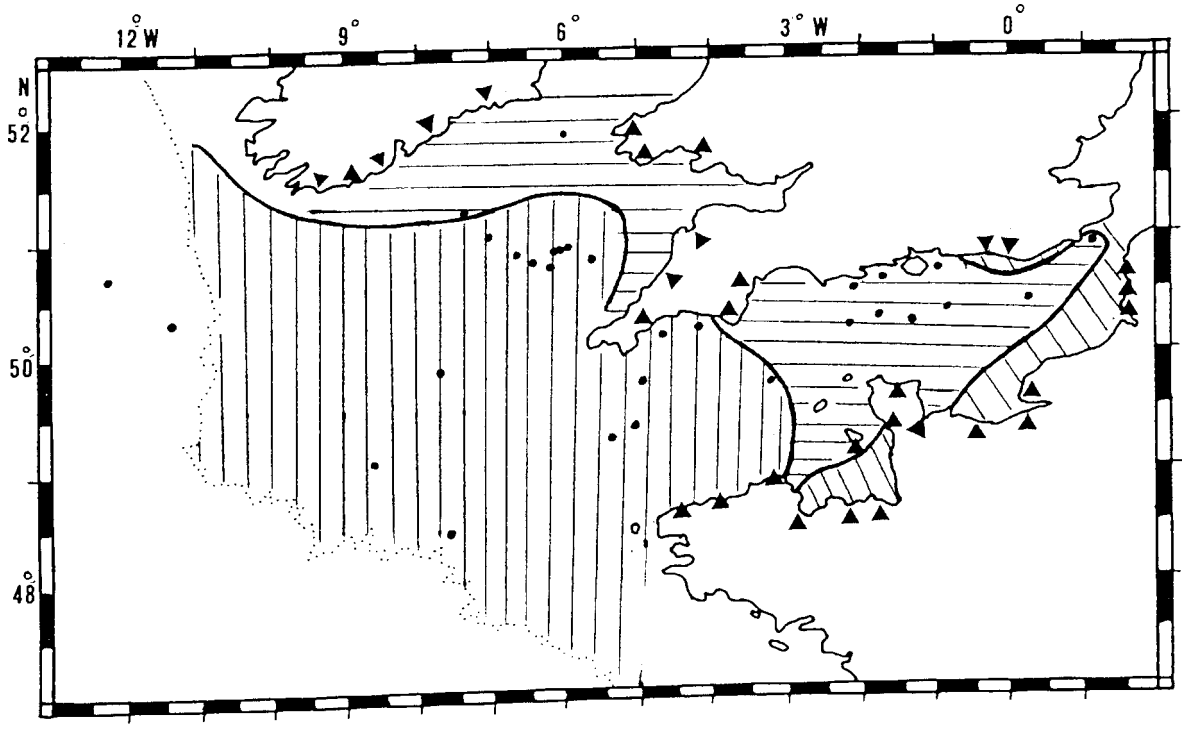


Figure 3.12.
Relative abundance of Emiliania huxleyi in the surface sediments.

> 90 %
89 to 60 %
< 60 %

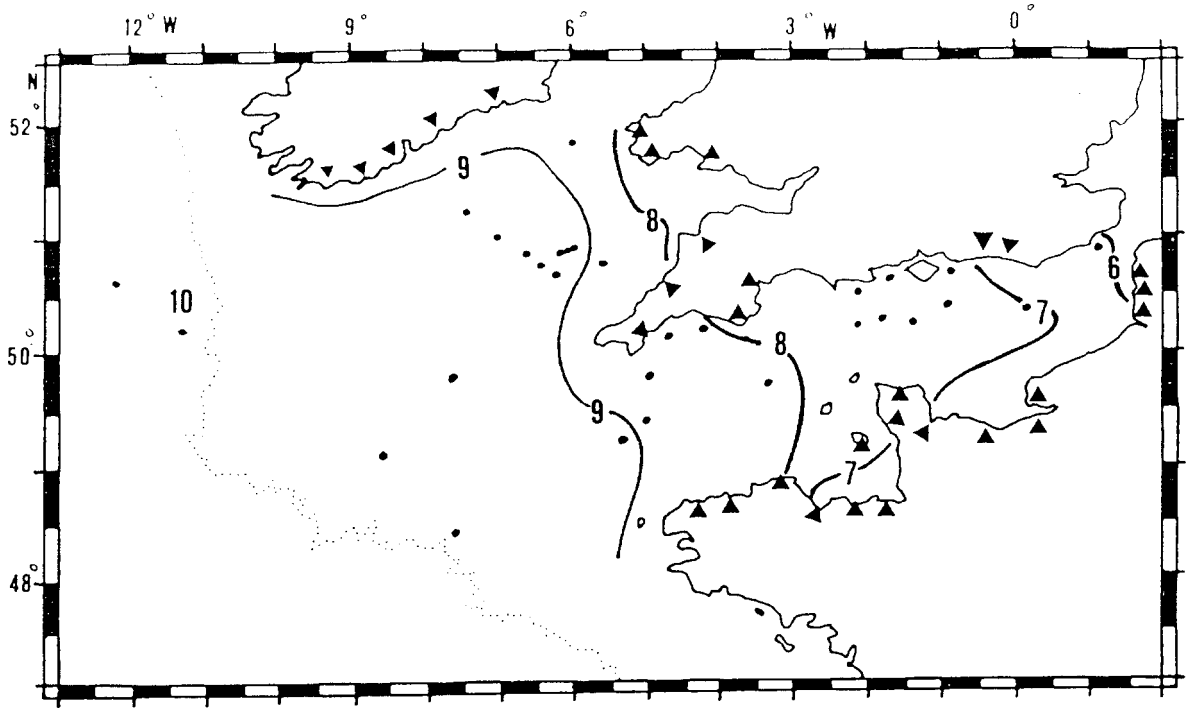


Figure 3.13.
Quantitative abundance of Recent coccoliths in the surface sediments. Contours represent 10^n coccoliths per gram of fine-grained silt (2–20 μm).

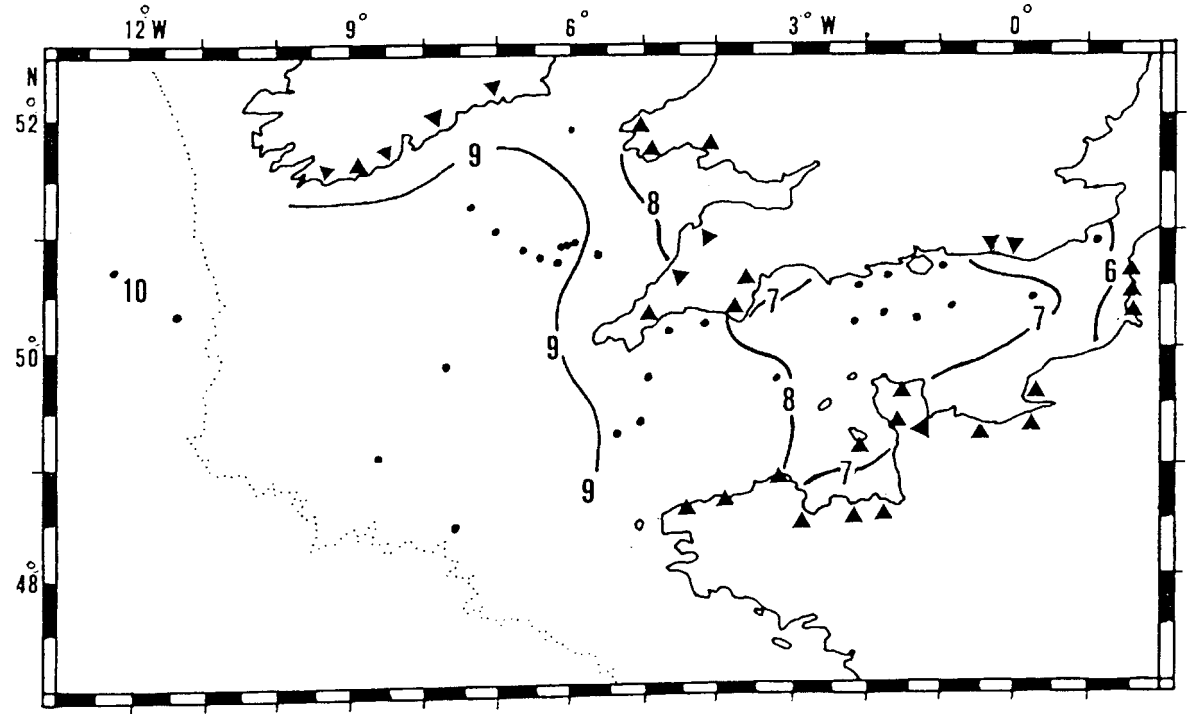


Figure 3.14.
Quantitative abundance of Emilinia huxleyi in the surface sediments. Contours represent 10^n coccoliths per gram of fine-grained silt (2–20 μm).

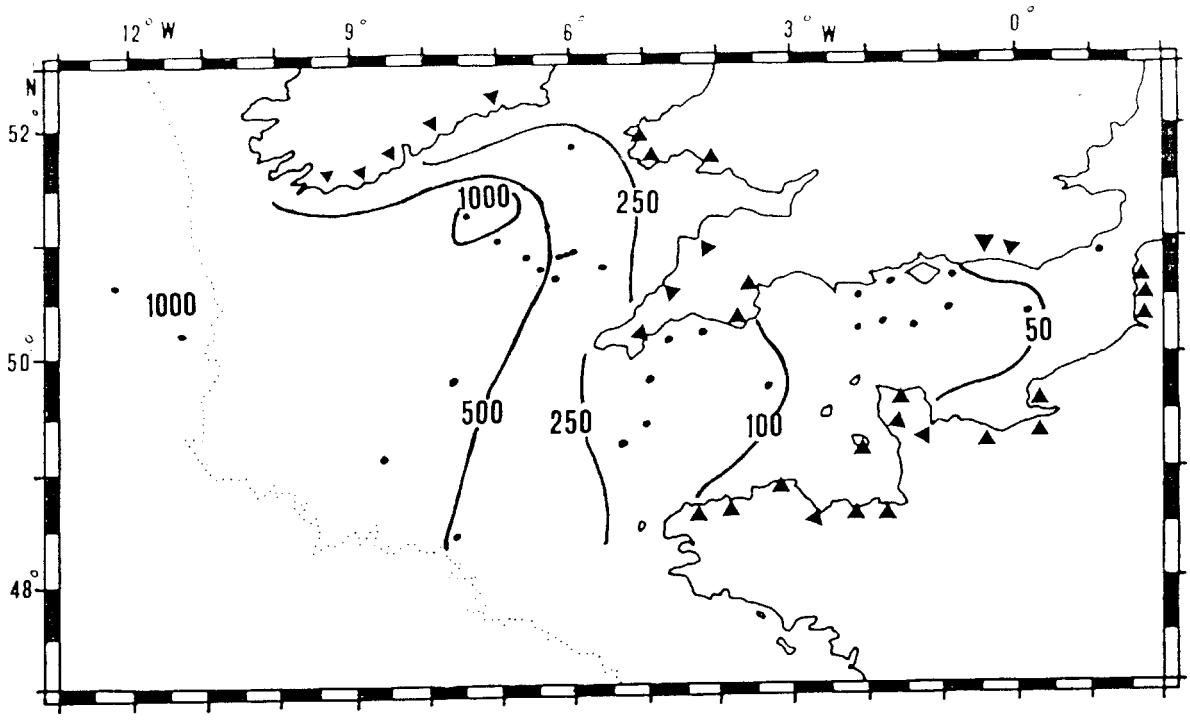


Figure 3.15.
Quantitative abundance of Coccolithus pelagicus in the surface sediments. Contours represent n x 10^5 coccoliths per gram of fine-grained silt (2-20 μm).

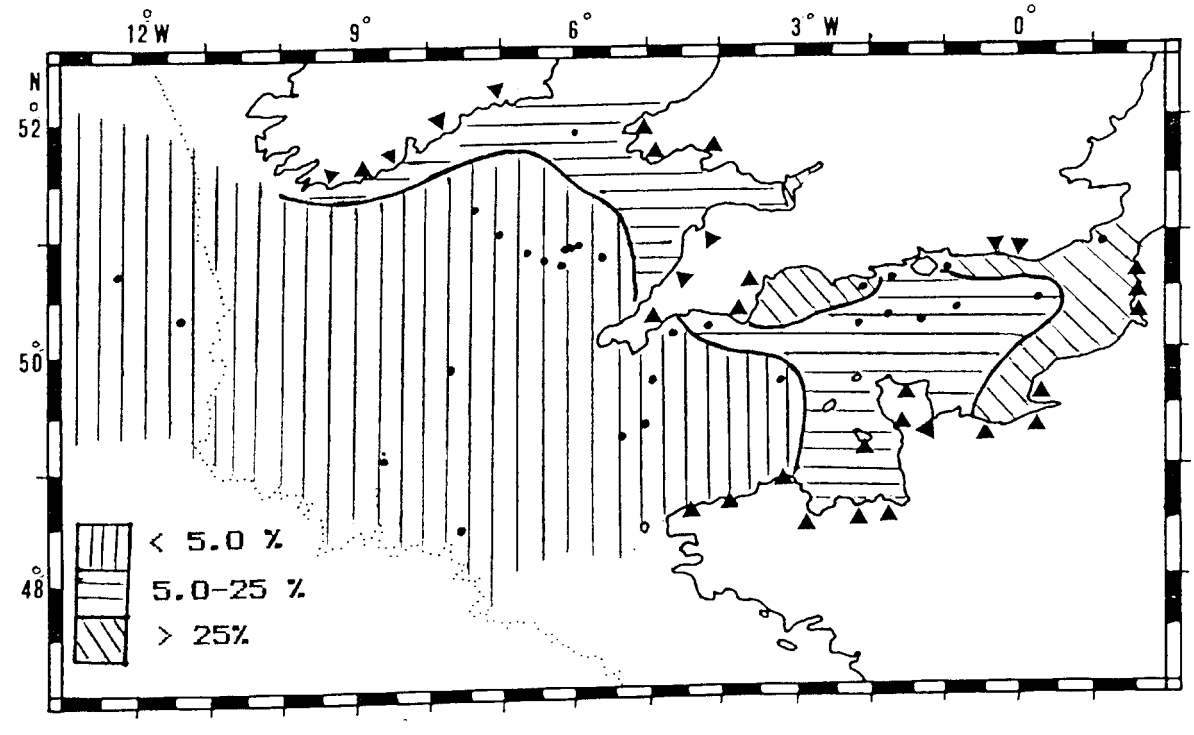


Figure 3.16.
Relative abundance of Coccolithus pelagicus in the surface sediments.

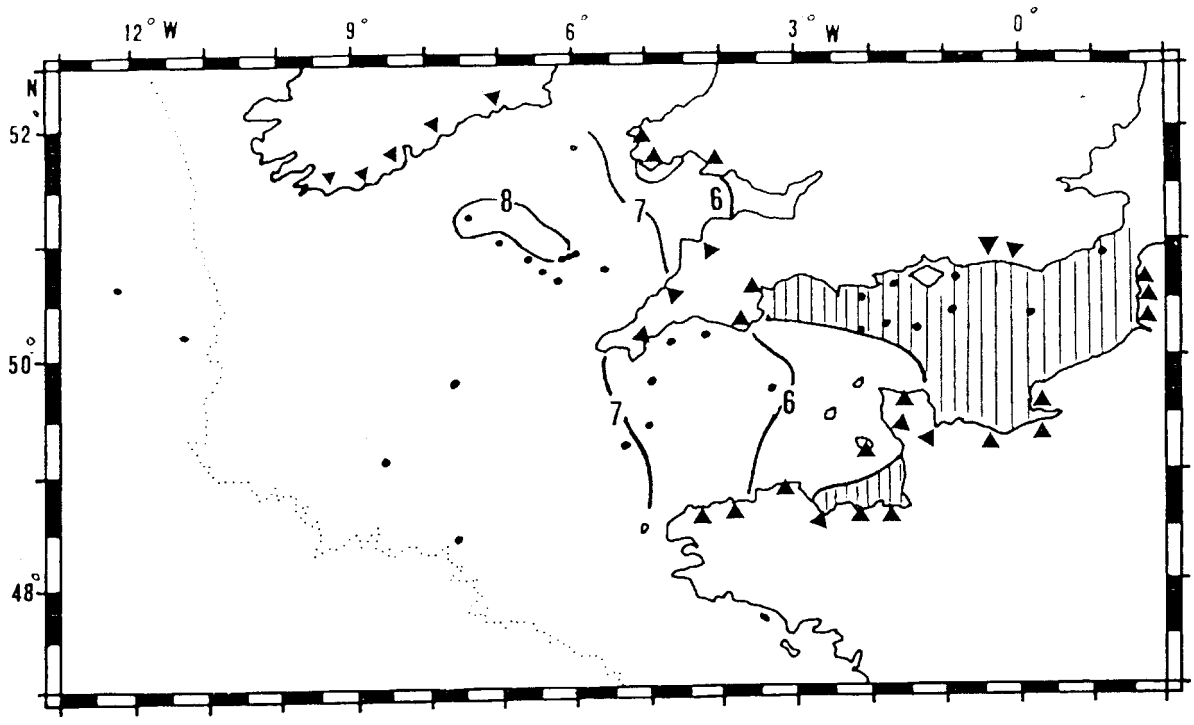


Figure 3.17.
Quantitative distribution of Syracosphaera pulchra in the surface sediments. Contours represent 10^n coccoliths per gram of fine-grained silt (2-20 μm).

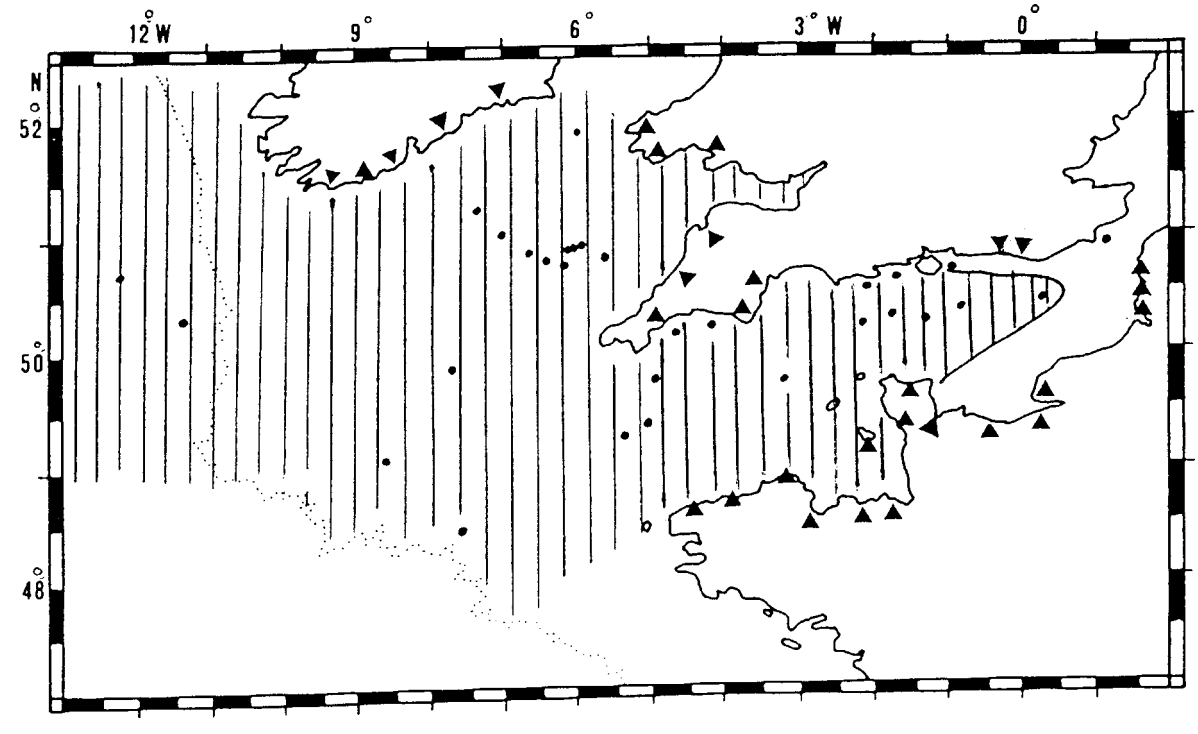


Figure 3.18.
Distribution of Gephyrocapsa caribbeanica in the surface sediments.

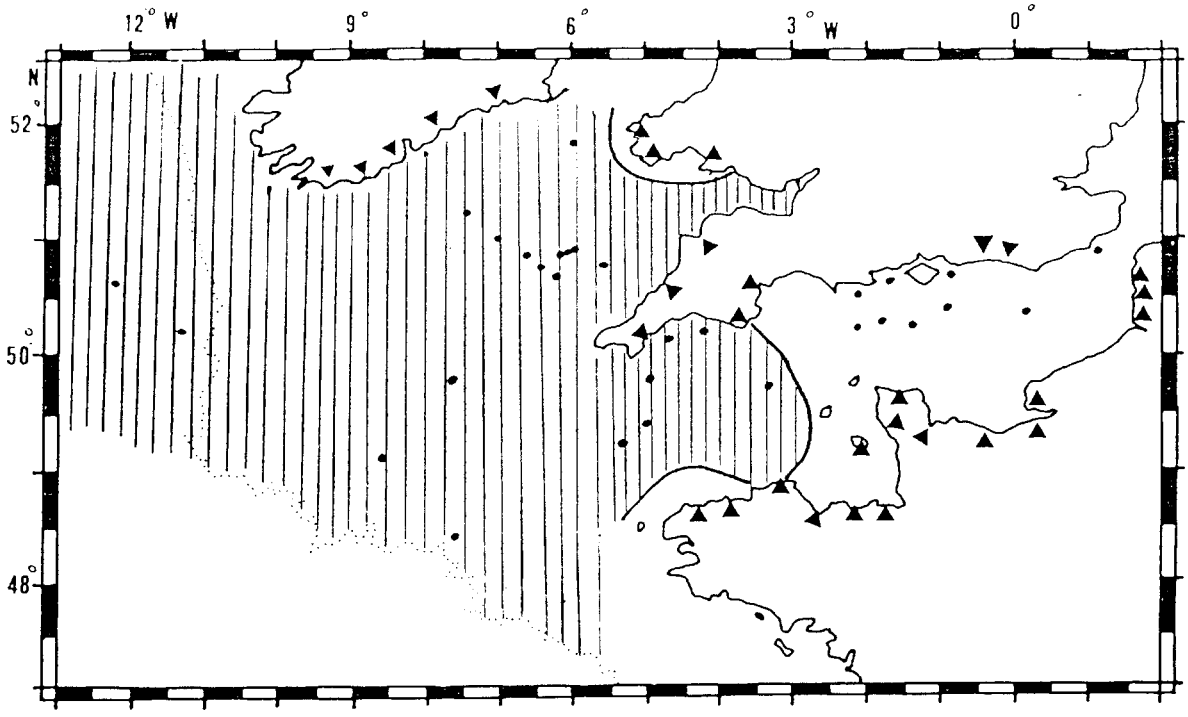


Figure 3.19
Distribution of Calcidiscus leptoporus in the surface sediments.

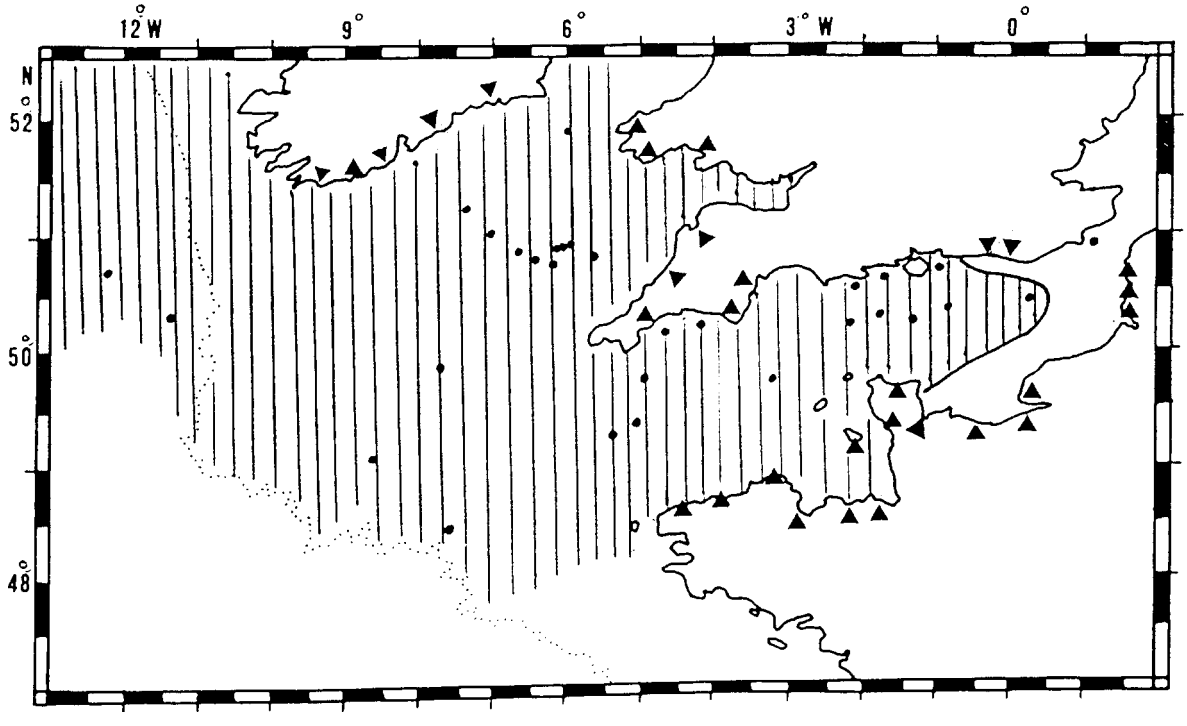


Figure 3.20.
Distribution of Helicosphaera carteri in the surface sediments.

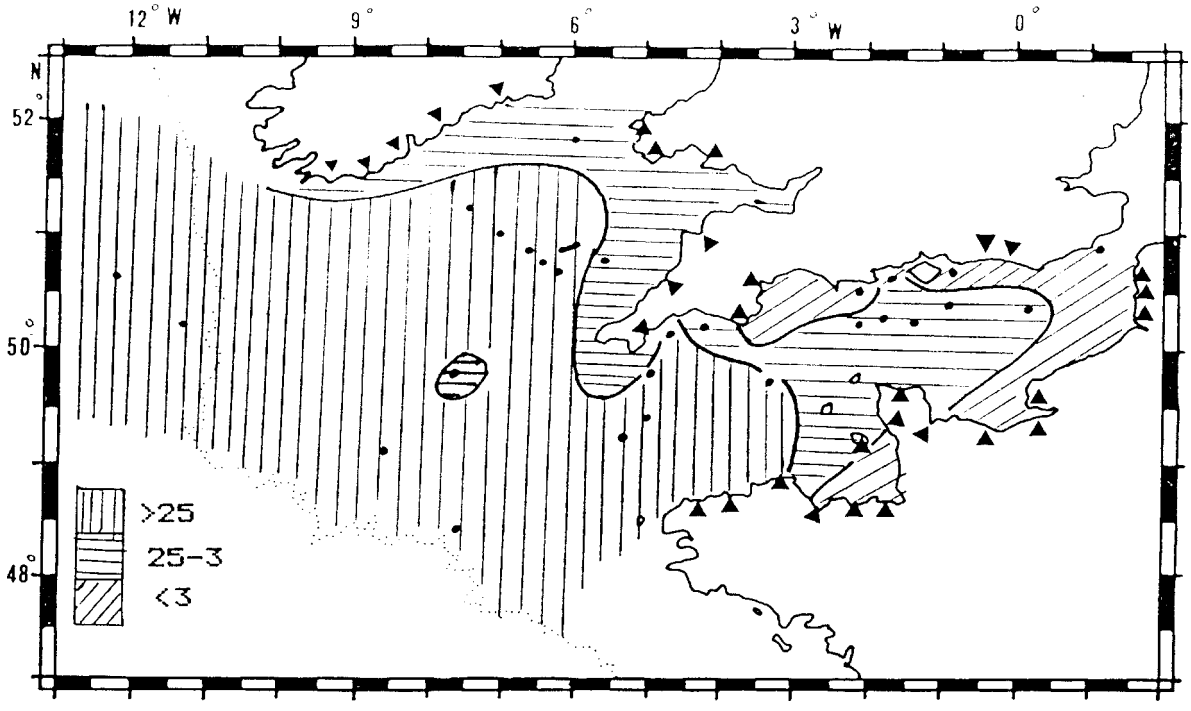


Figure 3.21.
E.huxleyi/ C.pelagicus ratio in the surface sediments.

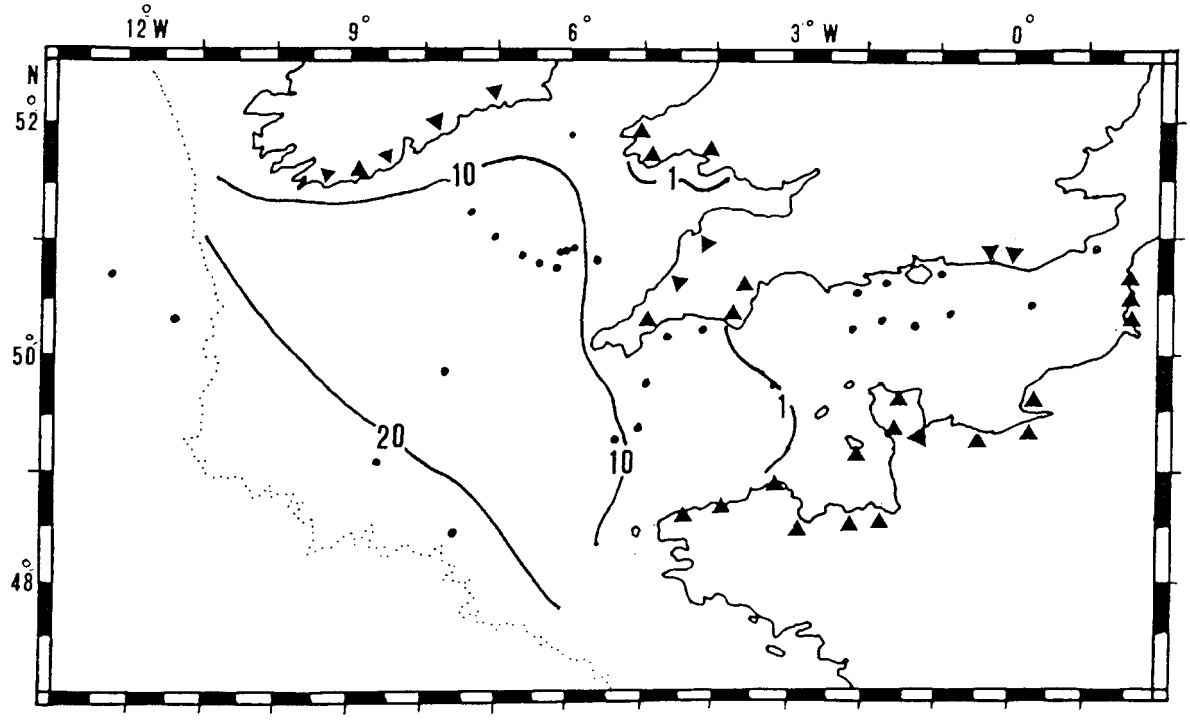


Figure 3.22.
% **Recent** coccoliths in the fine-grained silt fractions (2-20 μm) of the surface sediment.

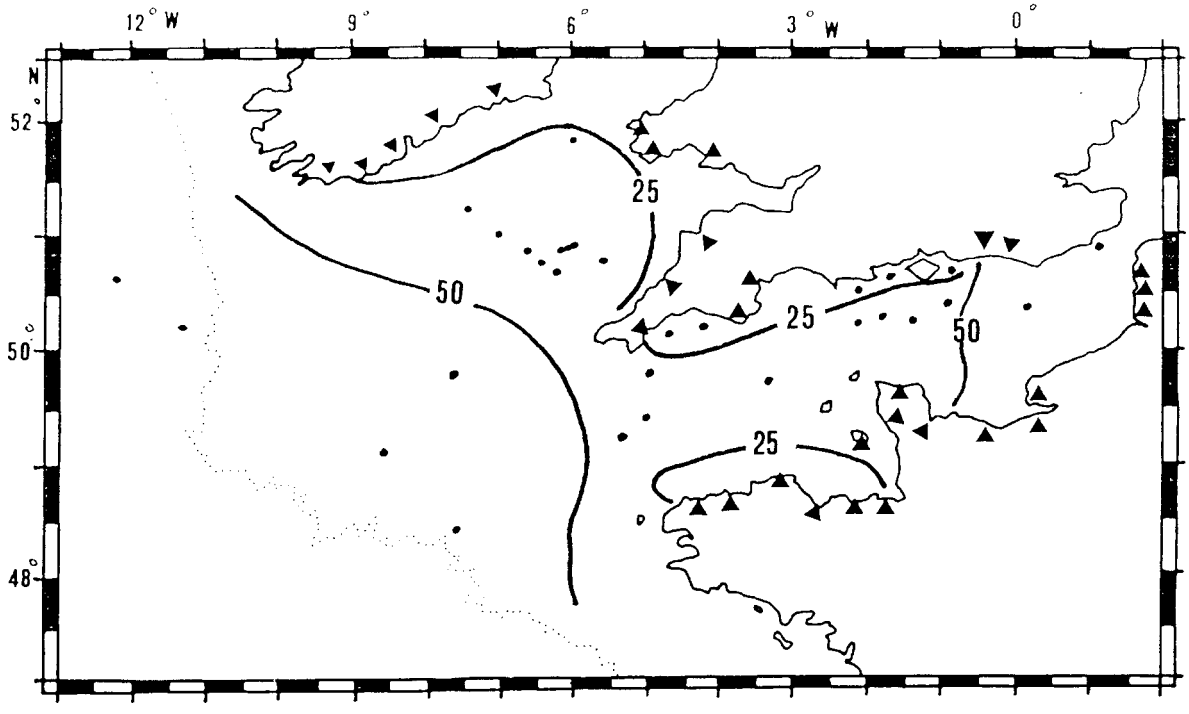


Figure 3.23.
% calcium carbonate in the fine-grained silt fractions (2-20 µm) of the surfacesediment.

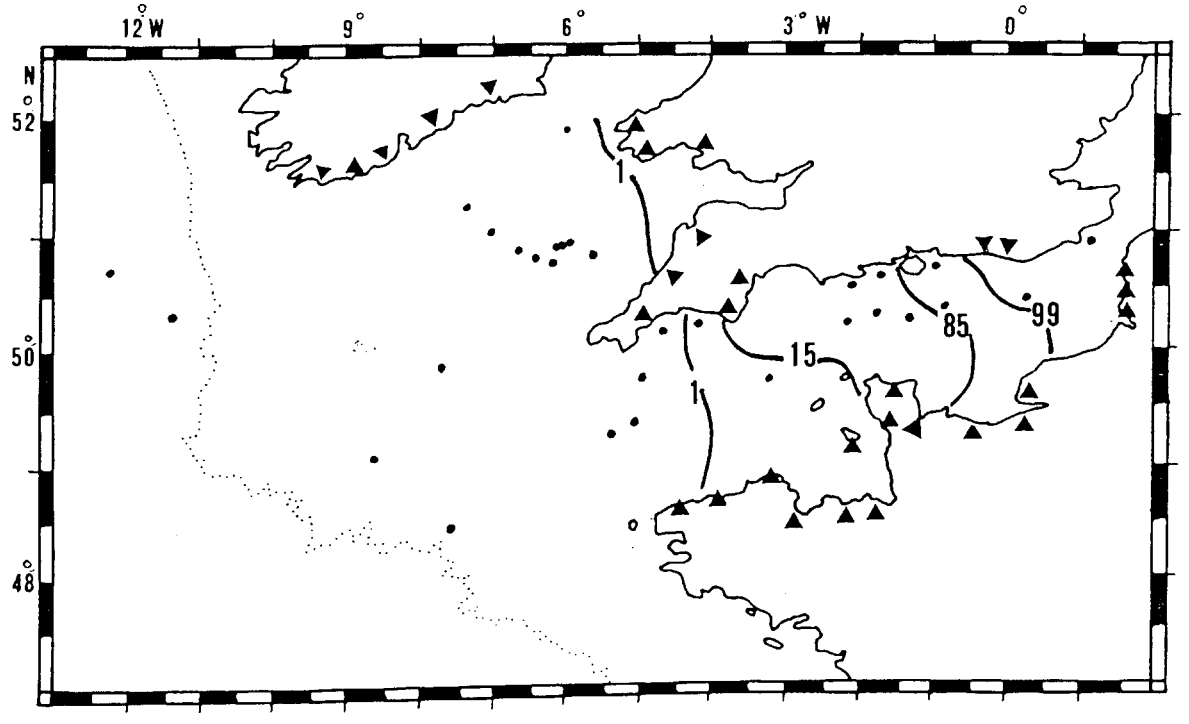


Figure 3.24.
% reworked coccoliths of total coccolith flora in the surface sediments.

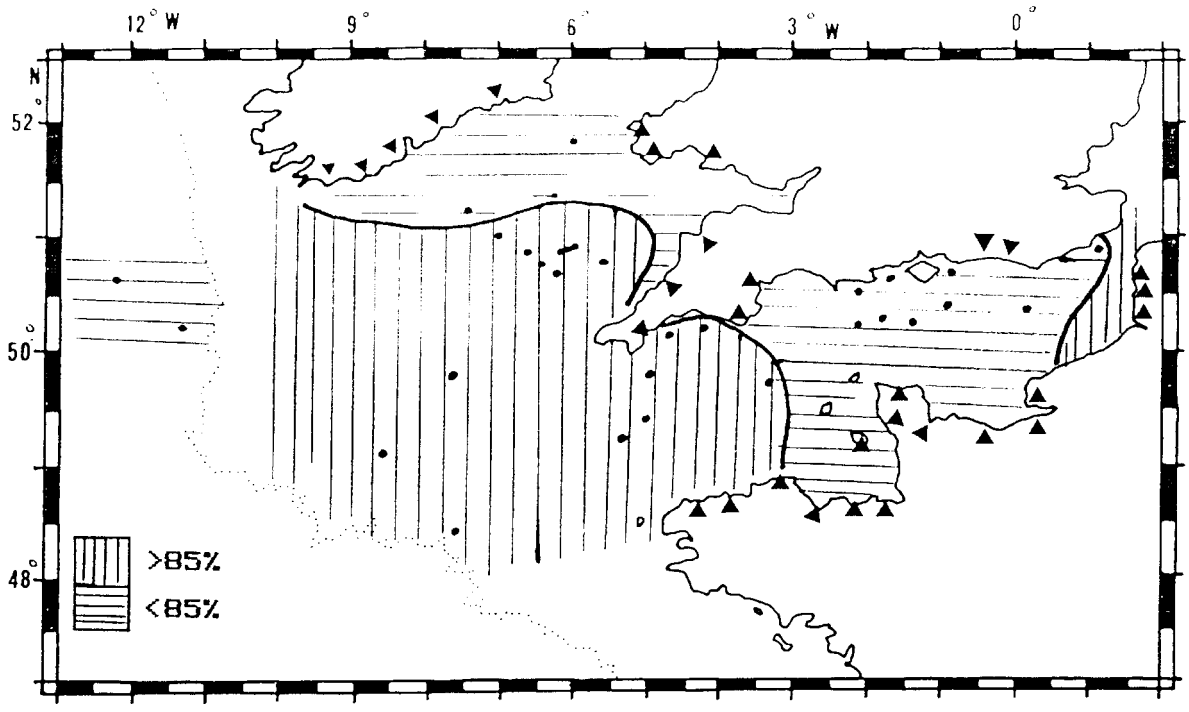


Figure 3.25.
Distribution of dominance values in the coccolith assemblages.

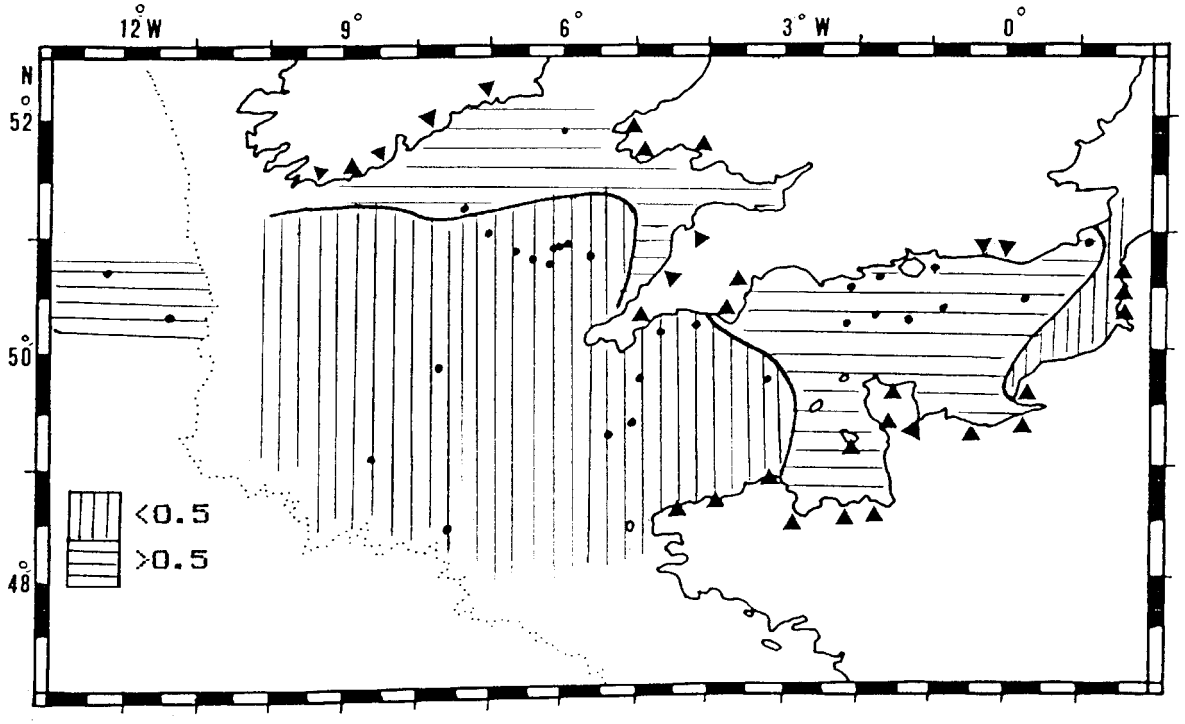


Figure 3.26.
Distribution of diversity in the coccolith assemblages as measured by the Shannon-Wiener Index (H).

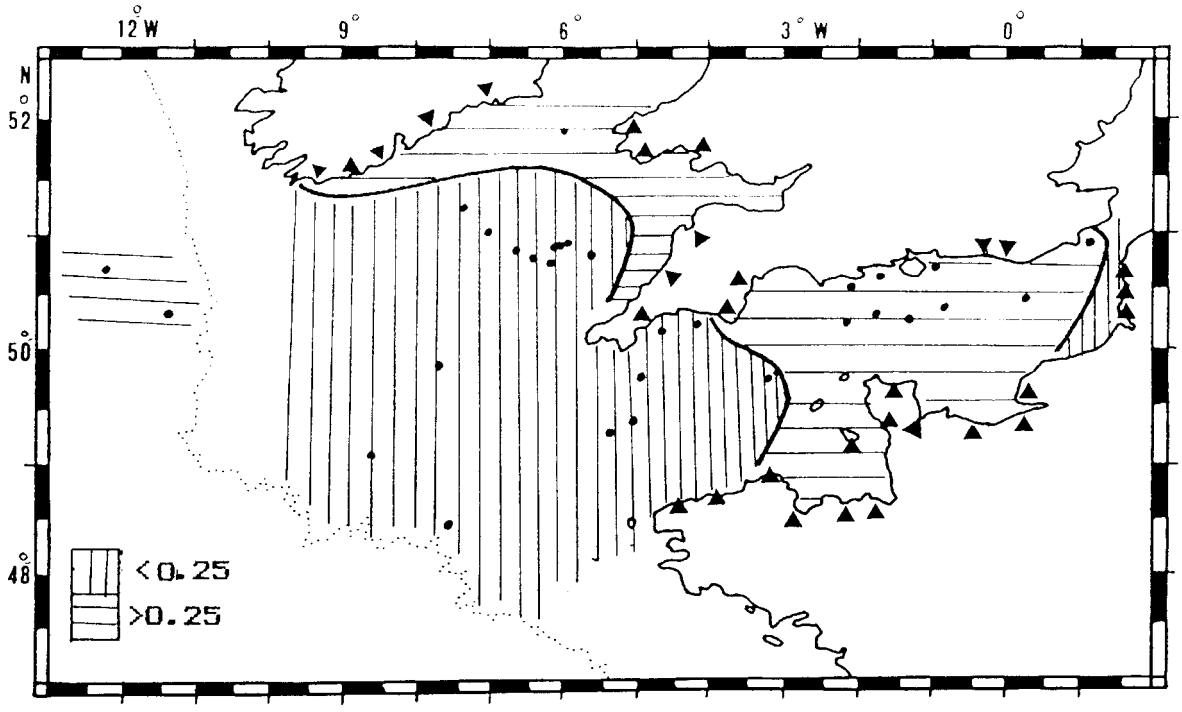


Figure 3.27.
Distribution of diversity in the coccolith assemblages as measured by the Simpsons Index (P).

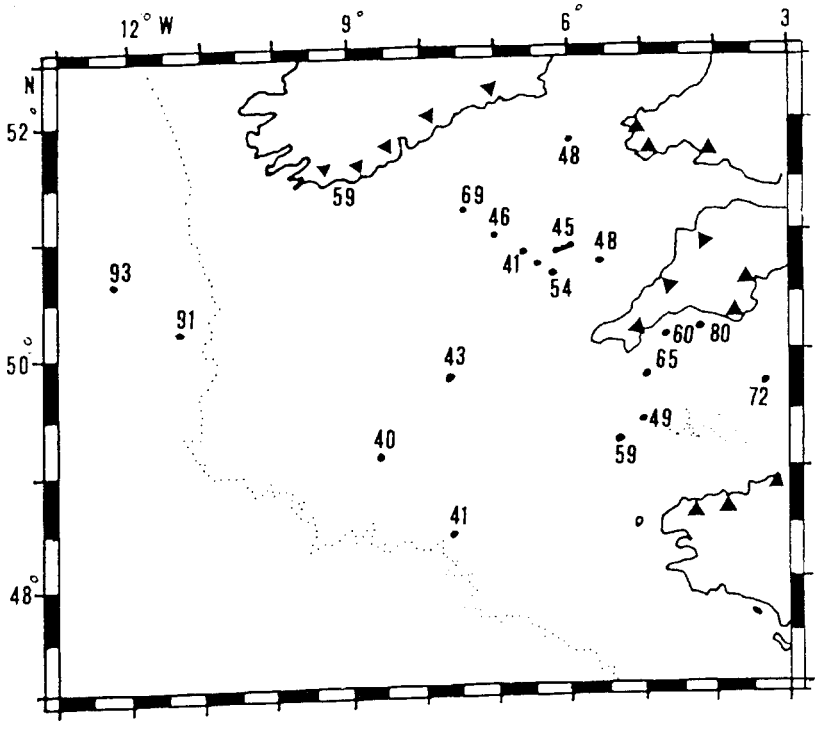


Figure 3.28.
Distribution of dominance values in the subordinate coccolith species assemblages.

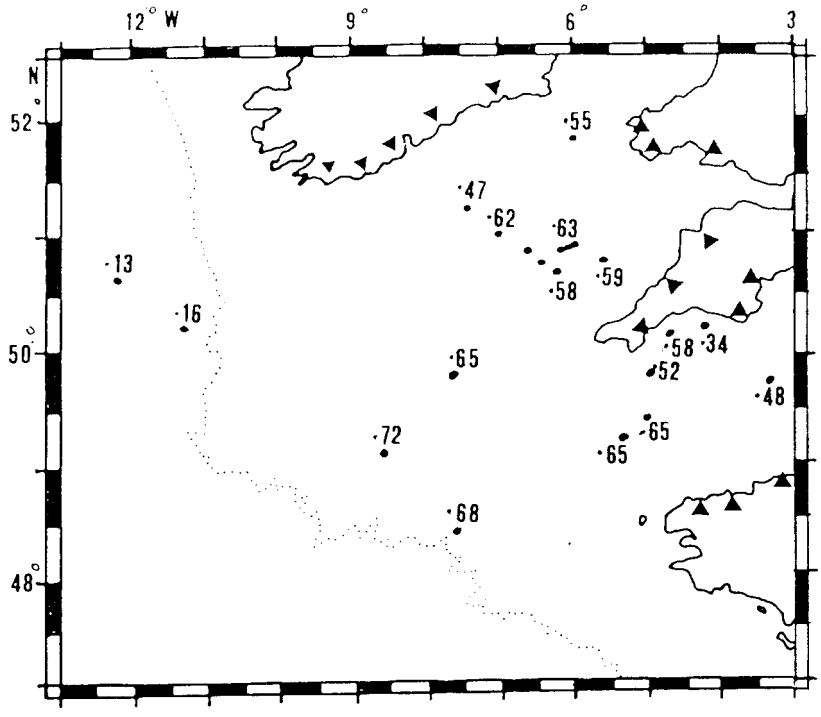


Figure 3.29.
Distribution of diversity in the subordinate coccolith species assemblages as measured by Simpson's Index (P).

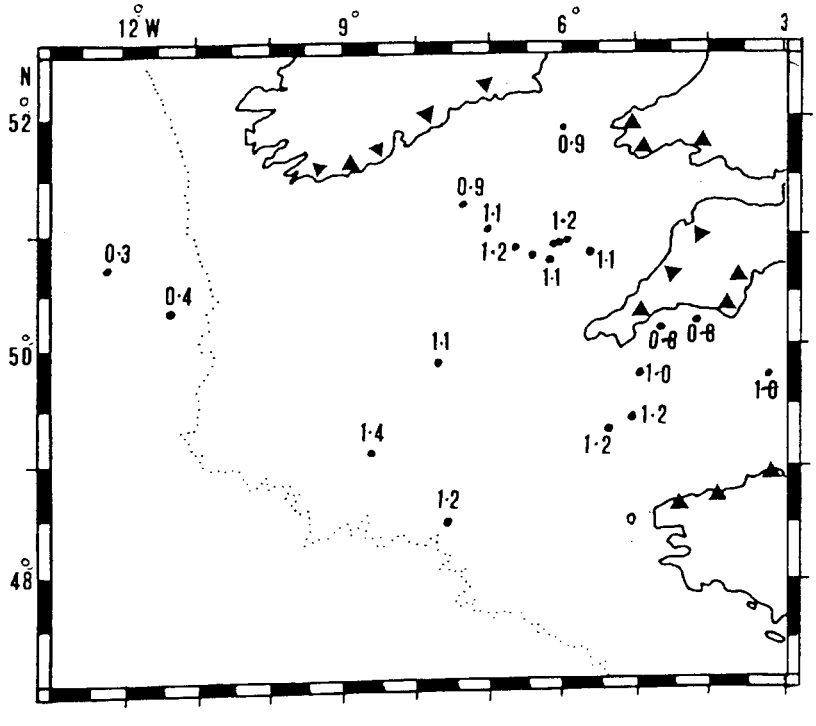


Figure 3.30.
Distribution of diversity in the subordinate coccolith species assemblages as measured by the Shannon- Weiner Index (H).

3.2.5. Coccolith assemblages in sediments from the continental slope to the west of the Celtic Sea.

Stations 50 and 51 are located on the continental slope at the western margin of the Celtic Sea, at depths of 1269 and 1257m respectively. Twenty species of Recent coccolith are recorded from the slope sediments. The quantitative abundance of coccoliths in these sediments is listed below.

Table 3.9.
Quantitative abundance of coccoliths and carbonate in the fine fraction (2-20μm) of the slope sediments.

Sample	*E.huxleyi*	*C.pelagicus*	Total	% cocc.	% carb.
	($\times 10^5$/g)	($\times 10^5$/g)	($\times 10^5$/g)		
50	210,000	1,230	310,000	56	68
51	280,000	1,280	430,000	51	62

cocc. = coccoliths, carb. = carbonate.

Coccolith abundances in the sediments (10^{10}coccoliths per gram) account for over 50 % of the fine fraction and up to 82 % of the carbonate fine fraction. The abundance of *C.pelagicus* is approximately double its mean abundance in shelf sediments from the Celtic Sea. The assemblages are dominated by 3 species , *E.huxleyi* (66 to 68 %), *Gephyrocapsa caribbeanica* (20.0 %), and *Calcidiscus leptoporus* (11.1 to 12.7%). These species account for over 97 % of the flora. The species composition of the assemblages is listed in Table 3.10.

Table 3.10 Relative abundance and species-composition of coccolith assemblages in the slope sediments.

	50		51	
	1	2	1	2
E.huxleyi	68.0		66.0	
C.pelagicus	0.4	3.5	0.3	2.0
S.pulchra	0.4	3.0	1.0	7.0
H.carteri	0.1	0.5	P	P
C.leptoporus	11.1	93.0	12.7	91.0
G.caribbeanica	20.0		20.0	
D.tubifera	-	-	P	P
R. clavigera	P	P	P	P
U. sibogae	P	P	P	P

P = <0.1 %

Counts (1) refer to the total assemblage , (2) refer to counts of the subordinate species. Minor species (1.0 to 0.1%) in the slope sediments are C.pelagicus, S. pulchra, and H.carteri.

Trace amounts (< 0.1 %) of the following species also occur;

Ceratolithus cristatus Kamptner
Coronosphaera mediterranea (Lohmann) Gaarder
Discosphaera tubifera (Murray and Blackman) Ostenfeld
Rhabdosphaera clavigera Murray and Blackman
Umbellosphaera tenuis (Kamptner) Paasche
Umbilicosphaera hulburtiana Gaarder
Umbilicosphaera sibogae (Weber-van Bosse) Gaarder
Scapholithus fossilis Kamptner
Syracosphaera histrica Kamptner
Syracosphaera nodosa Kamptner
Gephyrocapsa oceanica Kamptner

Gephyrocapsa ericsonii McIntyre and Be'
Pontosphaera messinae Schiller

3.2.6. Indices of species diversity.

Indices of species diversity were calculated for both the total and subordinate coccolith species assemblages. Dominance values are low in the total coccolith assemblages (66 to 68%) and high in the subordinate species assemblages (91 to 93%). Values of (H) (0.88 to 0.87) and (P) (0.48 to 0.49) from the slope sediments are higher than those from the Celtic Sea and the Channel. However (H) and (P) values for the subordinate species, 0.31 to 0.38 and 0.12 to 0.17 respectively, are lower in the slope assemblages.

3.3 DISCUSSION.

3.3.1 Comparison with previous work in the Celtic Sea and English Channel.

3.3.1.1. Sediment samples.

Murray et al.,(1983) are the only workers to have described the coccolith assemblages in Recent sediments from the area. They listed the coccolith species found in both sediment and plankton samples from the Western Approaches to the Channel; however, no percentage data describing the various coccolith species in the assemblages was presented.

The results of this study generally agree with and expand upon those described in the previous report. Emiliania huxleyi and Coccolithus pelagicus are ubiquitous in the Celtic Sea, whereas Calcidiscus leptoporus is limited to sediments from the Celtic Sea and the central western English Channel. Murray et al., also divided the area according to the number of species observed in the sediments. They found a pattern of decreasing diversity eastwards from the shelf-edge to the English Channel. Eight or more species occurred nearest the shelf edge. Intermediate diversities (4 to 7 species) occurred over most of the Celtic Sea and central western English Channel. This study, however, records higher diversities (8 or more species) throughout the shelf of the Celtic Sea and western English Channel (Fig. 3.11.). The area of lowest diversities (3 or fewer species) delineated by Murray et al., along the coast of Brittany and England, approximately correlates with the area of 4 to 6 species described in this study.

Eleven species of Recent coccolith were recorded by Murray et al., in sediments from the continental slope to the west of the Celtic Sea. Three of these, Caneosphaera

mollischi (Schiller) Gaarder, Syracosphaera corolla Lecal and Corisphaera gracilis Kamptner, are not observed in either slope or shelf sediments in this study. Murray et al., found that species diversity tended to increase with depth in the canyons in the slope. This increase in diversity was matched by an increase in the abundance of the coccoliths and by an increase in clay content of the samples. The scarcity of coccoliths in Whittard Canyon, from above 1095 m., was suggested by Murray et al. to be a result of current-activity winnowing the fines from the sediments.

Similar winnowing of Recent and Pleistocene coccoliths was recorded by Prell (1978) from the Columbia Basin in the Caribbean Sea. The foraminifera to total $CaCO_3$ ratio was found to be highest on and adjacent to the major escarpments, where the fine fraction coccolith-carbonate was being selectively removed. The increased currents associated with the escarpments were caused by streamlining and acceleration of water masses as they flowed around the obstructions. The two samples studied in this report (50 and 51), taken from the continental slope at depths of 1269 and 1275 m. respectively, however, showed no evidence of winnowing of the coccolith-fraction.

3.1.2. Plankton studies.

There have been numerous studies describing the distribution of phytoplankton in the Celtic Sea and English Channel (Pingree et al.,1975; Boalch, Harbour and Butler ,1978; Holligan and Harbour,1977; Southward,1980). These studies , however, have concentrated mainly on the occurrence of diatoms and dinoflagellates.

Satellite studies using the Coastal Zone Colour Scanner (CZCS) have shown the occurrence of coccolithophores in the plankton communities of the Celtic Sea. Since 1978, extensive patches of water giving strong reflectance of visible light have been recorded by the

CZCS during early summer along the the outer margin of the northwestern European shelf between 45°and 60°North latitude (Pingree et al.,1981 ; Holligan et al.,1983). Subsequent analysis of plankton samples confirmed that the reflectance was caused by a surface bloom of E.huxleyi (Holligan et al.,1983). The reflective water contained E.huxleyi at densities of up to 8,500 cells/ ml and was visually turbid with a pale turquoise colour.

The blooms had developed during the latter half of April or early May, and persisted until mid or late June. Later in the summer, smaller patches occasionally developed further on to the shelf. Each cell had a mean of 20 attached coccoliths, but detached coccoliths (up to 10^5 /ml)represented an estimated 37 to 64 % of the total number in the water column. Coccolithophores were also recorded by Murray et al., (1982) in six plankton samples from the Celtic Sea. The samples were collected in July ,1981 when the thermocline structure of the water was well developed. Coccoliths and coccospheres of E.huxleyi were recorded in some abundance, particularly near the shelf-break. Coccospheres of Homozygosphaera quadriperforata (Kamptner) Gaarder, the motile phase of Coccolithus pelagicus and a Syracosphaera sp. were also present. Whereas Helicosphaera carteri, Coronosphaera mediterranea, Syracosphaera corolla, and C.pelagicus (non-motile phase) occurred as discrete coccoliths.

Lackey and Lackey (1963) recorded the microscopic algae and protozoa in the waters around Plymouth. They noted the presence of a Syracosphaera sp. in the plankton from open-waters outside the breakwater. Hymenomanus carterae (Braarud and Fagerl.) Braarud and E.huxleyi were also recorded from the more sheltered waters inside the breakwater. A summary of the distribution of living coccolithophores in the waters of the slope and shelf regions of the Celtic Sea and English Channel is given in Table 3.11. The number of coccolithophores found in the plankton samples decreases from the slope (10 species) to the western English Channel (4 species). There are no

Table 3.11. Occurrence of living coccolithophores in plankton samples from the Celtic Sea and English Channel.
(Table modified after Murray *et al.* (1983))

SPECIES	SLOPE	CELTIC SEA	WESTERN CHANNEL
Braarudosphaera bigelowii		+ 1.	
Calcidiscus leptoporus	++ 1,4.	++ 1.	++ 2,3.
Coccolithus pelagicus	++ 1,4.	++ 1,4.	++ 2,3.
Coronosphaera mediterranea	+ 6.	+ 6.	
Emiliania huxleyi	+++ 1.	+++ 1,6,7.	++ 3,5.
Gephyrocapsa spp.	++ 4,6.		
Helicosphaera carteri	++ 4.		
Homozygosphaera quadriperforata		+++ 6.	
Hymenomanus carterea			++ 2,3.
Lohmanosphaera michaelsari	++ 1.	++ 1.	
Rhabdosphaera clavigera	++ 4.		
Syracosphaera corolla		+ 6.	
Syracosphaera pulchra	+ 6.	+ 1.	+ 1.
Umbellosphaera tenuis	+ 6.		
Total number of species	10	9	4

+++ common ++ present + rare
1, Gaarder (1954) ; 2, Manton and Leedale (1969) ; 3, Lackey and Lackey (1963); 4, McIntyre and Be (1967) ; 5, Lebour (1923) ; 6, Murray *et al.* (1983) 7, Holligan *et al.* (1983).

published records on the occurrence of coccolithophores in the eastern Channel. E.huxleyi dominates the coccolithophore assemblages of the slope and shelf waters of the Celtic Sea area. This dominance of the species is well-reflected in the coccolith assemblages preserved in the surface sediments where it may form up to 97.5% .

Coccolithus pelagicus is the next most common species in the plankton samples. It is found from the slope to the western English Channel. The species becomes more dominant in the plankton from the Channel. Lebour (1923) reported that C.pelagicus " occurs abundantly in centrifuged water samples from the Plymouth district , the western part of the Channel ,and outwards to the Irish Sea and the French Coast". The species occurred from October to May, but was generally absent in the period July to August. E.huxleyi was the only other species found. The records show it to occur in August, February and May, although the species was suspected to have a greater distribution as it was easily ' passed over' without recognition because of its small size.

Hymenomanus carterae and a Syracosphaera species have also been recorded from the waters of the western Channel. Hymenomanus species are commonly observed in coastal waters (Tappan, 1980). They have non-motile benthic phases which may survive extremes of temperature and salinity . Syracosphaera pulchra occurs in small numbers in sediments from the Devon and Brittany coasts (Fig.3.17.). This species probably represents the Syracosphaera sp. listed by Lackey and Lackey (1963) in the plankton samples from the Plymouth area.

Three species listed in the plankton samples from the Celtic Sea (Table 3.11.), Syracosphaera corolla, Homozygosphaera quadriperforata and Lohmanosphaera michaelsari, are not recorded from the sediments in this study. H.quadiperforata and L.michaelsari are both holococcoliths. H.quadriperforata was recorded in two shelf stations from the Celtic Sea (Murray et al.,1983).

L.michaelsari was found in two plankton samples near the shelf-edge (Gaarder, 1954). Holococcoliths are the least resistant of all types of coccolith structure. They tend to disintegrate when the coccolithophores are digested by herbivores ,or simply during the process of sinking to the sea floor. Holococcoliths are therefore seldom seen as fossils in sediments.

S.corolla is a caneolith-type coccolith, basket-shaped, with a central area of weak lamellae surrounded by a girdle and rim of strong elements. McIntyre and McIntyre (1971) conducted laboratory experiments using ultra-sonic vibration to determine the relative strength of modern coccoliths. They found that caneoliths were the first heterococcoliths to disintegrate . Syracosphaera pulchra , however, was found to be the most resistant of the caneolith coccoliths. Throughout the Celtic Sea and western English Channel S.pulchra generally shows moderate preservation. Most specimens show slight damage to their central lamellae. Occasional isolated rims of syracosphaerids are also seen in the sediments. These may represent the remains of the more delicate species, such as Syracosphaera corolla, which have disintegrated during deposition in the comparitively high energy environment of the Celtic Sea and English Channel.

3.3.2 Relation of the coccolith assemblages in the surface sediments to the hydrographic regions.

3.3.2.1 Introduction.

In the study area three main coccolith assemblages are distinguished ;

1) continental slope assemblages (sites 50 and 51),

2) outer continental shelf assemblages (Celtic Sea and English Channel),

3) inner shelf assemblages (central and eastern English Channel).

3.3.2.2 Continental slope assemblages.

Sediments on the continental slope at the western margin of the Celtic Sea may be designated as typically oceanic for the northeastern Atlantic. They are deposited from waters of normal marine salinity (~ 35.5 ‰), at depths in excess of 1 km. This region is not subject to the neritic influences that may be present within shallower waters on the continental shelf. Surface tidal streams are very weak in this region (<0.3m/s <0.5 kts).

Coccolith assemblages deposited in this region are characterised by the following parameters:

1) a high number of species occur in the assemblages (20 species),

2) high quantitative abundance of coccoliths (10^{10} coccoliths per gram),

3) high % coccolith abundance (>50 % of the fine fraction),

4)low to moderate dominance (< 68 %),

5) a dominance of 3 species Emiliania huxleyi,

Gephyrocapsa caribbeanica and Calcidiscus leptoporus

Twenty species of Recent coccolith were identified in the continental slope sediments. This species diversity compares very well with other studies in oceanic sediments at high latitudes , 18 species recorded by Bartolini (1970) from the western Mediterranean, 15 species recorded by Seisser (1975) from the South African continental slope (33° to 35° S latitude).

The abundance of Recent coccoliths in the surface sediments from the continental slope (10^{10}per gram), is the highest throughout the area studied and accounts for 51 to 56% of the fine-fractions. Fine-grained carbonate in these sediments varies between 62 and 68 % ,therefore coccoliths account for up to 82 % of the fine-fraction carbonate. This dominance of planktonic coccolith skeletons in the carbonate fraction is a good indicator of the oceanic environment of deposition on the slope. The high abundance of biogenic carbonate in the fine - fraction shows that low amounts of continental clastics are supplied to the area. This is confirmed by the absence of reworked coccoliths in the slope sediments. Reworked forms are a consistant, but minor component in continental shelf coccolith assemblages from the Celtic Sea.

The coccolith assemblages contain 3 dominant species, E.huxleyi (66 to 68%), G.caribbeanica (20%) and C.leptoporus (11.1 to 12.7%). This species-composition is typical for coccolith assemblages in the northeastern Atlantic. At 50° N latitude in the North Atlantic, coccolith assemblages are characterised by the following species-composition; E.huxleyi (67%), C.leptoporus (13%) and Gephyrocapsa species (18%) (McIntyre and Be', 1967).

C.leptoporus has a number of varieties based on the number of elements in the coccolith (McIntyre and Be', 1967; McIntyre et al., 1970; Gietzenauer et al., 1976, 1977). These varieties are useful in palaeoceanographical studies as they are thought to be latitude-controlled.

The varieties are not easily distinguished by means of optical microscopy and there are gradations between them . No attempt was made to separate these varieties in the species counts. However, selected samples from the slope sediments were analysed by S.E.M. to try and determine any varieties present.

C.leptoporus was previously thought to have 3 main varieties (McIntyre and Be', 1967). This view has now been modified and the largest of these forms, variety A, has been given a new species name (Calcidiscus mcintyrei) (McIntyre et al., 1970). The remaining forms grouped under C.leptoporus are thought to be ecophenotypes. The diagnostic feature of C.leptoporus var.C is a mean element count of twenty. It is the eurythermal form, with its maximum poleward boundary in the subpolar seas. While not found at latitudes as high as E.huxleyi, it is a palaeontologically useful form (McIntyre et al.,1970). The variety can be found in all water-masses between its poleward boundaries. C.leptoporus var.B has a mean element count of thirty, prefering warm tropical and subtropical waters. It is not as common as var.C and its biogeographical range has not been accurately determined.

Table 3.12 Characteristics of C.leptoporus assemblages in the slope sediments

var.	element no.	mean	diameter	mean	% total
B	33-30	31	9.1- 10.0μ	9.2	83
C	14-25	20	5.0- 7.2μ	5.9	17

As expected from the northern latitude of the Celtic Sea, C.leptoporus var.C, the eurythermal form, dominates the C.leptoporus flora in the sediments (83%). It forms 8.5 % of the total coccolith flora from the slope sediments. C.leptoporus var.C typically forms between 5.0 and 19.9 % of the coccolith assemblages from the

transitional zone sediments in the North Atlantic (Geitzenauer et al., 1977).

The dimensions of coccoliths secreted by E.huxleyi differ significantly at different temperatures in culture (Watabe and Wilbur, 1966). These variations have been observed in specimens from the North Atlantic (McIntyre and Be', 1967; Gietzenauer et al., 1977). Distinct warm-water and cold-water ecophenotypes are recognised. The warm-water form has a mean of 35 elements, both shields bear T-shaped elements, and a delicate grill covers the central opening on the proximal side. The cold-water form has has T-shaped elements in the distal shield only, with the proximal shield fused solid. It has high abundances north of 30°N latitude and low abundances in the equatorial Atlantic. The warm-water form usually dominates the assemblages where the water temperature exceeds 14°C.

E.huxleyi assemblages in the continental slope sediments of the Celtic Sea, as expected from their northern latitude, are dominated by the cold-water and transitional ecophenotypes. Warm-water forms only comprise a small component (<10%). Similar results are also obtained from shelf sediments. Summer temperatures in the Celtic Sea may exceed 14°C during the months of July and August. Scanning electron micrographs provided by Holligan et al., (1983) of E.huxleyi, collected from waters at the southwestern margin of the Celtic Sea (approx 48° 30' N, 8° 30' W) on 28 May 1982, show coccoliths and coccospheres dominated by the warm-water ecophenotype. Such results may indicate that the warm-water form occurs in larger numbers in waters to the southwest of the Celtic Sea, where warmer waters occur. The Celtic sea probably lies near the northern limit of the warm-water ecophenotype of E.huxleyi in the Atlantic.

The coccolith assemblages deposited on the continental slope at the western margin of the Celtic Sea reflect the oceanic character of the overlying waters.

3.2.3 Outer continental shelf coccolith assemblages.

Outer continental shelf coccolith assemblages are found in the Celtic Sea and in the western English Channel region approximately west of 4° W longitude. The waters of this region are of normal marine salinity (>35.0 ‰.) ,except for a small area in the northern Celtic Sea. The depth range in this region varies from approximately 44 to 170 m. The waters of this region are stratified in the summer months. In the Celtic Sea, a thermocline develops between 20 and 50 m depth during April and persists until December.

In the western English Channel stratification develops in late April or early May and persists until late December (Pingree, 1975). The eastern limit of thermocline development in the English Channel marks the eastern boundary of the outer shelf coccolith assemblages. Tidal currents have low velocities throughout the region, increasing from west to east across the Celtic Sea and western English Channel. They range from 0.5 kts in the central Celtic Sea to 1.5 to 2.0 kts within the western English Channel.

Sediments deposited in the outer shelf region have coccolith assemblages with the following characteristics:

1) a total of 18 species of Recent coccolith have beeen recorded,

2) 8 or more species occur in the assemblage from any one sample,

3) 3 species are ubiquitous, E.huxleyi, C.pelagicus and S.pulchra,

4) abundances of total coccoliths and E.huxleyi range from 10^8 to 10^9 per gram,

5) E.huxleyi dominates the assemblages (generally

forming over 90 %),

6) coccoliths form > 1% of the fine fractions,

7) less than 1% of the assemblages are comprised of reworked coccoliths,

8) abundances of C.pelagicus are in $> 10^7$ per gram,

9) C.pelagicus forms < 5% of the assemblages,

10) abundances of S.pulchra are $> 10^6$ per gram.

Eight or more coccolith species occur in the assemblages throughout this region. The eastern limit of this species diversity in the western English Channel corresponds with the maximum easterly distribution of stratified waters in the Channel (see Figs. 3.9 and 3.11). Highest coccolith abundances, 10^9 per gram, occur in the open-water sediments of the central and southern Celtic Sea and at the western approaches to the English Channnel. This corresponds to the region of least tidal streams within the continental shelf of the Celtic Sea. The salinity of the waters of this region varies from 34.75 to 35.4 %. .

Sediments deposited from waters where the maximum tidal streams are in excess of 1.5 kts, contain 10^8 coccoliths per gram. This region includes sediments deposited off the North Cornwall coast and in the western English Channnel. The salinity range of the waters overlying sediment containig 10^8 coccoliths per gram, varies from 35.3 to 34.75%. . Estuarine sediments deposited along the southern Irish coast, although in a region of weak tidal currents, also have similar values (10^8 per gram). This is probably a function of the very shallow water-depth found within these sites. Coccolith abundances may also be diluted due to clastic sedimentation in these coastal embayments and estuaries.

Variations in the abundance of E.huxleyi throughout the region parallel the trends just described for total coccolith abundances. A notable feature of coccolith

assemblages in the outer shelf region is the dominance of E.huxleyi. This species comprises over 90 % of the assemblages in open-waters from the central Celtic Sea and western English Channel. In this region the coccolith assemblages are also notable for their homogeneity, as the species-composition shows little variation. Shallow-water sediments along the coasts of Southern Ireland , north Cornwall and Wales have lower E.huxleyi values (mean 80.3 %). The open-water sediments from the outer shelf region are characterised by E.huxleyi/C.pelagicus ratios of >25.

The high dominance values in the coccolith assemblages from the outer shelf greatly affect the indices of species diversity . Both The Shannon-Wiener Index (H) and the Simpson Index (P) are low in the assemblages. Values of (H) and (P) throughout the southern Celtic Sea and western English Channel are (<0.5) and (<0.25) respectively. Higher values occur in the coastal regions of the northern Celtic Sea, where the dominance of E.huxleyi is reduced. In these shallow waters, H values for the coccolith assembalges range from 0.57 to 0.83, P values range from 0.27 to 0.49.

The percentage abundance of coccoliths in the fine fractions of the outer shelf sediments generally follows the contours of the quantitative coccolith abundances. Highest values (>20 %) occur in the deep-water sediments, nearest the shelf-break, where carbonate forms > 50% of the fine fraction. Coccoliths therefore account for > 30% of the fine-grained, carbonate fraction in the slope sediments. Throughout the open-water sediments of the Celtic Sea coccoliths form > 10 % of the fine fractions and 15 to 50% of the fine-grained carbonate fraction.

Fine fractions of sediments along the northern coastline of the Celtic Sea and in the western English Channel, have coccolith percentages ranging from 1 to 10% . Carbonate generally forms <30% of the fine fraction in

these coastal sdiments. Coccoliths account for 15 to 27% of this fine-grained carbonate along the Irish Coast and approximately 5% along the north Cornish coast.

The 1% coccolith-contour may be taken as the approximate division between the coccolith-rich sediments of the western English Channel and the coccolith-poor sediments of the central English Channel. The 1% value also corresponds with the abundance contour (10^8 coccoliths per gram) and traces out the maximum easterly limit of the thermocline development in the English Channel.

The variations in abundance of Coccolithus pelagicus in the sediments follow those described for total coccolith numbers. Highest coccolith numbers (>1000 $\times 10^5$ /g) occur in a small area of the central Celtic Sea at Nymphe Bank, where the tidal streams at spring tides are very weak (~0.3 m/s, 0.5kts.). Similar high abundances of the species are only found in continental slope sediments at the western margin of the Celtic Sea, where weak tidal streams also occur. Lowest abundances of the species occur in the western English Channel and off the north coast of cornwall (<250 x 10^5 per gram), where tidal velocities are > 1.5 knots.

The percentage abundance of the species in the outer shelf sediments is low (<5%) and varies little. This reflects the homogeneity of the coccolith assemblages in the region. Abundances in excess of 5 % may be found in coastal sediments.

Syracosphaera pulchra is the only other ubiquitous member of the outer shelf coccolith assemblages. Highest abundances (10^7 to 10^8 per gram) of the species occur throughout the Celtic Sea and western approaches to the Channel. Lower abundances (10^6 per gram) typify the sediments in the western English Channel and in the coastal regions of South Wales, where tidal currents are in excess of 1.5 kts. The decline in abundance of

S.pulchra eastwards towards the English Channel is therefore more pronounced than that reported for E.huxleyi and C.pelagicus.

Minor species (<3.0%) in the outer shelf coccolith assemblages include G.caribbeanica, B.bigelowii, C.leptoporus, D.tubifera and R.clavigera. These species are consistent members of the assemblages and their relative abundance varies little over the region, although they are more frequently recorded from the Celtic Sea sediments than those of the western English Channel. The other coccoliths found in the outer shelf sediments form scarce members of the assemblages (0.2% or less).

Reworked coccoliths are a constant but minor component of the outer shelf coccolith assemblages. Such low values, reflect the general absence of coccolith-bearing strata in the mainly Palaeozoic Celtic Lands that border the Celtic sea and western English Channel.

3.2.4 Inner shelf coccolith assemblages.

The inner shelf region comprises the central and eastern English Channel. The waters of this region are mainly of normal marine salinity except for shallow regions along the coasts of France and England. The English side of the Channel is more saline than the corresponding French side, where run-off from the River Seine reduces the salinity. The waters of the inner shelf region are tidally mixed throughout the year with no pronounced development of a seasonal thermocline. Tidal currents are high throughout the region (generally greater than 2 kts) and may reach 4 to 5 kts off the Cherbourg Peninsula. Most of the region has a depth ranging between 100 and 30m although depths less than 30m occur along both margins of the Channel.

Inner shelf coccolith assemblages have the following

characteristics;

1) coccolith diversity is restricted to 6 or fewer species,

2) coccoliths form less than 1% of the fine fractions,

3) coccolith abundances range from 10^7 to 10^5 per gram

4) E.huxleyi is less dominant (<90 %) and has a more varied relative abundance,

5) The ratio of E.huxleyi/C.pelagicus is <25,

6) C.pelagicus is the only ubiquitous member,

7) abundances of C.pelagicus are < 10^7 per gram,

8) relative abundance of C.pelagicus is >5%,

9) high reworked nannofossil component (> 15%).

Recent coccoliths are very scarce (<0.5%) in the inner shelf region. Species diversity (S) is low in the assemblages and is limited to the species E.huxleyi, C.pelagicus, H.carteri, S.pulchra, B.bigelowii and G.caribbeanica. With the exception of C.pelagicus and E.huxleyi, these species tend to have a sporadic occurrence in the assemblages. The other twelve species recorded in the outer shelf assemblages are absent from the assemblages present in the innner shelf region. Species diversity decreases from east to west across the region. Highest diversities, 4 to 6 species, occurs in the area west of the Isle of Wight. In the eastern English Channel 3 or fewer species occur in the assemblages, limited to the species E.huxleyi, C.pelagicus and B.bigelowii.

Indices of species diversity of the coccolith assemblages also decrease from east to west across the region. Dominance values are lowest in the central English Channel where they range from 47 to 76% . Such dominance values are lower than those calculated from the outer shelf coccolith assemblages. This is because of reduced numbers of E.huxleyi throughout the inner shelf assemblages. Higher dominance values (100%), occur at the eastern margin of the English Channel where Coccolithus

pelagicus forms a Recent monospecific flora. Values of the Simpson Index (>0.25) and the Shannon-Weiner Index (>0.5), typify the coccolith assemblages throughout much of the inner shelf area. Lower values occur at the eastern margin of the Channel.

The abundance of total coccoliths and E.huxleyi follow similar trends across the inner shelf region, both values decrease in an easterly direction. Abundances are highest in the axial, deeper water area of the central Channel (10^7 coccoliths per gram). This area corresponds to the main axis of the high salinity tongue of water (>35.0 ‰.) which extends along the central region of the Channel. Lower values typify sediments along the Brittany coast and in Baie de la Seine. In the latter region, run-off from the River Seine reduces the salinity coastally towards the Straits of Dover. In the area of large tidal streams (>3kts), north of the Contenin peninsula, no Recent coccoliths occur in the surface sediments (sites 57 and 59). In such regions, bedrock is frequently exposed by the scouring action of the currents. The abundance of C.pelagicus declines gradually across the region from >50 $x10^5$per gram in the west to ~10 $x10^5$in the east. It is the only ubiquitous member of the assemblages.

Large numbers of reworked coccoliths characterise the assemblages from the inner shelf region. Reworked Cretaceous forms dominate the coccolith assemblages east of the Isle of Wight, comprising over 85 % . These reworked forms are probably supplied from marine and submarine erosion of Chalk strata which outcrops on both sides of the central and eastern English Channel. The reworked assemblages are dominated by Watznaeuria barnesae, Zygolithus spp. and Predicosphaera spp. For more details of these reworked assemblages refer to Chapter 6.

Sediments from the shelf of the Celtic Sea and English Channel contain two distinct coccolith

assemblages. These have been termed outer continental shelf assemblages and inner shelf assemblages. The basis for this subdivision being the species diversity and the abundance of coccoliths in the two assemblages. The hydrography of the outer shelf and inner shelf regions are similar in most respects apart from the degree of tidal influence. The waters in the outer shelf region are stratified in the summer months, whereas in the inner shelf the waters are tidally mixed throughout the year. This degree of tidal mixing is the main feature which distinguishes the more neritic character of the inner shelf region.

Variations in coccolith abundance and diversity are attributed to the hydrological differences which distinguish the Celtic Sea waters from those of the English Channel. Sediments deposited beneath a pronounced thermocline in the Celtic Sea and western English Channel contain abundant coccoliths, a flora dominated by E.huxleyi but also containing many oceanic-forms. In the central and eastern English Channel where tidally mixed conditions occur all the year, a very sparse coccolith flora is contained within the surface sediments.

3.3 The correlation of coccolith abundance with selected environmental parameters from the Celtic Sea and English Channel.

Correlation coefficients of coccolith abundance against selected environmental parameters from the Celtic Sea and English Channel have been calculated. Only the open-water sediments were selected for analysis as these are expected to reflect best the properties of the overlying water mass. The log 10 of abundance of E.huxleyi, C.pelagicus, S.pulchra and total coccoliths were plotted against the variables of depth, salinity, tidal currents and the stratification parameter. Temperature was not included as it varies little over the area. The correlation coefficients of these variables are listed in Table 3.13.

Bar graphs illustrate the variation of the log of coccolith abundance against salinity, tidal streams and the stratification parameter (Figs. 3.33, 3.34, 3.35 respectively). These histograms represent the log of the mean coccolith abundance within each 0.1%. salinity, 0.5kt and each 0.5 division of the stratification parameter respectively. The diagrams presented by Pingree (1980) are the data base for the variable values. These values are extracted from the maps shown in Figs 3.7, 3.8 and 3.32. The coccolith abundances were also correlated with the water-depths listed in Table 3.1.

From the histograms it can be seen that there is a linear realationship between the log of the coccolith abundances and variations in the maximum tidal stream velocities and the stratification parameter. A strong negative correlation occurs between the log of the coccolith abundances and the tidal streams (r= -0.84 to

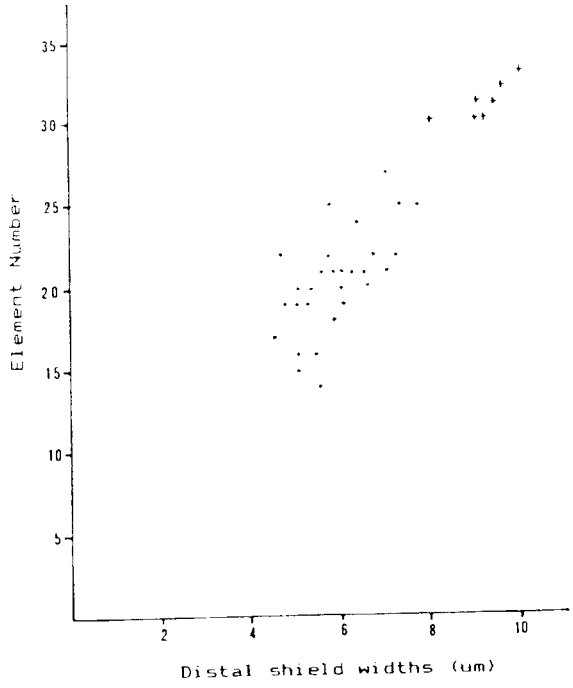


Figure 3.31
Plot of widths of Calcidiscus leptoporus distal shields versus the number of elements in the same shield.

+ warm-water form

• Cold-water form

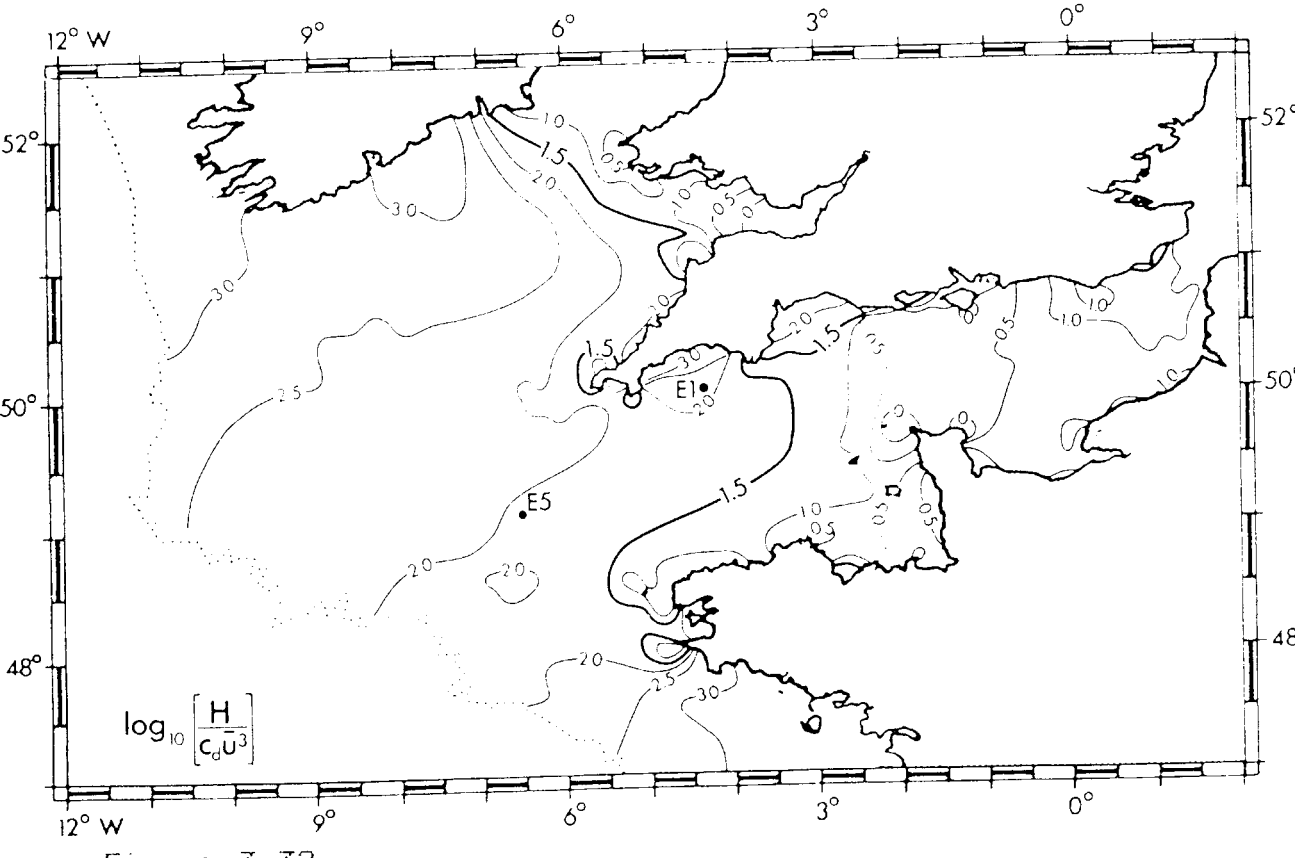


Figure 3.32.
Distribution of the stratification parameter H/cd U , plotted on a log scale. Low numbers (<1.0) are associated with well-mixed conditions and high numbers (>2.0) define areas where the water column stratifies in the summer. Frontal regions correspond with the 1.5 contour. (After Pingree, 1980).

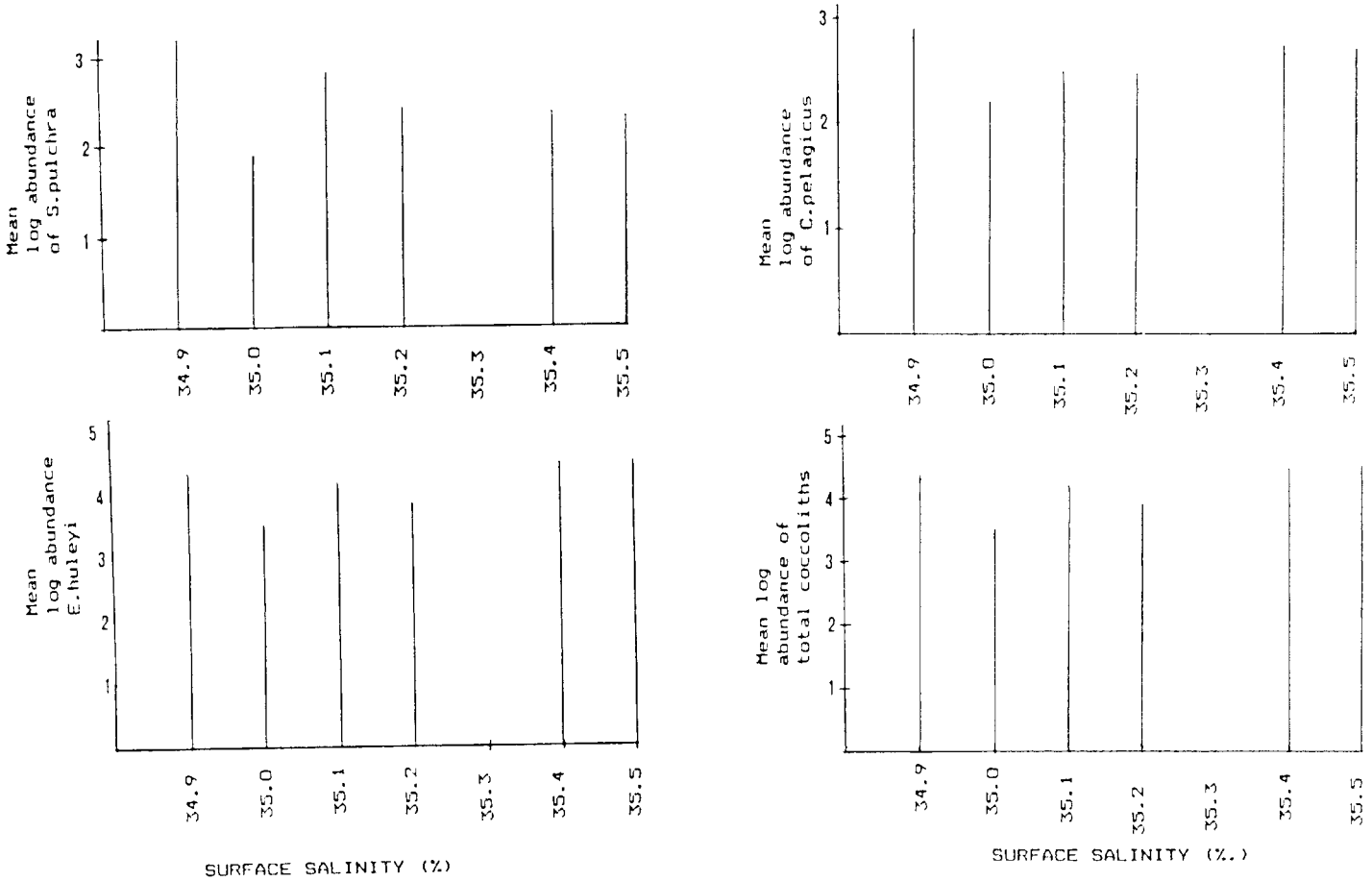


Figure 3.33.
Plots of coccolith abundance versus mean sea-surface salinity (%.) (summer). Histograms represent the log of the mean coccolith abundance within each 0.1%. of salinity. Salinity values are taken from Fig.3.7. Note that coccolith abundances in the histograms shown in Figs. 3.33. to 3.36 are all numbers $\times 10^{5}$ per gram.

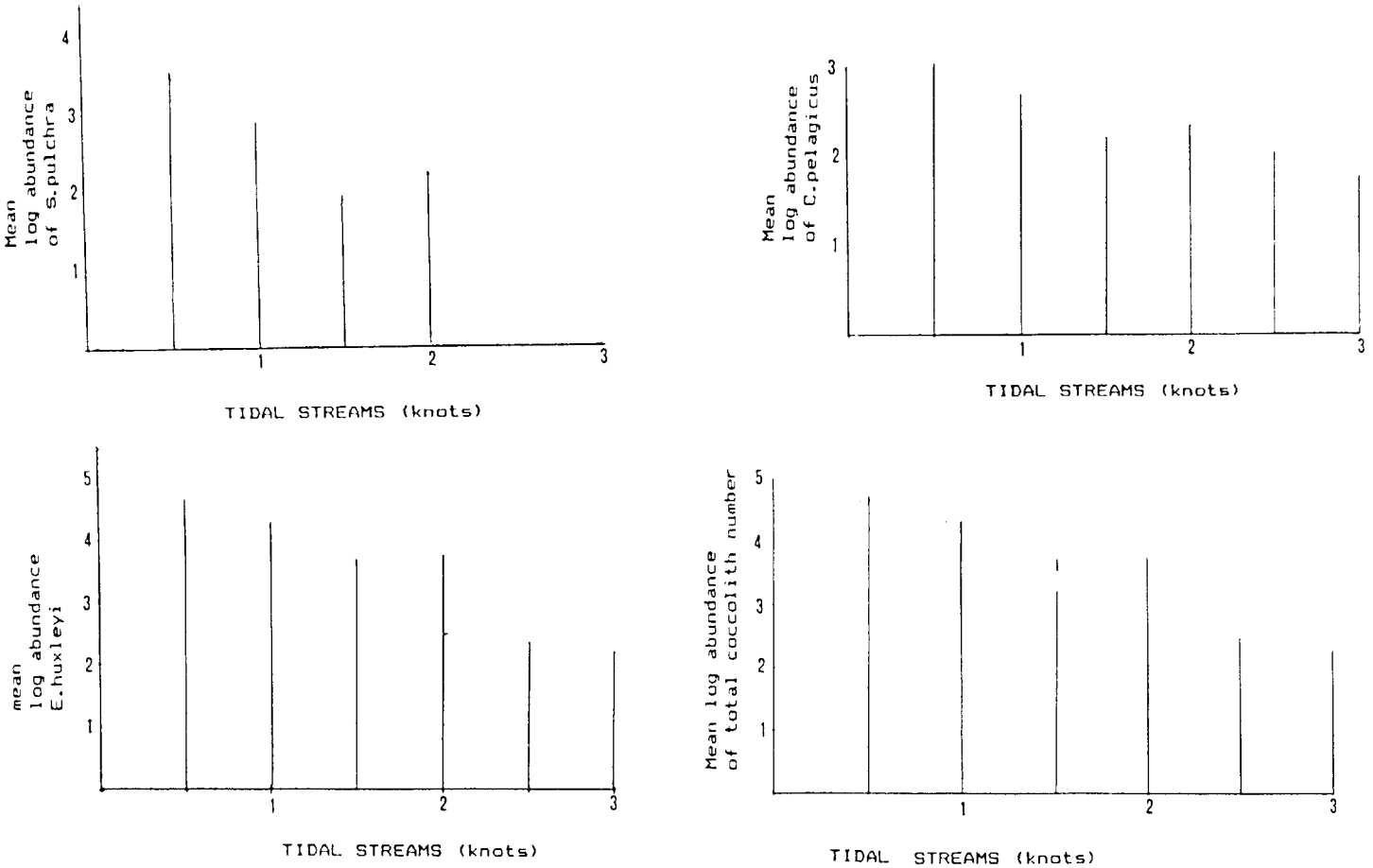


Figure 3.34.
Plots of coccolith abundance versus tidal stream amplitudes at spring tides in knots (surface values) Histograms represent the log of the mean coccolith abundance within each 0.5 knot division of the tidal streams. Tidal stream data taken from Fig. 3.8.

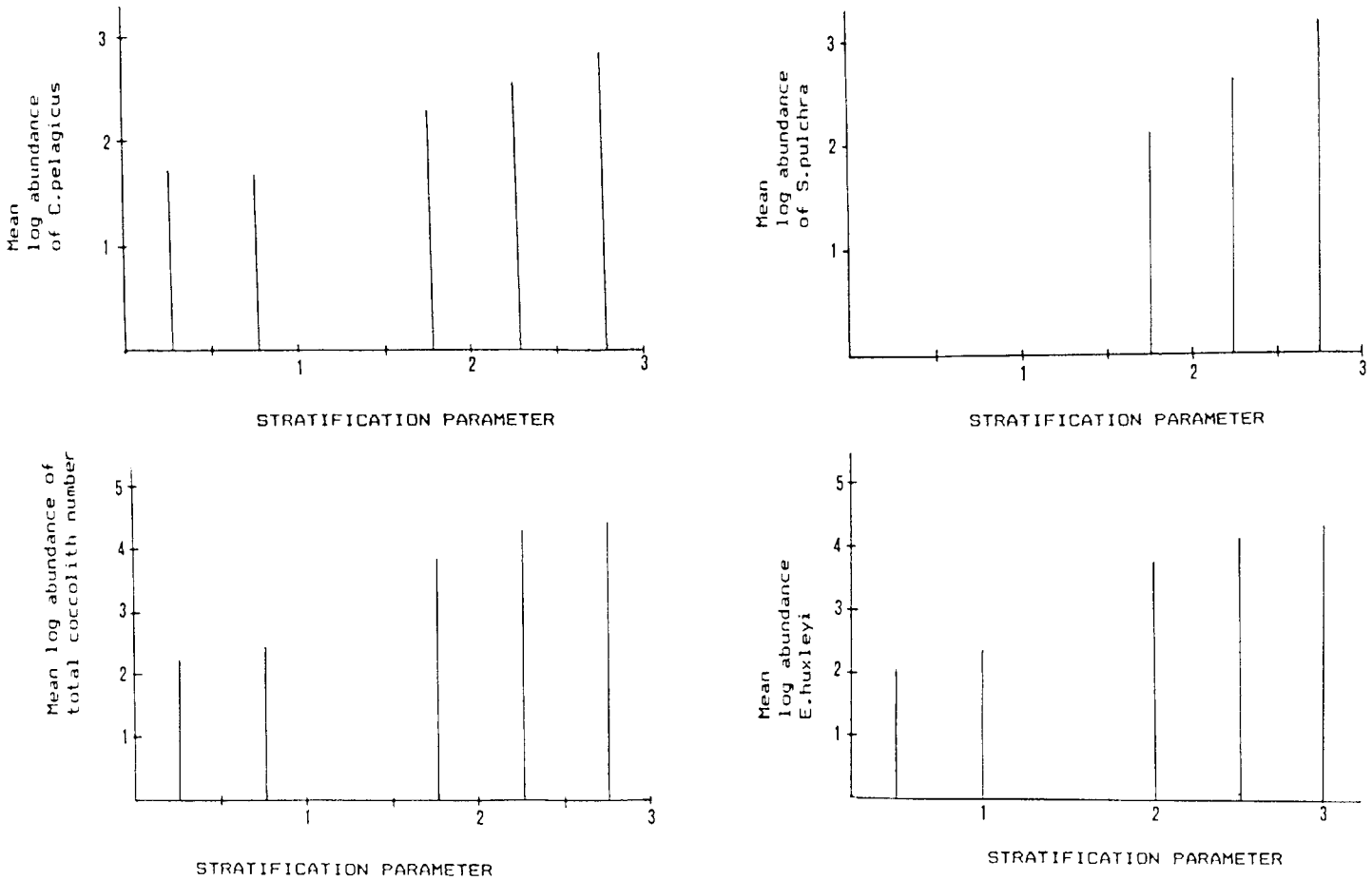


Figure 3.35.
Plots of coccolith abundance versus values of the stratification parameter (St = log [H/CdU 3]. Histograms represent the log of the mean coccolith abundance within each 0.5 division of the parameter. Values of St taken from Fig.3.32.

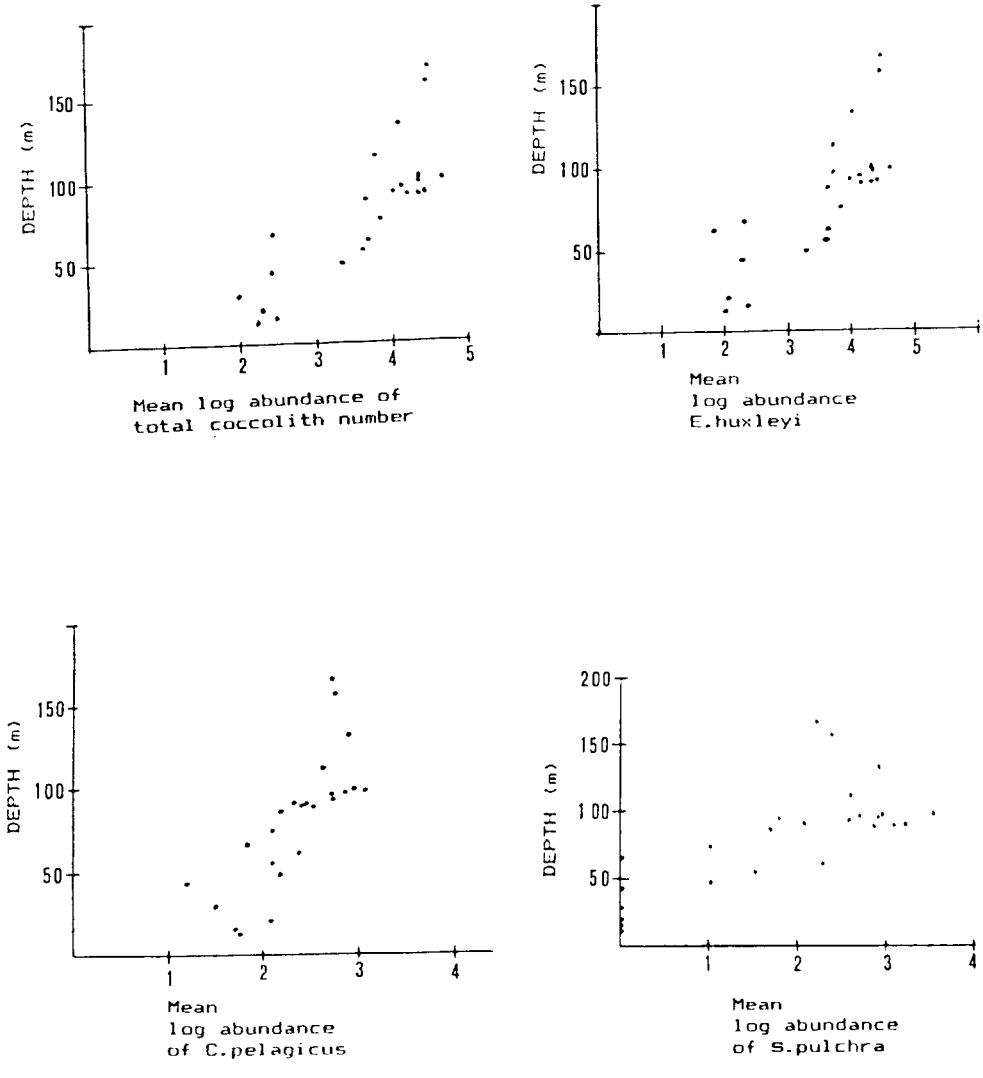


Figure 3.36.
Plots of coccolith abundance versus depth.

-0.96). A strong positive correlation occurs between the log of coccolith abundances and values of the stratification parameter (r=0.97 to 1.00).

The stratification parameter quantifies the degree of stratification of the water column and may be calculated from

$$St = \log 10 [H/CdU^3],$$

where Cd is the drag coefficient, which usually can be approximated and for the Celtic Sea is 0.0025 (Pingree, 1980),

H = water-depth

U is the maximum tidal stream velocity.

The stratification parameter is then easily calculated for a coastal region and contours of the parameter are shown in Fig 3.32. High values of the stratification parameter(>2) reflect stratification, while low values (<1.0) are associated with tidally mixed conditions. These contours reflect the distribution of the tidal stream velocities since they are raised to the cube power, which varies more over the region than the water-depth. The transition from stratified conditions to well-mixed conditions takes place at a critical value (St =1.5) The St =1.5 contour shown in Fig 3.32. maps out the maximum extension of stratified conditions in the Celtic sea and English Channel and also maps out the area of the outer shelf coccolith assemblages.

The histograms showing coccolith abundance plotted against salinity show no significant correlation. Mean coccolith abundances vary very little over the salinity range 35.5-34.9% . In fact, S.pulchra has a peak abundance at the 34.9 %. salinity value, which corresponds to the waters in the northern Celtic Sea. This water-mass here is associated with very weak tidal currents (~0.5 knots) (see Fig.3.8). All the other

coccolith abundances are also high at this low salinity.

The $\log_{10}$ of coccolith abundance has been shown to correlate most significantly with tidal currents, values of the stratification parameter and water-depth. Water-depth and in particular, tidal currents control the degree of tidal mixing and the amount of layering of the water column. The stratification parameter quantifies the degree of layering in the column. Salinity shows no significant correlation with the coccolith abundances.

Table 3.1 Correlation coefficients among coccolith abundances and among selected environmental parameters.

	Salinity	Tidal streams	Strat. par.	Depth
S.pulchra	-0.39	-0.84 *	1.00 **	0.74 **
C.pelagicus	0.24	-0.95 **	0.97 **	0.74 **
E.huxleyi	0.51	-0.96 **	0.98 **	0.73 **
Total numbers	0.49	-0.96 **	0.98 **	0.64 **
(n)	4	4	3	22

** signif cant at 99% confidemce level
* significant at 95% confidence level
(n) number of degrees of freedom

3.4 The transport paths of coccoliths within the Celtic Sea and English Channel.

The general flow of water through the Celtic Sea and English Channel and into the Irish Sea through St. Georges Channel, and into the North Sea through the Dover Strait, was established by the work of Matthews (1914) and Lumby (1935). Support for these conclusions was obtained using certain planktonic animals as indicators of water movement (Russel, 1935) and by more direct measurements of

water movements in the Strait of Dover.

Coccoliths are also likely to be transported in these general directions across the shelf of the Celtic Sea and English Channel. Exchanges of water containing coccoliths are likely to be more pronounced between the Celtic Sea and Irish Sea, than between the English Channel and the North Sea. Eight or more coccolith species occur in sediments deposited at the mouth of St. George's Channel, in the northern Celtic Sea. These species contribute 10^8 coccoliths per gram in the sediments. Significant numbers of coccoliths are therefore probably transported within the northward flow (mean 0.3 cm/s) of water from the Celtic Sea to the Irish Sea (see next chapter for details).

Coccolith numbers decrease steadily from west to east across the shelf of the Celtic Sea and western English Channel. Only 6 coccolith species are transported any significant distance across the frontal region in the western English Channel, whereas Atlantic water deposits only 3 species (contributing 10^5 coccolith per gram) at the eastern margin of the Channel. Murray et al. (1982) have documented the suspended load transport of foraminiferal tests in the Western Approaches and western English Channel. The distribution of living planktonic foraminifera, outer shelf benthic foraminifera tests and radiolaria, defined the penetration of Atlantic water in the top 40m of the water column into the English Channel. The landward-movement of the foraminiferal tests was confined to the mid-water column; however, a near bottom residual flow of benthic tests towards the shelf-edge was also suggested.

The importance of the net-landward transport of foraminifera tests in suspension was indicated by the presence in the Exe Estuary of 43 species of benthic foraminifera which are not known to live there (Murray,1980). There is little evidence, however, to suggest that coccoliths are transported in large numbers

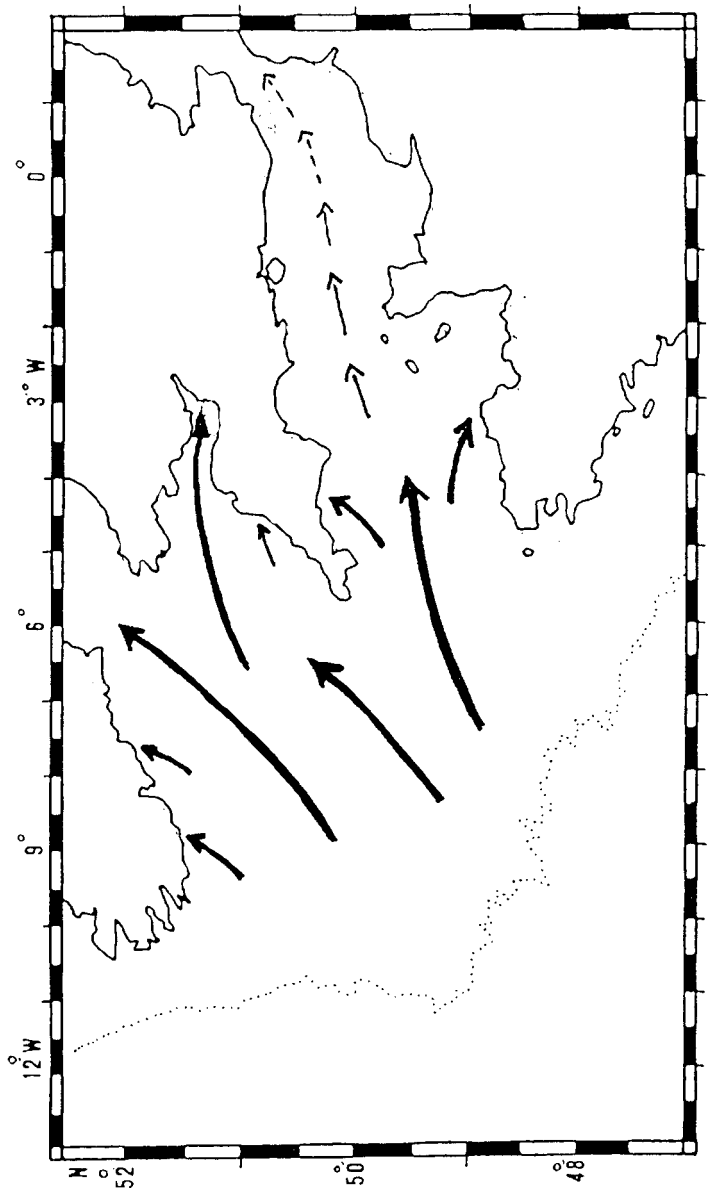


Figure 3.37
Suggested transport directions of coccoliths in the Celtic Sea and English Channel.

to this area of the coast. Coccoliths are rare (<1%) in the fine fraction of sediments deposited in the Exe and Teign estauries. The coccolith assemblages deposited at these sites are limited to 3 or fewer species.

In the English Channel east of the Cherbourg Peninsula, coccolith abundances of the order of 10^7 per gram occur only in sediments in the the axial region. This shows that most coccoliths are transported within the high salinity tongue which protrudes down the centre of the Channel. Few coccoliths are transported in coastal currents, particularly in Baie de la Seine, where coccolith abundances may fall as low as 10^5 per gram.

Coccoliths are also transported towards the northeastern margin of the Celtic Sea and into the estuaries of South Wales and the Severn Estuary. This transport direction was originally proposed by Sollas (1883) who was the first worker to question the origin of the mud in the Severn Estuary and its adjacent inlets. The catchment area of the River draining into the Bristol Channel and Severn Estuary is of the order of 25,000 km^2 or 1/6 th of England and Wales. However, as noted by Sollas (1883, p.612) "the Severn and its tributaries are not, except when flooded very muddy rivers". Sollas concluded that the marine microfossils (including coccoliths, foraminifera and sponge spicules) could only have been derived from the open-marine conditions found to the west of the Bristol Channel. He concluded that fine sediment is transported eastwards into the Bristol Channel and Severn Estuary.

This proposal has since been supported by the work of Murray and Hawkins (1976). They found an abundance of size-sorted benthic foraminifera, with a mean size of ~140 um, in intertidal mudflats and boreholes on the eastern side of the Severn Estuary and in suspended sediment samples in the Bristol Channel. The foraminiferal assemblages in the surface sediments were composed of an essentially indigeneous component, containing species living

in the area and also an allochtonous component, transported in from the sea to the west. This latter point was confirmed by the presence of stenohaline marine foraminifera in the suspended sediments from the Bristol Channel. Many of these species are presently living in the Celtic Sea (Murray,1970). The concentration of foraminifera in suspension is suggested to take place around longitude 5° W and to the east of it (Murray and Hawkins, 1976) (Table 3.14).

Table 3.14 Foraminifera in suspension in the Bristol Channel.

Sample point	Number of foraminifera per m of water
51° 21'N 05° 12'W	3.7
51° 21'N 04° 52'W	2400
51° 21'N 04° 04'W	9500
51° 21'N 03° 22'W	6000

Reasonably large numbers of coccoliths must also be transported with the foraminifera tests in the suspended load, as surface sediments deposited within the inner Bristol channel and the Lower Severn Estuary contain 10^7 coccoliths per gram. A maximum of 8 coccolith species is recorded from Minehead Harbour in the inner Bristol Channel, whereas between 3 and 7 species typifies surface sediments in the Severn Estuary. A characteristic feature of the coccolith assemblages in sediments from the Bristol Channel and Severn Estuary is their homogeneity. This was first noted by Sollas (1883, p.613) who stated that " the character of the mud from all places is so similar that a description of one would serve for all the rest". This consistency is reflected in their coccolith contents. For the area between the Parrot Estuary and Lydney the abundance of E.huxleyi and total coccolith numbers varies from 1.9 to 5.0 $\times 10^7$ and 3.7 to 6.3 $\times 10^7$ per gram respectively. Total coccolith numbers only decline below 10^7 per gram at station 16 in the upper reaches of the Severn Estaury.

The homogeneity of the Severn Estuary sediments is also reflected in their mineral composition. Suspended sediments within the turbidity maximum , which extends from Watchet to well above the Shoots, has been found to be reasonably constant (Kirby and Parker, 1983), with the mineral assemblages composed of illite 44 ± 9%, quartz 23 + 3%, chlorite 19 ± 6% and kaolinite 4 ± 4%. The carbonate content of the fine fractions of the surface sediments recorded in this study is 16 ± 4% from the same area. Coccolith abundance decrease in the upper reaches of the Severn Estuary (10^5per gram). Norton, north of Gloucester, is the furthest north (in an up-estuary direction) coccoliths are recorded in the sediments. The presence of coccoliths in the upper estuary shows that the up-estuary transport of marine sediments occurring in the Bristol Channel and lower Severn Estuary continues within the narrow upper tidal channels.

As mentioned previously, the source of the suspended sediment within the lower Severn estuary and Bristol Channel is thought to lie to the west, in the Celtic Sea. Belderson et al. (1971) identified a zone of muddy deposits in the Celtic Sea at the weak tidal currents end of the Bristol Channel. Culver (1980) considers this zone to be the principal source of fine sediment in the Bristol Channel and Severn Estuary.

The Celtic Sea has been described as a stormy sea where gales occur throughout the year, especially during the winter months (Cooper, 1967). Murray and Hawkins (1976) suggest that,under such conditions, reworking of the bottom sediment is likely to occur. Vertical mixing would bring the suspended sediment towards the surface where it would be driven by the prevailing westerly and southwesterly winds into the Bristol Channel. Once in the Severn Estuary, the sediments circulate within the powerful oscillatory, tidal currents system, until they pass over a tidal flat, where they may be deposited. Murray and Hawkins suggest that sediments are concentrated

PLATE 3

Shallow-water, marginal sites of coccolith deposition in the Celtic Sea area.

Fig.a Lydney Harbour (Severn Estuary) 'choked with mud'

Fig.1 Lough Hyne (southwest Ireland). Note the site of the rapids at the narrow entrance to the Lough.



1



2

on the south side of the Bristol Channel by currents under the influence of the Coriolis Effect.

Culver (1980) has proposed a differential two-way sediment transport within the Bristol Channel and Severn Estuary. Coarse sediment is transported in a general westward diection and fine sediments in a general eastward direction. The suspended sediment which reaches the Bristol Channel continues to move eastwards and is suggested to concentrate on the southern side of the estuary, by a northwest Atlantic 'residual' drift current, which is mainly effective in this sector (Banner and Collins, 1975). However, no such variance in coccolith abundance can be determined in the surface sediments along the southern and northern margins of the Estuary. This suggests that any initial concentration that may occur on the southern side of the Channel must be smoothed out by the oscillatory current system within the estuary.

Wang and Murray (1983) have used the composition of foraminiferal assemblages in estuarine deposits as indicators of tidal effects within the estuary. Estuaries are classified into three catergories: stratified, partially mixed and well-mixed, according to the degree of mixing . These divisions correspond broadly to the terms microtidal (<2m tidal range), mesotidal (2 to 4m) and macrotidal (>4m) respectively. Wang and Murray (1983) found that with an increase in tidal influence in an estuary there is a corresponding increase in the number of transported foraminifera tests , both as bed-load and ,more importantly, in suspension. The latter group are generally very small (<200 um) and include mainly stenohaline, open marine species. A similar trend should also be observed in the abundance of planktonic coccoliths within estuaries of different tidal strength.

Certainly, in the Severn Estuary, where the tidal range may reach 12m, reasonably large numbers of coccoliths (10^7 per gram) are consistently found in the

surface sediments. Similar numbers are also found in the estuarine sediments of Milford Haven (site 127) and the Loughour Estuary (site 126) which have a mean tidal range at spring tides of 6 to 8 m . These estuaries, however, would be expected to contain higher numbers of coccoliths, as they lie much closer to the suggested source area of the marine silt in the northern Celtic Sea. Therefore the transport path for the coccoliths would be much shorter for these estuaries than that for the Severn Estuary.

A large tidal range (up to 11m) occurs in the Gulf of St. Malo region, off the North Brittany coast. Coccolith abundances, however, reach only 10^6 per gram in estuarine sediments along this stretch of coast. Such low numbers of coccoliths probably reflect the general scarcity of coccoliths in offshore sediments around the Cherbourg peninsula ($\sim 10^7$ per gram ; <1% coccolith component), rather than a decrease in marine influence in these estauries. Coccolith abundances in the offshore region of the Celtic Sea adjacent to the Bristol Channel, though, are much higher (10^7 per gram) and this is reflected in the coccolith numbers contained in the surface sediments of the Severn Estuary.

The main transport paths of coccoliths across the shelf of the Celtic Sea and English Channel have been identified. Greatest numbers of coccoliths are transported northwards and northeastwards in the Celtic Sea rather than eastwards into the English Channel. Coccoliths have been used to indicate transport directions from the shelf into adjacent estuaries of the Celtic Sea and English Channel. The concentration of coccoliths in the surface sediments of the Severn estuary has confirmed the net-landward transport of fine suspended sediments in the Bristol Channel and Severn Estuary.



3.4 CONCLUSIONS.

Twenty-two species of Recent coccolith have been identified from the continental slope and shelf sediments of the Celtic Sea and English Channel. Coccolith abundance and species diversity decrease from west to east across the shelf of the Celtic Sea and English Channel.

Highest coccolith numbers (10^{10} per gram) occur in continental slope sediments at the western margin of the Celtic Sea. In these deep-water sediments, coccoliths account for 68 to 62% of the fine fractions and up to 82% of the carbonate fine fraction. The assemblages contain 3 dominant species; E.huxleyi (66 to 68%), G.caribbeanica (20%) and C.leptoporus (11.1 to 12.7%). This species composition is typical for coccolith assemblages found in the northeastern Atlantic. Two distinct coccolith assemblages can be delineated within sediments from the continental shelf of the Celtic Sea and English Channel:

1) outer shelf assemblages (Celtic Sea and western English Channel),

2) inner shelf assemblages (central and eastern English Channel).

Eighteen coccolith species are recorded from the outer shelf sediments of the Celtic Sea and western English Channel. Eight or more species occur in the assemblages from any one site. Abundances range from 10^8 coccoliths per gram in the central and southern Celtic Sea to 10^9 coccolith per gram in the Northern Celtic Sea. All coccolith species decline in abundance in these general directions. A characteristic feature of the assemblages in this region is their homogeneity. E.huxleyi dominates the assemblages, particularly in the open-water sites where it forms over 90 % . C.pelagicus and S.pulchra are the only other ubiquitous species in the assemblages.

These species generally form less than 5% of the assemblages. Gephyrocapsa caribbeanica occurs in most of the samples and averages 2.0% of the assemblages.

Minor species found in the assemblages (2.0 to 0.1%) include Helicosphaera carteri, Rhabdosphaera clavigera, B.bigelowii, U.sibogae, D.tubifera, Syracosphaera nodosa and Calcidiscus leptoporus. Variations in the relative abundance of these species are difficult to quantify because of their scarcity in the assemblages, though they occur in most of the samples studied. Trace amounts (<0.1%) of Umbilicosphaera hulburtiana, Syracosphaera histrica and Coronosphaera mediterranea, Scyphosphaera apsteinii and Pontosphaera discopora also occur in the assemblages.

Coccoliths are scarce (10^7 or less per gram) in the surface sediments of the inner shelf of the central and eastern English Channel. Coccoliths account for less than 1% of the fine fraction in this region. Species diversity is low in this region ranging from 4 to 6 species in the central Channel area to 3 or fewer species in the eastern Channel sediments. Coccolith abundances at the eastern margin of the Channel decline to ~ 10^5 per gram. The other twelve species recorded in the outer shelf are absent from the inner shelf coccolith assemblages.

The variations in coccolith abundance and species diversity are attributed to the hydrological factors which distinguish the Celtic Sea and western English Channel waters from those of the central English Channel.

The degree of stratification of the water column is suggested to be the most important difference between the Celtic Sea and western English Channel and the central English Channel. Water-depth, and in particular tidal currents control the degree of stratification. Stratification generally increases with depth, but is inversely related to the velocity of the tidal streams. Coccolith abundances are strongly positively correlated

with water-depth and are strongly negatively correlated with tidal stream velocities.

The stratification parameter quantifies the degree of stratification of the water column and may be calculated from

$$St = \log 10 [H/cd\ U^3]$$

where Cd is the drag coefficient (~0.0025), H= water-depth and U is the maximum tidal stream velocity. Values of the stratifaction parameter reflect the distribution of the tidal stream velocities , since they are raised to the cube power, which varies more over the region than the water-depth. High values of the St (>2) reflect stratification, while low values (<1.0) are associated with tidally mixed conditions. Coccolith abundances are positively correlated with values of the stratification parameter.

The degree of tidal influence within the water column is suggested to be the most important control on coccolith distribution in the surface sediments. In areas of low tidal currents (<2 kts), in the Celtic Sea and in the western English Channel sediments deposited beneath a pronounced thermocline contain abundant coccoliths , a flora dominated by Emiliania huxleyi, but, also containing many oceanic forms. This area corresponds to the outer shelf coccolith assemblages. In the central and eastern English Channel, where tidally mixed conditions prevail all year round, a very sparse coccolith flora is deposited. This region is subject to large tidal stream velocities (>2.0 kts) and correlates with the area of the inner shelf coccolith assemblages. Salinity has no significant control on the distribution of coccoliths in the assemblages in the Celtic Sea and western English Channel. However, in the eastern Channel greatest coccolith numbers are found associated with the high salinity tongue (>35.0 ‰), which extends down the axial region of the Channel.

The main transport paths across the shelf of the Celtic Sea and English Channel have been identified. Greatest numbers of coccoliths are transported northwards and north-eastwards within the Celtic Sea rather than eastwards into the English Channel. Coccoliths have been used to show transport directions from the shelf into adjacent estuaries and coastal embayments. Marine-derived sediments have been identified in many of the estuaries of the Celtic Sea and the English Channel. Large numbers of coccoliths are transported towards the Bristol Channel and the Severn Estuary from the northern Celtic Sea. These coccoliths are found uniformly deposited in consistent numbers throughout the sediments of the lower and middle reaches of the Severn Estuary.

Reworked coccoliths are a constant but minor component in shelf assemblages from the Celtic Sea and western English Channel. Such low values reflect the general absence of coccolith-bearing strata in the mainly Palæozoic Celtic lands that border the Celtic Sea. Larger numbers of reworked coccoliths characterise the assemblages from the inner shelf of the central and eastern English Channel. Reworked Cretaceous forms dominate the coccolith assemblages east of the Isle of Wight (generally >85%). These reworked forms are most probably supplied from marine and submarine erosion of Chalk strata which outcrops on both sides of the English Channel.

CHAPTER 4

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE IRISH SEA

CHAPTER 4

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE IRISH SEA

4.1 INTRODUCTION

4.1.1 Background and main aims.

There is no previous record of coccolithophore assemblages in either the waters or the Recent sediments of the Irish Sea. The main aim of this study is to delineate the species-composition and quantitative abundance of the coccolith assemblages in the Recent sediments. The hydrological factors which contribute to the variations of coccolith abundance in the sediments are presented. The assemblages from the Irish Sea are compared with those found in the Celtic Sea and the differences discussed.

4.1.2. Geographical area.

The Irish Sea is here defined as the sea area extending from a line joining Carnsore Point, Ireland and St. David's Head in the south to the North Channel between Larne and Corsewall Point (Bowden, 1980) (Fig.4.1). At the southern end of the Irish Sea, St. George's Channel forms a connection with the Celtic Sea. At the northern end is the North Channel, a narrow opening through which the waters of both the Irish Sea and the Firth of Clyde interconnect with the North Atlantic. The Malin Sea area, which lies to the northeast of the North Channel, is also included in this Chapter (Fig. 4.2). The Irish Sea has the form of a channel 300 km long and of widely varying width, connecting with waters of Atlantic origin at both ends. It forms a sea area of approximately 47,000 km^2 and receives fresh water run-off from a catchment area of about 43,000 km^2.

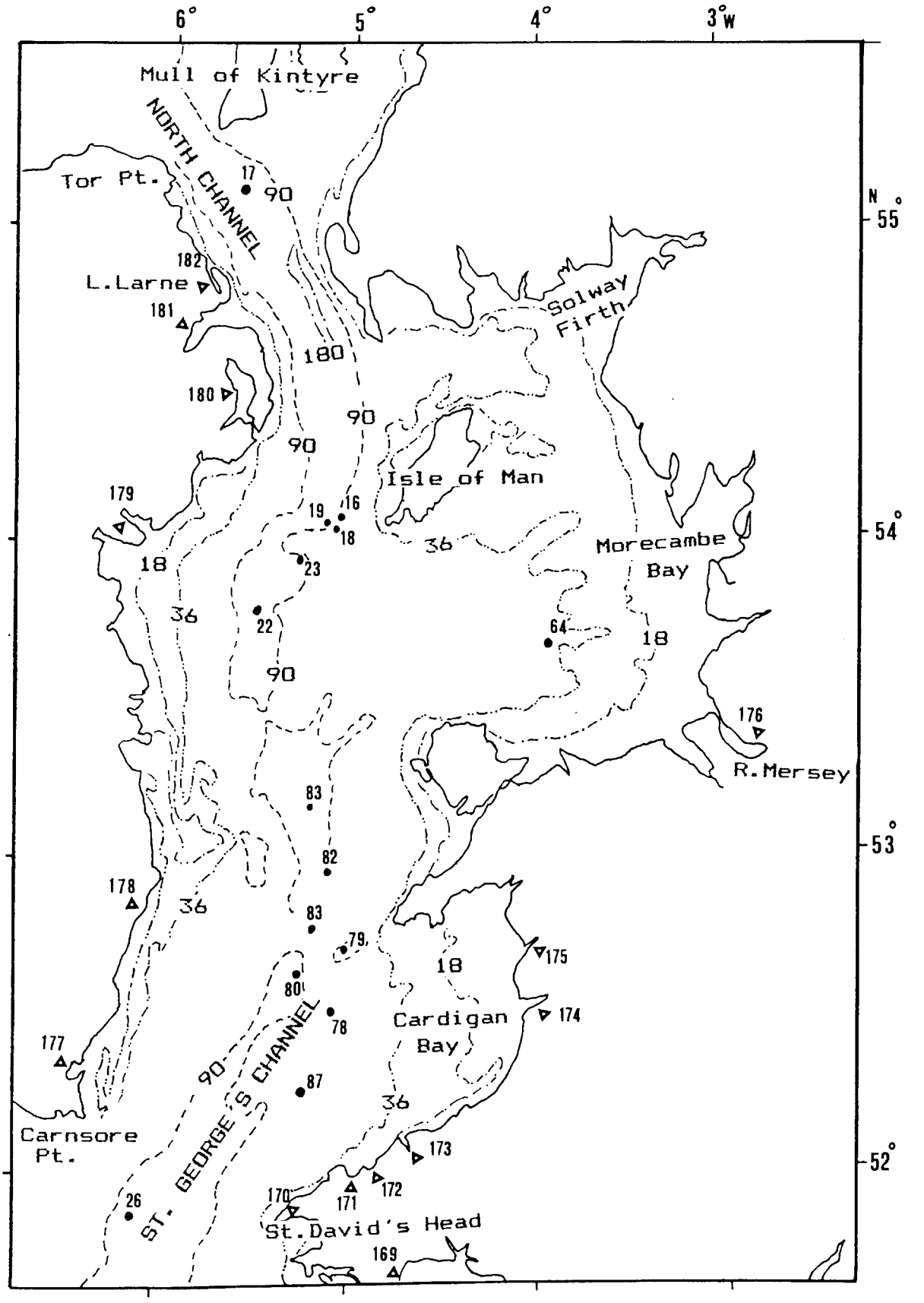


Figure 4.1.
Map of the Irish Sea showing the location of sample sites, water-depth contours (isobaths) (in metres) and the place names used in the text.

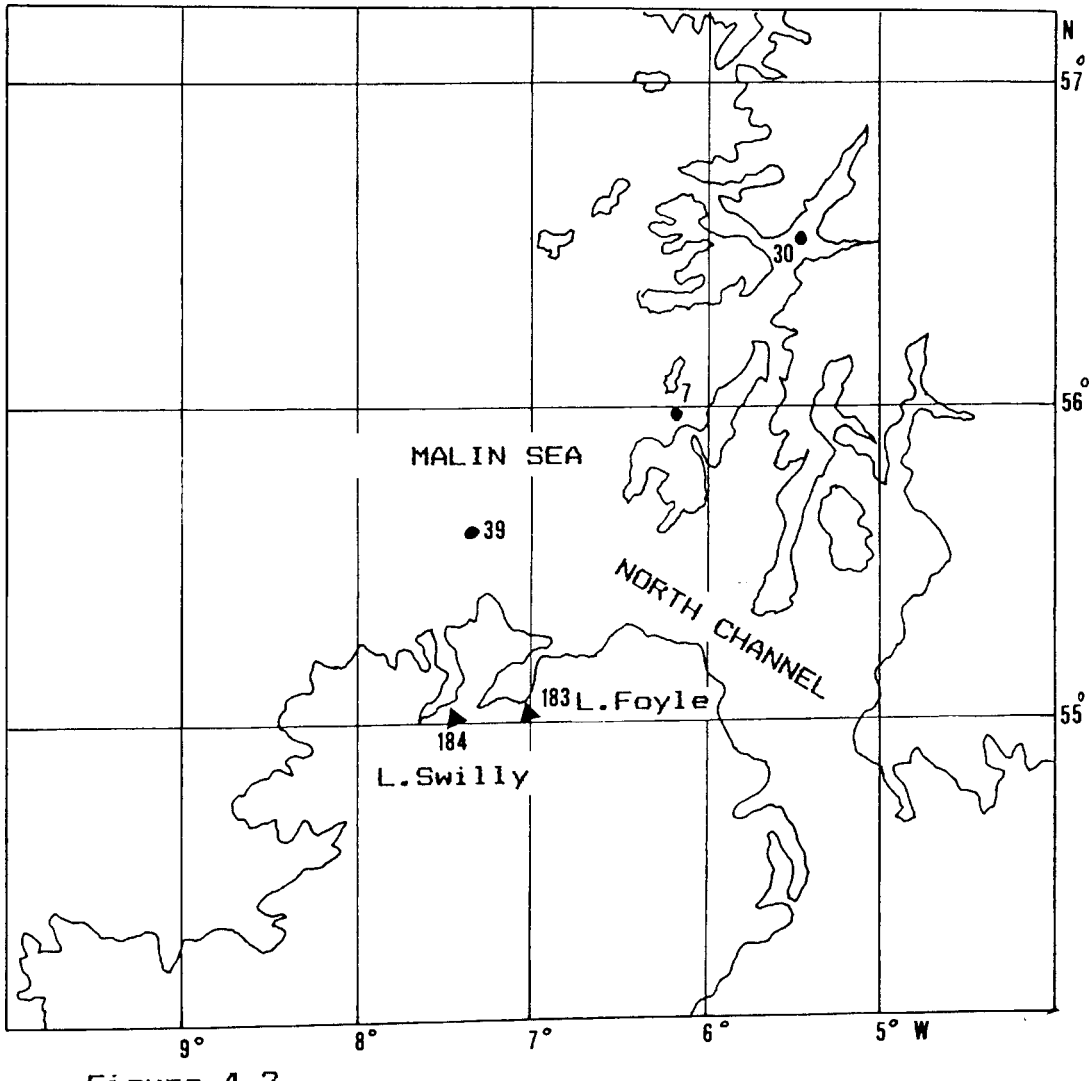


Figure 4.2
Location of sample sites in the Malin Sea area.

4.1.3. Bathymetry and topography.

The Irish Sea is comparatively shallow, with least depths between the Isle of Man and the English coast where the mean depth is only 30m. Large areas of sandbanks are exposed at low water off the northwest English coast. The most extensive of these occur in the Solway Firth, in Morecambe Bay and in the estuaries of the Ribble, Mersey and Dee. The North Channel west of Galloway at 275 m. forms the deepest part of the Irish Sea. A deep-water channel (> 80 m.) can be traced northwards through St. George's Channel, passing to the west of the Isle of Man to the North Channel.

4.1.4. Temperature distribution in the Irish Sea.

Annual mean temperatures do not vary much over the whole area. They decrease northwards from just over 11.0 °C at the southern end of the St. George's Channel to 10.0 °C in the North Channel . They also decrease towards land. Winter temperatures, represented by the February chart (Fig.4.3) decrease towards the coasts. A warm-water tongue (>7.5°C) flowing from the south may be traced up to the North Channel. Coldest areas (<5.0°C) lie along the northeast margin from Liverpool Bay to the Solway Firth. The distribution of summer temperatures is shown in the August chart (Fig.4.4). A body of cool water (<13.5°C) lies in St. George's Channel whereas temperatures in excess of 16°C occur in Cardigan Bay and along the coasts of northeast England and North Wales.

4.1.5. Salinity distribution in the Irish Sea.

The annual mean salinity in the Irish Sea decreases from south to north and from the axis of the deep-water channel to the coasts (Fig.4.5.). The salinity decreases from 34.9 ‰. at the southern end of St. George's Channel to 34.0 ‰. in the North Channel. The lowest values (32.5‰.) occur in the northeast, from Solway Firth to

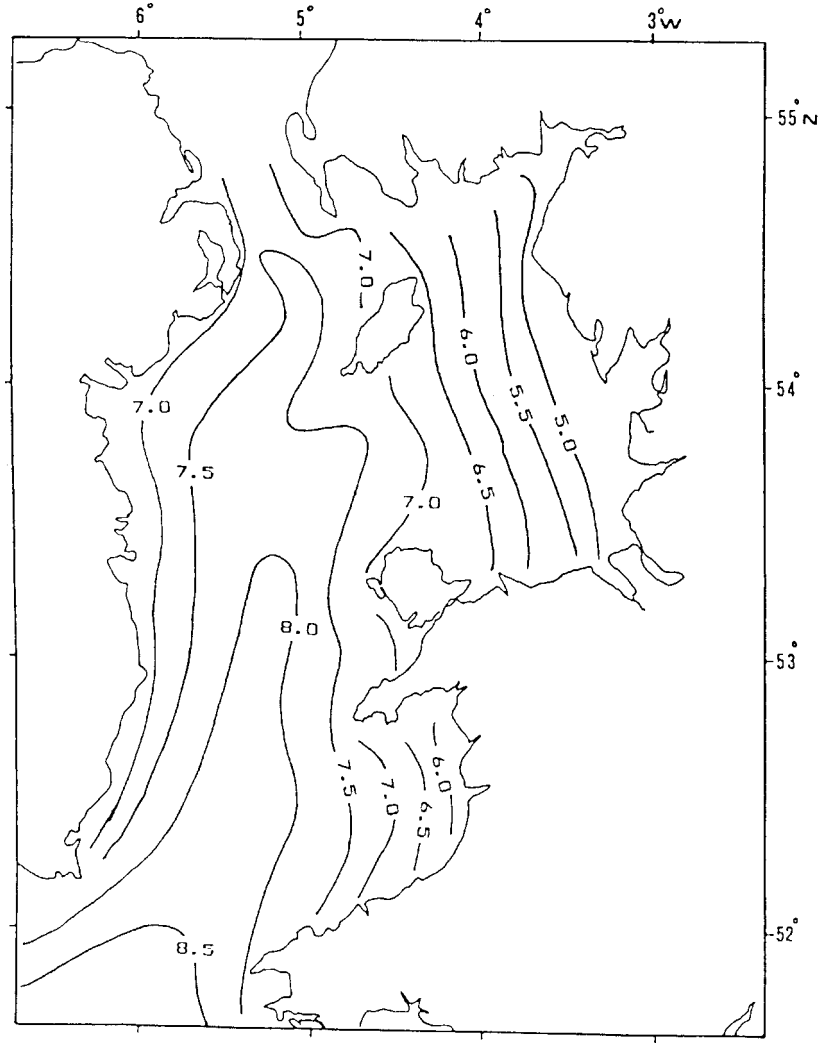


Figure 4.3.
Mean distribution of sea surface temperature (°C) for February (after Bowden, 1980).

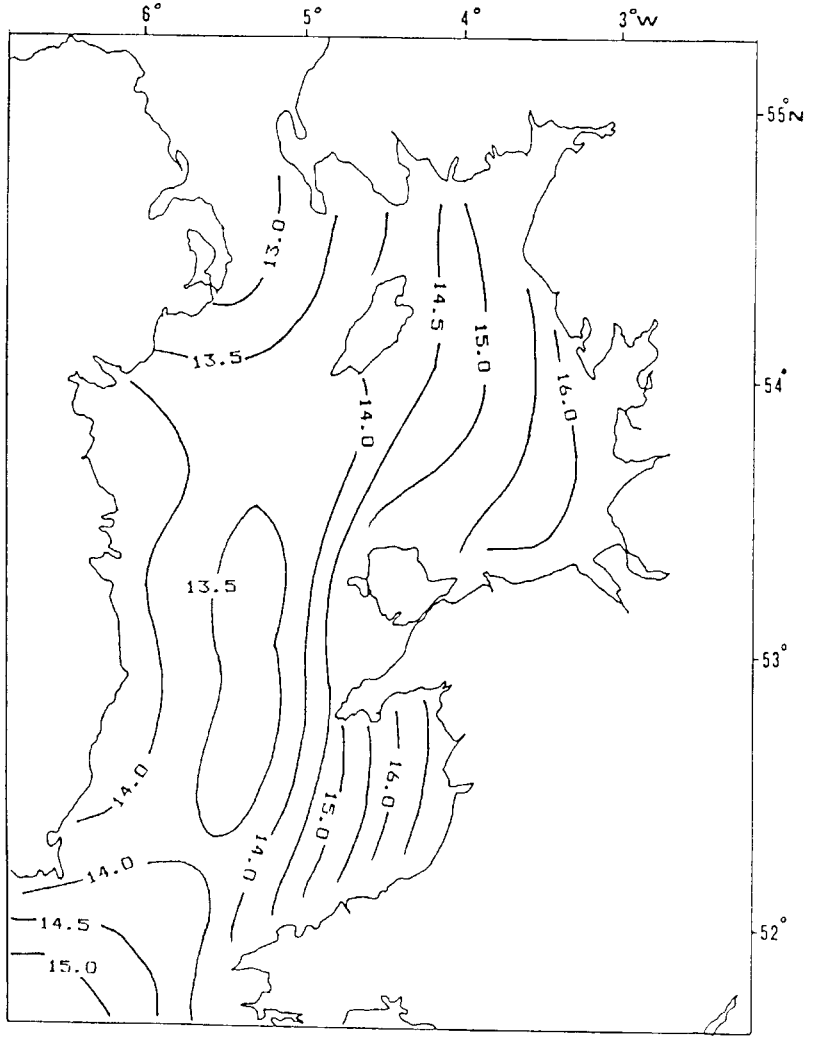


Figure 4.4.
Mean distribution of sea surface temperature (°C) for August (after Bowden, 1980)

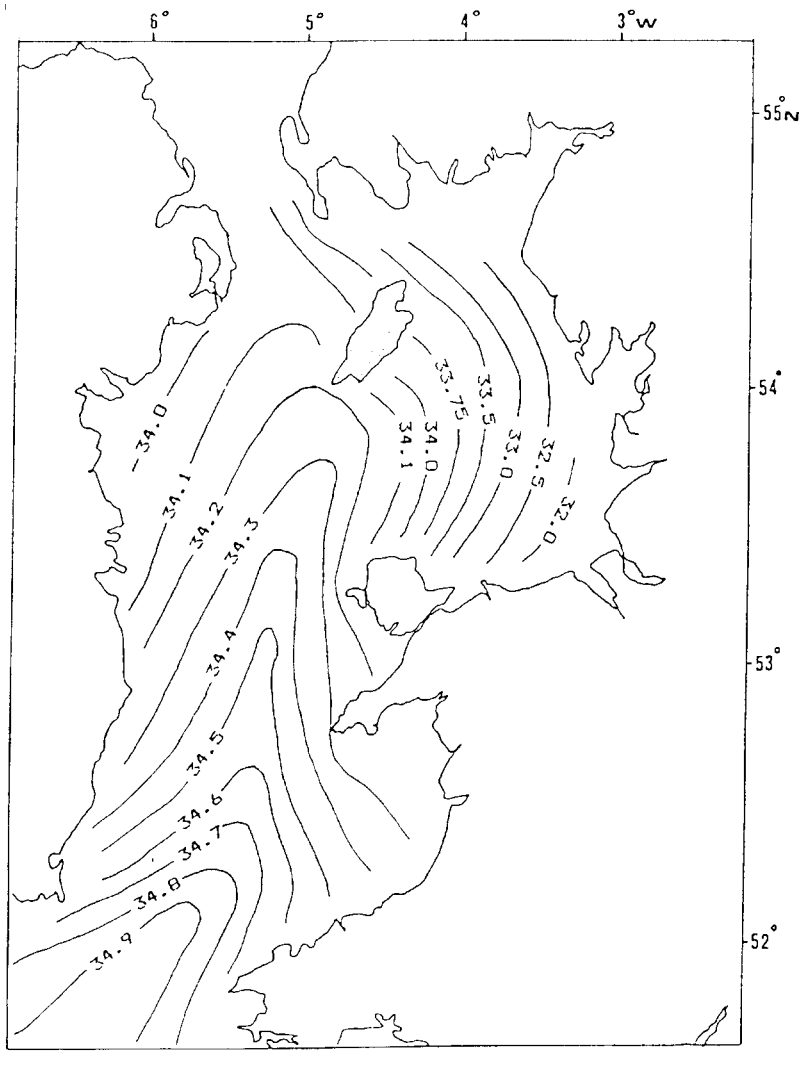


Figure 4.5.
Distribution of the annual mean sea surface salinity (‰.) (after Bowden, 1980).

Liverpool Bay. Seasonal variations of salinity are relatively small in most areas (Bowden, 1979).

4.1.6. Residual currents and circulation in the Irish Sea.

The decrease in salinity from south to north and from the centre to the coasts is a clear indication of a northward flow of Atlantic water through St. George's Channel. Bassett (1909) concluded from the shape of the isohalines and the isotherms that the main flow, after passing through St. George's Channel, turned eastwards and passed round the east of the Isle of Man. However, Ramster and Hill (1969) reported that the northerly residual currents in the deep channel to the west of the Isle of Man were significantly higher than those on the east. Additionally, Slinn (1974) recorded a core of high salinity water in the deep-water trough on the west side of the Isle of Man, indicating that a considerable part of the flow passed to the west.

Initial current-meter measurements in the North Channel (Proudman,1938) recorded a residual flow towards the south, contrary to the evidence from the salinity distribution and drift bottle experiments. Proudman concluded that this southerly flow represented a coastal current close to the Irish side, although the total net transport through the North Channel was northwards. This was later confirmed by Craig and Slinn (1957) and Craig (1959) using salinity and temperature data. They proposed a northerly flow on the east side of the North Channel, averaging 5km/day and occupying two-thirds of the total cross-section; the remaining one third of the cross-section on the west side of the North Channel having a southerly flow of about 1 km/ day.

Bowden and Hughes (1961) found a high correlation between the daily residuals of current and the wind direction over the North Channel area. During the winter months strong winds caused a northward or southward flow

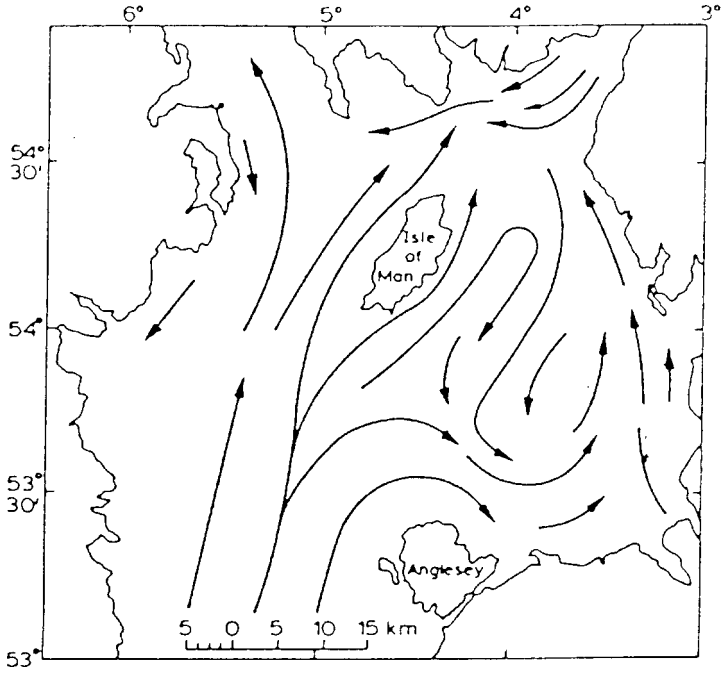


Figure 4.6.
Near-surface residual circulation in the Northern Irish Sea (after Ramster and Hill, 1969).

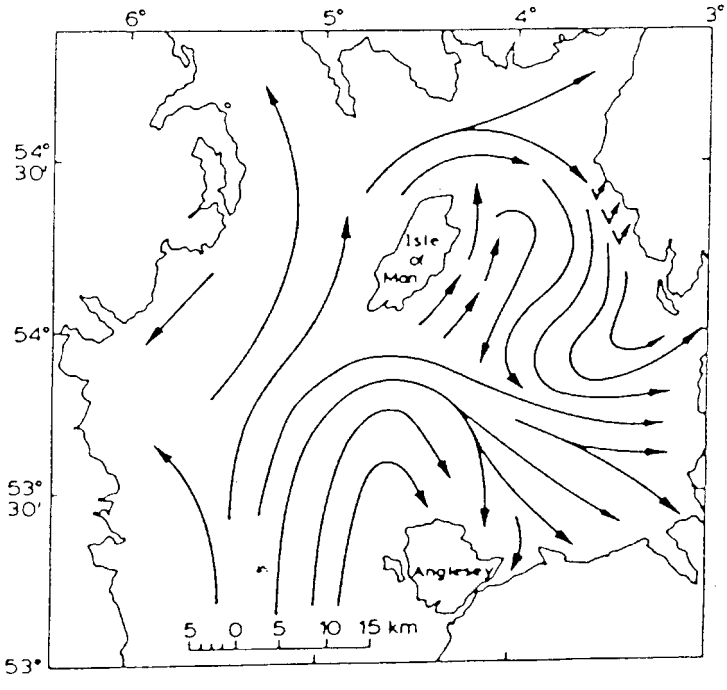


Figure 4.7.
Near-bottom residual circulation in the northern Irish Sea (after Ramster and Hill, 1969).

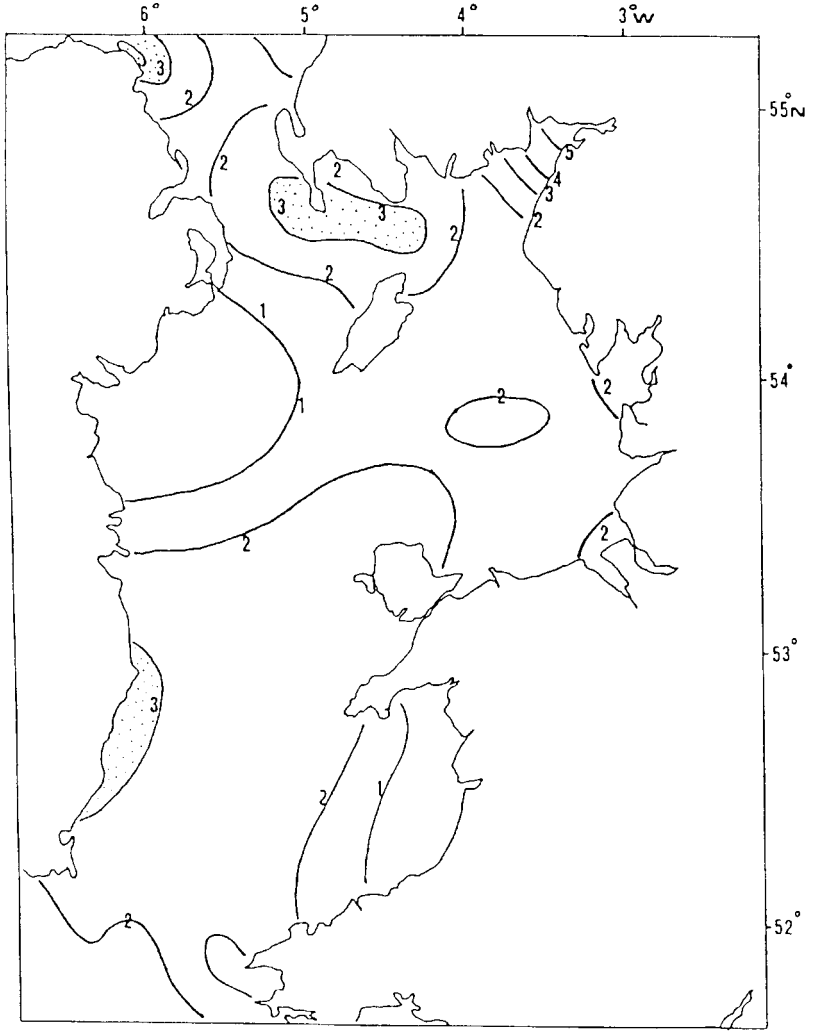


Figure 4.8.
Maximum tidal streams during mean spring tides (Knots) (after Lee and Ramster,1976).

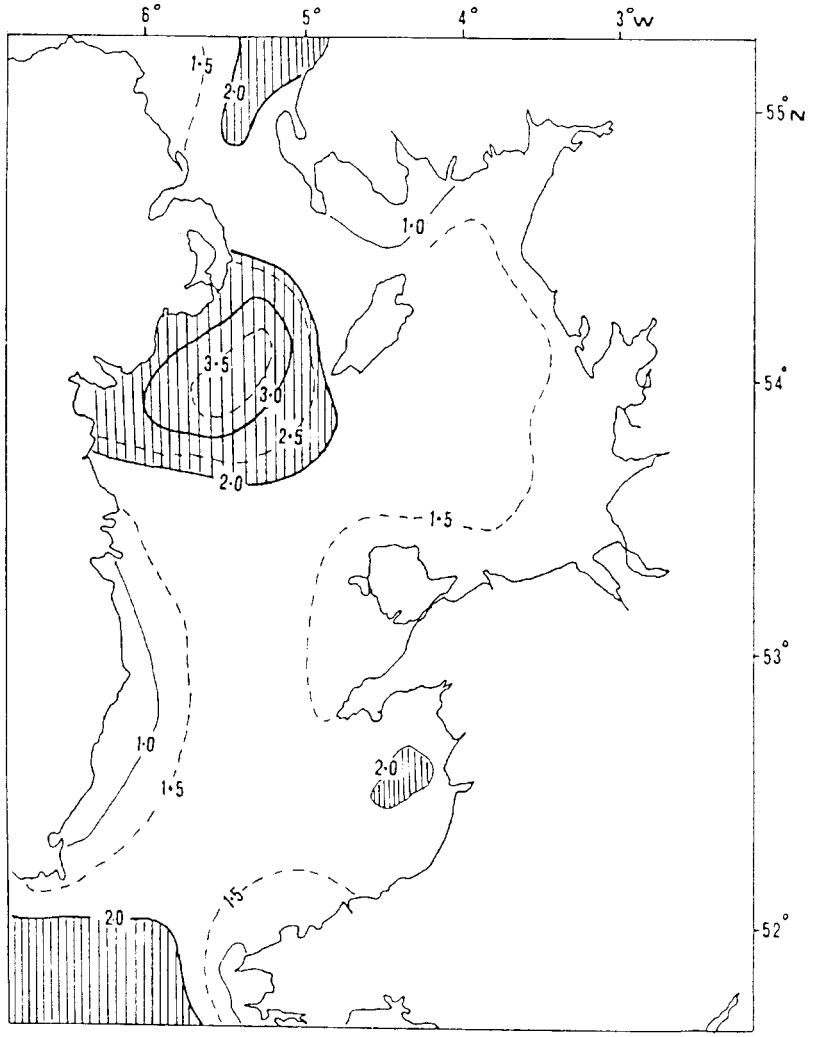


Figure 4.9.
Distribution of the stratification parameter. Contours of log 10 (H/U^3). Hatched areas correspond to areas of stratification during the summer months. (After Lee and Ramster,1976)

through the Channel as a whole. These winds produced flow velocities which, averaged over the whole section ,were approximately 1 % of the wind velocity. Ramster in 1973 reviewed all the available data describing the currents in the Irish Sea. He concluded that the circulation pattern shown in Fig.4.6, with the main northward flow to the west of the Isle of Man, is correct in its main features for the nine months of year from October to the following June. However, in the 3 summer months when the prevailing winds are south-westerly, more variable conditions may exist.

4.1.7 Tidal currents and mixing processes in the Irish Sea.

In the Irish Sea the amplitude of the tidal currents is an order of magnitude higher than the average residual current (Bowden, 1980). The highest tidal stream velocities (>4.0 knots) are found in the North Channel and near the Solway Firth (Fig.4.8.). Throughout most of the area the tidal streams exceed two knots. These high tidal stream velocities provide a supply of energy for mixing in both the horizontal and vertical directions. With the exception of a few areas, the water is well-mixed vertically throughout the year and vertical gradients of salinity and temperature are negligible (Bassett, 1907; Matthews,1912). The exceptions are a deep-water area to the southwest of the Isle of Man and an area of shallow water off the northwest coast of England (Bowden, 1980) (Fig.4.9.). Within the waters of both these areas a thermocline develops during the summer months. The waters to the southwest of the Isle of Man may have surface to bottom temperature differences exceeding 5 $^{\circ}$ C (Simpson,1971), and a difference of greater than 4 $^{\circ}$ C occurs over an area aproximately 55 km in diameter centred on 53° 45$^{\prime}$N 5°30$^{\prime}$W with a thermocline at a depth of about 20m. The south and east of this area is marked by a distinct front in which the surface temperature changes by as much as 1°C/km. The transition is more gradual to the north and the west.

4.1.8. Samples.

Sub-samples were taken from the Ocean-Bottom collection of the British Museum as described in the previous chapter. Sediments were collected from a number of estuaries along the coasts of West Wales, England and Ireland. Additional surface sediments were also supplied by the Institute of Oceanographical Science at Wormley. A list of these samples may be found in Table 4.1. Altogether 33 samples were examined :

1) 15 intertidal estuarine sediments,

2) 18 samples from the shelf of the Irish Sea and Malin Sea.

Table 4.1 Location and water depth of samples from the Irish Sea.

SAMPLE	LATITUDE	LONGITUDE	DEPTH (m)
BM 7	55° 58.1′ N	06° 05.3′ W	12
BM 16	54 03.6 N	05 02.0 W	135
BM 17	55 08.0 N	05 32.3 W	129
BM 18	54 03.8 N	05 03.6 W	-
BM 19	54 04.7 N	05 03.0 W	70
BM 22	53 48.7 N	05 27.0 W	98
BM 23	53 59.2 N	05 14.6 W	-
BM 26	51 49.6 N	06 00.7 W	112
OC 30	56 30.5 N	05 35.8 W	150
OC 39	55 36.6 N	07 28.4 W	68
BM 64	53 38.0 N	03 57.3 W	40
BM 78	52 33.4 N	05 03.2 W	77
BM 79	52 44.0 N	05 00.7 W	88
BM 80	52 40.1 N	05 13.9 W	113
BM 81	52 49.2 N	05 11.9 W	101
BM 82	52 58.7 N	05 05.3 W	96
BM 83	53 11.5 N	05 13.3 W	130
BM 87	52 17.5 N	05 14.5 W	75
ES 169	51 42 N	04 41 W	-
ES 170	51 52 N	05 11 W	-
ES 171	52 00.0 N	04 58.3 W	-
ES 172	52 11.5 N	04 50.5 W	-
ES 173	52 05.8 N	04 41.0 W	-
ES 174	52 31 N	04 02 W	-
ES 175	52 43 N	04 02 W	-
ES 176	53 19 N	02 51 W	-
ES 177	52 18 N	06 13 W	-
ES 178	52 59.0 N	06 02.0 W	-
ES 179	54 05.0 N	06 20.0 W	-
ES 180	54 32.0 N	05 41.0 W	-
ES 181	54 38.0 N	05 54.5 W	-
ES 182	55 48 N	05 40 W	-
ES 183	55 03 N	07 08 W	-

BM = British Museum sample , ES = estuarine sample.
OC = Institute of Oceanographic Science sample.

4.2 RESULTS.

Eight species of Recent coccolith occur in the surface sediments of the Irish Sea. The relative abundance and quantitative abundance of these species in the sediments are listed in Tables 4.3 and 4.2 respectively.

The maximum number of species encountered in any one sample is seven. This diversity occurs in sediments from the Malin Sea, to the southwest of the Isle of Man and at the mouth of St. George's Channel. Intermediate diversities (4 to 6 species) typify the sediments in the central and southern Irish Sea. Lowest diversities (2 to 3 species) occur in estuarine sediments from the loughs of Northern Ireland.

Recent coccoliths are present in all the sediments studied. Highest abundances occur in sediments from St. George's Channel. A distinct tongue of sediment containing > 2000 $x10^5$per gram can be traced northwards through the Channel (Fig.4.10). Another area of high coccolith numbers occurs to the southwest of the Isle of Man. Coccolith numbers decrease towards land with lowest abundances (< 10 x 10^5 coccoliths per gram) in coastal sediments of eastern Ireland and near St. David's Head. The percentage abundance of coccoliths in the fine fractions of the sediments correlates well with the distribution of the quantitative abundance of coccoliths in the sediments. Highest percentages occur in the axis of St. George's Channel and southwest of the Isle of Man (2 to 5%) (Fig.4.11). Intermediate values (1%) occur in the central Irish Sea. The lowest values occur in sediments deposited near the coasts (< 1.0 %).

The coccolith assemblages of the Irish Sea are

dominated by Emiliania huxleyi. The species is ubiquitous in the sediments. In open-water sediments it forms 78.5 to 94.0 % (mean 87.5 %) of the flora. It is less abundant in coastal sediments, comprising 67 to 77% along the eastern margin of the Irish Sea and 47 to 23 % within estuarine sediments from Ireland. The quantitative abundance of the species in the sediments closely follows the distribution of the total abundance of Recent coccoliths (see Figs. 4.10 and 4.12). Coccospheres of Emiliania huxleyi are recorded only from sample 26 at the mouth of St. George's Channel.

S.E.M. analysis of the coccoliths of Emiliania huxleyi from assemblages deposited in the southern Irish Sea and to the southwest of the Isle of Man failed to record any warm-water ecophenotypes . Most specimens had a solid proximal shield with the central opening closed. Very scarce forms with a partially fused central opening were also recorded.

Coccolithus pelagicus is the only other ubiquitous species in the assemblages (Figs. 4.13 and 4.14). The quantitative abundance of this species also follows the distribution of the total abundance of coccoliths in the sediments. Greatest numbers of this species occur in St George's Channel (> 200 $\times 10^5$ coccoliths per gram). Similar abundances occur in sediments deposited in the area between the Isle of Man and the Irish coast. Intermediate values of C. pelagicus typify sediments from the central Irish Sea (< 100 $\times 10^5$ coccoliths per gram). Lowest abundances occur in the estuarine sediments from Cardigan Bay and the coast of eastern Ireland.

The relative abundance of C.pelagicus in coccolith assemblages from open-water sediments in the Irish Sea is is generally constant (between 3.5 and 9.5 %) . Higher abundances occur in the coastal sediments , for example 18.5 to 29.0 % along the eastern coasts, and 41.0 to 77.0 % in estuarine deposits from eastern Ireland. Lowest values occur in the North Channel (2.0 %) and in the

sediments of the Malin Sea (< 0.3 %).

Syracosphaera pulchra occurs in sediments from the southern and northern entrances of the Irish Sea but is absent in the central area (Fig.4.15). In the north the species occurs in the Malin Sea , the North Channel and to the southwest of the Isle of Man. In the south the species is found in St. George's Channel and northwards to latitude 53° N. Abundances of the species reach 10^7 coccoliths per gram at the mouth of St. George's Channel, and between the Isle of Man and the Irish coast. They decline to 10^5 to 10^6 per gram in the North Channel and along the coasts of the southern Irish Sea. The relative abundance of the species ranges from low values in the marginal sediments (1.0%) to high values in St. George's Channel (6.5%) The species is absent from northeast Cardigan Bay and the central and northeastern Irish Sea sediments.

Gephyrocapsa caribbeanica is found mainly in sediments from the deep-water channel in the Irish Sea. It is absent from Cardigan Bay and estuarine sediments from the northeastern margin. Its relative abundance in the Irish and Malin seas ranges from 0.3 % to 5.0 %, but no systematic variation of abundance is observed.

Minor species found in the sediments (3.0 to 0.3%) include Calcidiscus leptoporus, Braarudosphaera bigelowii, Rhabdosphaera clavigera and Helicosphaera carteri. Calcidiscus leptoporus is absent from sediments in the central Irish Sea and to the east of the Isle of Man. At the southern margin of the Irish Sea this species is limited to St. George's Channel and an isolated occurrence in sediments from the Barmouth Estuary. In the north the species occurs in the Malin Sea , the North Channel and to the southwest of the Isle of Man.

Helicosphaera carteri has a widespread occurrence in sediments from the eastern Irish Sea. It is consistently found in Cardigan Bay and also occurs in Liverpool Bay.

Maximum abundance of the species occurs in the northeastern Irish Sea (3 %). Helicosphaera carteri also occurs in the Malin Sea and to the southwest of the Isle of Man, but has not been recorded in coastal sediments from eastern Ireland. Braarudosphaera bigelowii is a consistent but small component (mean 0.5 %) of the coccolith assemblages in the sediments of the Irish Sea and Malin Sea. It is only absent from estuarine sediments of eastern Ireland. Generally, only isolated pentaliths are found in the sediments, but from sample 23, southwest of the Isle of Man, a collapsed coccosphere of the species was found.

Rhabdosphaera clavigera is absent from the greater part of the Irish Sea. Its maximum abundance occurs between the Isle of Man and the Irish coast (0.5 %). The species has a sporadic occurrence in sediments from the southern Irish Sea .

Reworked coccoliths form a consistently small component of the total coccolith assemblage in the open-water sediments of the Irish and Malin seas (0.5 to 3.0%). Highest abundances of the reworked forms occur in Welsh estuaries (10.0 to 22.0 %). Intermediate abundances occur in the estuaries and loughs of eastern Ireland. The reworked forms are Cretaceous in age and are dominated by the species Watznaueria barnesae.

Carbonate values in the fine fractions of the sediments follow a broadly similar distribution to the coccolith abundances . Highest values (> 25 %) occur in St. George's Channel. In the deep water channel to the west of the Isle of Man they average 17 % . Lowest values occur in marginal sediments (3 to 16 %). The coccolith-carbonate component of the total carbonate in the fine fractions also shows distinct changes. Highest values of the percent coccolith-carbonate occur in sediments to the southwest of the Isle of Man (> 25 %) . High values also occur in St. George's Channel (15 to 19%). Lower values of between 3 and 4 % typify the

sediments from the central and eastern Irish Sea.

Table 4.2 Quantitative abundance of coccoliths and carbonate in the fine fractions (2- 20 μm) from the Irish Sea sediments.

Sample	Number of *E.huxleyi* 5 (x10 /g)	Number of C.pelag. 5 (x10 /g)	Number of *S.pulchra* 5 (x10 /g)	Total Number 5 (x10 /g)	(%) coccoliths of fine fraction	Wt.% CaCO
7	500	44	20	600	0.5	
16	690	40	20	800	0.5	16
17	3100	66	80	3300	1.0	16
18	1400	110	70	1600	2.0	18
19	2800	248	30	3300	2.0	17
22	3000	204	220	3700	3.0	17
23	2900	192	160	3400	5.0	20
26	5300	387	430	6500	4.0	36
64	250	60	-	310	0.5	39
78	6400	242	170	6900	4.0	21
80	2900	242	60	3200	4.0	26
81	2200	204	-	2500	1.0	26
82	1200	120	-	1400	1.0	25
83	1700	160	-	1800	1.0	24
87	1000	50	20	1100	1.0	13
169	2	34	-	40	<0.1	NR
170	1	1	<1	2	<0.1	NR
171	-	-	-	-	-	3
172	ND	ND	ND	ND	<0.1	ND
173	280	110	15	420	0.5	11
174	60	18	-	80	<0.1	11
175	110	38	-	150	0.25	15
176	100	25	1	130	0.25	13
177	23	23	-	46	<0.1	8
178	70	56	2	140	0.25	16
179	1	4	-	5	<0.1	8
180	<1	<1	<1	<1	<0.1	ND
181	ND	ND	-	ND	ND	ND
182	ND	ND	-	ND	ND	ND

ND = not determined, C. pelag. = *C. pelagicus*.

Table 4.3
Percentage abundance and species-composition of coccolith assemblages from the Irish Sea sediments.

Sample	% E.hx	% C.pl	% Sy.p	% H.ct	% C.lp	% G.cr	% B.bg	% Rh.c	Total number counted	% Rew.
7	83.7	7.3	3.0	-	1.0	5.0	-	-	300	1.5
16	86.7	5.0	2.7	0.3	0.3	5.0	-	-	300	1.0
17	92.7	2.0	2.3	-	0.3	2.7	-	-	300	1.0
18	83.7	6.7	4.3	-	-	4.7	-	-	300	1.0
19	87.0	7.7	1.0	0.3	0.3	3.3	-	0.3	300	1.0
22	83.7	5.7	6.0	-	-	4.0	0.3	0.3	300	0.3
23	85.7	5.7	4.7	0.3	0.3	3.0	0.3	-	300	1.7
26	82.0	6.0	6.7	0.3	0.3	4.0	0.7	-	350	0.5
30	92.0	8.0	-	-	-	-	-	-	200	-
39	96.0	0.3	2.0	0.3	1.0	0.3	-	-	300	3.0
64	77.0	19.0	-	3.0	-	-	1.0	-	200	11.0
78	92.5	3.5	2.5	0.5	-	-	1.0	-	200	2.5
79	94.0	3.0	2.0	-	-	-	1.0	-	200	4.0
80	88.5	7.5	2.0	0.5	-	0.5	1.0	-	200	1.0
81	88.5	8.0	-	2.0	-	0.5	0.5	0.5	200	2.0
82	88.5	8.5	-	-	-	1.5	0.5	0.5	200	1.5
83	89.5	9.5	-	-	-	0.5	0.5	-	200	1.5
87	91.0	4.7	2.0	-	-	0.7	1.7	-	200	2.0
169	4.0	87.0	-	2.0	1.0	-	5.0		200	7.0
170	52.0	45.0	2.0	1.0	-	-	-	-	100	4.0
171	-	-	-	-	-	-	-	-	-	-
172	67.0	29.0	2.0	1.0	-	-	1.0	-	200	10.0
173	67.0	26.0	4.0	2.5	-	-	0.5	-	200	22.0
174	77.0	22.0	-	1.0	-	-	-	-	100	11.0
175	72.0	25.5	-	1.0	1.0	-	0.5	-	200	18.0
176	77.0	18.5	1.0	1.5	-	2.5	0.5	-	200	2.5
177	47.0	55.0	-	-	2.0	1.0	-	-	150	3.0
178	55.0	41.0	2.0	-	-	2.0	-	-	200	4.0
179	23.0	77.0	-	-	-	-	-	-	150	1.0
180	P*	P*	-	-	-	-	-	-	-	-
181	P*	P*	-	-	-	-	-	-	-	-
182	90.0	10.0	-	-	-	-	-	-	50	-
183	84.0	5.0	3.0	2.0	3.0	2.0	1.0	-	200	0.5
184	89.0	1.0	4.0	-	-	-	-	-	200	1.0

E.hx = *E.huxleyi*, C.pl = *C.pelagicus*, Sy.p = *S. pulchra*, H.ct = *H. carteri*
C.lp = *C.leptoporus*, G.cr = *G.caribbeanica*, B.bg = *B. bigelowii*, Rh.c = *R.clavigera*. P* = species present but relative abundance not determined.
% rew. = % reworked coccoliths in total assemblage.

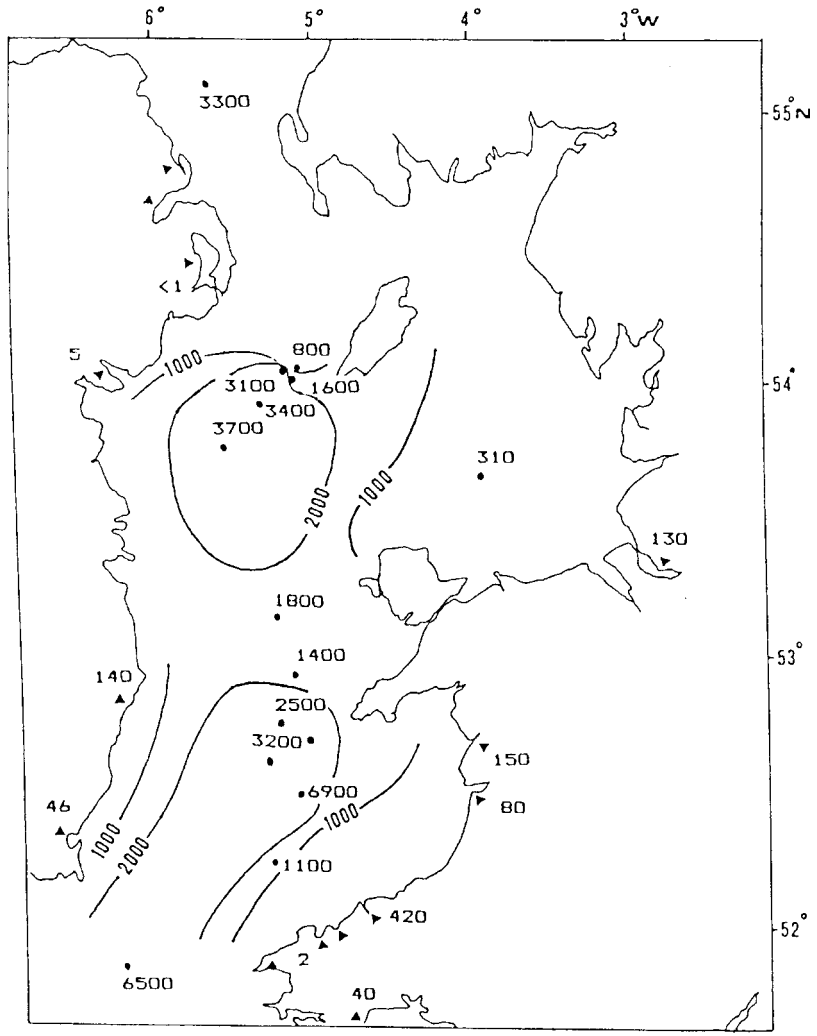


Figure 4.10.
Abundance of Recent coccoliths (x 10^5) per gram of fine-grained silt (2-20μm) in the surface sediments.

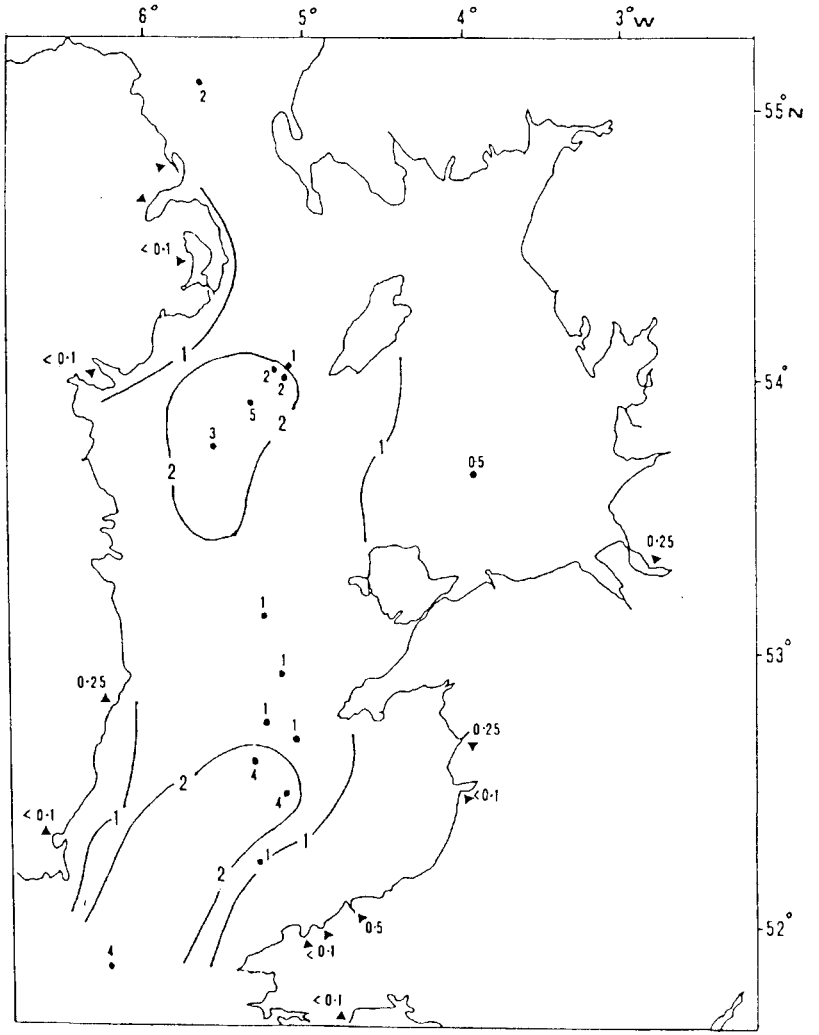


Figure 4.11.
% coccoliths of the fine fractions (2-20μm) in the surface sediments.

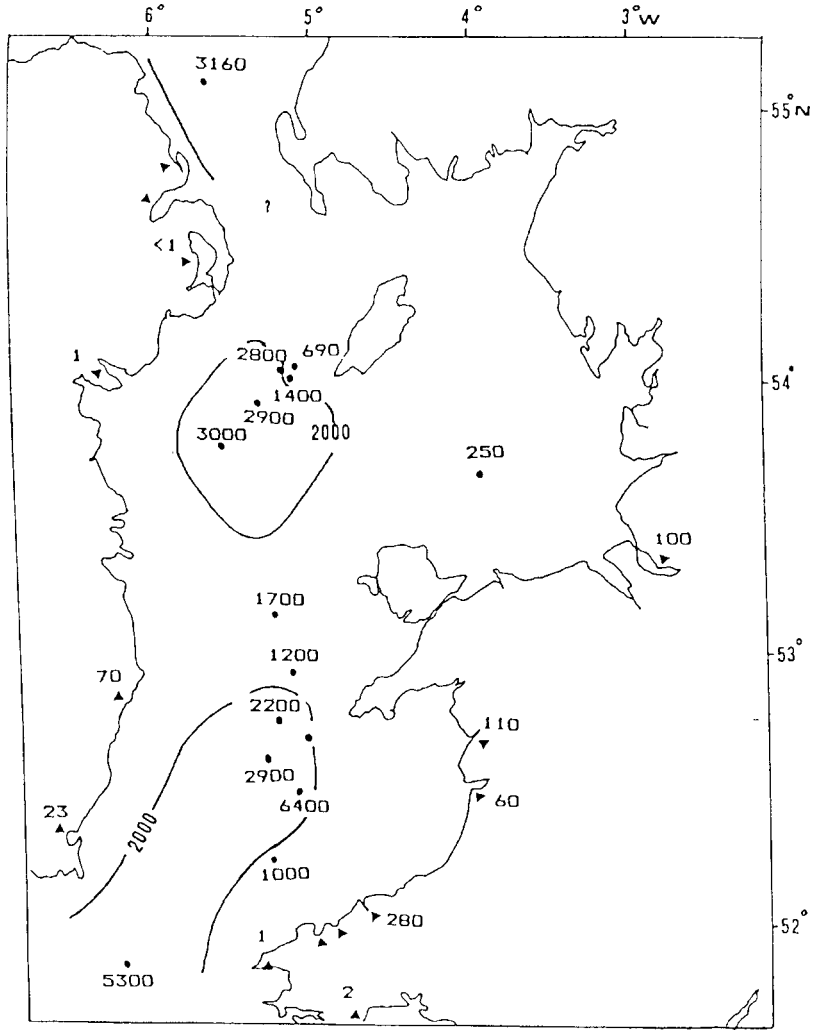


Figure 4.12
Abundance of Emiliania huxleyi (x 10^5) per gram of fine-grained silt (2-20μm) in the surface sediments.

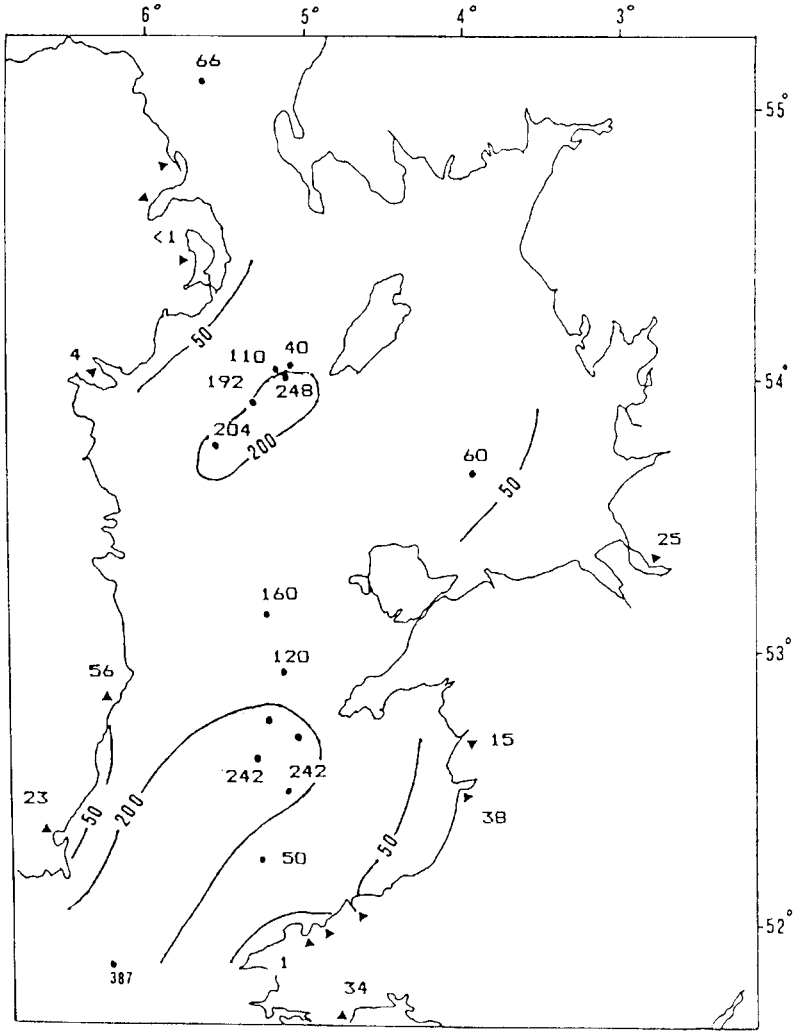


Figure 4.13.
Abundance of Coccolithus pelagicus (x 10^5) per gram of fine-grained silt (2-20μm) in the surface sediments.

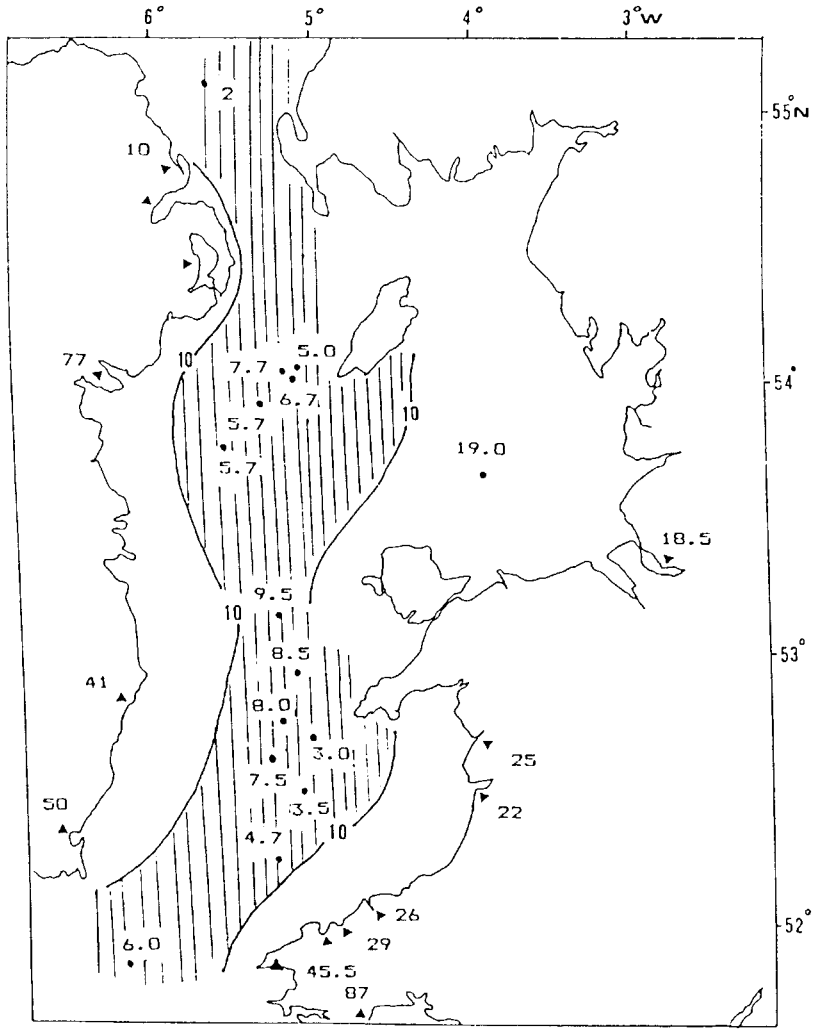


Figure 4.14.
% of Coccolithus pelagicus in the coccolith assemblages from the surface sediments.

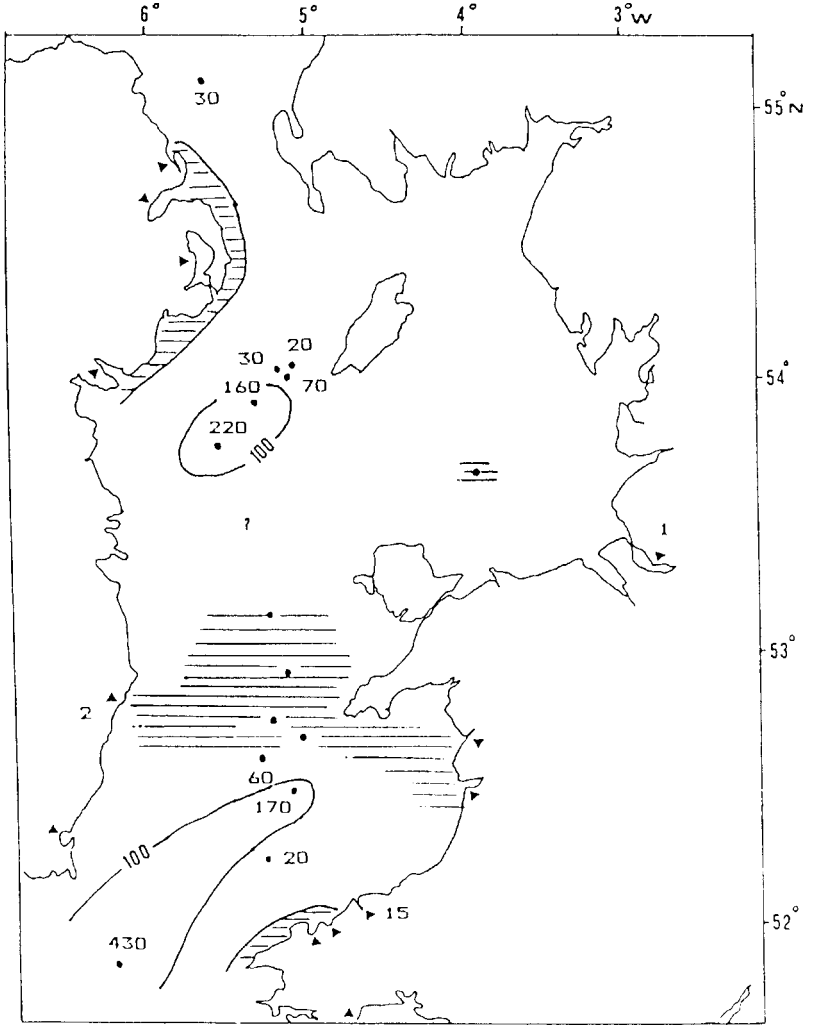


Figure 4.15.
Abundance of Syracosphaera pulchra (x 10^5) per gram of fine-grained silt (2-20μm) in the surface sediments. Hatched areas -species not recorded.

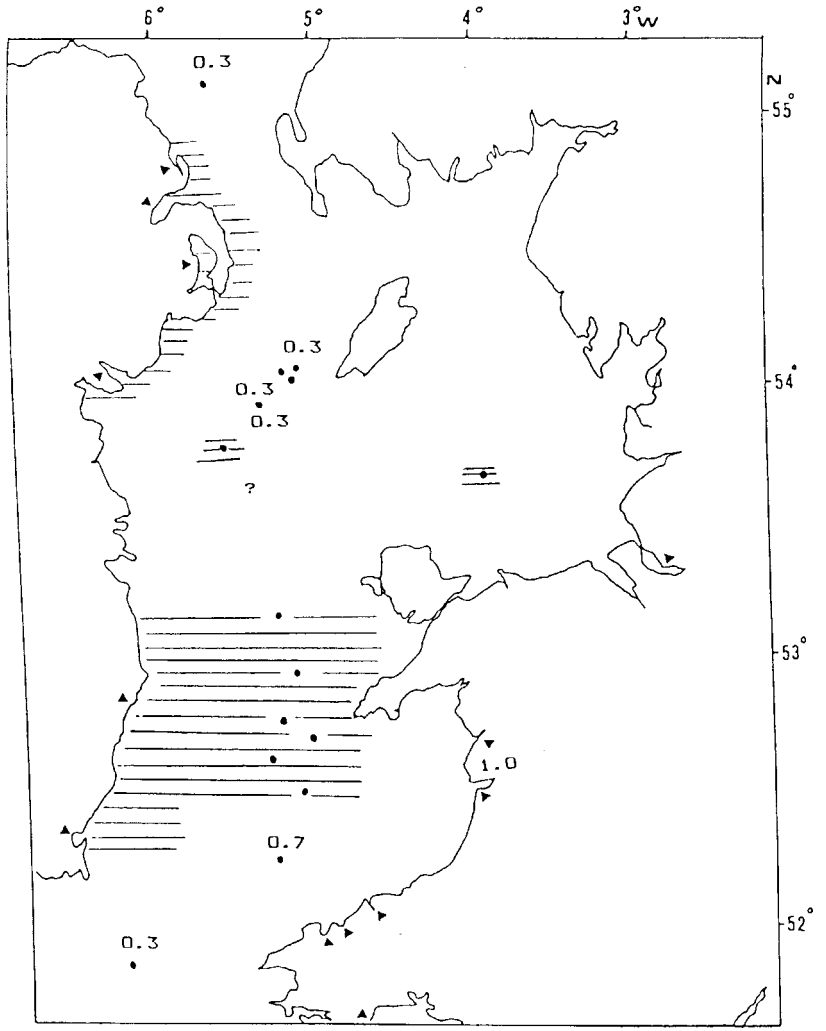


Figure 4.16
Distribution of Calcidiscus leptoporus in the surface sediments. Numbers refer to percentage abundance of the species in the assemblages. Hatched areas- species not recorded.

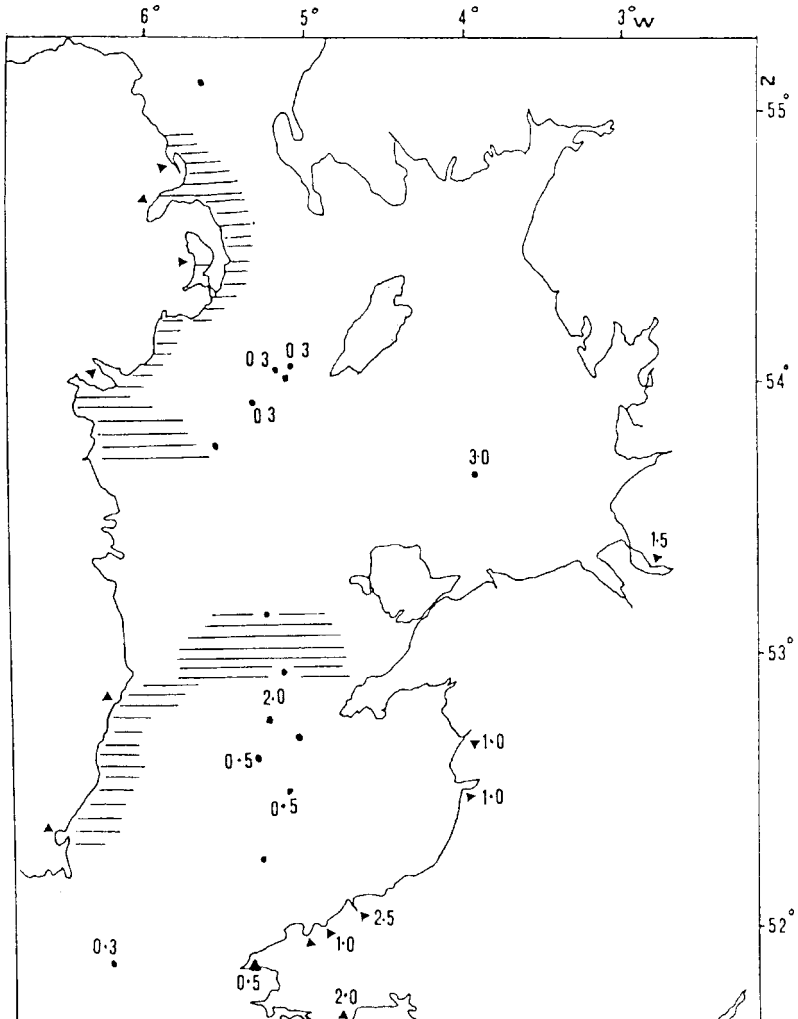


Figure 4.17
Distribution of Helicosphaera carteri in the surface sediments. Number refer to percentage abundance of the species in the assemblages.

4.3. DISCUSSION.

4.3.1 A comparison of the Irish Sea and Celtic Sea coccolith assemblages.

The coccolith assemblages found in the Recent sediments of the Irish Sea are similar to those in the Celtic Sea in the following respects:

1) Emiliania huxleyi is dominant.

2) Coccolithus pelagicus is the next-most abundant species.

3) The above species are ubiquitous in the assemblages

4) Both sea areas have a similar minor species component (2.0 to 0.5 %).

The relative abundance of E.huxleyi remains fairly consistent in the open-water sediments of the Irish Sea (range 78.5 to 92.5 % , mean 87.5 %) and the Celtic Sea (82.5 to 97.5 % , mean 91.5 %). However, maximum numbers of the species together with total numbers of coccoliths reach only 10^8 coccoliths per gram in the Irish Sea, whereas throughout much of the Celtic Sea abundances reach 10^9coccoliths per gram; therefore maximum abundances are an order of magnitude lower in the Irish Sea.

The quantitative abundance of Coccolithus pelagicus varies less between the two sea areas. However, C.pelagicus generally forms a larger percentage of the nannoflora in the Irish Sea (5 to 10%), whereas it forms only 0.5 % to 5.0 % of the nannoflora in the Celtic Sea. Open-water sediments from the Malin Sea have similar C. pelagicus values to those of the Celtic Sea (< 0.5 % of the total flora). The minor species component of the

assemblages, particularly in the southern Irish Sea and to the southwest of the Isle of Man, is similar to that of the Celtic Sea. Helicosphaera carteri, Rhabdosphaera clavigera , Braarudosphaera bigelowii and Calcidiscus leptoporus all occur as similar percentages of the total nannoflora in both Celtic Sea and Irish Sea assemblages. However, their distribution in the latter tends to be more sporadic.

The most notable difference between the Celtic Sea and Irish Sea assemblages is a sudden decrease in the number of species. Altogether 20 species of coccolith were recorded in the Celtic Sea assemblages, with eight or more species consistently found in the shelf area including many pelagic forms. Only eight species of coccolith have been recorded in the Irish Sea and all those 'more-pelagic' species listed as scarce in the Celtic Sea are absent in the Irish sea. In fact from the number of species present and the absence of the scarcer species, Irish Sea asemblages correlate well with the coccolith assemblages found in the central English Channel.

4.3.2 Nannofossil assemblages and hydrological conditions in the Irish Sea

The waters of the Irish Sea are more neritic in character than those of the adjacent Celtic Sea and Malin Sea. This characteristic is reflected in the increased tidal currents and a general reduction in salinity. The annual mean salinity in the Irish Sea is below that of normal marine waters (< 35.0 ‰) (see Fig 4.5). Highest salinities occur at the mouth of St. George's Channel (34.9 ‰) with lowest values in the northeastern Irish Sea (< 32.0 ‰). The main change in the character of the waters between the Celtic Sea and the Irish Sea is the degree of tidal mixing. North of a line joining Carnsore Point and St. David's Head strong tidal currents ensure that the water column remains vertically mixed throughout the year. South of this line is a zone of transition

between a region of strong stratification in the summer with almost stagnant, cold bottom-water , and a region where turbulence achieves some degree of mixing. This line , therefore , separates waters with a pronounced thermocline development in the Celtic Sea from those of the southern Irish Sea where no stratification occurs.

The neritic character of the waters of the southern Irish Sea increases from south to north along with the amplitude of the surface tidal streams. The sudden decrease in the number of species in the assemblages occurs at the transition from the stratified waters of the Celtic Sea to the tidally mixed waters of the Irish Sea. At this point half the species are lost; these include many of the typically oceanic forms such as Umbilicosphaera sibogae, Umbilicosphaera hulburtiana , Discosphaera tubifera and Scyphosphaera apsteinii.

Abundance of coccoliths in the Irish Sea decreases from south to north reflecting the increasing neritic character of the waters. However an isolated area of high coccolith numbers occurs in sediments just to the southwest of the Isle of Man. These assemblages also have a more pelagic character and contain the species Calcidiscus leptoporus and Rhabdosphaera clavigera. This area of high coccolith numbers corresponds to a region of weak tidal currents. In these deep waters a pronounced thermocline occurs at a depth of about 20m. The increased abundance of coccoliths in the sediment is a reflection of the more stable stratified water column, which may be likened to the Celtic Sea waters.

An explanation for the absence of the other species present in the Celtic Sea assemblages but absent in the coccolith assemblages to the southwest of the Isle of Man is that the strong tidal mixing environment of St. George's Channel may act as an ecological filter barrier . The pelagic species and deep water taxa not adapted to the strong tidal currents in St. George's Channel would be

unable to survive in the water column. Similar strong currents also exist in the North Channel, therefore the pelagic forms may also be prevented from entering the Irish Sea from the north. Winter et al. (1979) also proposed the occurrence of an ecological filter barrier to explain the absence of deep-water coccolith species in the deep waters of the Gulf of Elat. The absence of Florisphaera profunda Okada and McIntyre, a common deep-water species in similar latitudes , was attributed to the higher salinity of the Gulf (41%) as compared to the open-ocean. It appears that the higher salinity in the Gulf acts as an ecological filter barrier. Hence stenohaline pelagic species and deep-water taxa not adapted to the osmotic pressure conditions in the Gulf would be prevented from living there.

It is possible that the decrease in salinity of the waters of the Irish Sea also provide an unfavourable environment for many of the pelagic species. However, there is only a gradual decrease in salinity in the waters of the southern Irish Sea rather than a dramatic change . The water in St. Georges Channel has a salinity of 34.9 %. , only 0.1 %. below that of normal marine waters. It seems unlikely that a drop of about 0.1 %. could remove all the stenohaline pelagic species.

Figure 3.18 shows the variation of coccolith numbers plotted against surface salinity along a traverse from St, George's Channel to the North Channel, along the axial region of the Irish Sea. Although salinity decreases from 34.9 %. in St. George's Channel to 34.0%> in the North Channel coccolith abundances do not show the same trend. In fact, after an initial decline , they increase again at lower salinities (~34.2%.) in the region southwest of the Isle of Man. These increased coccolith numbers correspond to the area of weak tidal currents.

Tidal mixing of the waters is therefore suggested to have a more pronounced control than salinity distribution on the coccolith assemblages in the Irish Sea sediments..

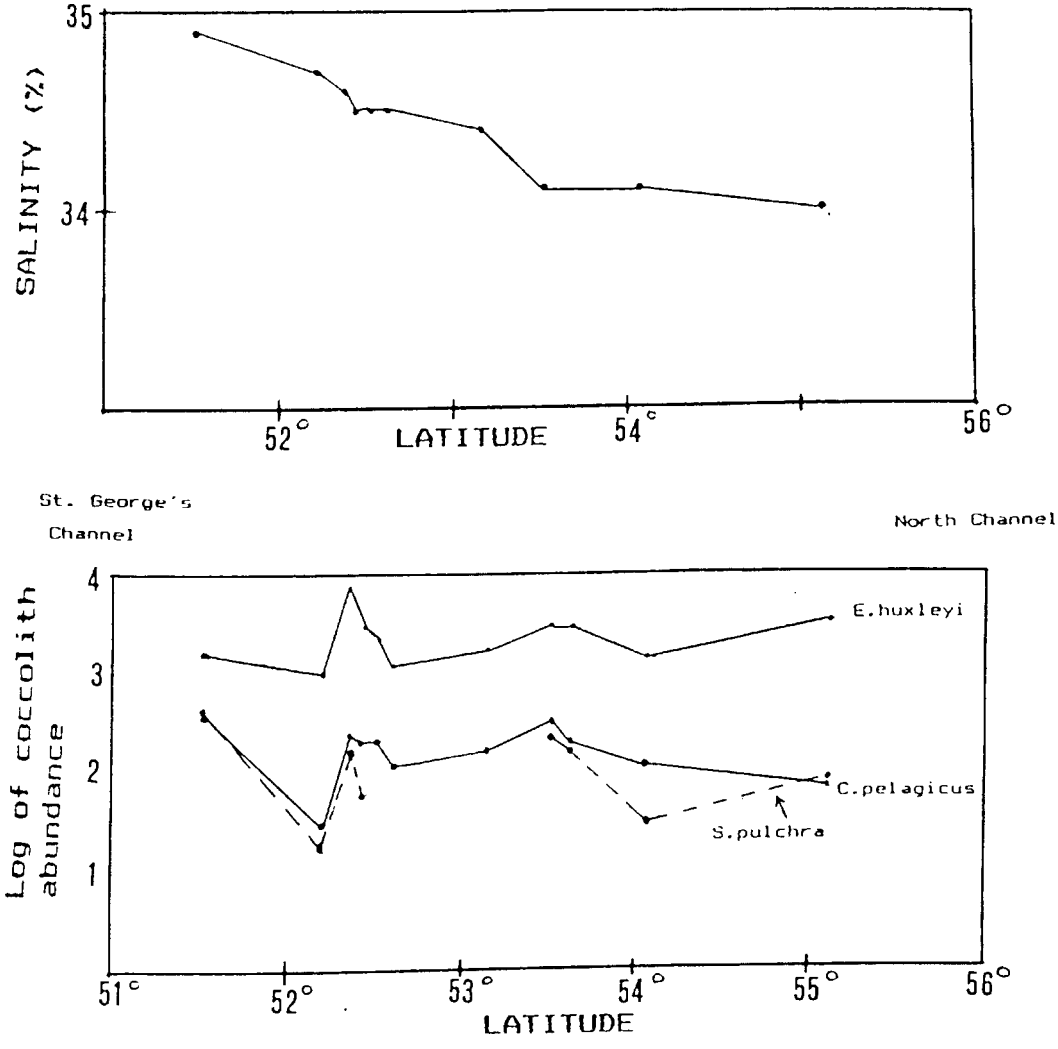


Figure 4.18
Variations of mean surface salinity (%.) and coccolith abundance, from a north - south traverse along the central region of the Irish Sea. Salinity values extracted from Fig.4.5.

It is interesting to note that in the central English Channel where the waters are of normal marine salinity (>35.0 ‰.) but where similar tidally mixed conditions occur, similar numbers of species (4 to 6) are present in the assemblages.

The deep-water areas along the axis of the Irish Sea remain relatively cool in the summer, reaching a maximum of only 13.5°C in August. These temperatures would favour the secretion of the cold-water type of structure of Emiliania huxleyi and explains the absence of the warm-water ecophenotype in the Recent sediments of the Irish Sea.

4.3.3. Relationship of the coccolith assemblages to the the residual currents in the Irish Sea.

The Irish Sea is connected with waters of Atlantic origin at both its ends, via St. George's Channel and the North Channel. Two possible pathways therefore exist for the transport of the coccolith species into the Irish Sea.

The most obvious path for coccolith transport is from the south via St.George's Channel. The species would travel within the northward flow of Atlantic water from the Celtic Sea into the southern Irish Sea. Strong evidence for this is given in St. George's Channel by the decreasing gradient from north to south in St. George's Channel of the following parameters :

1) The number of species in the assemblages.
2) Numbers of coccoliths per gram of sediment.
3) % coccolith component in the fine fractions.

All the coccolith species found in the Irish Sea sediments also occur in the Celtic Sea area. Therefore a potential source of the coccolith species occurs just to the south of the Irish Sea. Coccolith numbers are greatest in the axis of St. George's Channel and decrease

towards the margins . This correlates well with the main inflow of water to the southern Irish Sea. A northerly flow of plankton species through the Irish Sea was also proposed by Williamson (1952, 1956a) from periodic surveys of the plankton extending over several years .

Coccolith abundances continue to decline northwards in the Irish Sea as far as an isolated area of high abundances just to the southwest of the Isle of Man. These coccolith assemblages may be deposited by an extension of the northerly flow through St. George's Channel or by the southerly flowing current through the North Channel. In the latter case, the Malin Sea would be the potential source area. Six species of coccoliths occur in the Malin Sea and seven in the adjacent tidal embayment of Lough Foyle (site 184).

Potential support for a northerly source of plankton for the northern Irish Sea was provided by Williamson (1952, 1956a). He found evidence in May and June of a southerly flow near the Irish coast bringing plankton species from north of Ireland through the North Channel, possibly as far south as the Dublin - Holyhead line . However no such evidence is provided by the coccolith assemblages in the coastal sediments of the area. If transport of these coccolith species is occurring along with the other plankton, then the occurrence of diverse coccolith assemblages would be expected in the coastal sediments deposited on the Irish side of the North Channel. However, estuarine sediments deposited in Lough Larne , Belfast Lough , Strangford Lough and Carlingford Lough have very sparce coccolith assemblages containing only Emiliania huxleyi and Coccolithus pelagicus. From an examination of Fig 4.6 it is clearly evident that if the southerly flowing current is responsible for the deposition of the coccolith assemblages just to the southwest of the Isle of Man, it would have to be displaced by approximately one degree to the east. Therefore it is concluded that the bulk of the coccolith assemblages in the surface sediments of the Irish Sea are

supplied from the northward flow of Atlantic waters through the basin.

Corlett and O'Sullivan (1972) discussed the movement of plaice eggs in the northeastern Irish Sea and proposed a shoreward flow of water in the deeper layer as part of a density-induced circulation. The spawning grounds of plaice are offshore and initially the eggs and larvae remain in the surface waters. However, at the metamorphosis stage they sink to the lower layer and are subsequently transported to their nursery grounds in Morecambe Bay and the outer estuaries of the Ribble, Mersey and Dee. Coccolith assemblages in the Mersey estuary have a surprisingly high species diversity (6 species) . This high diversity may be explained by the coccolith species being transported from the central Irish Sea area in the density-induced circulation described by Corlett and O'Sullivan.

Further evidence of landward transport in Liverpool Bay was recorded by Price and Kendrick (1963). They recorded a seaward flow near the surface and a landward flow at the bottom at the entrance to Queen's Channel, the dredged entrance to the Mersey estuary. Additionally, Halliwell,in 1971,using 5000 seabed drifters in Liverpool Bay confirmed the existence of a landward flow near the bottom with movement being about twice as rapid in winter , a feature correlated with higher river discharge.

Coccolith assemblages in coastal sediments of west Wales (sites 169, 170) near the southern entrance to the Irish Sea, might be expected to contain high numbers of coccoliths. This part of the coastline is nearest to the high salinity core of waters in the St. George's Channel. However, these sediments have a very sparse and slightly unusual nannoflora. Only 10^6 coccoliths per gram occur in these sediments with Coccolithus pelagicus comprising the bulk of the assemblages (42.0 to 87.0 %) and Braarudosphaera bigelowii forms up to 5 % of the flora. This is the highest relative abundance of the species in

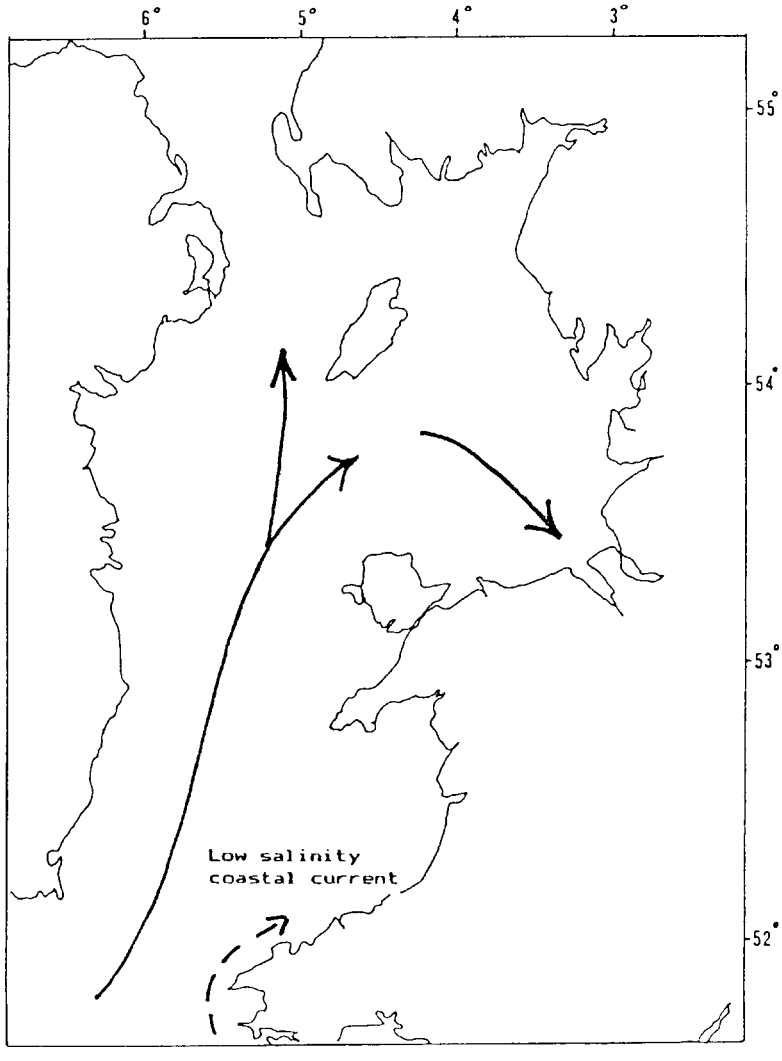


Figure 4.19
Suggested transport paths of coccoliths in the Irish Sea.

either the Celtic Sea or Irish Sea sediments.

Around St. David's Head there is an escape current of relatively low salinity water from the Bristol Channel to the Irish Sea (Cooper,1967). The water on the northern side of the Bristol Channel becomes heavily diluted by rain run-off and being less dense than the surrounding water, flows around St.David's Head and Strumble Head. This coastal current may modify the coccolith assemblages of the area. Such currents are relatively narrow and would only have a local effect in the Irish Sea. These currents are favoured by warm weather, heavy rainfall over the watersheds and by neap tides (Cooper,1967).

4.3.4 Origin of the surface sediments in the Irish Sea.

Most research on Recent sedimentation in the area has concentrated on the central and northeastern Irish Sea (Cronan, 1969, 1970; Belderson and Stride, 1969 ; Pantin, 1978) . However, Belderson (1964) has reported on Holocene sedimentation in the western half of the Irish Sea and Dobson et al. (1973) have described the sediment on the floor of the southern Irish Sea. The Irish Sea, because of its location between the uplands of Scotland , Wales, Ireland and the Lake District, was severely glaciated during the Pleistocene and the resulting glacial debris is presumed to cover much of the sea floor (Charlesworth, 1957). These glacial deposits now lie buried beneath younger sediments , or beneath a residual layer of reworked glacial debris. Cores have proved the presence of boulder clay off the east coast of the Isle of Man and and throughout the northeastern Irish Sea (McQuillin et al., 1968) .

Belderson (1964) has reported on the presence of residual glacial deposits over a wide area of St. George's Channel. These glacial deposits and other deposits to the south of the Isle of Man are being actively reworked by tidal currents and are being

transported to the north and east in the direction of strongest currents. The source of the surface sediments in the northeastern Irish Sea is most likely to be found south of the Isle of Man and in St. George's Channel.

Throughout the southern Irish Sea a widespread deposit of coarse cobbles and shell conglomerates with associated shell debris is found. The cobbles probably represent a lag deposit derived from boulder clay by the action of the advancing surf zone of the Flandrian Transgression (Stride, 1963). The broad central zone , comprising St. George's Channel, has a veneer more dominated by shell debris than by cobbles. Dobson et al. (1973) reported the bottom to be floored with a chaotic mixture of living shells , disarticulated shells, pebbles, cobbles and a coarse sand with shell fragments. Continuous sand is rare and restricted. The most important sources of calcareous detritus are the bivalves, cirripeds, bryozoans, gastropods and echinoids. Although Dobson et al. (1973) were not able to ascribe an age to these calcareous deposits , some were thought to be pre-Holocene.

Tidal currents decrease towards the English coast resulting in the deposition of muds in the northeastern Irish Sea. Locally, coarse deposits occur along the English coast , and may be the result of increased wave action as the sea floor shelves.

The clay-mineral assemblages have a uniform composition throughout the area of mud deposition in the central northeastern Irish Sea (Cronan,1970). They are dominated by members of the illite group (>75%) with subordinate amounts of chlorite and kaolinite. The abundance of illite in marine environments is considered to reflect supply from continental sources rather than in situ formation (Griffin et al., 1968). The clay-mineral assemblages in the central and eastern Irish Sea are believed to be of detrital origin and reflect the mineral composition of the source rocks from which the sediments

have been derived. These assemblages are similar to those found in glacial deposits on the floor of the Irish Sea (Cronan, 1970). The lack of variation in the composition of the clay-mineral assemblages in the Irish Sea suggests a single source for the sediments but does not preclude a local derivation of a proportion of the assemblages by freshwater run-off from the English coast, where similar clay-mineral assemblages occur in the Palaeozoic sediments.

Harland (in Pantin, 1978) recorded the Quaternary organic-walled microplankton from the northeastern Irish Sea. The surface sediments contain modern assemblages dominated by Lingulodinium machaerophorum (Deflandre and Cookson) Wall (69 to 90 %) with Spiferites spp. and Peridium spp. making up some 1 to 10% . L.machaerophorum is the cyst of Gonyaulaux polyedra Stein, a temperate to subtropical species , neritic in habit. Spiferites bentori (Rossignol) Sarjeant is the cyst of Gonyaulax digitalis (Pouchet) Kofoid, a boreal species, which also occurs in the Mediterranean and Caspian seas (Kofoid, 1911) and is not confined to a neritic habit. These species have similar distributions in present-day sediments around the coast of the British Isles , although L. machaerophorum is most concentrated in the eastern Irish Sea and in the enclosed bays on the west coast of Ireland.

Foraminiferal assemblages in a vibrocore section sampled from the southeast of the Isle of Man have been desribed by Hughes (in Pantin,1978). The assemblages have a high proportion of Elphidium clavatum Cushman (63 to 90%) and a low content (0 to 3%) of Cassidulina crassa d'Orbigny, and Ammonia batavus Hofker is absent. Such clavatum/ crassa assemblages are a common feature of late glacial marine deposits (Buch,1955; Fisher et. al., 1969). Hughes concluded from the high proportion of species which in present-day terms are associated with waters colder than those found around the British Isles , that the fauna is older than Recent.

The coccolith assemblages deposited throughout the surface sediments of the Irish Sea and the palynomorph assemblages described from the northern North Sea represent the present-day environment of the overlying waters. All the major coccolith species recorded in the sediments occur in similar percentages in the shelf of the Celtic Sea. The main difference betwen Celtic Sea and Irish Sea assemblages is the absence of the rarer 'more-pelagic' species in the Irish Sea. This is not surprising in view of the neritic character of the Irish Sea.

The occurrence of present-day nannoplankton and microplankton assemblages in the sediments indicates that at least in those respective size fractions the sediments of the Irish Sea have a Recent component. The coccolith fraction has a low reworked component (generally < 5 %); most of these forms are Cretaceous in age rather than Pleistocene. However, from sediment transport studies and the mineral composition of the gravel and clay fractions of the Irish Sea sediments it appears that the bulk of these deposits may be formed of Pleistocene-derived detritus.

4.4 CONCLUSIONS

1) Recent coccolith assemblages occur in the surface sediments throughout the Irish Sea.

2) Eight species of Recent coccolith occur in the sediments of the Irish Sea. These assemblages are dominated by Emiliania huxleyi, which may form up to 94.0 % of the total nannoflora. Coccolithus pelagicus is subordinate in the assemblages although its dominance increases in coastal sediments.

3) Coccolith abundance and number of species in the sediments decreases generally from south to north and from the axis of the deep-water channel to the margins of the basin.

4) The bulk of the coccolith assemblages in the Recent sediments of the Irish Sea are supplied from Atlantic water flowing north through St. George's Channel. Southward currents through the North Channel are thought to be of little importance in the transportation of coccolith species into the Irish Sea.

5) The distribution and abundance of coccoliths in the Recent sediments are controlled by currents and the water column conditions . Highest abundances occur in the more saline waters of the southern Irish Sea and in an isolated area of weak tidal currents to the southwest of the Isle of Man.

6) Large tidal currents at the mouth of St. George's Channel may act as an ecological filter barrier for many of the pelagic species found in the Celtic Sea

but missing from the Irish Sea .

In order to delineate more fully the biogeographic distribution of coccoliths in the Irish Sea, the following extensions of this study are suggested.

Firstly, a comprehensive survey of the species-composition of coccolithophore communities living in the waters of the Irish Sea should be conducted. This survey should be continued periodically throughout several years in order that seasonal variance in the coccolithophore communities may be determined. This information would allow one to determine to what extent the species-composition and distribution in the surface sediments reflects its biocoenose. Secondly, a study of the coccolith assemblages from the Recent sediments of the more shallow areas of the Irish Sea , particulary in the northeastern region, should be conducted. This would provide a greater geographical cover of sample sites in the area and might provide information on the landward currents towards Liverpool Bay.

CHAPTER 5

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE NORTH SEA

CHAPTER 5

COCCOLITH ASSEMBLAGES IN RECENT MARINE AND ESTUARINE SEDIMENTS FROM THE NORTH SEA.

5.1 INTRODUCTION.

5.1.1 Background and main objectives.

The most extensive and widespread record of coccolithophores in the North Sea was published by Braarud et al., (1953). They described the phytoplankton present in the surface waters of the North Sea and adjacent waters in May 1948. Murray (1985) has noted the coccolith species present in selected sediment samples from the North Sea area. However, there is no other record of the coccolith assemblages in the Recent sediments. Most other records of the occurrence of coccolithophores in the region have been based on plankton samples from the coastal waters and fjords of Norway and in the Norwegian Sea (Birkens and Braarud , 1952; Berge, 1962; Braarud et al., 1974; Schei, 1975). Brief details of the coccolith content of a core from the Norwegian Sea were also described by Belanger in 1982.

The main objectives of this study are to define the species-composition and abundance of coccolith assemblages in the Recent sediments of the North Sea. A brief survey of the coccolithophores and other plankton found in filter samples from the northern and central North Sea is also described. The relationship between the coccolith assemblages and the various hydrological regimes in the North Sea is discussed in some detail. The directions of coccolith transport into, and within the North Sea are also delineated.

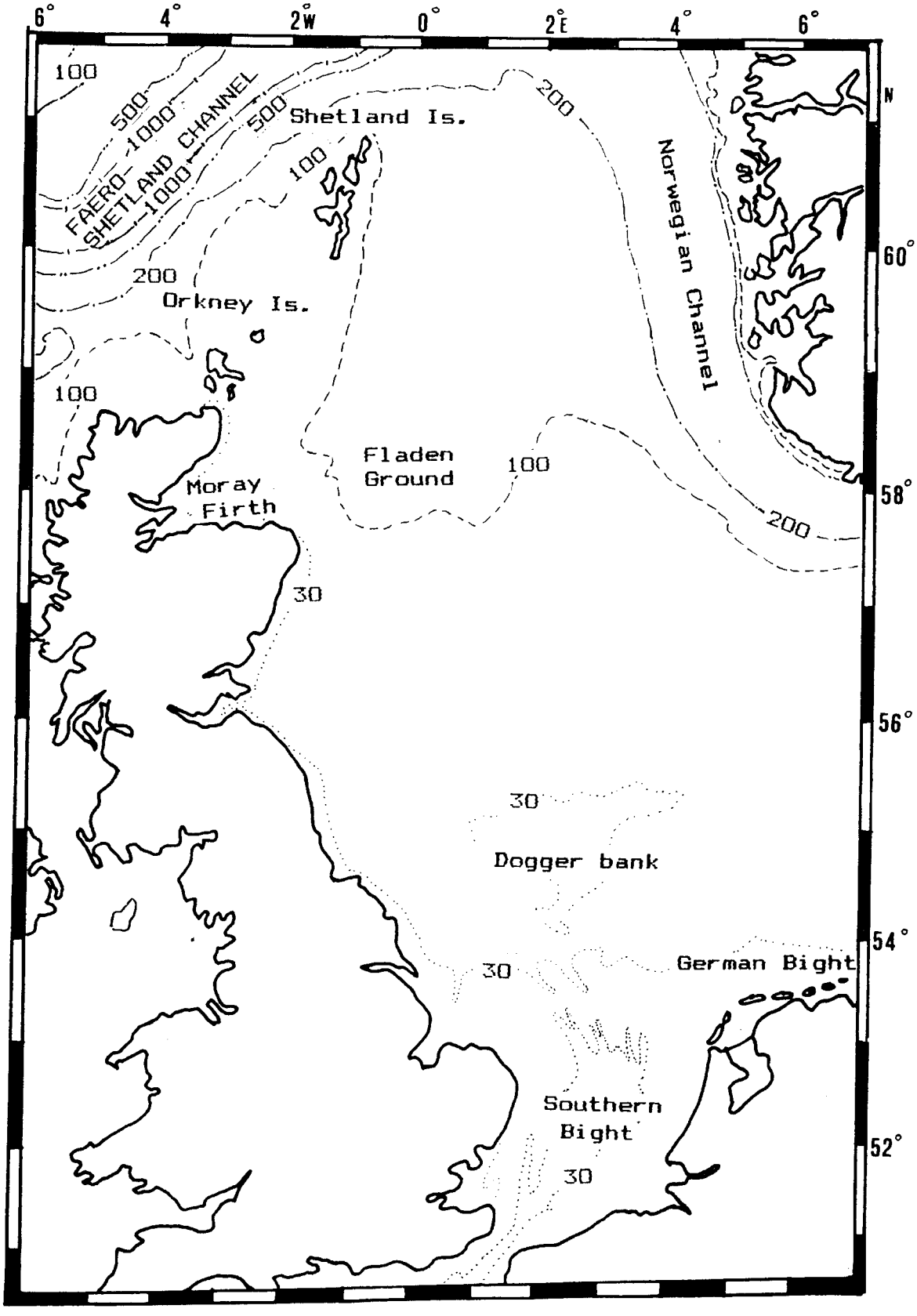


Figure 5.1.
Map of the North Sea showing water-depth contours (isobaths) in metres and the place names used in the text.

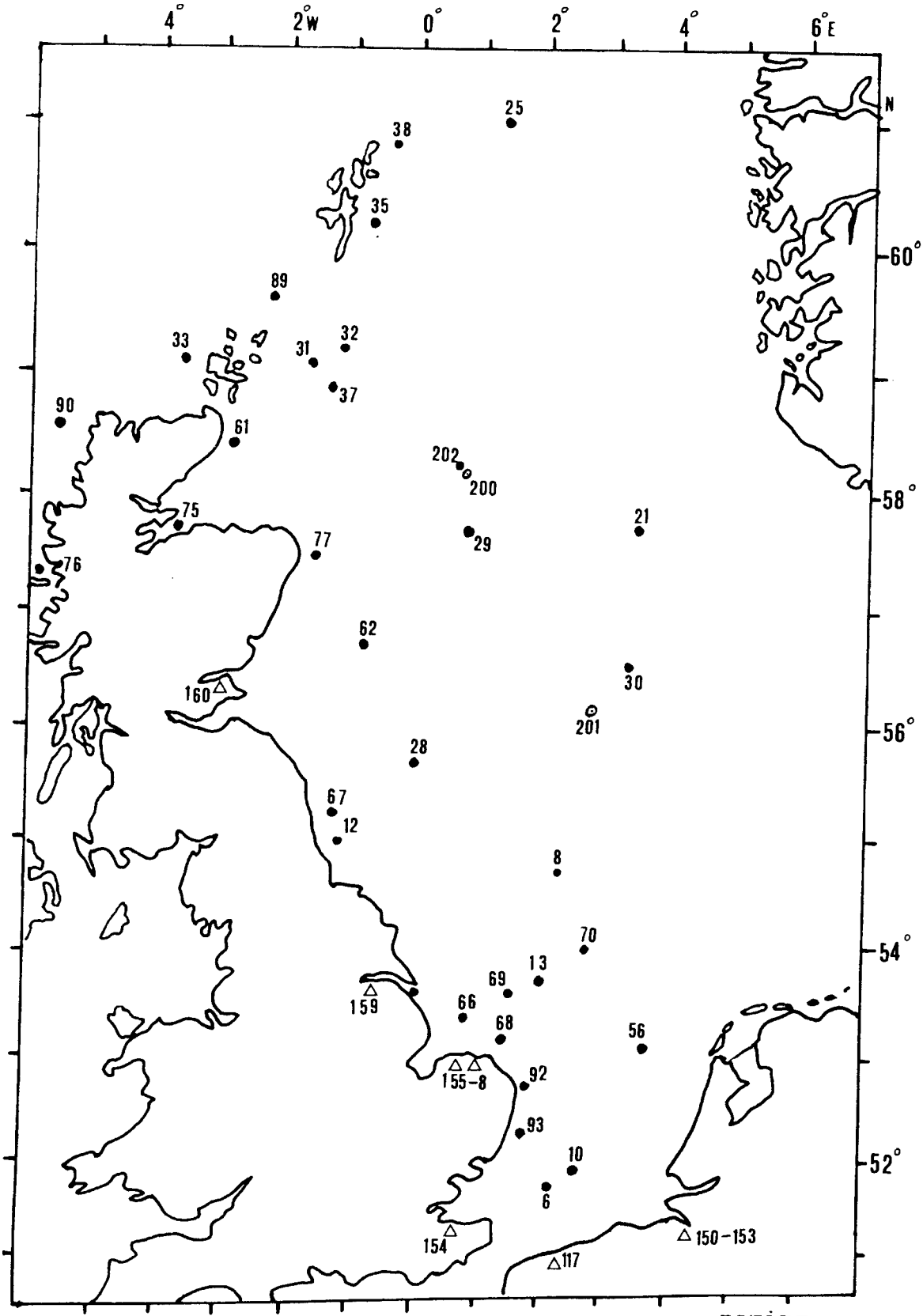


Figure 5.2.
Location of sample sites in the North Sea.

• marine sediment
△ estuarine sediment
⊙ filter sample

5.1.2 Geographical area.

The North Sea is an epicontinental sea bordered on three sides by land and open to the Atlantic waters in the north where it continues into the Norwegian Sea (Fig.5.1). In the south, the North Sea has a narrow connection with the English Channel through the Straits of Dover. To the east it is open to the Baltic through the Skagerak. The North Sea, including the Skagerak, has a surface area of 575,000 km^2, and occupies a generally shallow basin with a mean depth of about 100 m (Lee, 1980). It lies between latitudes 51° and 61° N and undergoes pronounced seasonal changes. The area of the North Sea sampled in this study lies to the west of 4°east longitude and excludes the regions off the Continental coast from Holland to Norway (Fig.5.2). Two samples from the Sea of the Minches, off the northwest coast of Scotland, are also included in this chapter.

5.1.3 Bathymetry and morphology .

The edge of the continental shelf (generally taken as the 200 m isobath) along the northern margin of the North Sea is poorly defined. The isobath trends northeast from the north of Shetland until reaching the eastern margin of the deep-water Norwegian Channel where it turns south and runs parallel to the Norwegian coast. This channel forms the largest single feature on the northwest European continental shelf (Caston, 1979) . The central part of this trough lies at a depth between 250 and 300 m, with maximum depths reached in the Skagerak (700 m).

A general trend of decreasing depth occurs throughout the central North Sea from north to south. The greater part of the northern North Sea, away from the Scottish coast and islands, lies at a depth of between 100 and 140 m . Depths in excess of 140 m occur to the north and west of the Shetland Isles. In the southern North Sea

the German Bight, bordered to the east and south by the Danish and German coasts respectively and extending westwards as far as the Dogger Bank , forms a relatively shallow and featureless area ranging in depth from 30 to 50m. Between Dogger Bank and the coast of Yorkshire the depth increases to a maximum in excess of 80 m. To the south of the German Bight lies a belt of shallow water, less than 30 m in depth,which extends almost continously from the English to the Dutch coasts between 53° N to 53° 50'N.

5.1.4 Temperature of the surface waters.

Maximum temperatures in the surface waters of the North Sea occur in August (Fig. 5.3). During this month mean temperatures range from 17 to 19°C along the German and Dutch coast and from 12 to 13°C along the Scottish coast and in waters around Orkney and Shetland. Winter temperatures reach their minimum in the waters of the North Sea in February (Fig.5.4), ranging from 7°C in the regions of inflowing Atlantic water near the Straits of Dover and east of Shetland to 2 to 3°C along the coast of Denmark.

5.1.5 Salinity distribution in the surface waters.

The mean monthly distribution of the surface salinity in the North Sea for the months of August and February are shown in Figs. 5.5 and 5.6 respectively. The inflows of Atlantic water to the east of Shetland and in the Straits of Dover are approximately 35.3 and 35.0 %. respectively throughout the year (Lee, 1980). These waters, though, have slightly higher values in winter than in the summer. In the northern North Sea the inflowing high salinity water (>35.0 %.) has its greatest southerly extension in February and its least in July.

5.1.6 Stratification in the North Sea waters.

The waters of the southern North sea south of 54° N

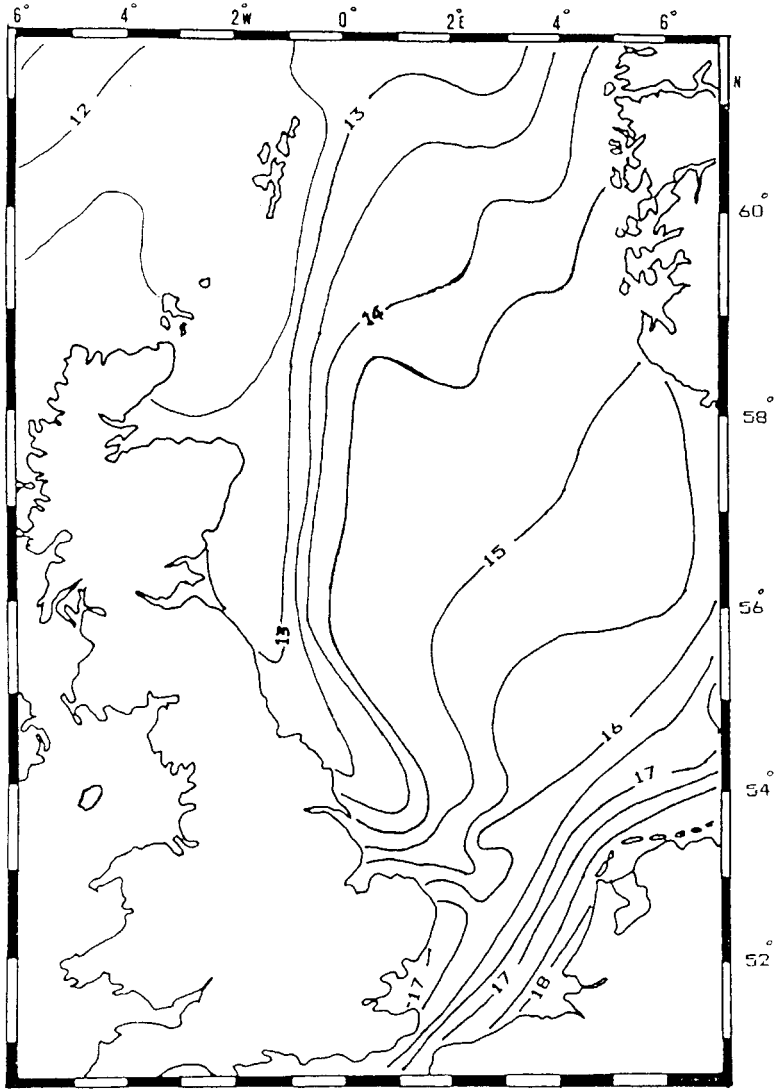


Figure 5.3
Mean distribution of sea surface temperature (°C) for August (after Lee, 1980).

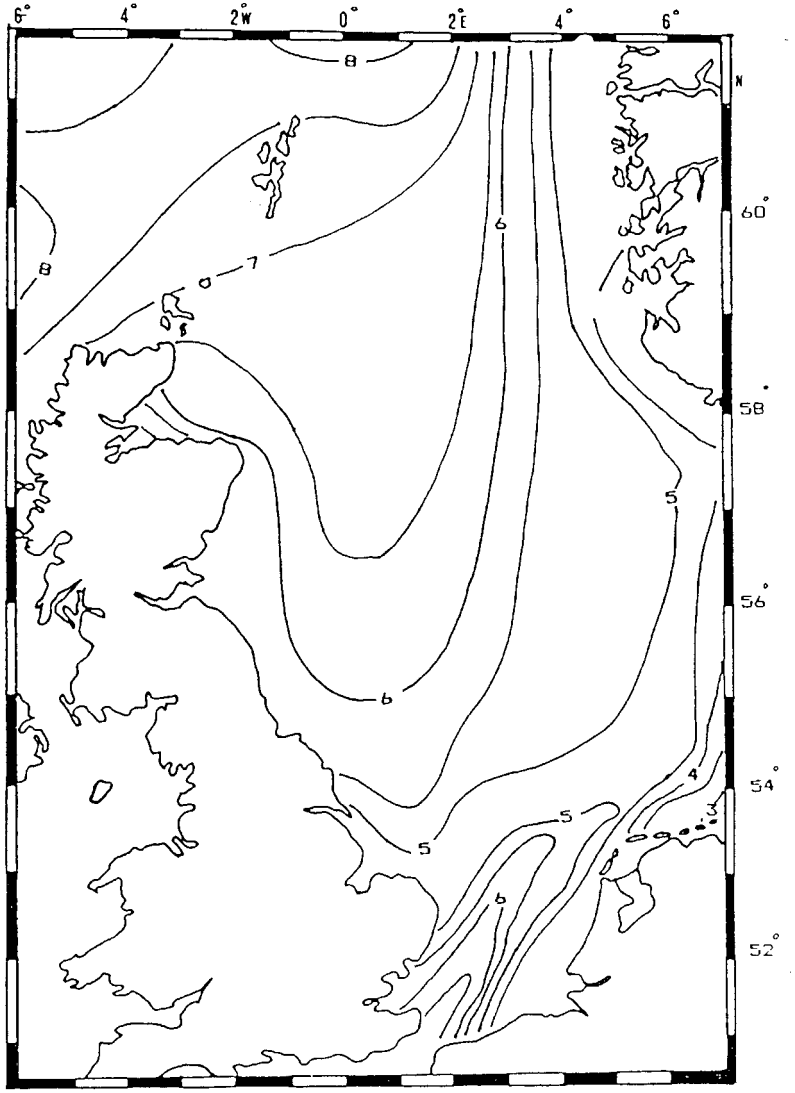


Figure 5.4
Mean distribution of sea surface temperature (°C) for February (after Lee, 1980).

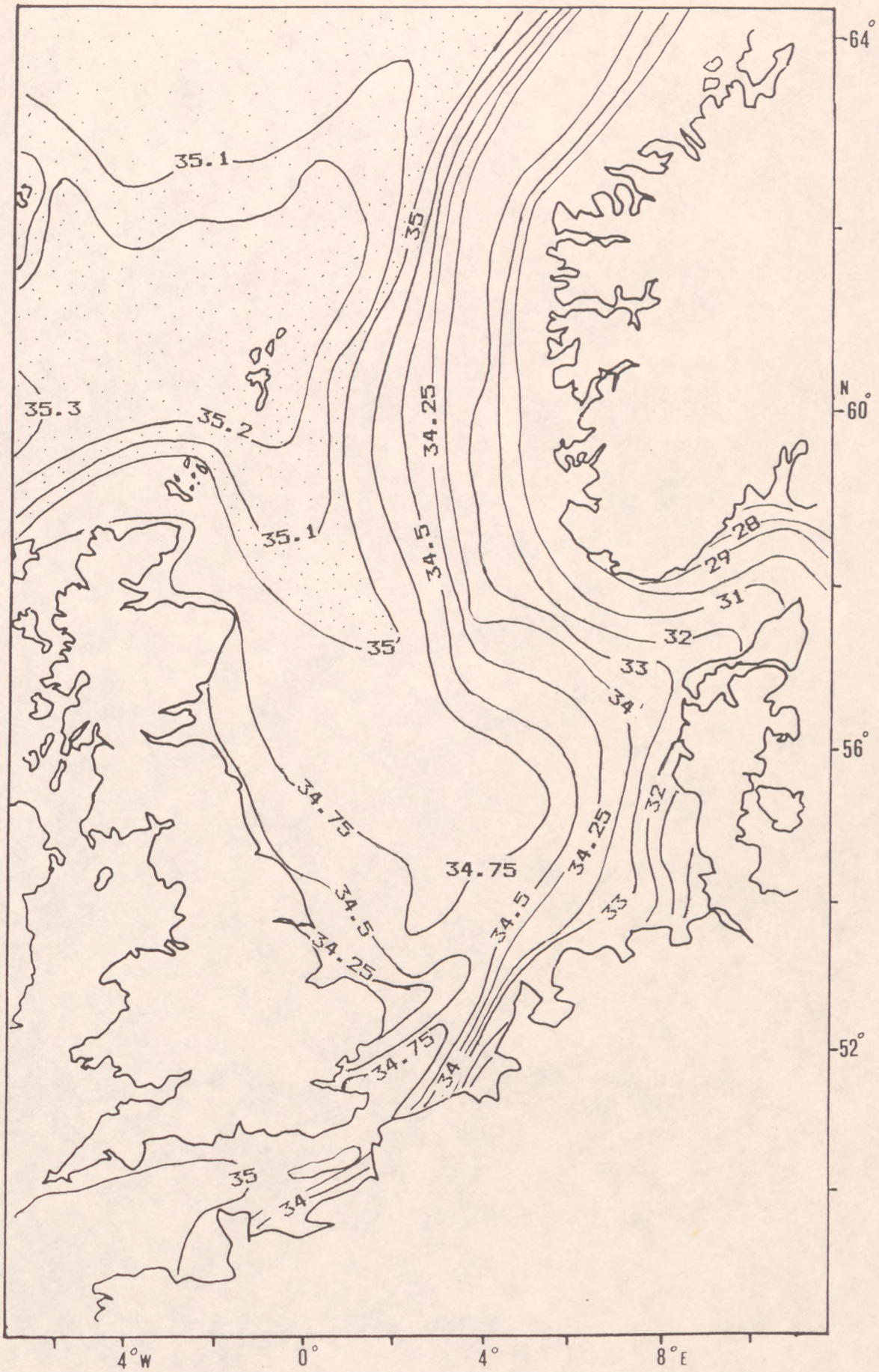


Figure 5.5.
Mean distribution of sea surface salinity (‰) for August (after Lee, 1980).

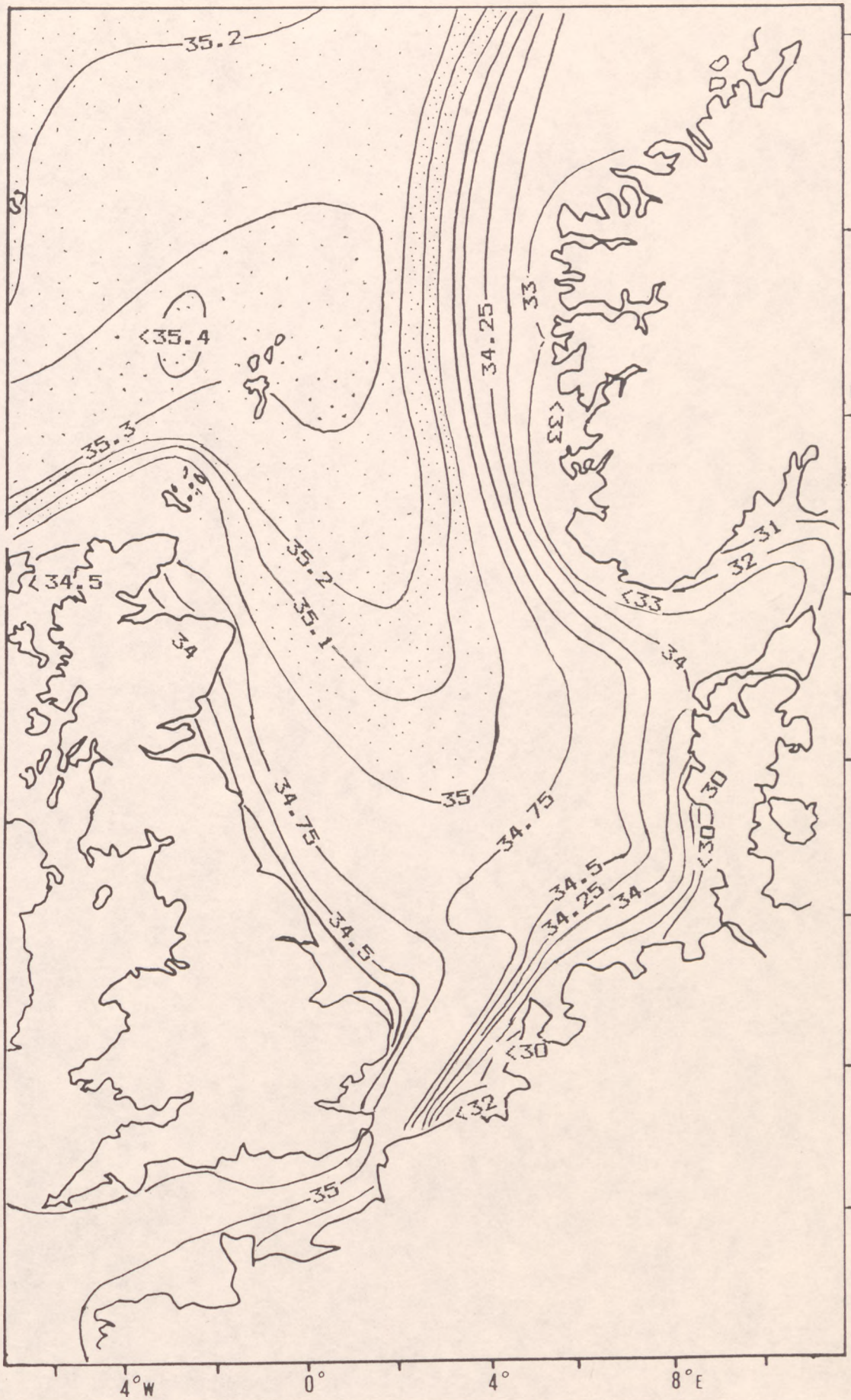
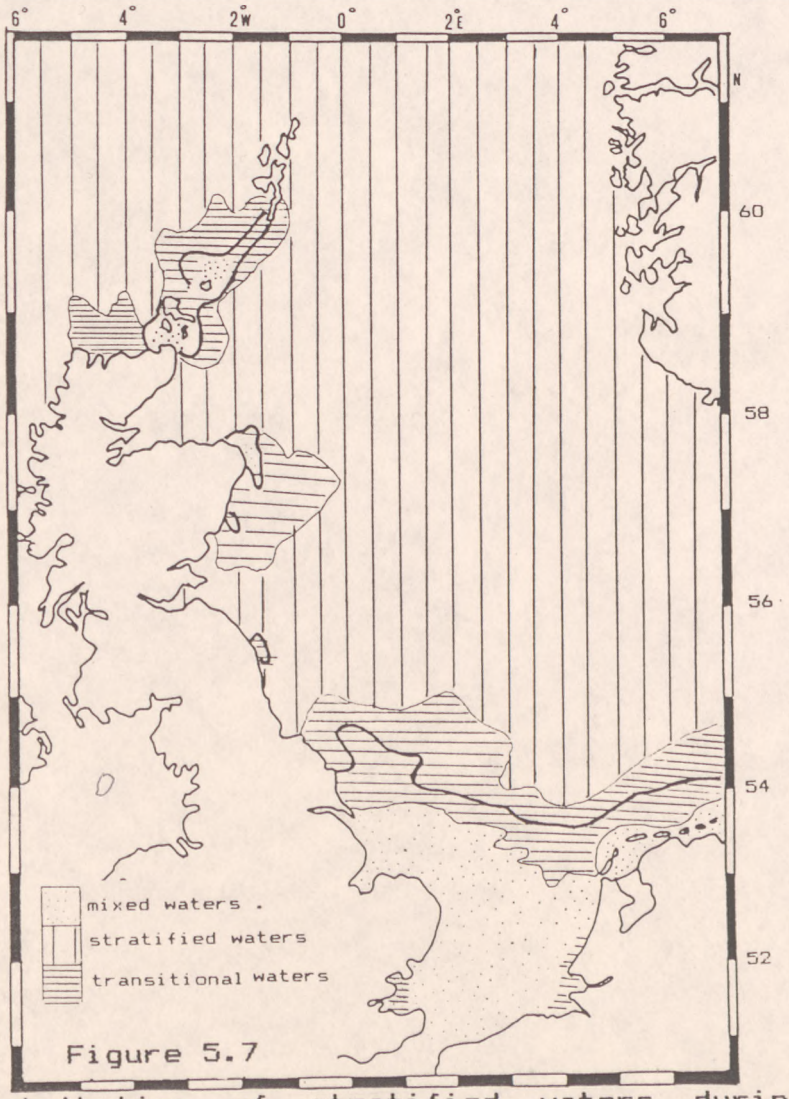


Figure 5.6
Mean distribution of sea surface salinity (‰) For February (after Lee, 1980).



Distribution of stratified waters during the summer in the North Sea. The continous line represents the frontal boundary, where St (stratification parameter) = 1.5.

(after Holligan,1978)

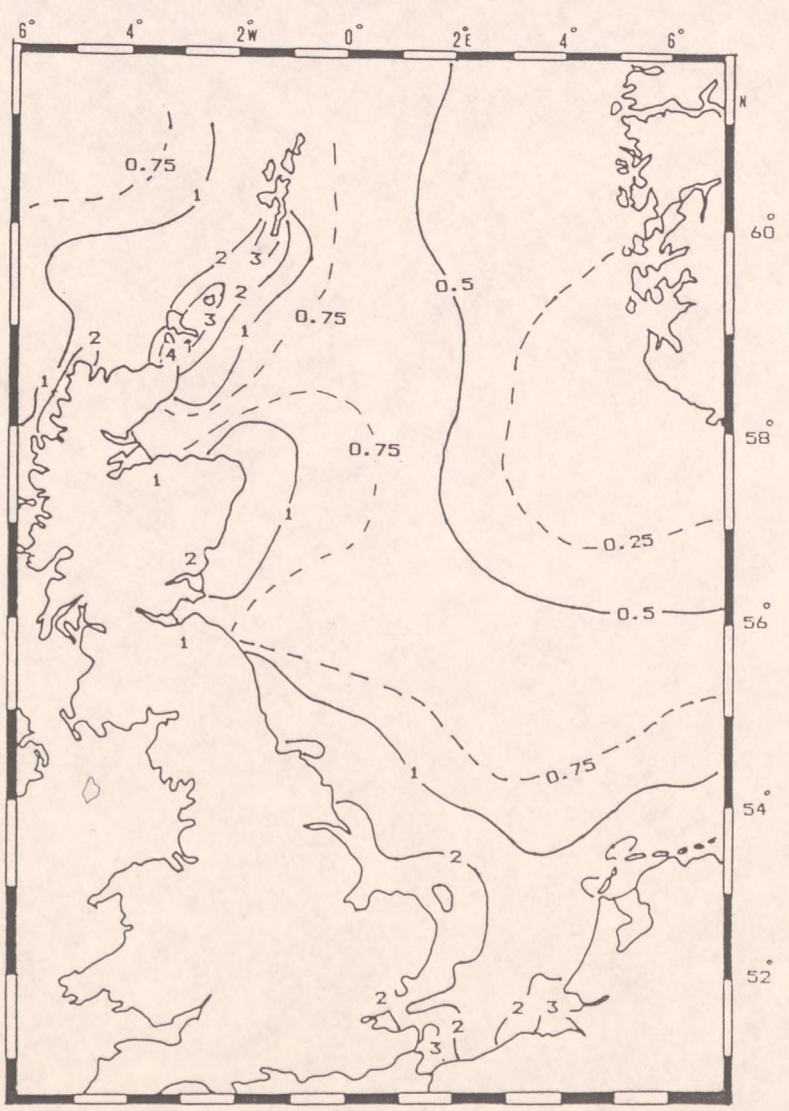


Figure 5.8.
Distribution of maximum tidal streams during mean spring tides (knots).

(after Lee and Ramster,1976)

; the German Bight , the Dogger Bank and along the English and continental coasts are homothermal and homohaline all the year round. An exception to this , however, occurs in a small region off the Dutch coast, where low salinity coastal water may ride over high salinity Atlantic waters (Postma, 1954; Fonds and Eisma, 1967). Waters throughout the central and northern North Sea are thermally stratified in the summer. The lower limit of the thermocline lies at a depth of between 20 and 50 m and the greatest temperature gradient is generally 0.3 to 0.7 °C/m (Tomczdeck and Goedecke, 1964). The thermocline development gives rise to temperature differences between the surface and bottom waters as large as 8°C in places. Fig. 5.7 shows the maximum distribution of the thermally stratified area over the period from June to September.

5.1.7 Surface currents in the North Sea.

Lee and Ramster (1976) have published the most recent rewiew of the surface current systems in the North Sea (Fig.5.8). Atlantic water with a salinity greater than 35 ‰. enters the North Sea between Shetland and Norway in the north. An additional,but smaller flow of Atlantic water occurs along the north Scottish coast, entering the North Sea between Shetland and Orkney. Within the North Sea itself this water flows south along the east coast of Scotland and England about as far south as the Wash and then flows east towards the coast of Denmark. Further south in the central North Sea the surface currents are regarded as being complex and wind-driven.

A current flowing southwest along the Norwegian coast out of the Baltic Sea follows the coastline to become the northward flowing coastal current. A second major stream of Atlantic water flows northeast from the Straits of Dover across the eastern half of the southern North Sea towards the Skagerak, where it mixes with Baltic waters and flows out of the North Sea along the Norwegian

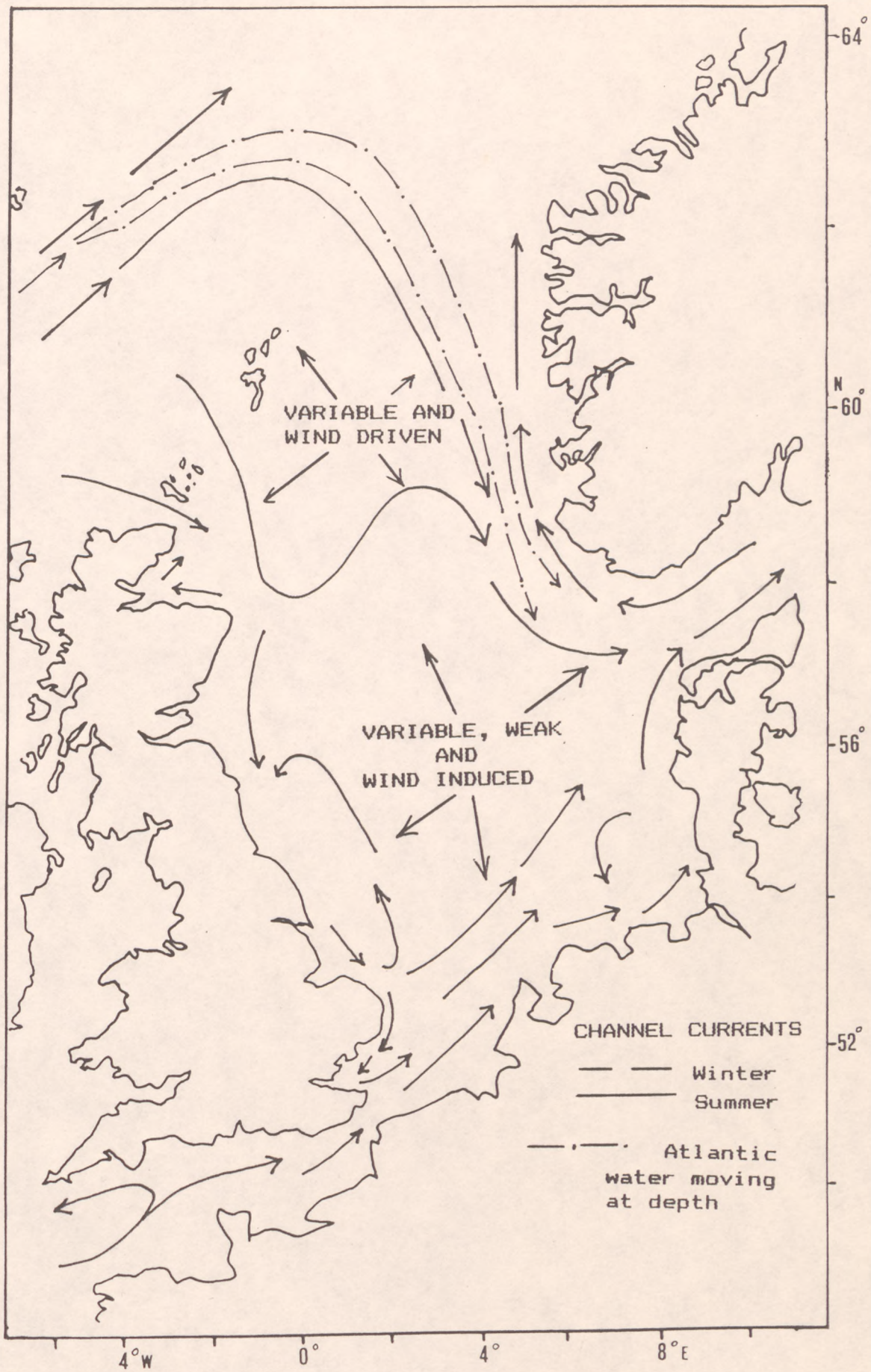


Figure 5.9.
Surface current system of the North Sea.
(after Lee and Ramster, 1976)

coast.

5.1.8 Distribution of the water masses in the North Sea.

There are three major inflows of water to the North Sea (Lee,1970);

1) high salinity water entering from the north between Shetland and Norway (North Atlantic),

2) high salinity water entering from the south via the straits of Dover (Channel),

3) the Baltic outflow , which is of lower salinity (Skagerak).

These three inflows provide the 3 primary water mass types; however, five secondary water masses are derived from them and the run-off from the land (Laevastu,1963). These are termed the Scottish Coastal, English Coastal, Continental Coastal, Northern North Sea and Central North Sea water masses. They generally extend throughout the water column.

Later investigations have revised and updated the distribution described by Laevestu (1963), and Lee (1980) has provided the most recent concept of the hydrological regions of the North Sea, as shown in Fig. 5.10. These regions will be discussed in more detail in section 5.3.6.

5.1.9 Samples

45 samples of surface sediment were examined from the North Sea comprising:

A) 34 open-water shelf sediments,

B) 11 estuarine sediments from the western and southern margins of the North Sea.

The location and water-depth of these samples is listed in Table 5.1. Four filter samples from the North Sea were also examined as listed in the Table below.

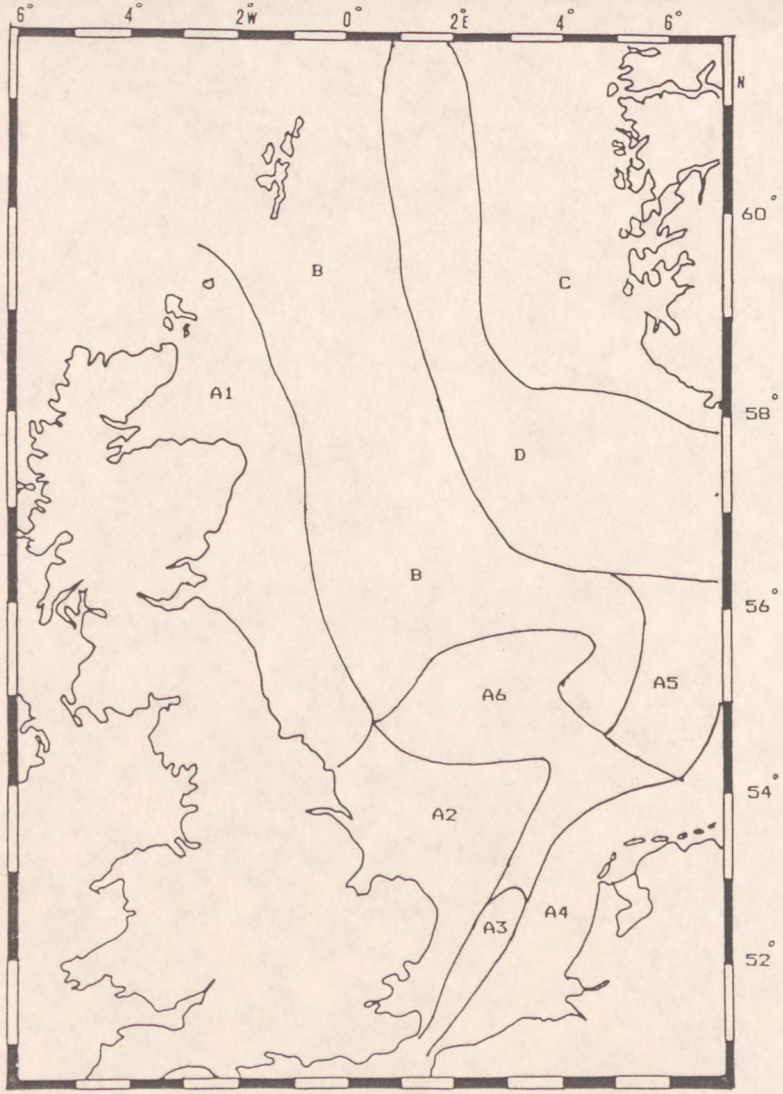


Figure 5.10
Hydrographic regions of the North Sea. (after Lee, 1980).

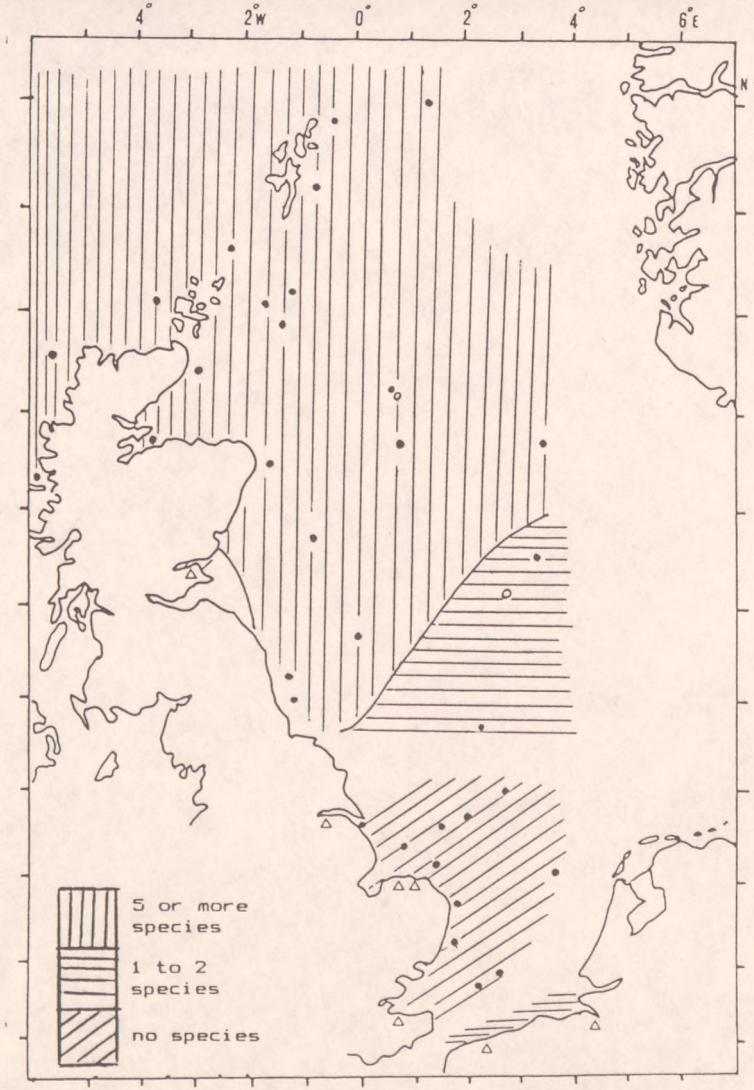


Figure 5.11.
Map showing the number of coccolith species present in the surface sediments.

Table 5.1 Location and water depth of samples in the North Sea.

SAMPLE	LATITUDE	LONGITUDE	DEPTH
	o '	o '	(m)
BM 6	51 44.6 N	02 07.1 E	47
BM 8	54 41.0 N	02 16.0 E	20
BM 10	51 50.0 N	02 10.4 E	47
BM 12	55 00.3 N	01 07.5 E	37
BM 13	53 37.0 N	02 01.0 E	1
BM 21	57 43.7 N	03 35.1 E	70
BM 25	61 00.5 N	01 19.7 E	148
BM 28	55 39.1 N	00 00.0 E	72
JM 29	57 44 N	00 54 E	~120
JM 30	56 32 N	03 13 E	~ 60
OC 31	59 02.9 N	01 44.6 W	84
OC 32	59 15.8 N	01 17.5 W	107
OC 33	59 03.9 N	03 46.8 W	106
OC 35	60 13.5 N	00 51.1 W	116
OC 37	58 57.2 N	01 25.9 W	114
OC 38	60 46.1 N	00 37.7 W	112
BM 56	53 05.6 N	03 41.9 E	NK
BM 61	58 26.0 N	03 04.4 W	39
BM 62	56 48 N	00 57.5 W	71
BM 65	53 37 N	00 02.3 W	10
BM 66	53 14.5 N	00 55.9 E	17
BM 67	55 13.1 N	01 18.8 W	57
BM 68	53 05.9 N	01 27.3 E	NK
BM 69	53 36.1 N	01 34.4 E	76
BM 70	54 00.6 N	02 40.8 E	65
BM 75	57 40.6 N	03 57.1 W	19
BM 76	57 22.2 N	05 55.5 W	157
BM 77	57 29.3 N	01 41.3 W	60
BM 89	59 26.0 N	02 11.7 W	78
BM 90	58 31.5 N	05 33.1 W	120
UE 92	52 35 N	01 45 E	18
BJ 93	52 12 N	01 40 E	10
FR 117	51 02 N	02 06 E	-
AN 150	51 13 N	04 25 E	20
AN 151	51 13 N	04 25 E	13
AN 152	51 13 N	04 25 E	13
AN 153	51 13 N	04 25 E	10
ES 154	51 22 N	00 32 E	-
ES 155	52 57.6 N	00 40.5 E	-
ES 156	52 57.5 N	00 44.7 E	-
ES 157	52 56.8 N	00 51.6 E	-
ES 158	52 57.2 N	01 01.3 E	-
ES 159	53 40 N	00 30 W	-
ES 160	52 26 N	02 51 W	-
WF 202	58 27.5 N	00 27.5 W	125

Table 5.2 Location and sampling period of filters in the North Sea.

Sample	Duration	Date	Latitude	Longitude
200-1	48 hours	August 1985	58°30'N	00°20'W
201-2	10 days	July 1985	56 20 N	02 50 E
201-3	'short period'	summer 1985	56 20 N	02 50 E
200-4	2 months	April/May 85	58 30 N	02 20 W

5.2 RESULTS.

5.2.1 Sediment samples.

Ten species of Recent coccolith are recorded from the surface sediments of the North Sea. The percentage abundance of these species in the assemblages is listed in Table 5.3. The quantitative abundance of selected species and total number of coccoliths in the sediments are listed in Table 5.4.

Species diversity of the coccolith assemblages in the sediments generally decreases from north to south in the North Sea (Fig.5.11). An area of sediment containing five or more species can be traced as far south as 55° N latitude, along the eastern coast of Britain. In the central North Sea, however, this diversity only extends south to 57°N latitude. The central North Sea coccolith assemblages typically contain 1 to 2 species. The greater part of the southern North Sea sediments do not contain any Recent coccoliths. Exceptions to this lie along the French and Belgian coast.

Recent coccoliths occur in all the sediments sampled from the northern and central North Sea, and in the two samples from the Sea of Minches. Greatest numbers of coccoliths (10^9per gram) occur in sediments west of the Orkney Isles and east of Shetland (Fig.5.12). A tongue of sediment containing > 10^9coccoliths per gram can also be traced southwards along the central region of the North Sea to approximately 57° 30'N latitude. South of this line, and in the coastal waters of the Moray Firth and around the Isles of Orkney and Shetland, the sediments contain 10^8coccoliths per gram. A gradient of declining coccolith abundances continues southwards in the sediments from the central North Sea. Coastal sediments along eastern England and sediments from the central North Sea contain between 10^6 and 10^7 coccoliths per gram. Recent coccoliths are absent in the southern North Sea, except along the French and Belgian coastline ($10^5$to 10^6per gram)

The changes in the percentage abundance of coccoliths in the fine fractions of the sediments correlate well with the changes in the total number of coccoliths per gram in the sediments. Highest abundances occur west of Orkney and in the central northern North Sea (>15%) (Fig.5.13). Intermediate values occur in sediments from the central North Sea (15 to 1%). South of latitude 56°N, Recent coccoliths form less than 0.1 % of the fine fractions.

The coccolith assemblages in the North Sea are dominated by Emiliania huxleyi. There is little variation in the relative abundance of the species throughout the northern North Sea sediments. The highest relative abundances of the species occur to the west of Orkney (>95 %). Lower values are typical of sediments in the central North Sea and along the east coast of Scotland (mean 92.7 %). No systematic variation in these values is observed. South of latitude 55° North E.huxleyi is not found in the sediments, except for an isolated occurrence within

sediments from the Schedlt Estuary (Antwerp Harbour). The quantitative abundance of E.huxleyi in the surface sediments of the North Sea closely follows the distribution of the total number of Recent coccoliths in the surface sediments (see Figs.5.12 and 5.14). The greatest abundance of both values (10^9 coccoliths per gram) occurs in surface sediments west of Orkney and in the central North Sea area. Both values also decrease from south to north throughout the region. The coccoliths of Emiliania huxleyi occur as discrete particles, although coccospheres of the species are recorded at the northern margin of the North Sea from sample 25.

Coccolithus pelagicus is the second most abundant species in the assemblages , although, except for two sites in the southern North Sea, it forms less than 5 % of the total flora. Lowest relative abundances of the species occur in the coastal sediments of the Moray Firth , around the Orkney Isles and in the Sea of the Minches (<1.5 %). Higher abundances of the species (mean 2.6%) occur in the central northern North Sea region. The greatest quantitative abundance of the species occurs at the northern margin of the North Sea (10^8 coccoliths per gram) (Fig.5.15.). In sediments from the central northern North Sea and west of Orkney this value declines to 10^7 per gram. A gradient of decreasing coccolith abundance continues southwards (Fig.5.15). Values of 10^6 coccoliths per gram are typical of sediments from the central North Sea. The species is absent from sediments over the greater part of the southern North Sea, except for an area along the French and Belgian coastlines (10^5 coccoliths per gram).

Syracosphaera pulchra occurs in sediments from the Minches and throughout the North Sea as far south as latitude 55° N (Fig.5.16.). It was not recorded in sediments from the southern North Sea. Highest quantitative abundance of the species (10^7 coccolith per gram) occurs in the North Minch , west of Orkney and throughout the northern North sea. Lower abundances occur

in sediments between the Isles of Orkney and Shetland , along the Scottish coast and south of latitude 57°N in the central North sea (10^5 to 10^6 coccoliths per gram). The percentage abundance of S.pulchra in the coccolith assemblages from the northern North Sea ranges from 8.3 to 1.0 % (mean 2.3 %). No systematic variation in these values is observed.

Minor species found in the coccolith assemblages (4 to 0.3%) include: Braarudosphaera bigelowii, Calcidiscus leptoporus , Gephyrocapsa caribbeanica , Helicosphaera carteri and Rhabdosphaera clavigera.

Calcidiscus leptoporus is found in sediments from the Minches, west of Orkney and in the northern North Sea as far south as latitude 56° 30'N (Fig.5.17.). It is absent from the central and southern North Sea sediments. Coccospheres of C.leptoporus are recorded in sample 75 from the Moray Firth. Highest relative abundance of the species occurs at the northern margin of the North Sea (2.7 %).

Gephyrocapsa caribbeanica occurs in sediments from the Minches and in the central North Sea as far south as 56° N latitude (Fig.5.18). It is not found in sediments along the eastern coast of Scotland and in the southern North Sea . G.caribbeanica averages 1.8 % of the assemblages in the central North Sea . Lower values occur in assemblages deposited between the Isles of Shetland and Orkney.

Helicosphaera carteri has a very limited distribuion in the assemblages and is only recorded from sediments around the Isles of Orkney and Shetland and in the central northern North Sea (Fig.5.19.). However, the species may have a wider distribution than presently described as it is a very scarce component of the assemblages (0.3 % max.) and may have been overlooked in some samples.

Rhabdosphaera clavigera is not observed in sediments

from the greater part of the North Sea . It has a patchy distribution being recorded from coastal sediments around Orkney and Shetland , in the Moray Firth and off the northeastern coast of England . An isolated occurrence of the species in the central North Sea is also recorded.

Braarudosphaera bigelowii occurs in coastal sediments off eastern Britain and in the Minches. Isolated pentaliths are also noted at the northern margin of the North Sea and near the entrance to the Dover Strait.

Scarce species in the assemblages (< 0.3%) are **Discosphaera** tubifera and Coronosphaera mediterranea. D.tubifera was not observed in the 300 specimen counts but was recorded at sites 25, 28, 31 and 77 during extensive searches of individual samples using optical microscopy. C.mediterranea was only recorded by SEM at sites 200 and 29 in the northern North Sea.

Reworked coccoliths are either absent or very scarce (< 1.0 %.) in the Sea of the Minches and in the northern North Sea sediments. Abundances increase southwards, particularly along the eastern coast of England. Reworked coccoliths form 100 % of the nannoflora throughout much of the southern North Sea as Recent coccoliths are generally absent. The reworked assemblages are dominated by Cretaceous forms similar to those found in the eastern English Channel and in the Solent. Reworked Tertiary coccoliths are also found within coastal sediments of eastern England and northern France including Chiasmolithus spp., Recticulofenestra umbilica and Neochiastozygus dubius.

5.2.2. Coccolith assemblages and other plankton in filter samples from the North Sea.

Coccoliths dominate the plankton component of the fine fractions (< 45 μm) in the filters from site 200 in

the northern North Sea. They are the only major source of biogenic carbonate in the samples. Coccoliths have greatest abundance in filter 1 where they form 25 % of the fine sediment. A maximum of six species were recorded in this sample. Emiliania huxleyi dominates the coccolith assemblages in the filters from site 200 and forms between 96.5 and 98.0 % . Coccolithus pelagicus and Calcidiscus leptoporus are the only other species to form over 1% of the assemblages.

The bulk of the coccoliths of Emiliania huxleyi in the samples occur as discrete particles (2 to 4 μm in diameter), although occasional coccospheres of the species are also seen. Both the cold-water variant and transitional forms of Emiliania huxleyi occur in the samples. Preservation of these coccoliths ranges from moderate to poor. Fragments of the spoke-like elements of the cold-water forms and also of the partially fused transitional forms are observed. The presence of both coccoliths and skeletal elements of these coccoliths leads to a bimodal distribution of carbonate in the samples with peak occurrences in the 2 to 4 micron and sub-micron range. Coccoliths are scarce (< 0.1 %) or absent in the fine fractions from filter site 201, from which only isolated coccoliths of E.huxleyi are recorded.

Siliceous biogenic material is scarce in the fine fractions of all samples and is limited to fragments of centric diatom frusules. Most of the biogenic silica is concentrated in the coarse fractions (> 45 μm) from site 200 where whole centric diatoms and very rare skeletons of the silicoflagellate Distaphanus speculum occur. Dinoflagellates are limited to the coarse fractions from site 201. They occur predominantly as motile or vegetative stage thecae; resting cysts are very scarce. The most common dinoflagellates recorded were Ceratium furca , Ceratium tripos, Dinophysis acuta and Peridinium species. Dinoflagellates have greatest abundance in filter 3 where they form 75 % of the coarse fraction.

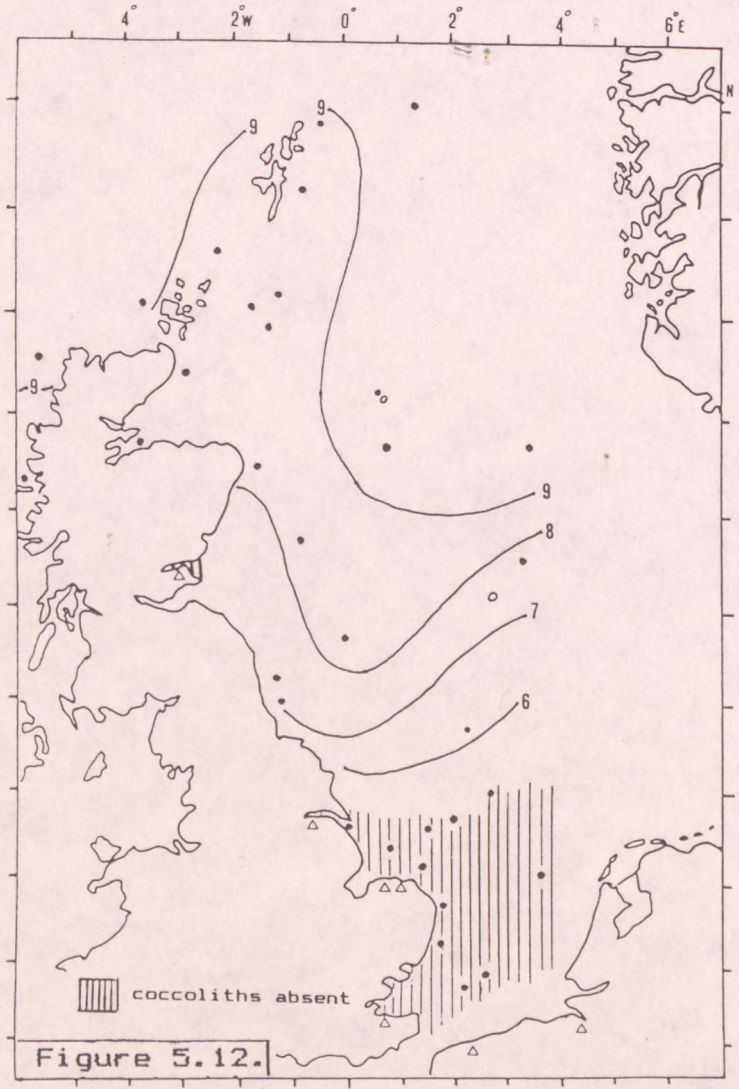


Figure 5.12.

Abundance of Recent coccoliths ($\times 10^N$) per gram of fine-grained silt (2-20μm) in the surface sediments.

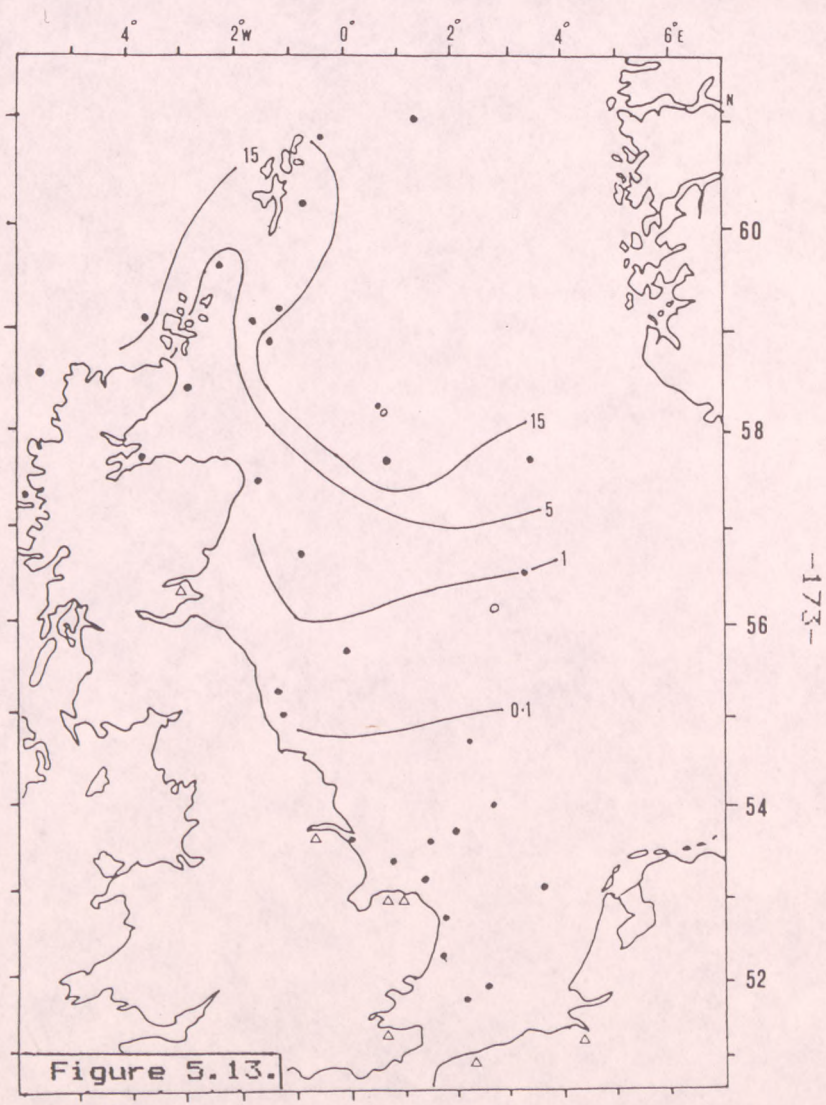


Figure 5.13.

% abundance of Recent coccoliths in the fine-grained silt fractions (2-20μm) from the surface sediments.

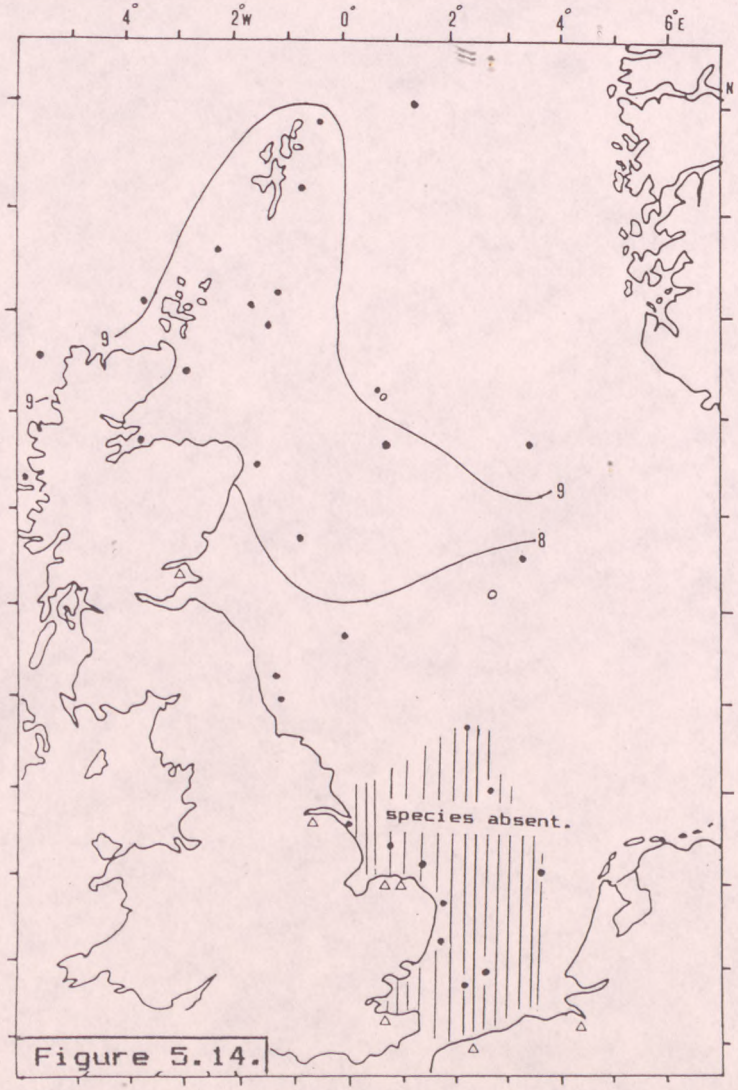


Figure 5.14.

Abundance of Emiliania huxleyi (x 10^N) per gram of fine-grained silt (2-20μm) in the surface sediments.

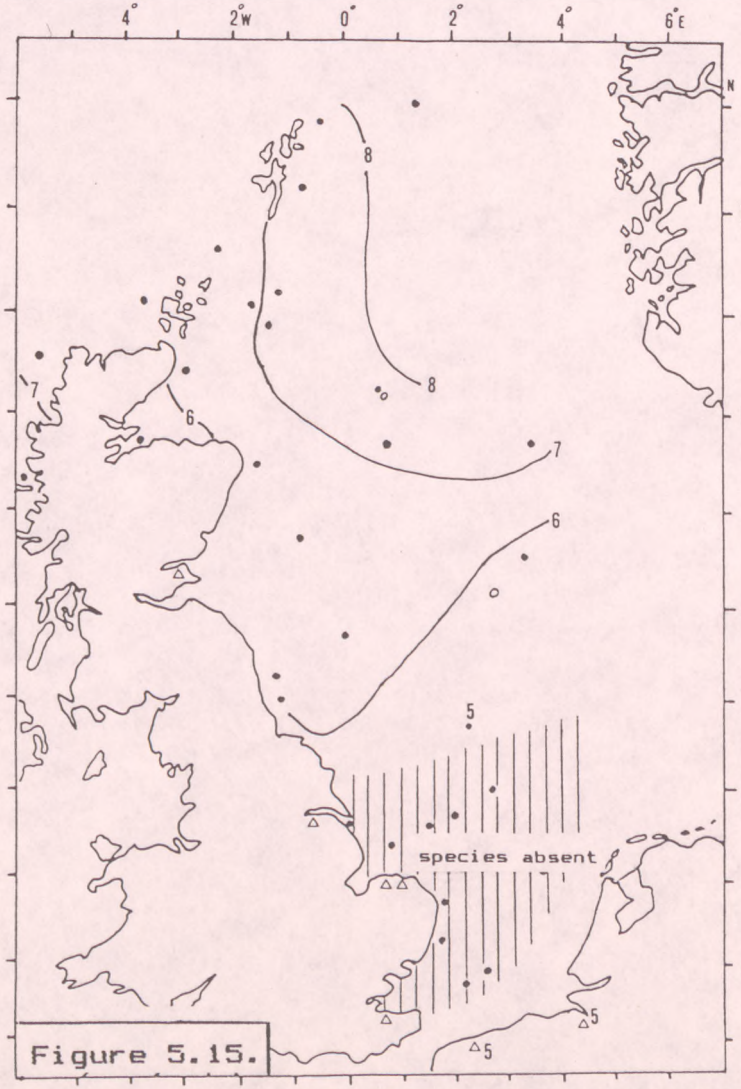


Figure 5.15.

Abundance of Coccolithus pelagicus (x 10^N) per gram of fine-grained silt (2-20μm) in the surface sediments.

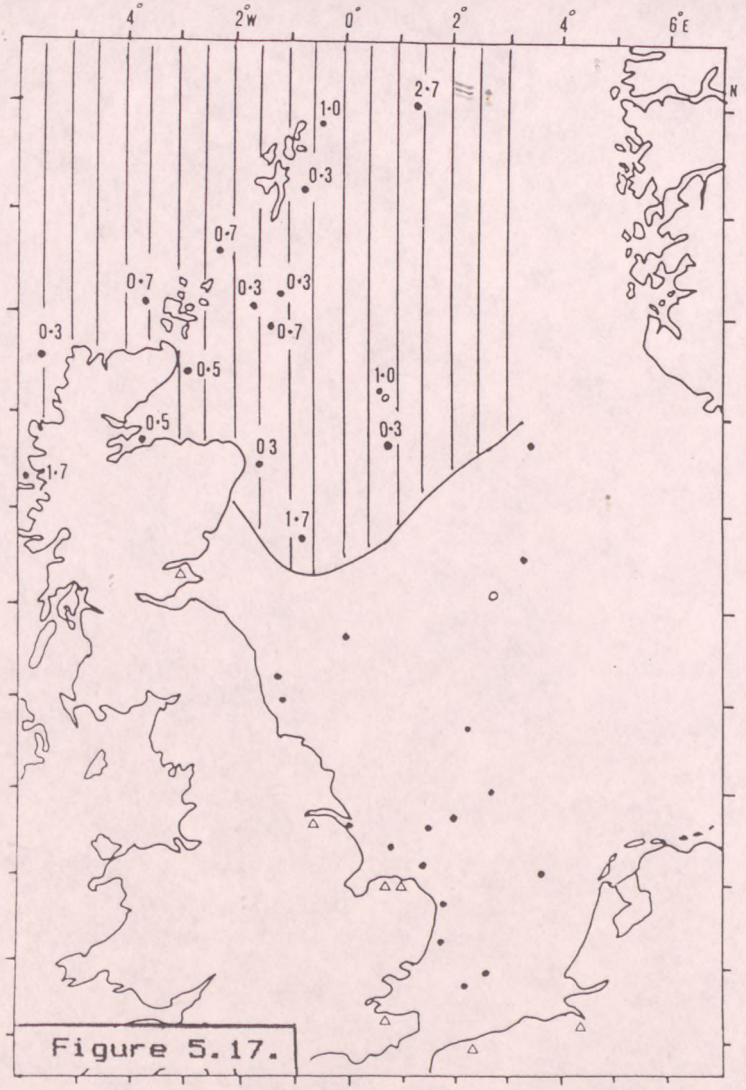


Figure 5.17.

Distribution of Calcidiscus leptoporus in the surface sediments. Numbers refer to the species % abundance in the total assemblage.

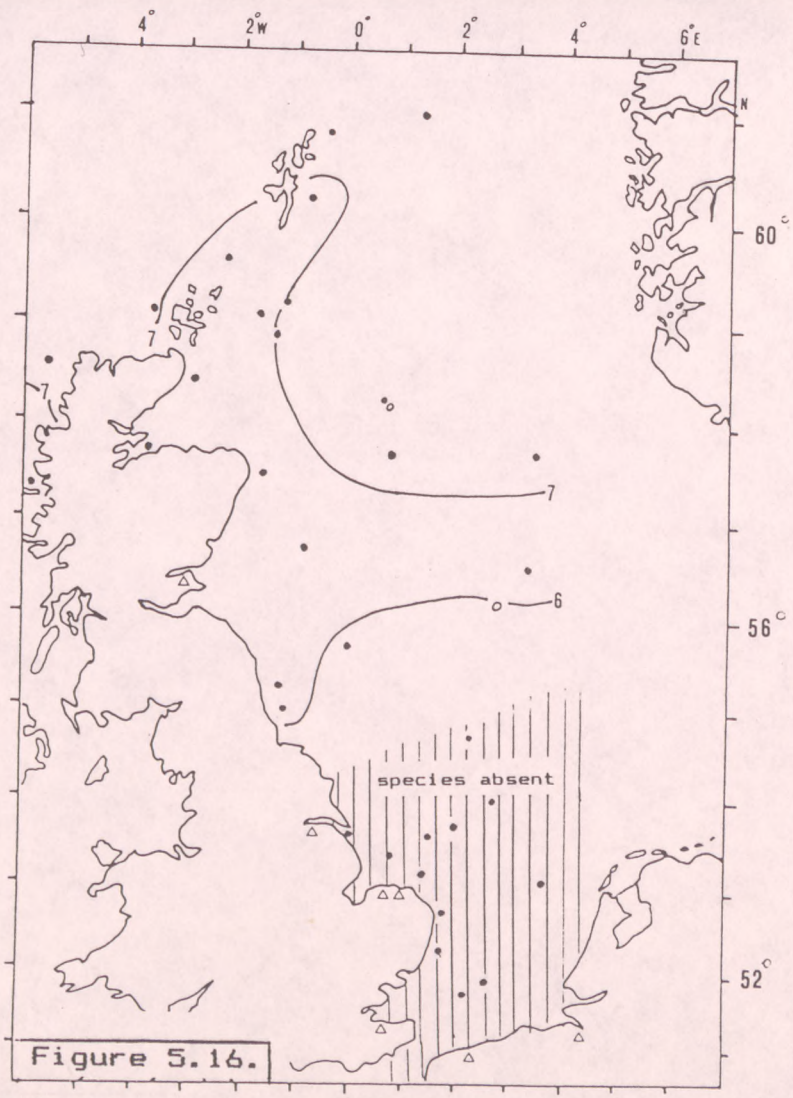


Figure 5.16.

Abundance of Syracosphaera pulchra (x 10^N) per gram of fine-grained silt in the surface sediments.

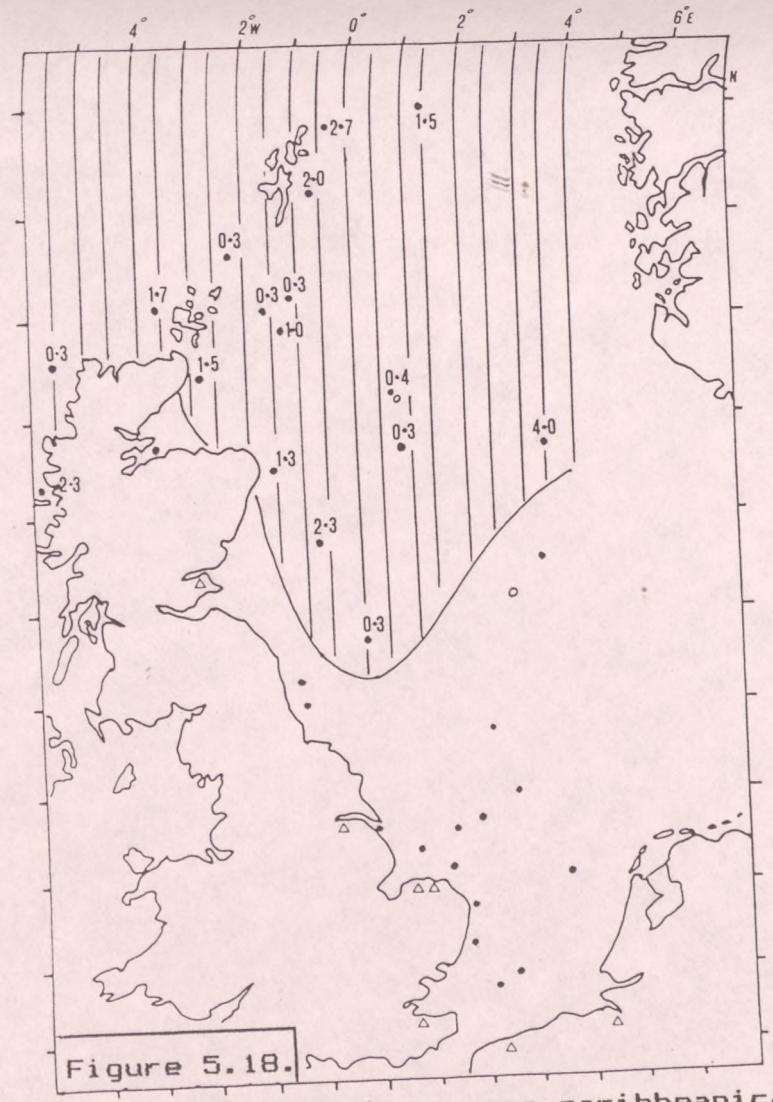


Figure 5.18.

Distribution of Gephyrocapsa caribbeanica in the surface sediments. Numbers refer to the species % abundance in the total assemblage.

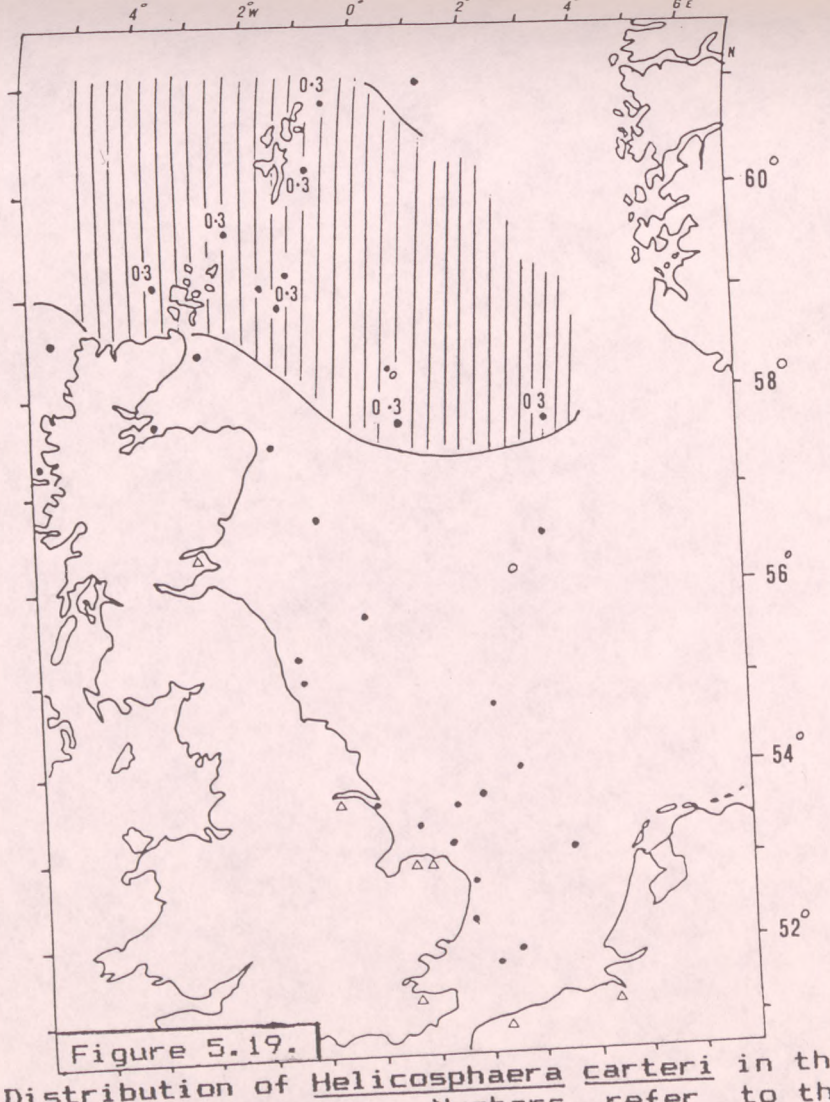


Figure 5.19.

Distribution of Helicosphaera carteri in the surface sediments. Numbers refer to the species percentage abundance in the total assemblage.

Table 5.3 Percentage abundance and species-composition of coccolith assemblages in the surface sediments of the North Sea.

SAMPLE	E.hx	C.pl	Sy.p	H.ct	C.lp	G.cr	B.bg	Rh.c	Total Number counted
6	-	-	-	-	-	-	-	-	
8	-	100	-	-	-	-	-	-	50
10	-	-	-	-	-	-	-	-	-
12	87.0	2.7	8.3	-	-	-	0.7	1.3	300
13	-	-	-	-	-	-	-	-	-
21	85.3	1.7	8.3	0.3	-	4.0	-	0.3	300
25	92.0	2.0	1.5	-	2.7	1.5	0.3	-	400
28	97.0	2.0	0.3	-	-	0.3	-	-	300
29	95.3	2.7	1.0	0.3	0.3	0.3	-	-	300
30	P*	P*	-	-	-	-	-	-	-
31	95.3	2.8	1.6	-	0.7	0.3	-	0.3	300
32	95.0	2.7	1.0	-	1.0	0.3	-	0.3	300
33	95.0	1.0	1.3	0.3	0.3	1.7	-	0.3	300
35	92.3	3.7	1.0	0.3	0.3	2.0	-	0.3	300
37	93.0	3.0	2.0	0.3	0.7	1.0	-	-	300
38	89.0	5.0	2.0	0.3	1.0	2.7	-	-	300
56	-	-	-	-	-	-	-	-	-
61	97.5	0.5	-	-	0.5	1.5	-	-	200
62	92.0	2.0	2.0	-	1.7	2.0	0.3	-	300
65	-	-	-	-	-	-	-	-	-
66	-	-	-	-	-	-	-	-	-
67	95.0	2.0	2.3	-	-	-	0.3	0.3	300
68	-	-	-	-	-	-	-	-	-
69	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-
75	96.5	0.5	2.0	-	0.5	-	-	0.5	250
76	91.7	1.3	2.3	-	1.7	2.3	0.7	-	300
77	94.7	1.3	2.0	-	0.3	1.3	0.3	-	350
89	95.7	1.7	1.7	0.3	0.3	0.3	-	-	300
90	96.7	1.0	1.7	-	0.3	0.3	-	-	350
92	-	-	-	-	-	-	-	-	-
93	-	-	-	-	-	-	-	-	-
117	-	98.0	-	-	-	-	2.0	-	50
150	P*	P*	-	-	-	-	-	-	-
151	P*	P*	-	-	-	-	-	-	-
152	P*	P*	-	-	-	-	-	-	-
153	P*	P*	-	-	-	-	-	-	-
154	-	-	-	-	-	-	-	-	-
155	-	-	-	-	-	-	-	-	-
156	-	-	-	-	-	-	-	-	-
157	-	-	-	-	-	-	-	-	-
159	-	-	-	-	-	-	-	-	-
160	-	-	-	-	-	-	-	-	-
200	91.7	6.2	0.1	0.1	1.0	0.4	0.1	0.1	730

E.hx = E.huxleyi , C.pl = C.pelagicus , Sy.p = Syracosphaera pulchra
H.ct = Helicosphaera carteri, C.lp = Calcidiscus leptoporus
G.cr = G.caribbeanica, B.bg = B.bigelowii , Rh.c = Rhabdosphaera clavigera
P* = species present but accurate percentage not determined.

Table 5.4 Numbers of coccoliths ($\times 10^5$/gram of fine silt (2–20 μm)), % coccoliths and wt.% carbonate in the fine fractions of surface sediments from the North Sea.

SAMPLE	number of *E.huxleyi*	number of *C.pelag.*	number of *S.pulchra*	total cocc. number	% cocc.	wt %. carb.
8	–	<10	–	<10	<.1	23
12	680	21	60	780	.5	44
21	10,000	200	1,100	11,800	9	26
25	49,000	1064	800	53,000	21	55
28	970	20	3	1,000	.7	17
29	9,900	280	100	10,400	15	37
30	<99	6	–	<99	P	ND
31	3,200	68	40	3,400	5	ND
32	ND	ND	ND	ND	7	ND
33	39,000	409	530	41,000	16	55
35	6,000	242	65	6,500	11	58
37	8,600	279	190	9,300	16	57
38	6,900	388	150	7,800	17	58
61	7,800	40	–	8,000	3	28
62	3,500	76	76	3,800	2	33
67	480	10	12	500	.5	11
75	1,500	8	20	1,600	1	20
76	3,500	50	90	3,800	8	22
77	2,500	34	50	2,600	4	34
89	5,200	92	90	5,400	4	59
90	11,000	116	200	11,6000	17	69
117	–	<10	–	<10	–	57
150	<10	<10	–	<10	–	17
202	11,000	772	30	12,000	15	ND

ND = not determined, cocc. = coccoliths . No modern coccoliths were recorded in samples 6,10,13, 68,69,92 and 93.

Table 5.5.

Percentage abundance and species composition of the coccolith assemblages in filter samples from the North Sea.

	site 200		site 201	
	(1)	(4)	(2)	(3)
Emiliania huxleyi	96.5	98.0	100	–
Coccolithus pelagicus	2.1	1.0	–	–
Calcidiscus leptoporus	1.1	0.6	–	–
Rhabdospaheara clavigera	0.1	0.3	–	–
Scyphosphaera apsteinii	0.1	–	–	–
Pontosphaera discopora	0.1	–	–	–
number of species	6	4	1	0
% coccoliths (< 40um)	20–25	10–15	<0.1	–

Table 5.6. Occurrence of plankton in the > 40 um fractions.

Site sample	diatoms	dinoflagellates	silicoflagellates
200 -1	+	–	–
200 -4	++	–	+
201 -2	+	++	–
202 -3	–	+++	–

– absent + present ++ common +++ abundant

5.3 DISCUSSION.

5.3.1 A comparison with previous work in the North Sea.

5.3.1.1 Sediment samples.

Murray (1985) noted the occurrence of coccoliths in sediments from the North Sea (Forties and Ekofisk areas) and the continental shelf to the west of Scotland (see Table 5.7).

The dominant species in all samples was Emiliania huxleyi. Greatest species diversity (3 to 5 species) occurred in sediments from the west coast of Scotland and in the Forties area, whereas lower diversities (1 to 2 species) occurred in the Fair Isle Channel and at Ekofisk. A similar trend of decreasing species diversity of coccolith assemblages southward in the North Sea is observed in this study. Slightly higher species diversities (5 or more), however, occur in sediments from the west coast of Scotland and also in the northern North Sea sediments. Similar low diversities (1 to 2 species) are recorded at Ekofisk and the rest of the central North Sea area. The main difference noted here is the increased species diversity of coccolith assemblages in the Fair Isle Channel (5 or more species) as opposed to the 1 to 2 species previously reported.

Altogether eight species of Recent coccolith were recorded by Murray. Two of these, Caneosphaera mollichii and Gephyrocapsa oceanica are not recorded in this study. However, additional species noted here but not recorded in the previous study include Rhabdosphaera clavigera, Syracosphaera pulchra, Braarudosphaera bigelowii, and Discosphaera tubifera. Caneosphaera mediterranea is only recorded from sites 29 and 200 in the Forties area in this study, although it probably has a much wider distribution

Table 5.7.
List of coccolith species recorded by Murray (1985) in sediments from the North Sea and in continental shelf to the west of Scotland.

	west of Scotland	Orkney/ Shetland	Forties	Ekofisk
Calcidiscus leptoporus	+	–	+	–
Caneosphaera mollischii	+	–	–	–
Coccolithus pelagicus	+	+	+	+
Coronosphaera mediterranea	+	+	+	+
Emiliania huxleyi	+	+	+	+
Gephyrocapsa oceanica	+	–	+	–
Helicosphaera carteri	–	+	–	–
number of species	3–5	2–3	3–5	1–2

Table 5.8. List of coccolith species recorded by Braarud et al. (1953) in the waters of the North Sea.

Acanthoica quattrospina Lohmann
Anthosphaera robusta (Lohmann) kamptner
Braarudosphaera bigelowii (Gran and Braarud) Deflandre
Calyptrosphaera hylina Gaarder
Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan
Caneosphaera molischi (Schiller) Gaarder
Coccolithus pelagicus (Wallich) Schiller
Coronosphaera mediterranea (Lohmann) Gaarder
Emiliania huxleyi (Lohmann) Hay and Mohler
Lohmanosphaera michaelsari Gaarder
Ootolithus fagilis (Lohmann) Okada and McIntyre
Rhabdosphaera clavigera Murray and Blackman
Syracosphaera caudata Gaarder

Table 5.9.
List of coccolith species present in the Celtic Sea sediments but absent from the North Sea sediments.

	Max. temperature range C
Ceratolithus cristatus	*
Gephyrocapsa oceanica	12-30
Gephyrocapsa ericsonii	12-27
Syracophaera nodosa	2-27
S.histrica	10-27
Scyphosphaera apsteinii	*
Umbellosphaera tenius	13-28
Ubilicosphaera foliosa	13-30
U.hulburtiana	13-30
Scapholithus fossilis	

* not precisely known but prefers tropical waters.
Temperature data after Okada and McIntyre (1979)

in the North Sea. Murray recorded C.mediterranea from sediments from the west coast of Scotland, the Fair Isle Channel and also at Forties.

5.3.1.2 Plankton samples.

Braarud et al., (1953) documented the occurrence of coccolithophores in the North Sea and the adjacent waters during May 1948. Thirteen species of coccolithophores were identified in the plankton samples (see Table 5.8). The coccolithophore communities found in the plankton samples were dominated by Emiliania huxleyi. This species generally had an abundance at least an order of magnitude greater than any of the other species. E.huxleyi together with Anthosphaera robusta were the only species that were sufficiently common in the waters of the North Sea to allow a distributional map of their occurrence to be drawn. E.huxleyi occurred in the plankton throughout the northern North Sea and extended as far south as 56°N latitude (Fig.5.20.). An isolated occurrence was also noted off the coast of Denmark. Throughout the rest of the southern North Sea the species was not recorded. Greatest abundance of E.huxleyi occurred in the waters between Faeroe and Shetland and in the central Northern North Sea (>125,000 cells/litre). A gradient of decreasing abundance occurred in the waters from south to north over the central North Sea region. At latitude 57°N the species abundance decreased to less than 5,000 cells per litre.

The distribution and abundance of E.huxleyi in the surface sediments described in this report correlates well with the findings of Braarud et al. (1953). E.huxleyi dominates the coccolith assemblages in the surface sediments of the North Sea and generally forms over 90% of the nannoflora. Greatest abundance of the species also occurs in the northern North sea with a similar trend of decreasing abundance occurring southwards. The general absence of coccolith species in the plankton samples from the southern North Sea is also reflected in the surface

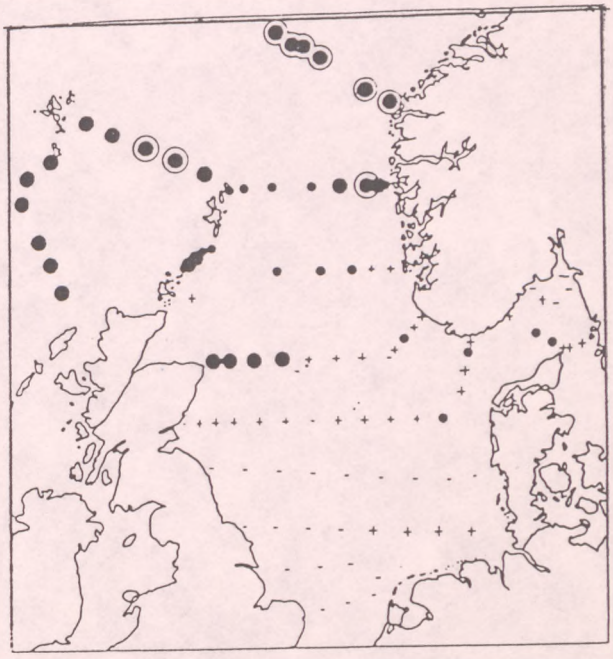


Figure 8.20
Distribution of E. huxleyi in plankton samples during May 1948. (After Braarud et al., 1953).

Maximum numbers at each station (cells per litre).

+ 0— 5,000
• 5,001—25,000
● 25,001—125,000
⊙ 125,001—

sediments of the area where only scarce occurrences of E.huxleyi and C.pelagicus are recorded. The dominance of E.huxleyi in the coccolithophore assemblages of the North Sea is also well reflected in the filter samples from site 200, where the species forms 96.5 to 98.0 % of the assemblages.

Most other records of the occurrence of E.huxleyi in the North Sea have been described from plankton samples in the coastal waters of Norway. The species is undoubtedly the most dominant coccolithophore in the coastal waters of south Norway. It has been recorded in numbers of 75 million cells/ l in the Oslo fjord and 115 million cells per litre on the Norwegian west coast at 33 %. salinity and 11° C (Berge, 1962). Smaller numbers (>20,000 cells per litre) of the species have been reported in the Skjomen, a fjord in north Norway (Schei,1975).

E.huxleyi was also reported from sediment traps attached to a drifting buoy launched at 58° 42.5' N, 0° 28.5'E (Cadee, 1985). These traps followed the water layer at 10-20m depth from April 27 to May 25, 1983 . Peak abundances of the coccolithophores in the surface waters (14.5 million cells/cubic metre) occurred on May 7. However, these traps on May 8-9 also contained large aggregates (up to 300 µm) of intact E.huxleyi cells embedded in mucoid material. Such aggregates of algal cells are thought to facilitate rapid removal from inhospitable environments that may occur in the surface waters (Smetacek, 1985).

Anthosphaera robusta was generally the second most abundant coccolith species recorded in the plankton samples of Braarud et al. (1953). Highest abundances of the species (5,000 to 25,000 cells per litre) occurred at the northern boundary of the North sea. The species is a common component in the plankton from the coast of Norway. It has been recorded in numbers of 42,000 cells per litre from Hardanger fjord (south west Norway) (Braarud et al.,

1974). The species also occurred in large numbers in Skjomen (>20,000 cell/l) (Schei, 1975). A.robusta has not been recorded from the waters of the southern North Sea.

Coccolithus pelagicus was recorded by Braarud et al. (1953) in the waters of the northern North Sea, particularly between the Faeroe Isles and Shetland Isles. The species was also reported from the coastal waters of Shetland during August, 1910 (Gaarder, 1954). The other species recorded by Braarud et al. were rare components of the plankton and they all had a very sporadic occurrence in the waters of the northern North Sea and in the Norwegian Sea. Seven species Acanthoica quatrospina, Anthosphaera robusta, Calyptrosphaera hyalina, Lohmanosphaera michaelsari, Oolithotus fragilis, Caneosphaera mollischi and Syracosphaera caudata are not recorded from the surface sediments sampled in this report. All of these species are of delicate construction, unlike the robust placolith-type coccoliths.

L.michaelsari and C.hyalina are holococcoliths and are seldom seen as fossils. The other species have caenolith-type coccoliths. Caenoliths and holococcoliths are the most fragile of all types of coccolith construction (McIntyre and McIntyre,1971). All these delicate species, observed in the plankton samples but absent from the surface sediments, are probably destroyed during descent through the water column. Disintegration would be enhanced by the generally turbulent and high energy conditions present in the shelf waters of the North Sea.

Gephyrocapsa caribbeanica, Syracosphaera pulchra, Helicosphaera carteri and Discosphaera tubifera are present in the Recent sediments of the North Sea but were not recorded in the plankton survey of Braarud et al. (1953). D.tubifera was however, recorded at sites in the central and northeastern North Sea in April,1920 by Wulff (1925).

5.3.2. A comparison between the coccolith assemblages in the bottom sediments with those trapped in the filters from sites 200 and 201.

Nine species of Recent coccolith were recorded in bottom sediments of site 202 , while only six and four species occured in filters 1 and 4 respectively. This difference in species diversity should be expected, as the filter samples only record the coccoliths present in the water samples at a specific height in the water column at the time of the sampling period, which represents only 48 hours in filter 1 and two months in filter 4. The surface sediment sample forms a continuous record of the coccolith species that occur throughout the water column. Seasonal blooms of coccoliths not recorded by the periodic sampling using the filters should be noted in the bottom sediments, unless the species have delicate coccoliths that disintegrate during their descent through the water column. Such species would include holococcoliths and caneolith-type coccoliths.

Four coccolith species; Syracophaera pulchra, Gephyrocapsa caribbeanica, Helicosphaera carteri and Coronosphaera mediterranea, occur in the bottom sediment but are absent in the filters. B.bigelowii occurs spasmodically in the surface sediments of the northern North Sea and is a scarce component of the coccolith assemblages (1% or less). G.caribbeanica, H.carteri and S.pulchra are present throughout the northern North Sea sediments, especially in areas of strong Atlantic influence. The absence of these species in the filter samples is probably due to the short sampling periods. Two species ; Pontosphaera discopora and Scyphosphaera apsteinii, are present in the filter samples but are absent in the sediment samples. Both species have delicately constructed coccoliths which are probably destroyed during descent through the water column

The other main difference between the coccolith assemblages in filter samples 1 and 4 and in the bottom sediments is the mode of preservation of the individual coccoliths. Preservation of coccoliths (especially those of Emiliania huxleyi) in the filter samples is generally only moderate, with many of the coccoliths showing signs of breakage. However, identification of these coccoliths in the filters was not hindered as there was little evidence of dissolution of the individual skeletal elements. Coccoliths of E.huxleyi in the bottom sediments show a wide range of dissolution features (see Pl.13). Many skeletal elements of the distal shields have lost their T-shaped ends; this is uncommon in filter sample coccoliths, where even broken skeletal elements this feature intact. The skeletal elements of E.huxleyi in the bottom sediments usually taper to a blunt end, and are frequently reduced to half their original length (Pl.13, Fig.6.).

Further evidence of dissolution in coccoliths of E.huxleyi is the loss of the central grill. Some coccoliths are reduced to a mere vestige of their original structure (Pl.13, Fig.8.). Other coccolith species also show signs of dissolution, eg. Helicosphaera carteri (Pl.17, Fig.4.). Some coccoliths in the bottom sediments also have diagenetic overgrowth or are clay-coated. In contrast to this, coccoliths in the filter samples generally have a 'fresh' appearance.

Coccoliths are scarce or absent in the filter samples from site 201 and are limited to the species Emiliania huxleyi. This scarcity of coccoliths in the water column is also reflected in the surface sediments of the area, where only Emiliania huxleyi and C.pelagicus occur and abundances reach only 10^6 individuals per gram of sediment.

5.3.3 Evidence for the origin of the plankton component in the filters.

The depth of water in the region of site 200 is approximately 120m. Filters 1 and 4 trapped sediment from the water column at a depth of 55m (182 ft) below the sea surface. The filters are therefore located approximately 65m above the seabed. Because the filters are not located within the surface layer of the water column the origin of the sediment trapped in the filters may be in some doubt. Some sediment may be supplied from resuspended bottom detritus. To determine the origin of this sediment a detailed investigation of the plankton and detrital components of both the bottom sediment and filter sediment was carried out.

Superficially, the coccolith assemblages resemble those found in the bottom sediments; there is a dominance of E. huxleyi, with C.pelagicus and Calcidiscus leptoporus subordinate. There are significant differences between the two assemblages, however, which do not point to a common origin.

Transitional and cold-water forms of E.huxleyi occur in both sediment and filter samples. However, the mode of preservation in the filter samples is generally much better than those found in the surface sediments. Both intact coccoliths and broken elements have pristine T-shaped elements in the filter samples and most of the coccoliths are generally free from clay. Such features would not be typical of coccoliths resident at the sediment-water interface for any length of time, or for coccoliths involved in the potentially damaging processes of deposition, erosion and resuspension. Moreover, there is no readily available source of well-formed T-shaped elements in the bottom sediments. Most of the coccoliths of E.huxleyi do not have T-shaped ends to their skeletal elements in the bottom sediments. Therefore if a significant component of bottom sediment coccoliths of E.huxleyi is present in the filter, more evidence of dissolution in the filter sample coccoliths would be expected.

Transitional and cold-water coccoliths of E. huxleyi have an open structure which is more delicate than the fused imbricated structure of coccoliths of Coccolithus pelagicus and Calcidiscus leptoporus. If resuspension and reworking of bottom coccoliths into the filter samples were occurring then an increase in the more durable forms and a decrease in the more delicate forms would be expected. However, the reverse occurs in the filter samples where E.huxleyi has an abundance ranging from 96.5 to 98.0 % as opposed to 91.7 % in the bottom sediments. Additionally, delicate species such as Scyphosphaera apsteinii and Pontosphaera discopora, which only occur in the filter samples, would probaly not survive resuspension and transport through the water column. The absence of the species S.pulchra, G.caribbeanica and H.carteri in the filter samples and their consistent presence in the bottom sediments of the northern North Sea is a further indication of separate origins for the filter and sediment assemblages.

Other evidence which points towards a primary origin of the sediment in the filters is supplied by the plankton component in the coarse fractions. Centric diatom frustules are common in the coarse fractions of the filter samples but are absent in the bottom sediments. Diatom frustules are scarce in Recent bottom sediments throughout the North Sea and are hardly ever seen in suspension, even in the rather productive southern North Sea (Eisma and Kalf, 1979). Tests of foraminifera are the only significant biogenic debris in the coarse fraction of bottom sediments at site 200. Such tests are scarce in the filter samples. The coarse fraction of bottom sediments at site 200 is mainly of detrital origin, being composed of quartz grains with subordinate amounts of feldspar,amphibole and very scarce grains of glaucony. The coarse fractions of the filter samples , however, lack these detrital components.

The filter samples were collected during spring and

summer months when a thermocline is developed in the water column. During such conditions resuspension of bottom sediment only occurs to some 40m above the seabottom in the Fladenground region of the North Sea (58° 42.5'N, 0° 28.5' E) (Davies and Payne, 1984). The filters are located approximately 65m above the seabed, therefore it is probable that they are located too high in the water column to trap any resuspended sediment when the waters are stratified.

Motile dinoflagellate thecae of Ceratium furca, Ceratium tripos, Dinophysis acuta and Protoperidinium spp. dominate the plankton component of the coarse fractions from site 201. Dinoflagellate thecae, unlike cysts, are not robust and are generally never preserved in bottom sediment. The plankton component from site 201 is therefore undoubtedly of primary origin. From the points outlined above it is concluded that the coccoliths and other plankton filtered from the water column are of primary origin and are not derived from resuspended bottom sediments.

5.3.4. A comparison of the North Sea and Celtic Sea coccolith assemblages.

The major difference between the coccolith assemblages of the two areas is the number of species found in the sediments. Twenty species were recorded in sediments from the Celtic Sea and western English Channel, whereas only ten occur in the northern North Sea region. This difference in species divesity is not simply caused by a more neritic watermass in the North Sea region. In fact, a large area of the northern North Sea and the continental shelf to the west of Scotland comes under a strong Atlantic influence similar to that present in the Celtic Sea and western Channel. These differences are thought to result from the more northern latitude and the cooler temperature of the waters entering the North Sea across its northwestern margin. The surface waters enter the North Sea from a latitude of about 61° N, with

spring/summer temperatures usually below 12° C, whereas surface waters entering the Celtic Sea from the southwest, at a latitude of about 48° N, easily reach a temperature of 16° C during the summer.

Table 5.9 lists those species present in the Celtic Sea sediments but absent from the North Sea sediments. Most are warm-water coccoliths and only form a minor component of the Celtic Sea assemblages. Three of these species are only present at the extreme western margin of the Celtic Sea (Ceratolithus cristatus, Scapholithus fossilis and Umbellosphaera tenuis). It is likely that the bulk of the species listed in table 5.8 from the Celtic Sea are at or near their northern biogeographic limit in the Atlantic Ocean (refer to section 8.3.1). The maximum temperature range of these species is also listed in the table. Species such as Umbilicosphaera sibogae, U.hulburtiana and Umbellosphaera tenuis which have a lower temperature limit of 13° C, but would prefer much warmer waters, are therefore absent from the major N. Atlantic inflow to the northern North Sea.

The coccolith assemblages recorded in the surface sediments of the northern North Sea are similar to those in the Celtic Sea sediments in the following respects;

1) the dominance and quantitative abundance of E.huxleyi,

2) the relative and quantitative abundance of the subordinate species C.pelagicus and Syracosphaera pulchra,

3) both assemblages have a similar minor species component (0.3 to 2.0%).

The relative abundance of E.huxleyi has a consistent range in the northern North Sea (85.3 to 97.5% ,mean 93.5%) and in the Celtic Sea (82.5 to 97.5%, mean 91.5%). The quantitative abundance of E.huxleyi and the total number of coccoliths in the sediments have similar maximum values (10^9 per gram) throughout the open water sediments of the Celtic Sea and in the continental shelf regions to

the northwest of Scotland and in the northern North Sea. Coccolithus pelagicus averages 2.0% in the northern North Sea area and 2.6% in the Celtic Sea sediments.

The quantitative abundances of the species in the sediments of the two regions are also consistent. Maximum values (10^9 per gram) are restricted to relatively small areas; in the northern Celtic Sea and at the northern margin of the North Sea. Values of 10^8 are typical of sediments deposited from the open-waters of both regions. Syracosphaera pulchra is slightly more abundant (3.8%) in the Celtic Sea than in the North Sea sediments (2.2%). The minor species component (2 to 0.03%) of the assemblages of both areas are similar. Helicosphaera carteri, Calcidiscus leptoporus, Rhabdosphaera clavigera, Discosphaera tubifera, B.bigelowii and Gephyrocapsa caribbeanica have consistent relative abundances in both regions. B.bigelowii, D.tubifera and H. carteri, however, tend to have a more sporadic occurrence in the North Sea sediments.

Coccolith assemblages preserved in Recent sediments of the Celtic Sea/ western English Channel and in the North Sea have been shown to be similar in many respects. The only major difference is the absence in the latter region of the minor warm-water species-component present in the Celtic Sea/western Channel sediments. The reduced species diversity is thought to reflect differences in the temperature of the inflowing water of the two regions ,rather than variation in the strength of oceanic influence of the two regions.

5.3.5. Transport paths of coccoliths within the North Sea Area.

Atlantic water with a salinity > 35%. enters the North Sea through the Straits of Dover in the south and between Shetland and Norway in the north. These are the two main possible pathways for the transport of coccolith species into the North Sea basin. The third inflow to the

North Sea from the Baltic is not considered a potential supplier of the coccolith assemblages studied in this report as it has a salinity generally between 24 and 30 ‰. (Lee, 1980) and only flows out in a narrow path , hugging the coast-line of West Norway.

The most obvious transport path for the coccoliths into the North Sea is from the northwest. Using this path the coccolith species would travel within the southward-flowing mass of Atlantic water around the eastern coast of Shetland and entering the central area of the northern North Sea. Strong evidence for this transport path is provided by the decreasing gradients from north to south of the following parameters;

1) the number of species found in the assemblages,

2) the number of coccoliths per gram of sediment,

3) the percentage coccolith component in the fine fractions.

All the species recorded in the northern North Sea sediments are found in sediments deposited by Atlantic waters on the continental shelf off the west coast of Scotland. Therefore a potential source of the coccolith assemblages occurs to the northwest of the North Sea region. The transport of coccolith species through the Faeroe-Shetland Channel and into the northern North Sea was first proposed by Braarud *et al*. (1953). He found that in May 1948 large numbers of *E.huxleyi* characterised the Atlantic water flowing into the area. Additionally the species was found in even greater numbers in 'older' Atlantic water present in the southern part of the Norwegian Sea, and commonly occurred in the waters of the northern North Sea, in which a mixture of Atlantic water had taken place.

The inflow of water between the coast of Norway and Shetland contributes approximately 42,000 km^3/y of the

total inflow (51,000 km^3/y) into the North Sea across its northern margin. A smaller additional imput of water occurs through the Fair Isle Channel. It takes place on the Orkney side of the channel and is estimated to be 9,000 km/y (Dooley,1974). Analysis of the total abundance of cocccoliths in the surface sediments shows that a tongue of bottom sediment with maximum abundance values (10^9coccoliths per gram) traces out the path taken by the inflowing Atlantic Water east of the Isle of Shetland. This confirms that the greatest number of coccoliths are brought into the North Sea with the main inflow of Atlantic water. Lower numbers of coccoliths (10^8per gram) are deposited from the Atlantic water flowing between Orkney and Shetland. Coccolith species are transported within this coastal current to about as far south as 54°S.

The other main inflow of Atlantic water into the North Sea via the Dover Strait from the south is not thought to be an important supplier of coccoliths . The species diversity of the coccolith assemblages present in the English Channel sediments declines in an easterly direction towards Dover Strait. At the eastern margin of the Channel only a very sparse nannoflora is deposited from the overlying waters, limited to the species Coccolithus pelagicus, Emiliania huxleyi and Braarudosphaera bigelowii. Braarud et al. (1953) found a general absence of coccolithophores in plankton samples at the eastern entrance to the English Channel. They concluded that "in May 1948 no recent contribution of water similar to the influx in the north had taken place in the south".

Recent coccoliths are only recorded from sediments within the Scheldt estuary at Antwerp and along the French coast within the southern North Sea. The only record of E.huxleyi in plankton samples throughout the southern North Sea is limited to a few cells recorded off the Dutch coast by Braarud et al. (1953). The coccoliths found within the Schedlt Estuary are unlikely to have been supplied from similar small populations of the species

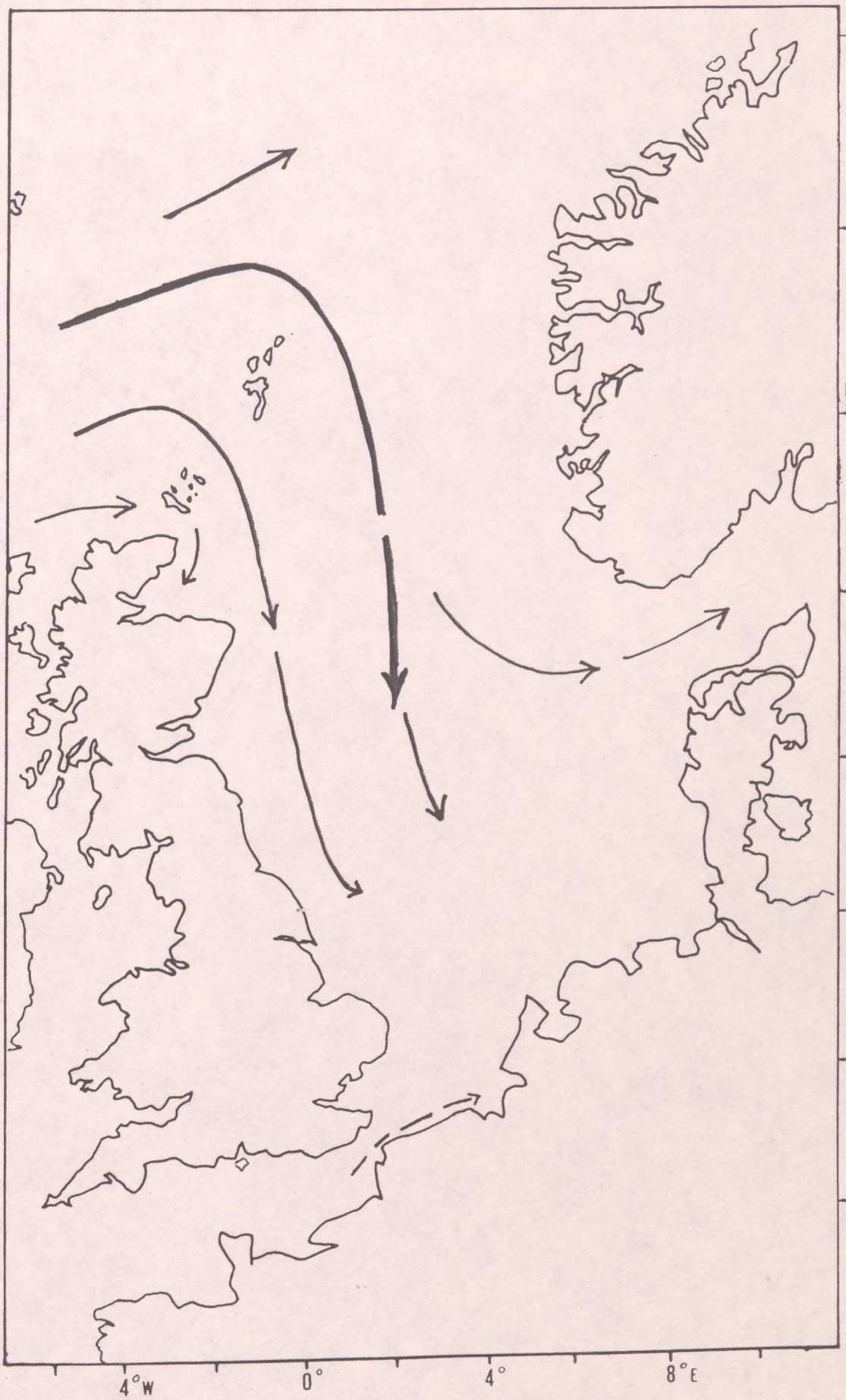


Figure 5.21
Suggested transport paths of coccoliths within the North Sea.

just offshore of Holland as this transport direction would be against the general northeast flow of the coastal water within the region. The Continental Coastal Water would be unsuitable for local coccolithophore growth as it has high turbidity and high trace metal concentrations. The coccoliths are probably transported within the suspended load of the inflowing water from the Channel. Suspended matter concentrations in coastal waters of the Dover-Calais Strait may reach up to 11 mg/l (Eisma, 1981). In the Schedlt Estuary there is a net inflow of suspended sediment from the sea (Terwindt, 1967,1977).

5.3.6. Relationship of the coccolith assemblages in the Recent sediments to the overlying hydrographic regions.

The North Sea has been divided into a set of hydrographic regions by Laevastu (1963) as previously described in section 5.1.8. The most recent concept of these regions is shown in Fig. 5.10. Each region contains a particular water type and can be identified from its properties of salinity, temperature and nutrient levels. Recent sediments were sampled from regions A1, A2, A3, A4, A6, and B in this study.

Region A occupies the coastal zones (except off Norway), and the shallow area of the North Sea from the Dogger Bank southwards. This region can be divided into 4 sub-regions; Region A1 extends along the Scottish and English eastern coast from Orkney to Flamborough Head and is characterised by the south-going flow of medium salinity (34 to 35 ‰) Scottish Coastal Water, with mixed water containing both coastal and oceanic components further offshore. Highest abundances of coccoliths (10^8 per gram) occur in sediments deposited to the southeast of Orkney and off the northeastern coast of Scotland. All the species recorded in the North Sea are present in this area. These waters are closest to the main body of the Atlantic inflow into the northern North Sea and are stratified throughout the summer months.

Coccospheres of Calcidiscus leptoporus were recorded in sediments from the Moray Firth in this region. The decreasing influence of Atlantic water is reflected south of Aberdeen where the 10^8 contour of coccolith abundance bends away from the coast indicating the main oceanic component is present further offshore. This area of decreased coccolith numbers also occurs in an area of

increased tidal-mixing. The water column along the eastern coast of Scotland and northern England is transitional in character between a stratified region and a tidally mixed region. This region is usually characterised by a rich diatom flora including the species Asterionella japonica, Chaetoceros spp. and Nitzschia delicatissima (Braarud et al., 1953).

Region A2 extends along the English coast south of Flamborough Head. It is mainly occupied by English Coastal Water with mixed Coastal Water and Channel components further offshore. The waters of this region have a low salinity, <34 to 34.5 ‰. ,high nutrient levels and high turbidity (Lee, 1980). This region is neritic in character and does not come under the oceanic influence which characterises the Scottish coast further north. The waters are homohaline and are tidally mixed throughout the year. No Recent coccolith species were recorded from the sediment in this region. The neritic character of the region is reflected in the occurrence of an estuarine type diatom flora, where Chaetoceros danius and benthic diatoms mixed with Asterionella spp. are characteristic (Braarud et al., 1953)

Region A3 extends from the Strait of Dover through the middle of the Southern Bight. The waters are homohaline and contain the north-going flow of high salinity Channel Water. No Recent coccoliths were recorded from the surface sediments from this region. Coccolithophores were absent from this region in the plankton survey of Braarud et al.,. This region is characterised by a restricted flora containing mainly benthic species.

Region A4 extends along the continental coast from Calais to Limfjord and represents the Continental Coastal water mass of Laevastu (1963). The region is occupied by a northward flow of low salinity (34‰.) coastal water. This sub-region is rich in nutrients but has high trace

metal contents and high turbidity (Lee,1980). Scarce coccoliths of E.huxleyi, Coccolithus pelagicus and Braarudosphaera bigelowii are found in sediments along the French coast and in the Schedlt Estuary. These species are unlikely to be living in the coastal waters but are probably transported within suspended sediment introduced from the Channel (see section 5.3.5). Braarud et al. (1953) did not record coccolithophores from plankton samples in this region except for a small area off the Dutch coast. Here a few cells of Emiliania huxleyi (<5,000 cells/l) were recorded from the surface waters. This particular area corresponds to the only region of the southern North Sea where the water column may become stratified. Stratification occurs as low salinity coastal water rides over high salinity Atlantic water (Postma, 1954; Fonds and Eisma, 1967). The plankton recorded in this region included a high number of bottom species such as Melosira sulcata, Biddulphia spp., and Navicula spp. (Braarud et al., 1953).

Region A6 contains the Dogger Bank and the area immediately to the south of it. Its waters, apart from isolated areas on the Dogger Bank, are homohaline and are of mixed origin, having components of Scottish and English Coastal, Channel and North Atlantic Water. These waters have medium salinity , medium nutrient salt levels and low trace metal levels (Lee, 1980). Recent coccoliths were only recorded from sample 8, near the northern margin of this area. The coccolith flora in these sediments is very sparse (10^5 per gram) and is limited to the species Coccolithus pelagicus. These coccoliths are probably supplied from water mixed with a North Atlantic water component. The plankton of the region is characterised by a diatom and dinoflagellate flora. The dinoflagellates include Exuviaella baltica and in some places Ceratium spp. Diatoms are particulary common in the Dogger Bank region where Rhizosolenia spp. dominate (Braarud et al.,1953). These large numbers of diatoms occur where the bottom configuration leads to an upwelling of deeper waters, accompanied by turbulence. Such processes

generally are observed near banks and the bottom shoals (Bigelow, 1927).

Region B is characterised by thermal stratification in the summer months and by vertical salinity gradients over most of the area. This region forms the deeper central part of the northern North Sea and extends from the northern margin to the Dogger Bank. The northern part of this region contains high salinity (>35%.) North Atlantic Water. Turbidity is low and nutrient salt levels low to medium (Lee,1980).

This northern area of Region B correlates with the highest number of modern coccoliths within the surface sediments of the North Sea (10^9per gram). Five or more coccolith species occur in sediments deposited throughout the area and all the Recent coccoliths recorded from the North Sea sediments occur here. Lower numbers of coccoliths occur near Orkney and Shetland (10^8per gram). Higher tidal currents in this area cause turbulence with the result that the water column is practically homogeneous.

Coccolith numbers and species diversity of the assemblages decrease steadily southwards in Region B. South of about latitude 58° N coccolith abundances drop below 10^9 per gram. At 55°N numbers decline to 10^6per gram. The decline in coccolith numbers southwards is parallelled by a decline in oceanic influence in the overlying water column. The southern part of region B is largely occupied by North Atlantic Water in the winter months but in the summer the surface layer is dominated by mixed water containing Scottish Coastal, Continental Coastal, Skagerak and a minor North Atlantic component. This region has high to medium salinity and low turbidity (Lee, 1980). Coccolith assemblages deposited here are limited to the species Coccolithus pelagicus and Emiliania huxleyi. The southern margin of Region B at 55° N correlates approximately with the maximum southerly extention of Recent coccoliths in the sediments of the

central North Sea area. This margin also generally divides an area of stratified waters in the central North Sea from tidally mixed waters in the southern North Sea during the summer months.

Similar changes southwards in the plankton present in the overlying waters of this region were recorded by Braaarud et al. (1953). In the northern North Sea the inflowing Atlantic water was characterised by a flora poor in numbers of species but rich in populations of E.huxleyi and the dinoflagellate Exuviella baltica. E.huxleyi often occurred in abundances in excess of 125,000 cells per litre. Diatoms were extremely scarce in the northern North Sea. The vegetation indicated that in this region the oceanic Atlantic Water had only mixed very slightly with waters containing the charateristic neritic diatom flora. Further south, the diatom populations increased with Chaetoceros spp., Thalassiosira bioculata and Nitzschia delicatissima the most prominent. These diatom populations quickly replaced E.huxleyi as the dominant component of the plankton. The coccolithophore only occurred in numbers <5,000 cells per litre south of latitude 58°N.

Near the southern margin of region B, the plankton was limited to a poor vegetation of dinoflagellates, mainly Exviaella baltica and Ceratium spp. No coccolithophores of the species Emiliana huxleyi were recorded in the plankton samples south of latitude 56.5°N. A similar plankton composition was recorded in filter samples from site 201 near the southern margin of region B in this study. Abundant dinoflagellates occurred in these filters but coccoliths were extremely scarce (< 0.1%).

5.3.7 Correlation of coccolith abundance with salinity and water-depth in the North Sea.

High coccolith numbers (10^9 per gram) are associated with the high salinity (>35.0%.) inflow to the North Atlantic. This suggests that salinity is an important control on coccolith abundance in the bottom sediments. Similar high coccolith abundances, however, also occur in the following area of low salinity waters:

1) Scottish Coastal Water north of Scotland (~34.8%.),
2 northern Sea of the Minches (~34.8%.),
3) east of the high salinity inflow in the northern North Sea (sample 21) (~34.0%.),

Bar graphs in Fig 5.22 illustrate the variations of the log of coccolith abundance in open-water samples from the northern and central North Sea plotted against salinity. These histograms represent the log of the mean coccolith abundance within each 0.1 %. division of surface salinity (summer values). From the histograms it is evident that salinity is not significantly correlated with changes in coccolith abundance. Similar histograms have not been presented for correlating coccolith abundance with the tidal stream data, because of the difficulty found in plotting the exact values of the tidal streams shown in Fig. 5.7, and also because the bulk of the samples plot in the 1.0 to 2.0 knot division. Graphs showing the variation of coccolith abundance versus water-depth are shown in Fig. 5.23. Coccolith abundance has a strong positive correlation with water-depth.

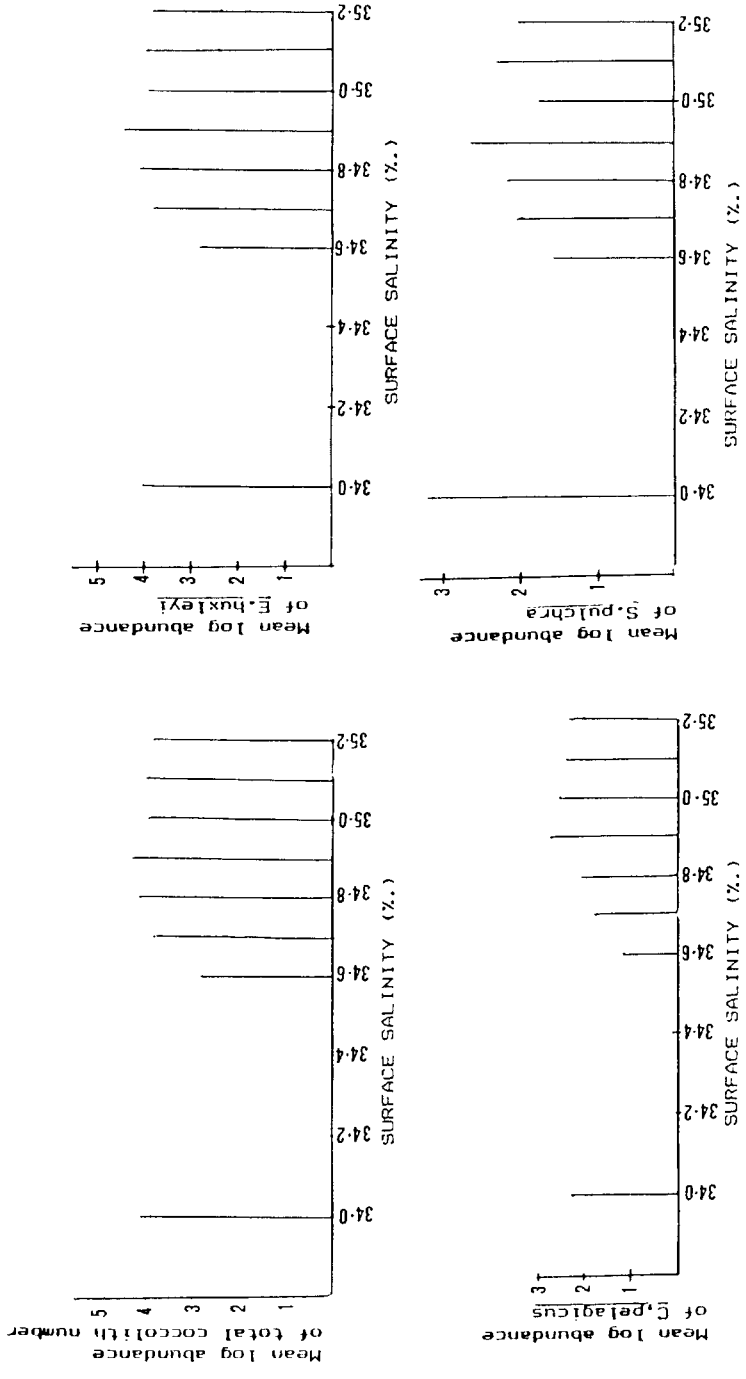


Figure 5.22
Plots of coccolith abundance versus mean sea-surface salinity (%.) (summer). Histograms represent the log of the mean coccolith abundance within each 0.1%. of salinity. Salinity values are taken from Fig.5.5 Note that the coccolith abundance represent numbers $\times 10^6$ per gram.

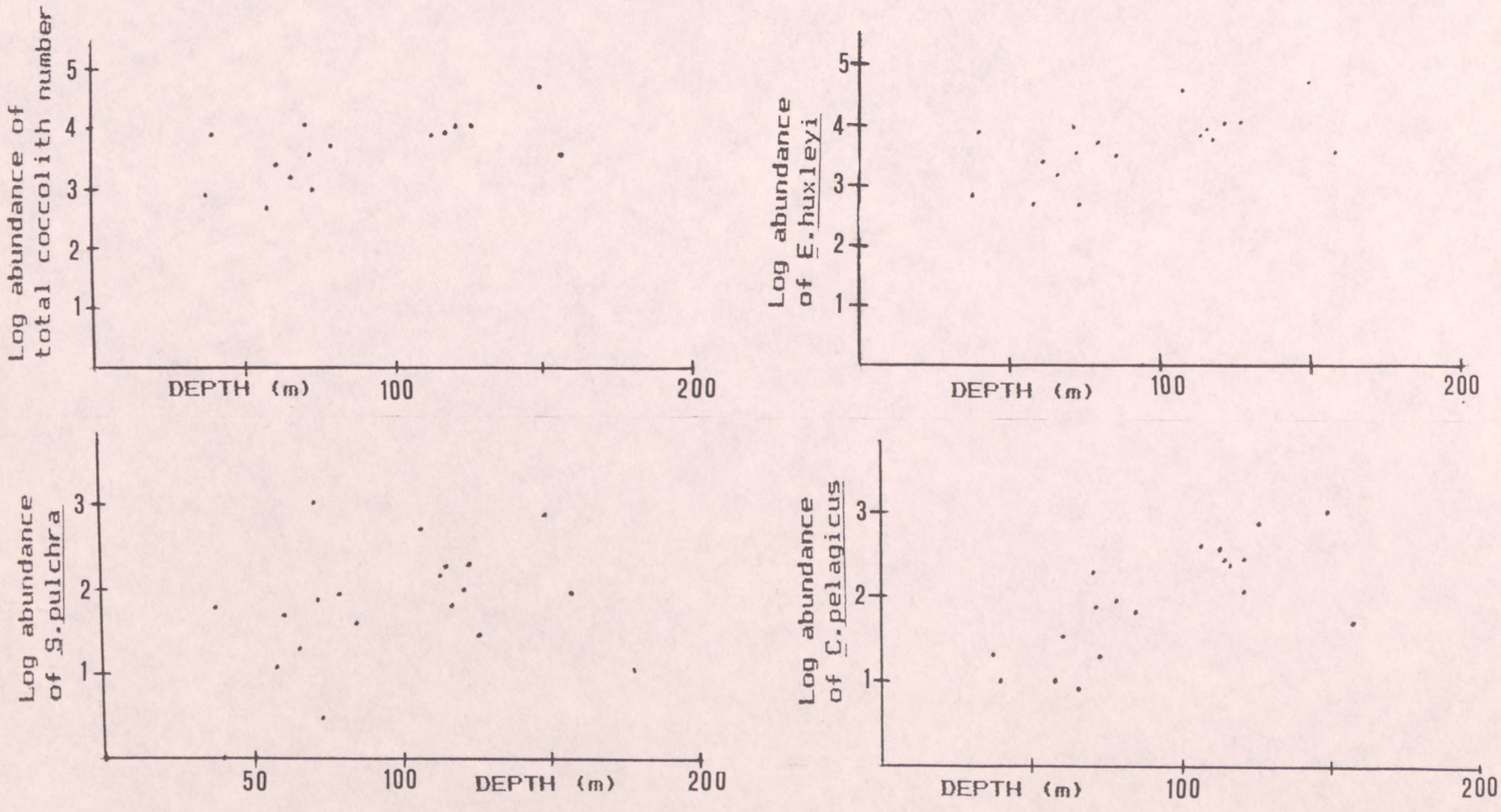


Figure 5.23
Plots of coccolith abundance versus depth.

Table 5.10
Correlation coefficients among coccolith abundance (log 10 values) and among salinity and water-depth.

	Salinity	Depth	
S.pulchra	-0.55	0.52	*
C.pelagicus	0.33	0.73	**
E.huxleyi	0.13	0.60	**
Total number	0.09	0.61	**
Degrees of freedom	6	17	

* significant at the 95% confidence level
** significant at the 99% confidence level

4. CONCLUSIONS

Ten species of Recent coccolith were recored from the sediments of the North Sea; Emiliania huxleyi, Coccolithus pelagicus, Calcidiscus leptoporus, Syracosphaera pulchra, Gephyrocapsa caribbeanica Helicosphaera carteri, Braarudosphaera bigelowii, Rhabdosphaera clavigera, Discosphaera tubifera and Coronosphaera mediterranea.

The coccolith assemblages are dominated by E.huxleyi, which averages 93.5 % of the population in the northern North Sea sediments. Subordinate species (1 to 2.5%) include C.pelagicus, S.pulchra and G.caribbeanica. The other species form only a minor component (<1.0%). Filter samples analysed from the northern North Sea also showed a dominance of E.huxleyi in the overlying waters. A comparison bewtween the coccolith assemblages in the filters and in the surface sediments delineated differences in the state of preservation between the two sample types. Coccoliths present in the surface sediments frequently showed signs of dissolution of their skeletal elements, whereas coccoliths fitered from the water column are generally in a more pristine condition.

The distribution and abundance of coccoliths in the surface sediments of the North sea are controlled by currents and the varying hydrographic conditions present within the overlying waters.

Highest coccolith numbers (10^9 per gram) are deposited at the northern and northwestern margins of the North Sea , where Atlantic influences are pronounced. These waters are stratified in the summer and have surface salinities varying from 32.2% to 34.0% . Coccolith assembalges deposited in this region contain five or more species. Coccolith abundance and species diversity in the sediments decreases steadily from north to south over the

region , reflecting the decreasing influence of North Atlantic water and the increasingly mixed character of the water mass. Recent coccoliths are generally absent in the southern North Sea sediments south of 55°S. The waters in this region are more neritic, tidally mixed and have a low salinity (<35.0 ‰). The extent of the Atlantic influence and the degree of tidal-mixing of the water column are suggested to be the most important controls on coccolith abundance in the North Sea sediments.

The bulk of the coccolith assemblages found in the Recent sediments from the North Sea are supplied from the North Atlantic inflow between Shetland and the Norway coast. Smaller numbers of coccoliths are also transported into the northern North Sea through the Fair Isle Channel. Northward flowing Channel water from the Dover Strait is not an important supplier of Recent coccolith species to the area.

The coccolith assemblages preserved in the northern North sea sediments are similar, in most respects, to those found in the open-water sediments of the the Celtic Sea and western English Channel . The main difference is the absence in the North Sea sediments of the minor warm-water component of the Celtic Sea assemblages. These differences reflect the colder temperature of the inflowing Atlantic water into the northern North Sea.

The abundance and species diversity of coccoliths in the Recent sediments can be used as a good indicator of the degree of Atlantic influence and also the degree of tidal mixing throughout the waters of the North Sea. The movement of Atlantic water southwards along the eastern coast of Britain and in the central North Sea can be traced by the distribution of coccoliths in the Recent sediments.

CHAPTER 6

TRANSPORT AND DEPOSITION OF COCCOLITHS AND OTHER FINE SEDIMENT WITHIN THE SOLENT ESTUARINE SYSTEM

CHAPTER 6

TRANSPORT AND DEPOSITION OF COCCOLITHS AND OTHER FINE SEDIMENT WITHIN THE SOLENT ESTUARINE SYSTEM.

6.1 INTRODUCTION

6.1.1 Background and main objectives.

The previous record of coccolith occurrence in Holocene sediments from the Solent region is a brief note by Hodson and West (1972) who recorded Coccolithus pelagicus and reworked Cretaceous forms in estuarine deposits at Fawley. There is no record of the occurrence of coccolithophores in the waters of the Solent.

Hodson and West, in 1970, have also documented the calcareous nannoflora from an Upper Bracklesham horizon at Fawley. Hamilton and Hajjatzadeh (1982) & Aubry (1983, 1985) have included samples from the Hampshire Basin in their coccolith biostratigraphical studies on the Cainozoic of northwestern Europe.

The main objectives of this study are to define the coccolith assemblages in the surface sediments of the Solent Estuarine System. The variations in the abundance of Recent coccoliths in the sediments are related to the hydrography of the Solent. The distribution of reworked coccoliths in the assemblages is used to delineate local sources of sediment supply. Variations in the mineral composition of the fine sediments and the possible causes of these differences are presented.

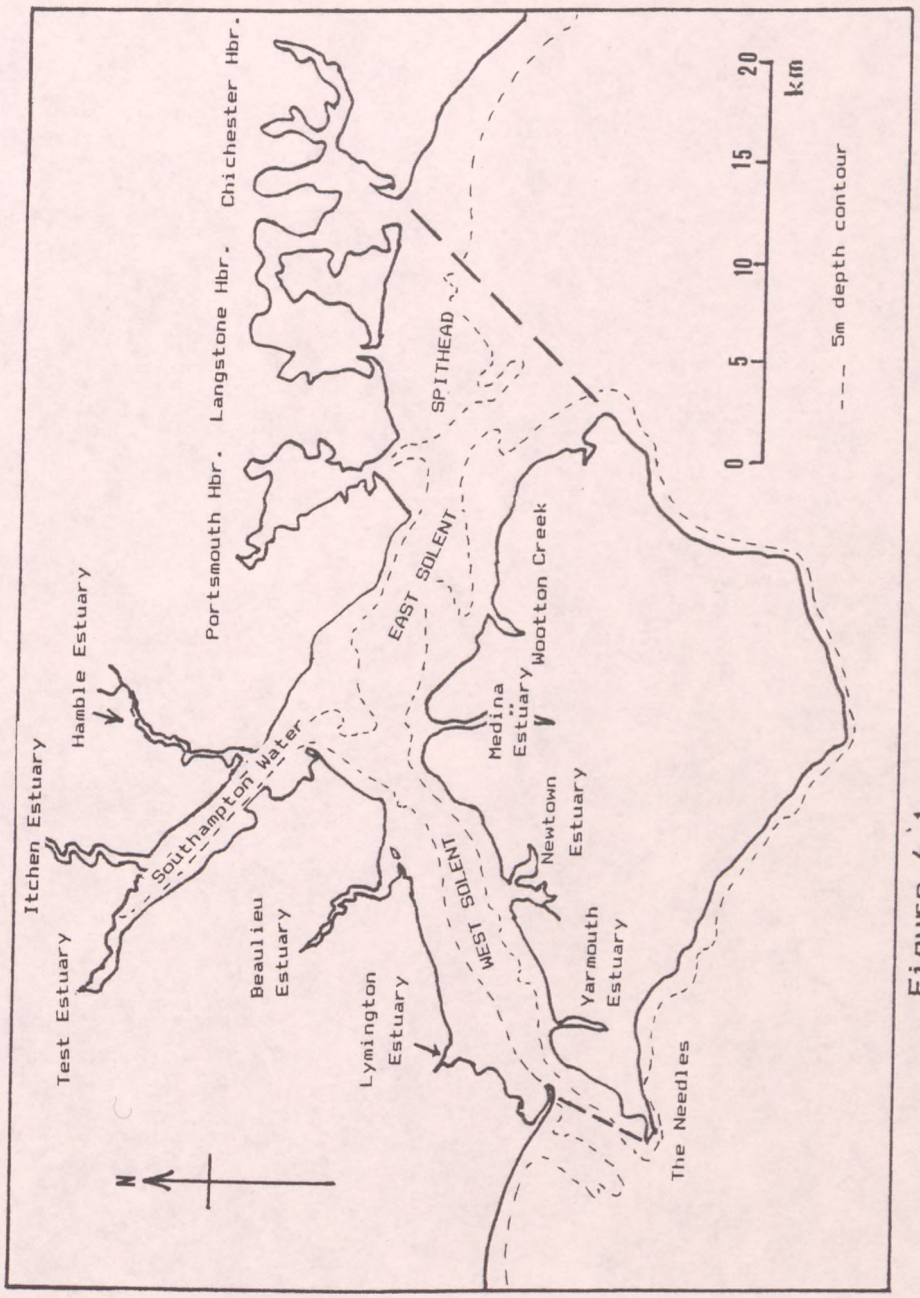


Figure 6.1.
Map of the Solent Estuarine System.

6.1.2 The geographical area.

Geographically, the Solent Estuarine System comprises the Solent, Spithead, Southampton Water, the harbours of Portsmouth, Langstone and Chichester, as well as the numerous estuaries in the area. (Fig. 6.1.). The only areas of the Solent not included in this study are the three large harbours of Portsmouth, Langstone and Chichester. The Solent, as defined here, extends for a distance of some 40 km from the open waters of Spithead in the east to Hurst Castle in the west.

6.1.3 Origin of the Solent Estuarine System.

The present configuration of the Solent Estuarine System has been derived from the Flandrian Transgression of the sea into a previously extensive Tertiary and Quaternary Solent river system which drained the Hampshire Basin (Fox, 1862; West, 1980). During the Pliocene Period relative sea-level stood at greater than 200 m O.D. in southern England (Wooldridge and Linton, 1955; Jones, 1981) with most of the present day coastal regions submerged. Subsequently the land rose relative to the sea, but during pauses, gravel-covered terraces were cut (Dyer,1971).

Throughout the Pleistocene Period significant falls and rises in sea-level occurred during repeated glacial and interglacial ages. When sea-level fell the general drainage pattern of the basin as seen today occurred in the area, with the eastward flowing Solent River and its tributaries. Southampton Water contains submerged gravels which indicate that the river had incised to a considerable depth during the Devensian age (Everard, 1954; West, 1980). East of the Isle of Wight the Solent River Channel was incised to at least -45m below the present sea level (Dingwall,1975; Dyer, 1975). According to West (1980) the Chalk ridge between the Isle of Wight and Purbeck was breached by a major valley during the

Devensian age when sea-level was lower. During the Flandrian Transgression, as sea-level rose, the lower courses of the Solent River and its tributary streams were drowned. The Solent now isolates the Isle of Wight from the mainland of Hampshire.

Where streams had incised deep, confined valleys, the narrow estuaries of the Lymington, Beaulieu, Test ,Hamble, Yar and Medina were formed. Where streams flowed in broad, unconfined valleys , the complex intertidal basins of Portsmouth, Langstone, Chichester and Newtown were formed.

6.1.4 Hydrography and water-circulation of the Solent.

The tidal conditions within the area are complex (Macmillan,1964; Webber, 1980) with a tidal range that can attain 5m at Southampton. Slack water occurs only for a for a short period during the tidal cycle and the currents are asymmetrical. Slack water coincides with high and low water in Southampton Water and its tributary inlets , and is complicated with a double peak on the flood tide. The effect of the high stand is to shorten the period of the ebb to around 4 hours instead of the usual 6 hours. The flood has a normal duration , but an intermediate near-stand of around an hour occurs about 2 hours after low water (Fig 6.2). The result of this unusual tidal curve is that ebb currents are faster than the corresponding flood .

The net change in tidal volume for the Solent (Hurst Narrows to Ryde- Gilkicker Point) has been estimated at 540 $\times 10^6$ and 270 $\times 10^6 m^3$ for a typical spring and neap tide respectively (Blain, 1979). Southampton Water contributes approximately 20 % of these total volumes.

The salinities of the open-waters of the Solent and Spithead have a mean value of 34.3 %. (Phillips, 1980). The central part of the Solent receives the bulk of the freshwater input to the system and salinities may fall

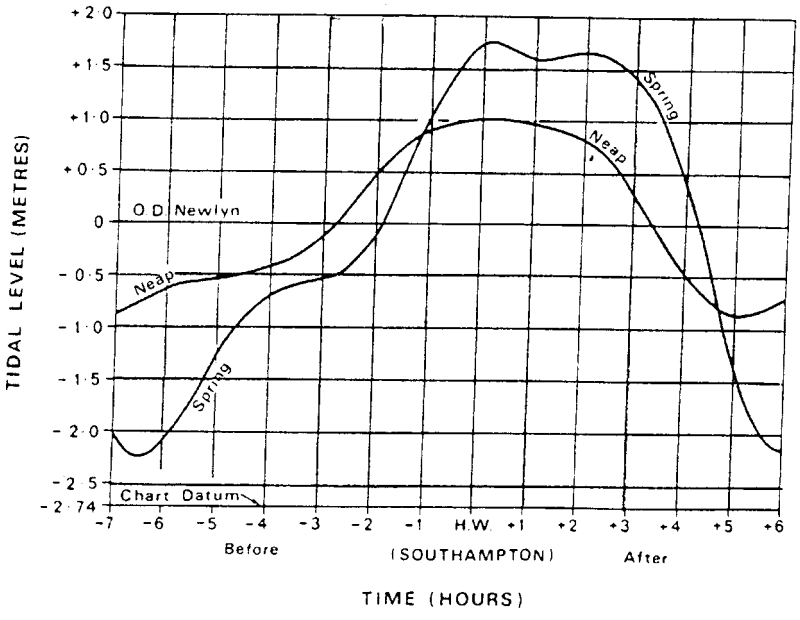


Figure 6.2.
Typical tidal curve for Southampton Water (Town Quay) (after Webber, 1980).

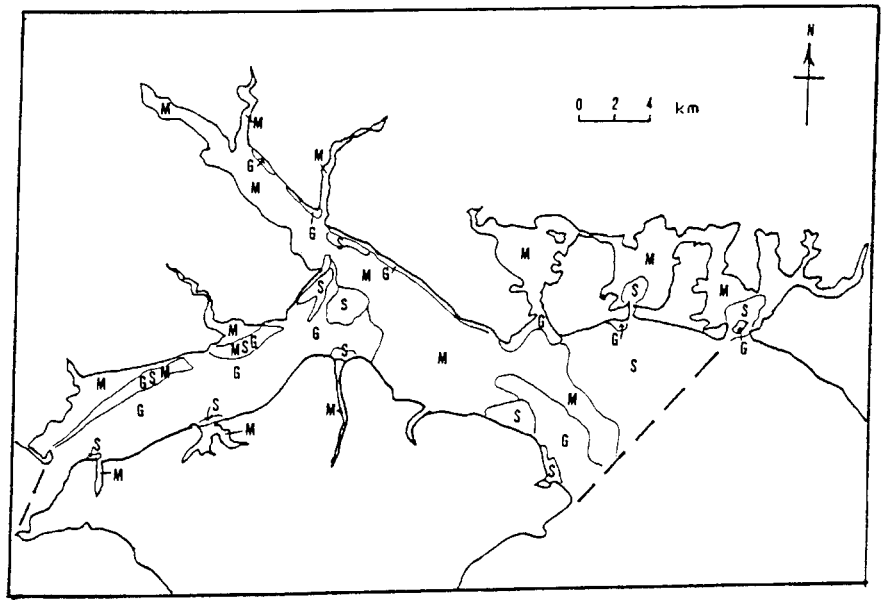


Figure 6.3.
Distribution of surface sediment types in the Solent. M= mud, S= sand, G= gravel . (after Dyer, 1980).

to 38.8%. , whereas Spithead ,which is more exposed to the open sea , has a salinity range of between 34.5 and 34.6 %. . Salinities of less than 30 %. occur in the upper reaches of Southampton Water and in most of the other tributary inlets in the area. The salinity regimes of these estuaries are discussed in more detail below.

The total catchment area which drains into the Solent comprises 3000 km^2. The bulk of this is underlain by Chalk , the remainder lies on Tertiary , Pleistocene and Recent coastal plain sediments. The rivers Test and Itchen, which enter at the head of Southampton Water, contribute about 45 % of the inflow to the Solent. This volume of water, however, only represents 1/75 th of the neap tidal prism when considering Southampton Water (Webber, 1980).

The rivers draining into the Solent Estuarine system can be grouped into three systems:

1. Chalk rivers
2. Tertiary rivers (excluding the New Forest).
3. New Forest rivers (mainly Tertiary).

Most of Hampshire is drained by the Chalk rivers , the Test, Itchen and the Meon. These rivers form some of the finest Chalk rivers in Britain (Doherty and Pilkington, 1983). The Chalk hills of central Hampshire act as a large reservoir supplying water to the Test ,Itchen , Meon, and their tributaries , the Dun, Dever and Alver. Their waters are characteristically clear and alkaline , and show little variation in temperature or volume throughout the year. The smaller tributaries of these rivers commence as 'winterbournes' at different levels within their valleys as the water table rises and falls with the season.

The rivers which drain the Tertiary sands and clays are quite different from those on the Chalk. The Tertiary deposits form less permeable rocks and run-off occurs

quickly after rainfall. The river flow is generally more variable and the valleys are more liable to flood. This group includes the Hamble, Wallington, Alver and a few small streams draining the coastal belt between Southampton and Chichester.

Within the New Forest, numerous acid streams drain the Tertiary sands and clays, Pleistocene gravels and Holocene peat. These flow into the Beaulieu or Lymington or directly into the Solent (e.g., the Avon Water, Blackwater, Highland Water and the Ober Water).

6.1.5 Recent Sediments of the Solent Estuarine System.

Throughout most of the open waters of the East and West Solent regions , seismic profiling has shown the Recent sediments to be less than 2m thick (Dyer, 1980). Bare rock, however, is not very extensive. It only occurs on the steep slopes of the channel in West Solent, especially in the vicinity of Tertiary limestone ledges. Hodson and West (1972), using data compiled from about 1200 shallow boreholes, have shown that much deeper deposits occur within Southampton Water and the adjacent inlets. Recent estuarine deposits up to 21m thick were encountered at Fawley. These deposits partly fill the southwestern side of the drowned valley of Southampton Water.

The approximate areas of the main types of intertidal sediments are listed in Table 6.1. Those sediments which have accumulated in the estuaries and harbours are mainly composed of fine silts, rich in organic matter. Undoubtedly some of these sediments originated within river valleys prior to their submergence by rising sea level. These include fluviatile silty clays, peat and calcareous tufa (Godwin and Godwin, 1940). Other beds were deposited from estuarine waters and include organic rich silts and clays, interbedded with beds of peat and frequently containing saltmarsh vegetation and Scrobicularia and other tidal-flat molluscs (West, 1980).

Table 6.1 :
Appproximate area of the main intertidal sediments in the Solent (after Tubbs, 1980).

Type	area (hectares)
Mud-flats (with intermixed flint pebbles)	5465
Sand-flats	792
Mixed saltmarsh	430
Spartina marsh	2470

In general, sands and gravels occur at the mouths of the estuaries, whereas silts and muds predominate in the upper regions of the estuaries. Accretion of estuarine sediments has been locally assisted by the formation of mixed saltmarsh, and more extensively by rapid growth of Spartina marshes. Saltmarsh is best developed along the northern border of West Solent. The channel of the West Solent is predominantly floored by gravels containing variable proportions of coarse sand. The gravels consist of sub-angular flint pebbles in matrices of brown limonite-stained coarse sands. Muds and sandy muds occur extensively throughout Southampton Water and the East Solent.

6.1.6 Introduction to the coccolith assemblages in the surface sediments of the Solent region.

Four species of Recent coccolith are found the surface sediments of the Solent Estuarine System; Coccolithus pelagicus, Emiliania huxleyi, Helicosphaera carteri and Braarudosphaera bigelowii. These assemblages are dominated by Coccolithus pelagicus. Only very rare occurrences of the other species (< 5%) were noted in the

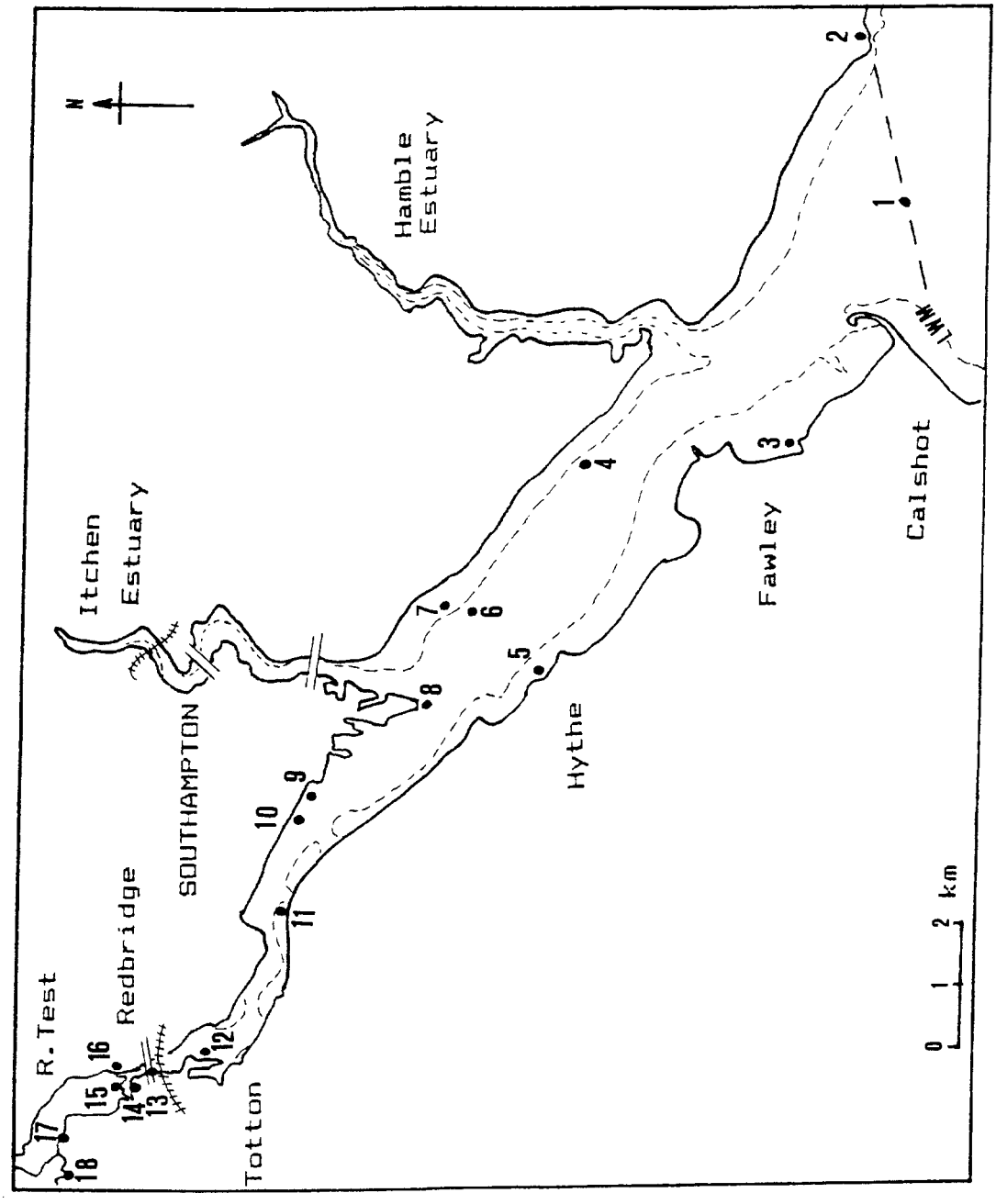


Figure 6.4.
Sample locations in Southampton Water and the Test Estuary.

sediments. Because of the general absence or scarcity of other Recent coccolith species in the sediments , all quantitative data describing the occurrence of Recent coccoliths in this chapter is limited to the species Coccolithus pelagicus. In this study the Solent Estuarine System has been divided up into the following seven broad regions ;

1) Southampton Water and the Test Estuary
2) Itchen Estuary
3) Hamble Estuary
4) Beaulieu Estuary
5) Lymington Estuary
6) The estuaries along the northern coast of the Isle of Wight
7) Spithead, East Solent and adjacent estuaries.

Regions 1 to 5 have been sampled extensively and sedimentation within these individual estuaries will be discussed in some detail. Regions 6 and 7 have only been studied by means of isolated samples and consequently only a brief discussion will be presented for these areas.

6.2 RESULTS

6.2.1 Southampton Water and the Test Estuary.

6.2.1.1 Location and geomorphology.

Southampton Water forms a roughly linear body of water approximately 11 km long, and 2km wide. The southern limit of Southampton Water is defined in this study as a line running from Calshot Bell Buoy to Hillhead Haven (Fig. 6.4.). This line also approximates to the southern limit of the port of Southampton.

The main channel of Southampton Water has been dredged to a depth of approximately 13m below mean tidal level. Near the mouth of the water on the western shore

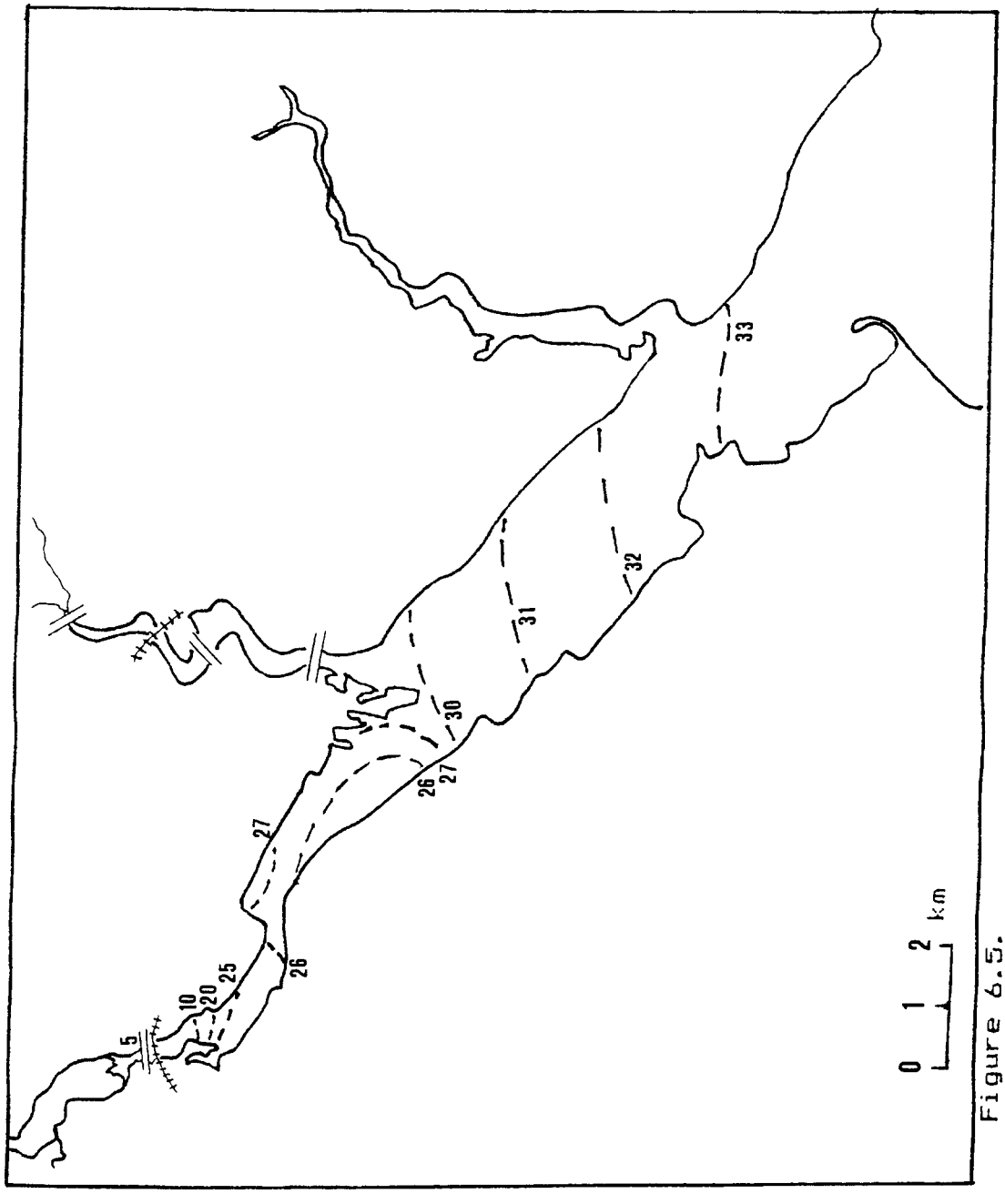


Figure 6.5.
Distribution of high water, surface salinity (‰) throughout Southampton Water and the Test Estuary. (modified after Dyer, 1973 and Romans, 1979).

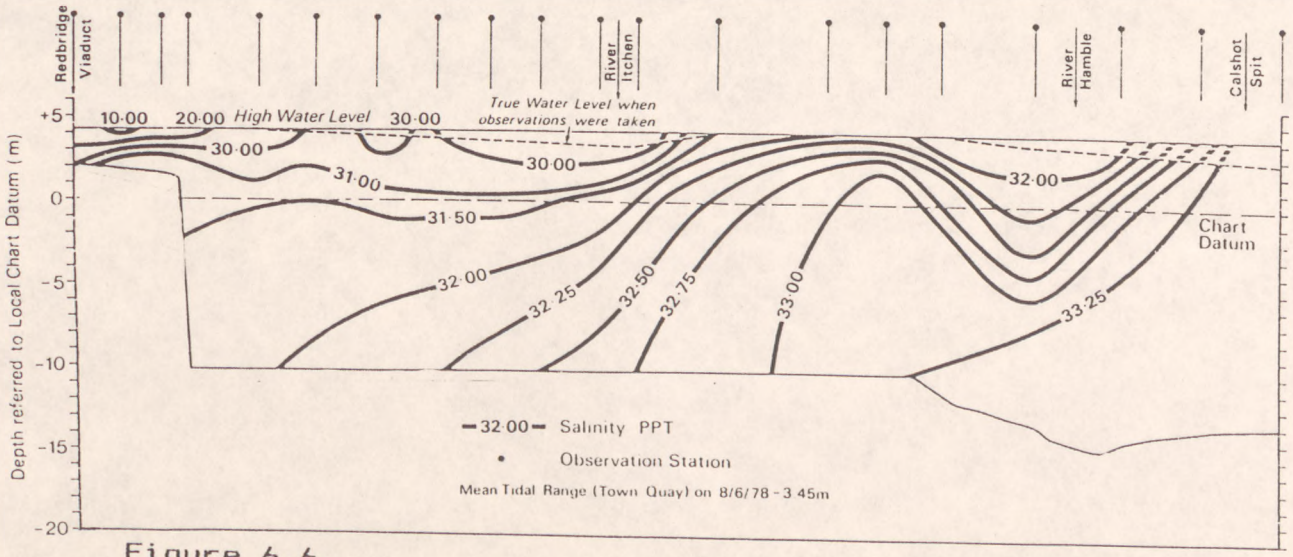


Figure 6.6.

32 Longitudinal distribution of salinity in Southampton Water and the Test Estuary (after Webber, 1980).

PLATE 4

The upper Test Estuary

Fig.1 Exposed mud flats at Redbridge.

Fig.2 *Phragmites* reed-beds near the tidal-limits in the upper Test Estuary.



1



2

is the barrier beach of Calshot Spit, a stable shingle bank which has grown in height as sea-level has risen (Hodson and West, 1972). Saltmarsh borders the extensive mud-flats along this sheltered western side. The eastern shore of Southampton Water is very different; its steeply beached shore is cut by winds and waves into the Pleistocene gravels. These gravels are overlain by a thin veneer of mud within the intertidal zone. At the southeastern end of Southampton Water lies the mouth of the Hamble Estuary. Towards the northwestern, landward end Southampton Water bifurcates into the estuaries of the Test and the Itchen.

The lower Test Estuary is the site of the vast expanse of Southampton Docks. This area has been the subjected to periodic dredging and reclaimation schemes since the late nineteenth century. Beyond the docks, the shipping and industrial areas are quickly replaced by extensive areas of mixed marsh and Spartina marsh. Above the saltmarsh lie the upper meadows, parts of which were once water meadows . These lie beyond the influence of saline water.

6.2.1.2 Hydrology.

Dyer (1980) has recorded the distribution of high water surface salinities throughout Southampton Water and the Test Estuary (Fig.6.5). Webber (1980) has recorded the longitudinal distribution of salinity in the same area (Fig 6.6). The lower half of Southampton Water is almost homogeneous, with little stratification ; salinity increases only gradually towards the Solent. A salinity gradient occurs across the estuary with the fresher water on the northern side. Stratification increases towards the head of the estuary. Collins (1979) found pH values from Southampton Water ranged from 7.4 to 8.2 with a mean of 7.8.

6.2.1.3 Coccolith abundance in the sediments.

Eighteen sediment sample were collected from Southampton Water and the Test estuary (Fig.6.4) . The coccolith abundances in these sediments are listed in Table 6.3. Coccoliths of Coccolithus pelagicus are found distributed throughout the sediments of Southampton Water and in the lower Test Estuary. Their greatest abundance occurs towards the mouth of Southampton Water at Fawley, station 3 (57 $x10^5$). The sediments deposited from the main body of Southampton Water have a fairly constant C.pelagicus abundance ranging from 57 to 42 $x10^5$, with the lowest values being recorded from the upper part of Southampton Water.

Sediments deposited within the more confined waters of the lower Test Estuary have coccolith abundances approximately half those found in Southampton Water (13 to 21 x 10^5 per gram). At Marchwood , station 11, abundances fall to less than 10^6 coccoliths per gram . Station 13, at Redbridge ,21 km from the mouth of Southampton Water, is the furthest distance from the mouth of the estuary coccoliths have been recorded in the sediments. Their abundance at Redbridge has declined to < 10^5 coccoliths per gram. No Recent coccoliths are recorded in sediments from sites 14 to 16 in the upper Test Estuary, and in the freshwater sediments of the rivers Test and Blackwater.

Reworked coccoliths occur throughout Southampton Water and the Test Estuary and also in the fluviatile sediments. Highest abundances are found at the mouth of Southampton Water (541 $x10^5$ per gram) and also at Dock Head (741 $x10^5$/g), at the entrance to the Test and Itchen estuaries. Abundances of reworked coccoliths are generally greater than 10^7 individuals per gram in the main part of Southampton Water. However, they decline rapidly within the lower reaches of the Test Estuary where only $x10^6$ coccoliths/gram occur. In the the upper Test Estuary and in the fluviatile sediments from the Blackwater and in River Test reworked coccoliths are very scarce (10^4 to 10^5

Table 6.2. List of sample localities from Southampton Water and the Test Estuary.

	Sample site	grid reference	description of sample
1	Calshot Bell Buoy	SU 012 506	subtidal mud
2	Hillhead Hbr.	SU 023 535	intertidal mud-flat
3	Fawley	SU 033 467	intertidal mud-flat
4	Solent 11	SU 064 466	subtidal channel mud
5	Hythe	SU 074 433	intertidal mud-flat
6	Solent 10	SU 088 443	subtidal channel mud
7	Netley	SU 093 443	intertidal mud-flat
8	Dockhead	SU 095 426	subtidal channel mud
9	101-Berth	SU 112 414	subtidal channel mud
10	Solent 2	SU 113 412	subtidal channel mud
11	Marchwood	SU 114 393	intertidal mud-flat
12	Eling	SU 132 370	saltmarsh channel mud
13	Redbridge	SU 135 368	intertidal mud-flat
14	Totton	SU 143 363	intertidal channel mud
15	Ruddymead	SU 147 368	intertidal channel mud
16	U Test 3	SU 149 368	intertidal channel mud
17	River Test	SU 152 357	muddy gravel
18	River Blackwater	SU 154 350	river mud

Table 6.3 Summary of coccolith data in the fine fractions from Southampton Water , the Test Estuary and the River Test.

Sample	Dist. from Estuary Mouth (km)	Approx. surface salinity (‰)*	Number of modern coccoliths ($\times 10^5$/g)	Number of reworked coccoliths ($\times 10^5$/g)	% reworked coccoliths
1	0	34	56	493	90
2	0	34	51	541	91
3	4	33	57	227	80
4	6.5	33	52	184	78
5	9.5	31	42	201	82
6	10.0	30	46	200	81
7	10.2	30	46	200	88
8	12.0	30	33	748	95
9	14.0	28	21	318	94
10	15.0	26	13	78	86
11	17.0	25	6	36	86
12	19.0	20	-	<1	100
13	21.0	5	<1	78	>99
14	22.0	1	-	<1	100
15	22.5	1	-	22	100
16	22.6	1	-	<1	100
17	23.6	fw	-	6	100
18	24.2	fw	-	<1	100

* salinity at spring high water, after Dyer (1973), Webber (1980) and Romans (1979).

per gram). The percentage of reworked coccoliths of the total coccolith populations in the sediments from Southampton Water ranges from 78 to 91 %,with the higher values being recorded from the mouth of Southampton Water and at Dockhead. Lower values typify sediments from the lower Test Estuary (86%). However, further up the estuary and in the fluviatile sediments of the Rivers Test and Blackwater where modern coccolith are absent from the sediments, the reworked component reaches 100% of the total assemblage.

6.2.1.4 Mineral composition of the sediments.

Sediments in Southampton Water have carbonate values in their fine-fractions (2 to 20 μm) ranging from 15 to 21 % , with the highest values occurring at the mouth of the inlet. Intermediate carbonate abundances (10 to 13%) are found in the lower Test Estuary. Further up the estuary the carbonate values are variable. Low values were recorded from mud deposited in a saltmarsh channel (site 12) and also near the tidal limits within the reed beds (site 14). Sediments deposited above the the reed beds within the upper Test Estuary have higher carbonate abundances (29%). The highest carbonate abundance (58%) is recorded from fluviatile sediments from the River Test. X.R.D. analysis of the bulk sediments and the fine fractions shows that the carbonate component is predominantly composed of low Mg-calcite. Aragonite is only recorded in in isolated samples from Southampton Water and in the deep-water channel within the Dock area.

X.R.D. analysis was also used to show variations in the calcite/quartz ratio in the bulk sediments and the silt fractions. Peak height ratios were used here to show variations in the mineral content of the sediments (Table 6.4). Calcite/quartz peak height ratios for bulk sediments from Southampton Water range from 0.05 to 0.46 with the higher values recorded from the mouth of the inlet and near the Docks. Highest values occur in the upper Test Estuary and in the River Test sediments (0.9 to

Table 6.4 Summary of carbonate data for sediments from Southampton Water and the Test Estuary.

Sample	(%) CaCO (2-20μm)	Abundance of carbonate laths (2-20μm)	Abundance of calcite rhombs (2-20μm)	Qtz/cal peak ht.ratio (Bulk sample)	(2-20μm)
1	20	+++	++	0.26	0.26
2	20	+++	++	0.29	0.25
3	15	+++	++	0.09	0.12
4	21	+++	+	0.22	0.19
5	15	+++	++	0.19	0.14
6	18	+++	++	0.05	0.23
7	18	+++	+	0.32	0.20
8	17	++	+	0.46	0.46
9	13	+++	+++	0.20	0.35
10	11	+	+	0.15	
11	10				0.10
12	<1	-	-	<0.01	<0.01
13	19	-	+++	0.25	
14	3	-	+	<0.01	<0.01
15	29	-	+++	0.90	2.17
16		-	+++	1.85	
17	58	-	+++		
18		-	+++	0.38	

+++ = abundant, ++ = common, + = present, - = absent.

Table 6.5 Summary of non-carbonate mineral content of the sediments from Southampton Water and the Test Estuary.

Sample	Abundance of glaucony (2-20μm)	feldspar/quartz XRD peak ht. ratio (bulk sediment)
1	++	
2	+++	0.01
3	+++	
4	++	
5	++	<0.01
6	+	<0.01
7	+	<0.01
8	+	
9	+	<0.01
10	+	<0.01
11	-	<0.01
12	-	
13	-	
14	-	
15	-	0.05
16	-	0.13
17	-	
18	-	0.04

+++ = abundant, > 1 in one field of view
++ = common , 1 in one field of view
+ = present, < 1 in one filed of view

This measure of relative abundance is used in tables throughout the Chapter.

1.85). Calcite/quartz peak height ratios for the silt fractions in Southampton Water range from 0.14 to 0.46 (mean 0.19). Above the docks in the lower Test Estuary, lower values occur (0.29 to 0.01). The greatest value was recorded at site 15 in the Upper Test Estuary (2.17). The carbonate in the fine fractions other than that provided from the coccoliths is mainly composed of fibres and laths derived from the maceration of skeletal fragments , and calcite rhombs. The skeletal laths are particularly common within the lower half of Southampton Water but are generally rare or absent in the Test Estuary.

Calcite rhombs are common in sediments deposited at the mouth of Southamton Water but rapidly decline in abundance up the inlet. Calcite rhombs are also important contributers to the fine sediment within the Upper Test Estuary and in the River Test. Occasional siderite rhombs were also reported from the mouth of Southampton Water.

Feldspar/quartz peak height ratios were also calculated for the sediments. Potassic feldspar is generally rare (feld/qtz pk. ht. ratio < 0.01) or absent within sediments deposited throughout Southampton Water. However, sediments deposited within the upper Test Estuary and in the Blackwater River have much higher ratios, ranging from (0.05-0.13).

Glaucony is common in sediments deposited at the mouth of Southampton Water and generally decreases in abundance up the estuary. Glaucony is absent in sediments from the River Test and its Estuary.

6.2.2 Itchen Estuary.

6.2.2.1 Location and hydrology.

The Itchen Estuary forms the northeastern tributary of Southampton Water. The shape of this estuary has undergone less modification than that of the Test, which

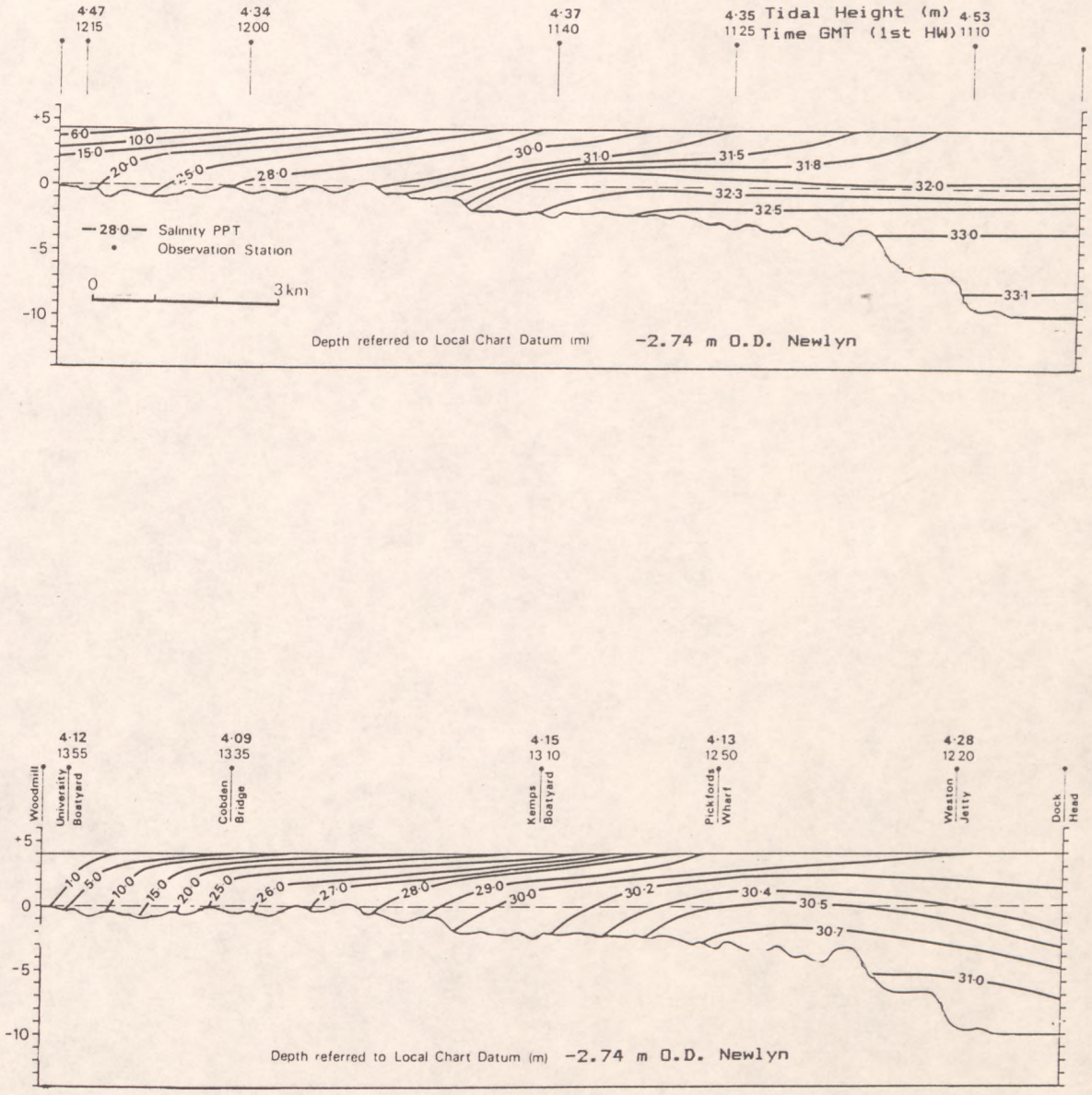


Figure 6.7.
Longitudinal distribution of salinity in the Itchen Estuary. (after Webber, 1980).

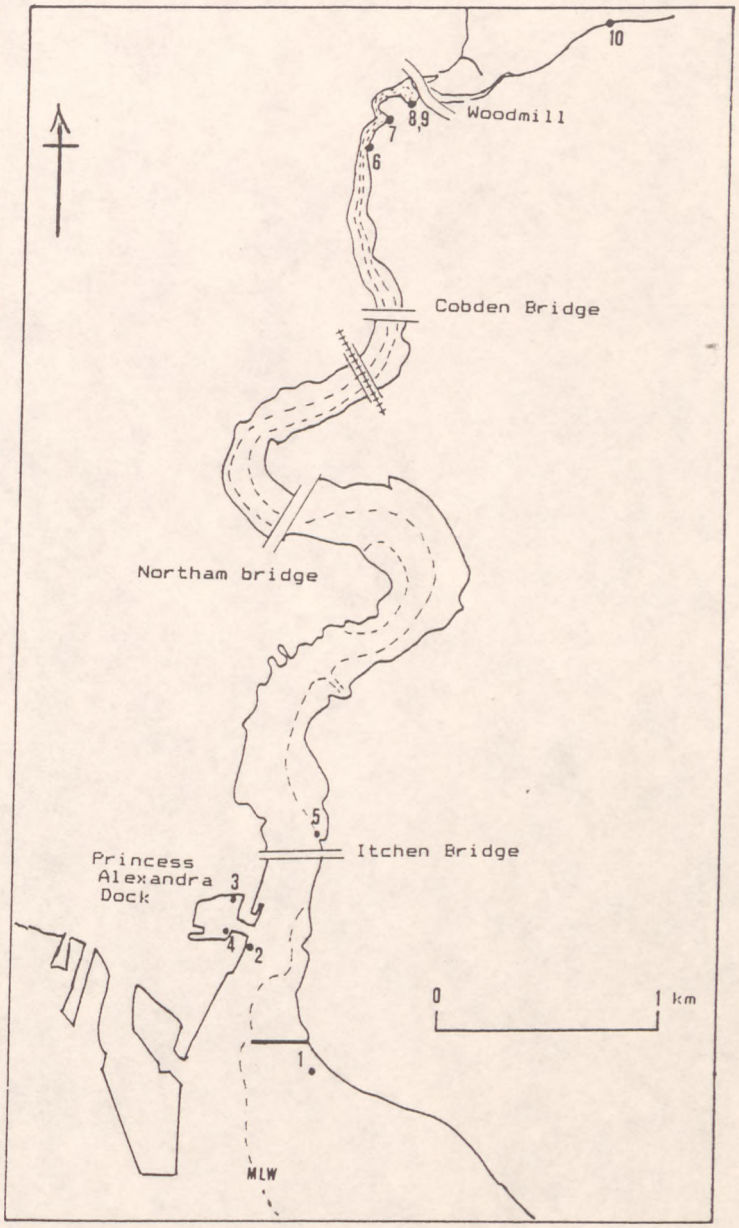


Figure 6.8.
Location of sample sites in the Itchen Estuary.

has a river inflow twice that of the Itchen (Phillips, 1980). It has only a short navigable length now, and is tidal up to Woodmill, a distance of some 7.2 km. In contrast to the Test Estuary there are no extensive areas of saltmarsh at the head of the Itchen Estuary.

The Itchen Estuary displays a more 'natural' salinity regime with considerable stratification at all states of the tide and fairly regular longitudinal salinity gradients (Phillips,1980) (Fig 6.7.). The estuary receives a large pollution load from two sewage treatment works , one at the mouth of the estuary and the other one near its head. The concentrations of ammonium and phosphate in the surface water show distinct peaks in the upper reaches of the estuary because of the presence of sewage effluent.

6.2.2.2. Coccolith abundance in the sediments.

Ten sediment samples have been studied from the River Itchen and its estuary (Fig. 6.8.). The coccolith abundance in these sediments is listed in Table 6.7.

The abundance of Recent coccoliths in the sediments of the Itchen Estuary decreases up the estuary away from the influence of Southampton Water. Highest abundances occur at the mouth of the estuary (38 $x10^5$ coccoliths per gram). At the tidal limits of the estuary at Woodmill, the abundance of modern coccolith has dropped to 4 $x10^5$ per gram. Reworked coccoliths occur in numbers greater than 10^7 per gram at all stations throughout the Itchen Estuary. Abundances range from 287 $x10^5$ per gram at the mouth of the estuary to 165 $x10^5$ in the upper reaches of the estuary. Fluviatile sediments sampled 1 km upstream from the tidal limits contain 18 x 10^5 reworked coccoliths per gram. The percentage of reworked coccoliths of the total coccolith floras are high throughout the sediments of the Itchen Estuary. They range from 88 % at the mouth of the estuary to >99% within the upper reaches of the estuary.

6.2.2.3 Mineral composition of the sediments.

Carbonate abundances in the fine fractions of the sediments generally increase up the estuary. Values range from 8% near the estuary mouth to 62% at the tidal-limit, at Woodmill. Fluviatile sediments from the River Itchen contain 35% fine-grained carbonate. Calcite/quartz peak height ratios in the fine fractions at the mouth of the Itchen Estuary are typical of those found throughout Southampton water (range 0.24 to 0.40). However, sediments deposited in the upper reaches of the Itchen Estuary and in the River Itchen have very high ratios ranging from 1.00 to 2.92. The carbonate component of the fine fractions of the Itchen estuary is predominantly composed of calcite rhombs with smaller amounts of coccoliths and skeletal laths. Calcite rhombs are especially common within the upper reaches and in the fluviatile sediment. The rhombs range in size from 2 to 10 microns and include both 'fresh' and corroded crystals. Skeletal laths are only common at the mouth of the estuary but are generally absent at the tidal limit. Glaucony is rare in the sediments.

Table 6.6 Location and description of sample sites in the Itchen Estuary.

	Sample site	grid reference	description
1	Weston Point	SU 102 435	intertidal mud-flat
2		SU 106 432	intertidal mud-flat
3	P.A. Dock	SU 109 432	subtidal mud
4	P.A. Dock	SU 107 430	subtidal mud
5	Itchen Bridge	SU 116 435	intertidal mud-flat
6	Bittern Park	SU 144 437	intertidal mud-flat
7	Riverside Park	SU 148 438	intertidal mud-flat
8	Woodmill	SU 152 439	intertidal mud-flat
9	Woodmill	SU 152 439	intertidal mud-flat
10	River Itchen	SU 155 447	river mud

Table 6.7 Summary of the coccolith content in the fine fractions from the Itchen Estuary.

Station Number	Dist. from mouth (km)	Approx. surface salinity (‰)*	No. of modern coccoliths ($\times 10^5$/g)	No. of reworked coccoliths ($\times 10^5$/g)	(%) reworked coccoliths
1	0	30	38	287	88
2	0.5	30	24	276	92
3	0.9	30	20	300	94
4	0.9	30	18	398	96
5	1.1	30	25	238	90
6	5.6	10	4	124	97
7	6.0	10	5	165	97
8	7.2	6	4	148	97
9	7.2	6	1	215	<99
10	8.2	fw	-	18	100

fw = fresh water sample.
* surface salinity taken from Webber (1980) at high water.

Table 6.8.
Summary of the mineral composition of the fine fractions (2-20 μm) from the Itchen Estuary.

Sample	(%) CaCO	Cal/qtz. peak ht. ratio	carbonate laths	calcite rhombs	glaucony
1	18	0.06	++	++	+
2	12	0.40	++	++	-
3	8	0.32	+	++	-
4	12	0.35	++	+	-
5	14	0.16	++	++	+
6	28	1.00	+	+++	-
7	42	1.00	+	+++	+
8	28	1.10	+	+++	-
9	62	2.92	-	+++	+
10*	35	1.44	-	+++	-

* fresh water sediment,

6.2.3 Hamble Estuary.

6.2.3.1 Location and hydrology.

The River Hamble rises near Bishops Waltham and some 17.5 km downstream flows into the northeastern side of Southampton Water just north of Calshot Castle. For much of its length from Bishops Waltham it is a shallow stream floored by sands and gravels. The River Hamble is tidal up to the weir at Botley Mill, a distance of 10.4 km. Downstream from Botley the channel meanders through extensive mud-flats which lie uncovered at low-water.

Water surveys on the River Hamble have been carried out by the Water Research Laboratory at Stevenage in 1964 and in 1968, and also by Collins in 1967. These surveys used a combination of fixed-point and mobile sampling methods. The degree of stratification of the estuarine water in the Hamble depends on the state of the tide and the position of the water types. The river inflow forms 0.45 % and 0.85 % of the tidal prism for spring tides and neap tides respectively (P.Tosswell, 1983 pers. comm.) . At low water, the amount of freshwater entering the system is quite large in comparison to the amount present and there is mixing of the two water types. This occurs at all low waters (Collins,1967) (Figs.6.11 and 6.13).

At high water, neap tides the existing currents are not strong enough to mix the river water , and vertical salinity gradients exist along the whole estuary (Fig.6.12). At spring high waters , the large volume of sea water entering the system causes greater currents than at neaps , and ensures complete mixing of the water column (Fig.6.10). At times of high and low water, and especially at the former, which lasts for two hours, there is no bulk movement of estuarine water and consequently the incoming river water tends to flow over the top of the estuarine water, causing a vertical salinity gradient in the lower part of the estuary. In general, variations in

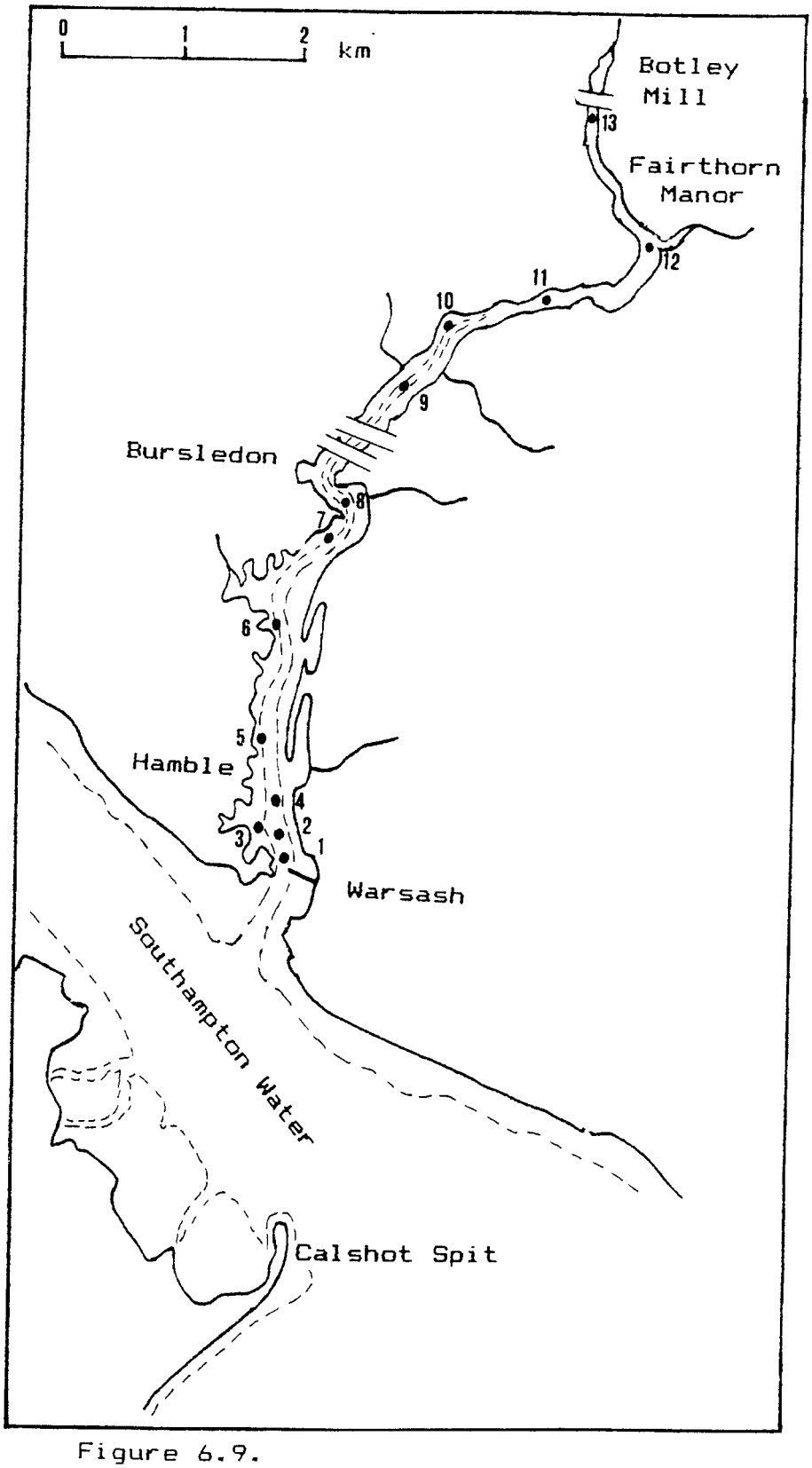


Figure 6.9.
Sample locations in the Hamble Estuary.

Salinity distribution (%.) in the Hamble Estuary.

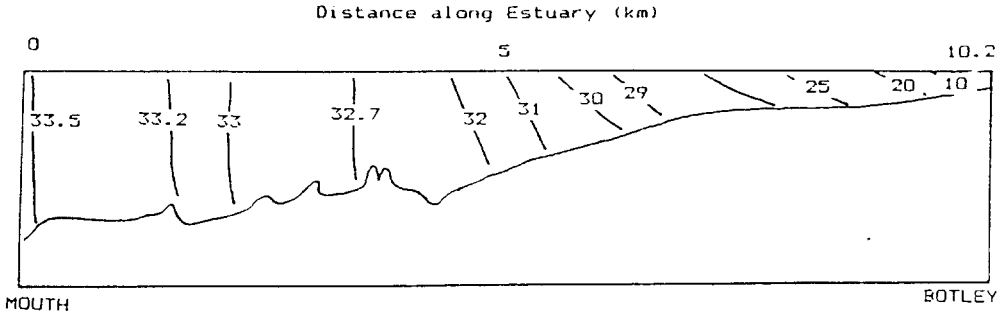


Figure 6.10.
Salinity distribution (%.) at high water (spring tide) on 20.8.67 (after Collins, 1967).

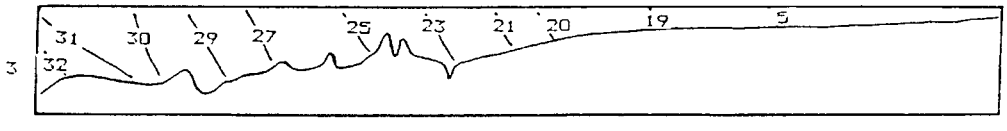


Figure 6.11.
Salinity distribution (%.) at low water (spring tide) on 20.8.67 (after Collins, 1967).

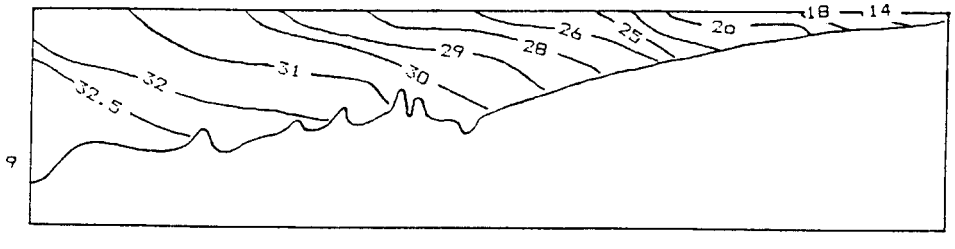


Figure 6.12.
Salinity distribution (%.) at high water (neap tide) on 13.8.67 (after Collins, 1967).

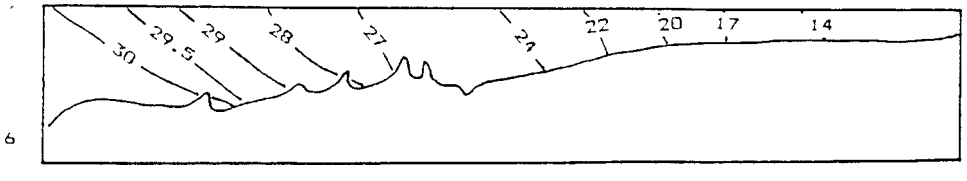


Figure 6.13.
Salinity distribution (%.) at low water (neap tide) on 13.8.67 (after Collins, 1967).

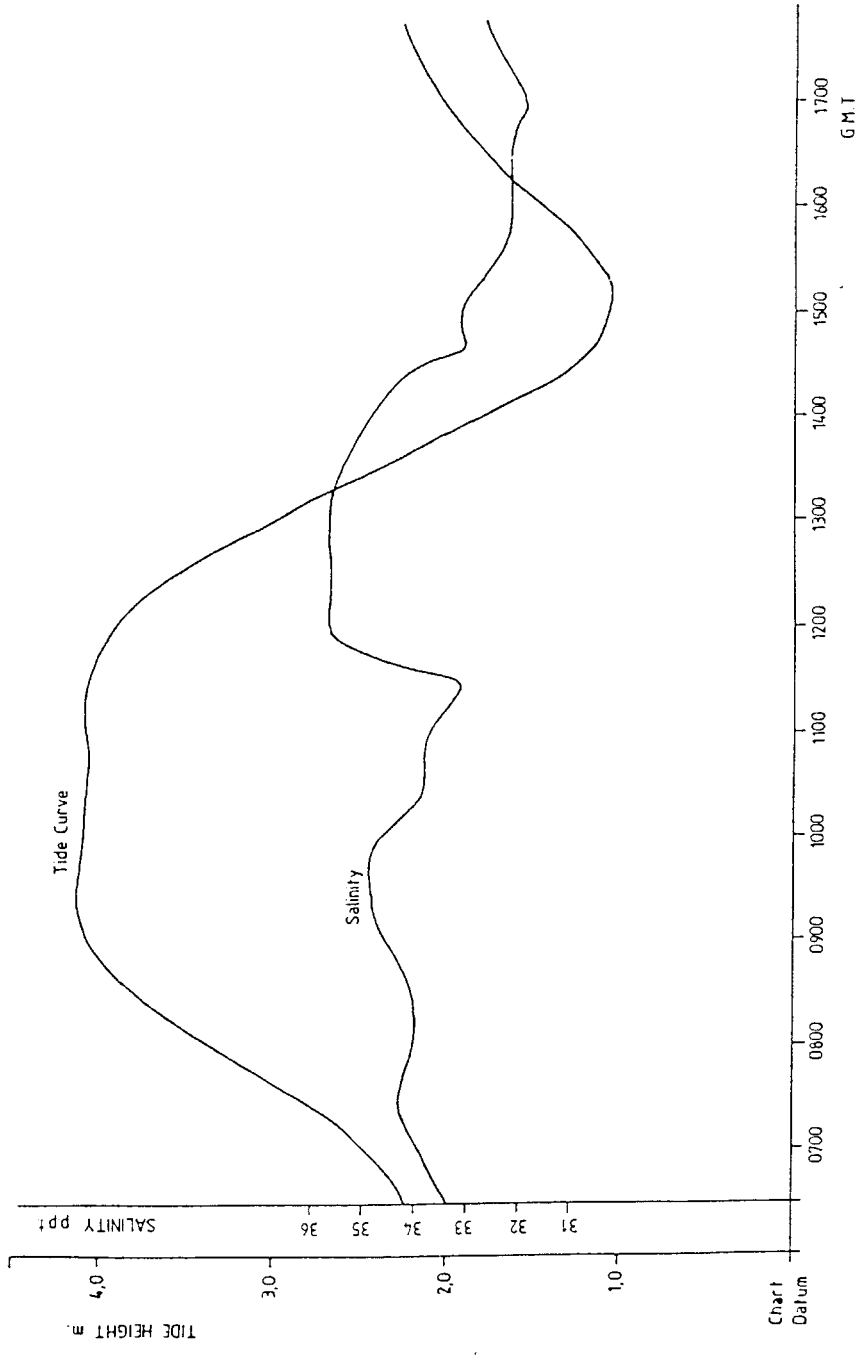


Figure 6.14.
Variation of surface salinity (‰) at Port Hamble on 29/7/81 (after Tosswell, 1984).

salinity follow the tidal-level, except that the maximum salinity is found to occur just after the second high water (Fig.6.14).

6.2.3.2 Coccolith content.

Twelve gravity cores (stations 1 to 12) and a surface grab sediment (sample 13) were taken along a traverse from the mouth to the head of the estuary (Fig 6.9.). The analyses of the silt fractions from these sediments are shown in Tables 6.10, 6.11 and 6.12.

The abundance of modern coccoliths decreases upsteam , away from the mouth of the estuary. The transition from the more 'open waters' of Southampton Water to the waters of the Hamble Estuary is marked by a decrease in the abundance of C.pelagicus in the sediments,from $> 50 \times 10^5$ individuals to $< 30 \times 10^5$ per gram. Stations 1 to 7 have a fairly consistent C.pelagicus abundance ranging from 18 to 28 (mean 24 $\times 10^5$ per gram). A further marked decrease occurs at station 8, four km from the mouth of the estuary, where abundances have dropped to 6×10^5 per gram. Further upstream values of modern coccoliths in the sediments fall below 10^5 per gram. No coccoliths of C.pelagicus are found further than 6.4 km up the estuary. Sediments deposited in the upper reaches of the Hamble Estuary are barren of modern coccoliths.

Reworked coccoliths occur throughout the lower and middle reaches of the Hamble Estuary. They have their greatest abundance at the mouth of the estuary where $> 10^8$ individuals/gram occur. A significant component of the reworked fraction is made up of Eocene forms , particularly Chiasmolithus bidens, Ismolithus recurvus, Neochiastozygus dubius and Recticulofenestra species. Both Chalk and Eocene reworked coccoliths decrease up the estuary away from the influence of Southampton Water. In the upper reaches of the Hamble Estuary , the reworked component has dropped to less than 10^5 per gram. No reworked coccoliths were recorded from sediments deposited

at the tidal limits of the estuary at Botley Mill.

6.2.3.3 Mineral composition of the fine fractions.

The percentage carbonate in the silt fractions of the Hamble Estuary decreases upstream and follows the same trends as previously described for C.pelagicus. Highest abundances (> 15 %) occur in the lower Hamble Estuary. Values drop to around 1% in the upper reaches. Variations in the calcite/quartz X.R.D. ratios for the fine sediments reflect the greater abundance of carbonate in the lower and central sections of the estuary. Stations 1 to 8 have a fairly consistent ratio varying from (0.11 to 0.29) with the highest values found near the mouth of the estuary. Towards the upper reaches of the estuary the ratio values drop below 0.1 . Cal/qtz ratios for the bulk sediments show a simiar trend to the fine fractions in the Hamble sediments. Values are fairly constant within the lower and middle sections of the estuary (range 0.11 to 0.19). These values decline rapidly in the upper reaches where ratios of <0.01 are recorded. Aragonite was only detected in small amounts in the lower estuary.

Fine-grained carbonate in the sediments of the lower estuary is mainly composed of reworked coccoliths, calcite rhombs and skeletal laths. Calcite rhombs are only common at the mouth of the estuary and are scarce in the upper sections. Skeletal laths are common from the mouth to the middle sections of the estuary, but decline in numbers within the upper estuary. Siderite rhombs were also noted in sediments at the mouth of the Hamble.

The non-carbonate fraction, other than quartz, is mainly composed of glaucony , potassic feldspar and small amounts of pyrite. Glaucony grains are particularly common in sediments at the mouth of the estuary. The abundance of potassic feldspar, as indicated by the feldspar/quartz peak height ratios, ranges from <0.01 at the mouth of the Hamble to 0.12 near the tidal limit. Rare grains of microcline feldspar were also observed by optical microscopy of the fine fraction.

Table 6.9
Location and description of samples from the Hamble Estuary.

Station number and locality	Grid reference	desciption
1 Warsash Jetty	058 489	sub-tidal mud
2 Warsash	062 488	" " "
3 Fairley Hbr.	063 486	" " "
4	065 487	" " "
5 Port Hamble	071 486	" " "
6 Mercury shipyard	081 496	" " "
7 Universal Shipyard	088 489	" " "
8 Brookland	092 493	" " "
9 Brixedon	103 498	" " "
10 Dock Copse	110 505	" " "
11 Burridge Farm	113 515	" " "
12 Sewage works	117 521	" " "
13 Botley Mill	129 515	Intertidal mudflat

Table 6.10 Summary of coccolith abundances in sediments from the Hamble Estuary.

Sample	Dist. From Mouth (km)	Approx. Surface Salinity* (‰)	Number of modern coccoliths $(\times 10^5 /g)$	Number of reworked coccoliths $(\times 10^5 /g)$	% reworked coccoliths
1	0.5	33.5	22	1090	98.0
2	0.8	33.5	25	1390	98.2
3	0.9	33.5	29	1160	97.6
4	1.1	33.4	22	880	97.5
5	1.6	33.3	28	520	94.4
6	2.4	33.2	8	160	95.2
7	3.6	32.7	28	880	96.9
8	4.0	32	6	300	98.0
9	5.6	30	<1	<10	ND
10	6.4	28	<1	<10	ND
11	7.2	27	-	<1	100
12	9.0	23	-	<1	100
13	10.1	<1	-	-	-

* salinity at high water, spring tide, taken from Collins (1967)

Table 6.11 Summary of carbonate data for sediments from the Hamble Estuary.

Sample	(wt%) CaCO (2-20μm)	Abundance of carbonate laths (2-20μm)	Abundance of calcite rhombs (2-20μm)	calcite/quartz X.R.D. peak ht. ratios 2-20μm	(bulk sample)
1	16	+++	++	0.42	0.19 A
2	17	+++	++		0.29
3	18	+++	++	0.40	0.21 A
4	17	+++	++	0.43	0.13
5	15	+++	++	0.21	0.18
6	10	+++	+	0.15	0.11 A
7	13	+++	+	0.25	0.16
8	10	+++	++	0.26	0.17
9	3	++	+	0.01	0.08
10	3	+	++	<0.01	0.08
11	3	+	+	<0.01	<0.01
12	1	+	+	<0.01	<0.01
13	1	-	+	<0.01	<0.01

A = Aragonite deteted on X.R.D. trace.

Table 6.12 Summary of the non-carbonate mineral content of the fine fractions.

Sample	Feldspar/qtz peak ht. ratio	Abundance of glaucony
1	<0.01	+++
2	<0.01	+++
3	<0.01	+++
4	<0.01	++
5	0.13	++
6	<0.01	+
7	<0.01	++
8	0.04	+
9	<0.01	+
10	0.07	++
11	0.04	+
12	0.12	-
13	<0.01	-

6.2.4 The Beaulieu Estuary.

6.2.4.1 Location and hydrology.

The Beaulieu River rises in the New Forest and flows into West Solent ,as does the Lymington River, but it has a longer and wider estuary than the latter. The estuary is a relatively simple system with a single source of freshwater and salt-water. It is approximately 9 km long , 3 km wide at the mouth, but narrows to less than 80 m in the upper estuary. The channel is relatively shallow ranging from 1 to 8 m in depth. The Beaulieu River and its estuary lie in a area that is sparsely populated , except for Beaulieu Village and its waters are generally unpolluted. Spartina marshes flank the estuary , particularly at the mouth.

Much of the estuary is homogeneous and vertically mixed , but at the head of the estuary there is considerable stratification (Umnuay,1982). At high water the salinity generally varies from 34.5 ‰. at the mouth to 18.5 ‰. at Beaulieu Village (Fig.6.15.) (Wilson,1982). The river drains a complex of leached, peaty and fertile alluvial soils from bogs and heaths particularly in valleys and basins.

6.2.4.2 Coccolith and mineral content of the sediments.

Five surface grabs of estuarine sediments (sites 1 to 5) and two of freshwater sediments (sites 6 and 7) were sampled from the Beaulieu River (Fig.6.15.). The analyses of the bulk sediments and the silt fractions from these sites are listed in Tables 6.14. and 6.15. respectively.

Recent and reworked coccoliths only occur at the mouth of the estuary where they are very rare ($<10^5$ per

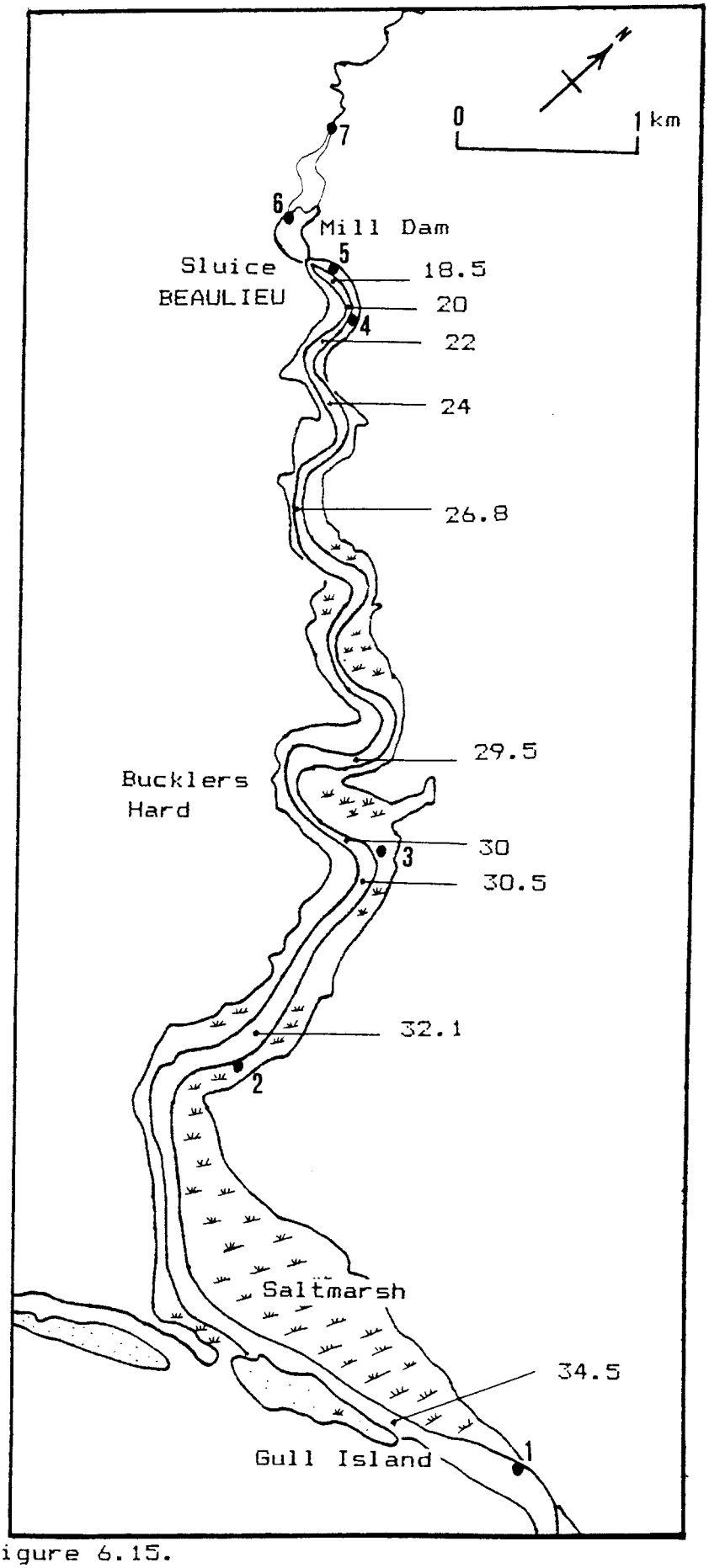


Figure 6.15.
Sample location and salinity distribution (‰) in the Beaulieu Estuary. Salinity values after (Wilson, 1982).

Table 6.13 Location and description of sample sites in the Beaulieu.

Sample site	grid reference	description
1	SZ 986 442	intertidal mud-flat
2	SZ 988 412	" "
3	SU 003 417	" "
4	SU 023 392	" "
5	SU 024 388	" "
6	SU 024 384	fluviatile mud
7	SU 029 383	fluviatile mud

Table 6.14 Summary of coccolith and carbonate data for the fine silt Fractions (2-20 um) from the Beaulieu Estuary.

Sample	Dist. from mouth (km)	Number of modern coccoliths $(\times 10^5$ /g)	Number of reworked coccoliths $(\times 10^5$ /g)	Abundance of Carbonate laths	Wt. % Carbonate
1	0	<1	<1	-	0.5
2	2.5	-	-	-	0.5
3	4.0	-	-	-	-
4	8.7	-	-	-	-
5	9.2	-	-	-	-
6	9.7*	-	-	-	-
7	10.4*	-	-	-	-

* fluviatile sediments.

Table 6.15 Summary of data for the bulk sediments from the Beaulieu.

Sample	Dist from Mouth	(Wt%) Organic matter	(Wt%) Carbonate	Calcite/ quartz XRD peak ht. ratio	Feldspar quartz XRD peak ht ratio
1	0	3.7	7.9	0.04	<0.01
2	2.5	9.6	3.8	0.05	0.02
3	4.0	9.2	2.6	0.04	0.03
4	8.7	3.9	P	<0.01	<0.01
5	9.2	3.5	P	<0.01	0.02
6	9.7*	5.9	P	<0.01	0.05
7	10.4*	13.4	P	<0.01	0.10

* fluviatile sediments P = < 0.5 %

Table 6.16
Location and description of sample site in the Lymington Estuary.

Sample	grid reference	decription
1	335 940	intertidal mud-flat
2	332 937	intertidal gravelly mud-flat
3	333 948	intertidal gravelly mud-flat
4	334 949	intertidal mud-flat
5	338 956	intertidal mud-flat
6	322 960	intertidal mud-flat

per gram). They were not recorded from sediments deposited throughout the rest of the estuary and from the fluviatile sites. Fine-grained carbonate (2 to 20 μm) is extremly scarce throughout the estuarine and fluviatile system (0.5 %) and its occurrence is limited to sites 1 and 2, near the mouth of the estuary. No carbonate laths or fibres were recorded in the sediments. The carbonate content of the bulk sediments is a little higher than that found in the fine silt fractions and ranges from 7.9 % at the estuary mouth to less than 0.5 % in the upper estuary. Calcite/quartz X.R.D. peak height ratios for the bulk sediments range from 0.05 at the mouth to less than 0.01 in the upper estuary and in the fluviatile sediments.

The abundance of feldspar in the sediments as indicated by the feldspar/quartz peak height ratios generally increases with distance up the estuary. Values range from 0.02 at the estuary mouth, to 0.1 in fluviatile sediments deposited above the estuary. Glaucony is common in the sediments at the mouth of the Beaulieu Estuary but is generally rare or absent in the upper reaches.

6.2.5 Lymington Estuary.

6.2.5.1 Location and hydrology.

The Lymington River drains a wide area of the New Forest, and flows into west Solent opposite the western end of the Isle of Wight. The estuary is one of the smallest in the Solent and is tidal for approximately 2.3 km. At the mouth of the estuary are extensive areas of Spartina marshes.

There is little published information on the distribution of salinity throughout the estuary. However, at Lymington Quay, the Southern Water Authority's routine sampling point, the average salinity at high water is about 30 %. (Phillips,1980).

PLATE 5

The Lymington Estuary

Fig.1 View of the tidal channel flanked by saltmarsh.

Fig.2 View of saltmarsh at the mouth of the estuary.



1



2



Figure 6.16.
Location of sample sites in the Lymington Estuary.

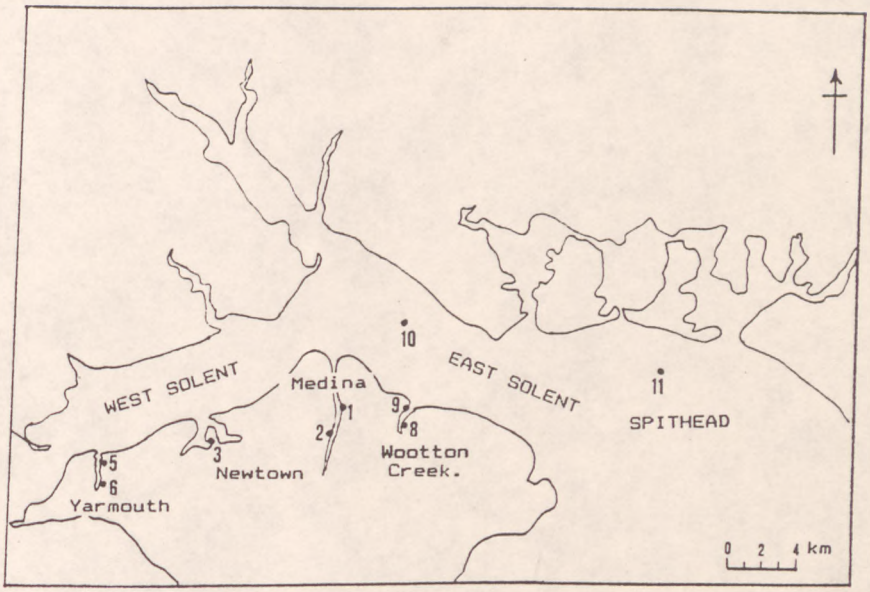


Figure 6.17.
Sample sites in West Solent, Spithead and in the Isle of Wight Estuaries.

6.2.5.2 Coccolith and mineral content of the sediments.

Six surface grabs of sediment were taken along a traverse from the mouth to the head of the Lymington Estuary (Fig. 6.16.). The analyses of the bulk sediments and the fine silt fractions are shown in Tables 6.18. and 6.19. respectively.

Recent and reworked coccoliths are either absent or very rare in the sediments of the Lymington Estuary ($<10^5$ per gram). The abundance of fine-grained carbonate is also very low (1% or less) and no skeletal laths are present within the sediments. Carbonate percentages in the bulk sediments are higher than those in the fine fractions and range from 2 to 7% . Calcite/quartz peak height ratios in the bulk sediments ranges from < 0.01 to 0.03. Potassic feldspar was also detected by X.R.D. analysis and is more common in the middle reaches of the estuary where feldspar/qtz ratios averaged 0.04. Glaucony occurs throughout the sediments of the estuary, but is most common at the mouth.

Table 6.17 Summary of data for the fine fractions of the Lymington Estuary.

Sample	Dist. from estuary mouth (km)	Number of modern coccoliths $(\times 10^5$ /g)	Number of reworked coccoliths $(\times 10^5$ /g)	% carbonate
1	0	<1	<1	1
2	0	<1	<1	P
3	0	–	–	–
4	1.1	<1	<1	P
5	1.9	–	–	–
6	2.3	<1	<1	1

P = < 0.5 %

Table 6.18 Summary of data for the bulk samples from the Lymington Estuary

Sample	Dist. from estuary mouth (km)	Organic matter (wt%)	Carbonate (wt%)	Calcite/qtz XRD peak ht. ratio	Feldspar/qtz XRD peak ht. ratio
1	0	3.9	3	0.02	0.02
2	0	1.8	2	0.01	<0.01
3	1.0	15.8	2	<0.01	0.04
4	1.1	7.6	3	0.01	0.04
5	1.9	4.9	7	0.03	<0.01
6	2.3	6.9	3	<0.01	<0.01

Table 6.19
Location and description of Isle of Wight sample localities

Station number	grid reference	description
1 Medina	508 928	intertidal mud-flat
2 Medina	504 911	" "
3 Newtown estuary	422 905	tidal channel mud
5 Yarmouth estaury	353 895	intertidal mud-flat
6 Yarmouth Estuary	348 873	" "
8 Wotton Creek	548 919	" "
9 Wotton Creek	554 932	" "

Table 6.20
Summary of coccolith data for estuarine sediments from the Isle of Wight

Estuary and sample No.	Distance from estuary mouth (km)	Number of modern coccoliths ($\times 10^5$/g)	Number of reworked coccoliths ($\times 10^5$/g)	(%) reworked coccoliths
1 Medina	3.5	30	471	94
2 Medina	5.5	27	365	93
3 Newtown	1.0	24	298	93
5 Yarmouth	0.5	ND	~100	94
6 Yarmouth	3.0	–	–	–
9 WoottonCreek	0.4	16	155	91
8 WoottonCreek	1.9	8	120	94

6.2.6 Estuaries of the northern coast of the Isle of Wight.

6.2.6.1 Introduction.

Four estuaries on the northern coast of the Isle of Wight were studied:

1) Yarmouth Estuary
2) Newtown Estuary
3) Medina Estuary
4) Wootton Creek

6.2.6.2 Yarmouth Estuary.

Yarmouth is the most westerly of the estuaries on the northern coast of the Isle of Wight and is situated almost directly opposite the Lymington Estuary. The estuary covers an area approximately 1.5 km and is tidal for a distance of some 3km. The estuary is flanked by saltmarsh, particularly along its lower section. Sediments were sampled from two sites in the Yarmouth Estuary (Fig. 6.17.). Recent and reworked coccoliths occur at the mouth of the estuary with the latter comprising 94 % of the total assemblage. Both forms were absent in sediments deposited at the tidal limits of the estuary.

6.2.6.3 Newtown Estuary.

Newtown Estuary lies midway between the towns of Yarmouth and Cowes on the northern coast of the Isle of Wight. From its narrow entrance the estuary broadens out into a complex series of low-lying marshes and creeks. Sediment from one of these creeks (Causeway Lake) was analysed in this report (Fig.6.17.). This sediment contains 24 $\times 10^5$ and 298 $\times 10^5$ Recent and reworked coccoliths per gram respectively. Reworked coccoliths form 92.5% of the total nannofossil assemblage. Carbonate forms 11% of the fine fraction of the sediment. Feldspar/quartz ratios are low in the sediments of the estuary (< 0.01). Glaucony is a rare component of the sediment.

6.2.6.4 Medina Estuary.

The Medina Estuary , centrally placed on the Isle of Wight, lies between East and West Cowes. It forms a narrow linear inlet 7 km long with its tidal limit lying at Newport. The width of the estuary varies from 0.5 km at its mouth, to less than 100m within the upper reaches. South of Cowes the estuary is nearly choked with mud.

Details of the salinity distribution throughout the estuary are poorly known. However, high salinities can occur on spring tides as far as Newport, where the salinity may vary from almost zero to 30 %. over the tidal cycle (Phillips,1980) In February the water column at Newport was stratified at high water springs to such an extent that a 25 %. salinity difference was detected in a total depth of 2 m.

Two samples from the Medina Estuary were studied in this report (Fig.6.17). Both Recent and reworked coccoliths decrease in number with distance from the mouth. Reworked coccoliths form between 93% and 94 % of the total nannofossil assemblages in the sediments. Reworked Chalk and Tertiary forms occur in the sediments. The most common Tertiary forms are Neochiastozygus dubius and Chiasmolithus bidens. Carbonate forms 11 % of the fine-fraction at site 1. The feldspar/quartz ratio is low in the sediments (<0.01).

6.2.6.5 Wootton Creek.

Wootton Creek is a short tidal inlet approximately 2 km in length on the northeastern coast of the Isle of Wight. The inlet is dammed at its upper end and receives a small fresh water inflow from the Blackbridge Brook. Two samples were studied from Wootton Creek (Fig 6.18). Recent coccoliths decline in numbers from 16 to 8 $x10^5$ per gram from the mouth to the head of the inlet. Reworked coccoliths show a similar trend and decrease from 155 $x10^5$

at the mouth to 120 x 10^5per gram at the head. Both Chalk and Tertiary forms occur in the sediments. Chiasmolithus bidens is the most common of the Tertiary coccoliths in the creek sediments. Carbonate forms between 11 and 10 % of the fine fraction in these sediments. The feldspar/quartz ratio of the sediments is low (0.02).

6.2.7. East Solent and Spithead.

Two sediments were sampled from the open-waters of East Solent and Spithead (Fig.6.17.). These sediments are relatively rich in fine-grained carbonate (18%) and modern coccoliths (> 50 x10^5/g). They also contain large numbers of reworked coccoliths, mainly Cretaceous forms (339 to 740 x10^5/g).

Table 6.21
Summary of carbonate data for estuarine sediments from the Isle of Wight

Sample	(wt%) carbonate	Abundance of carbonate laths	Abundance of carbonate rhombs	Calcite/qtz peak ht. ratio	
				Bulk sample	(2-20 μm)
1 Med.	11	+	++	0.05	0.48
2 Med.	ND	+	++		
3 Newtn.	11	+	++	0.03	0.11
6 Yarmth.	-	-	-	-	-
9 Wotton	11	+	++		
8 Woton	10	+	+	0.02	0.11

Table 6.22
Summary of non- carbonate mineral content of the sediments

Sample	Abundance of glaucony	Feldspar/qtz peak ht. ratio	(wt%) organic matter
1 Medina	+	<0.01	9.4
2 Medina	+		8.9
3 Newtown	+	<0.01	11.4
6 Yarmouth	+		
9 Wotton	+		16.1
8 Wotton	+	0.02	10.9

Table 6.23 Mineral composition and coccolith content of sediments from East Solent and Spithead

Area	East Solent	Spithead
Sample no.	(10)	(11)
Number of modern coccoliths ($\times 10^5$/g)	57	53
Number of reworked coccoliths ($\times 10^5$/g)	740	339
% reworked coccoliths	93	86
wt. % carbonate (2-20 μm)	18	18
carbonate laths	++	++
glaucony	++	+

6.3. DISCUSSION.

6.3.1 A comparison of the coccolith assemblages in the Solent region with those from the English Channel.

As noted in section 6.1.6, four species of Recent coccolith occur in the surface sediments of the Solent Estuarine System : Coccolithus pelagicus, Emiliania huxleyi, Helicosphaera carteri and Braarudosphaera bigelowii. All these species occur in the surface sediments of the central English Channel where four to six species occur in the assemblages. The Solent assemblages however, are characterised by a very high dominance of Coccolithus pelagicus (95% to 100%). In the central and eastern English Channel a greater range of relative abundance of the species occurs in the sediments (50% to 100%). Because of the dominance of C.pelagicus and the rarity and somewhat isolated occurrence of the other species in the Solent sediments, no tables listing species-composition and relative abundance are given.

The quantitative abundance of C.pelagicus in the open-water sediments of the Solent is characteristic of abundances of the species in sediments found in the central English Channel ($\sim 50 \times 10^5$ coccoliths per gram). A notable feature of the Solent sediments is the very low abundance of Emiliania huxleyi. This species forms approximately 5% or less of the coccolith assemblages in the Solent whereas throughout the central and eastern English Channel sediments it ranges 74 to 25 %. The quantitative abundance of E.huxleyi declines from 10^7 per gram in the Channel sediments to $< 10^5$ per gram in the Solent. No systematic variation in the abundance of E. huxleyi in the Solent could be determined because of the species scarcity in the sediments.

Single coccoliths of Helicosphaera carteri and Braarudosphaera bigelowii are occasionally recorded in the Solent sediments. These species are also scarce

components of coccolith assemblages in the English Channel (<2%). The occurrence of Helicosphaera carteri in the Solent sediments is the most easterly reported distribution of the species in the English Channel. Braarudosphaera bigelowii, however, is found distributed throughout the marine and estuarine sediments of the English Channel. B.bigelowii ranges from the Lower Cretaceous to Recent. It occurs in Bracklesham sediments exposed at Fawley (Hodson and West, 1970). The pentaliths recorded in the Solent sediments are not thought to be of reworked origin; they have a 'fresh' appearance and have smooth crystal margins.

6.3.2 Variations in the abundance of Recent coccoliths in the Solent sediments.

In this section the variations in abundance of Recent coccoliths in the sediments of the Solent will be correlated with changes in the hydrology of the various regions.

6.3.2.1 East Solent and Spithead.

As mentioned in section 6.3.1 abundances of C.pelagicus in the open-water sediments of East Solent and Spithead are typical of those found in the central English Channel sediments (~ 50 $\times 10^5$ coccoliths per gram). Salinity reduction is slight throughout the region with the mean surface salinity being 34.3 % (Phillips,1980). The sediments in East Solent and Spithead therefore may be considered to be of fully marine origin .

6.3.2.2. Southampton Water and the Test Estuary.

Coccolith abundances in the Recent sediments of Southampton Water are also typical of those found in the fully marine sediments of East Solent and the central Channel region. Sediments deposited in the main area of Southampton Water from Calshot Spit to Netley have

consistently high C.pelagicus abundances ~ 50 x 10^5 per gram. The surface salinities of the overlying waters range between 34 and 30.5 ‰. (Dyer, 1973). The high salinities in this region are also reflected in the occurrence of a fairly typical marine fauna. Mytilus edulis is dominant throughout the mud banks, particularly towards the northern end of Southampton Water. Other dominant bivalves include the common cockle Cerastoderma edule, Ostrea edulis, Mercenaria mercenaria and the American imported species Crepidula fornicata.

The first significant decrease in abundance of Recent coccoliths occurs at Dock Head, Southampton, and in the more confined waters of the lower Test Estuary where surface salinities fall below 30 ‰. (Fig.6.23.). Surface sediments in the lower Test Estuary have Recent coccolith abundances ranging from 13 to 33 x10^5 individuals per gram. A hydrological survey of the Test estuary from Dock Head to Redbridge was carried out by Romans (1979). Figs. 6.19 to 6.23. show the first high water and low water surface and bottom salinities for a spring tide (25.6.79) in the Test Estuary. There is a clear decrease in salinity towards the head of the estuary with the more saline water being concentrated in the dredged channel, particularly at low water. From Fig. 6.23., it can be seen that the bottom salinity at low water shows an abrupt salinity decrease at Eling , at the head of the dredged channel. A salinity change of 10 ‰. occurs over a very short distance. The greater marine influence in the dredged channel is relected in moderately high coccolith numbers in the surface sediments (10^6 per gram). In contrast, in the upper estuary above the dredged channel coccolith abundances range 10^4 to 10^5 individuals per gram.

Redbridge is the furthest point up the estuary at which Recent coccoliths have been recorded in the sediments. Here surface and bottom water salinities may reach 5 and 29 ‰. respectively on spring tides. Fluviatile conditions generally are dominant at Redbridge where for a period of six hours at low water the water

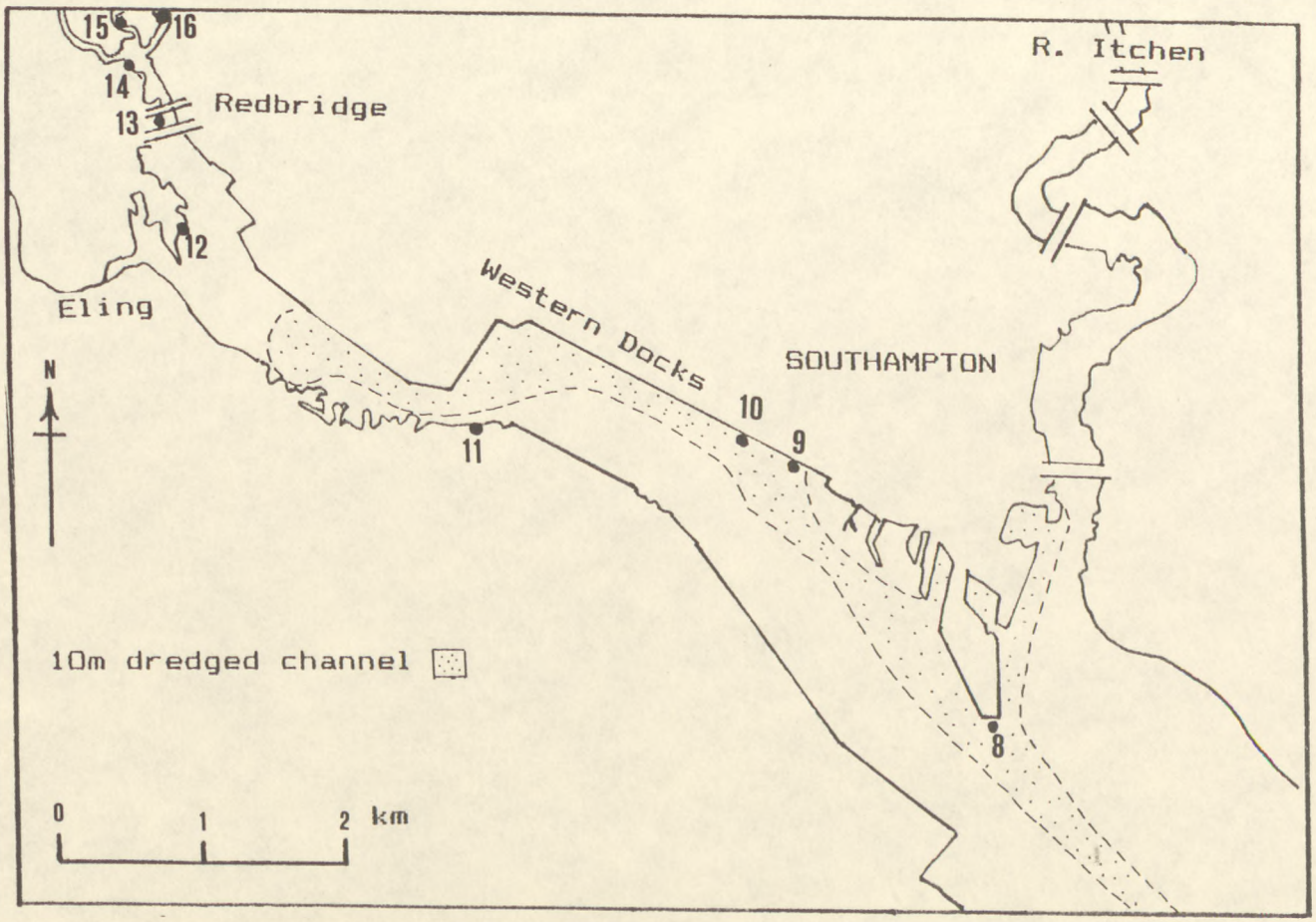


Figure 6.18.
Map of the Test Estuary.

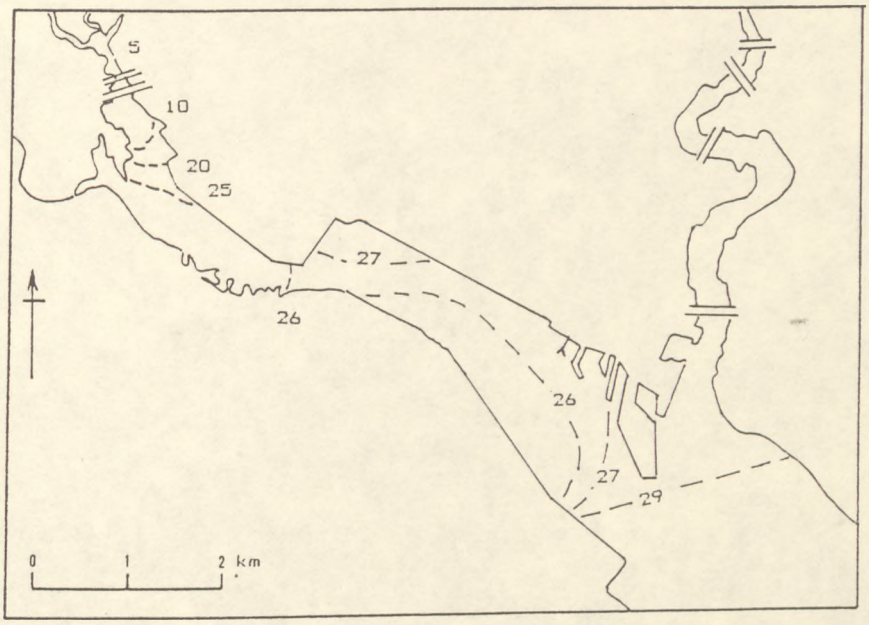


Figure 6.19.
Distribution of surface salinty (%.) at high water (spring tide) on 25/6/79 (after Romans, 1979).

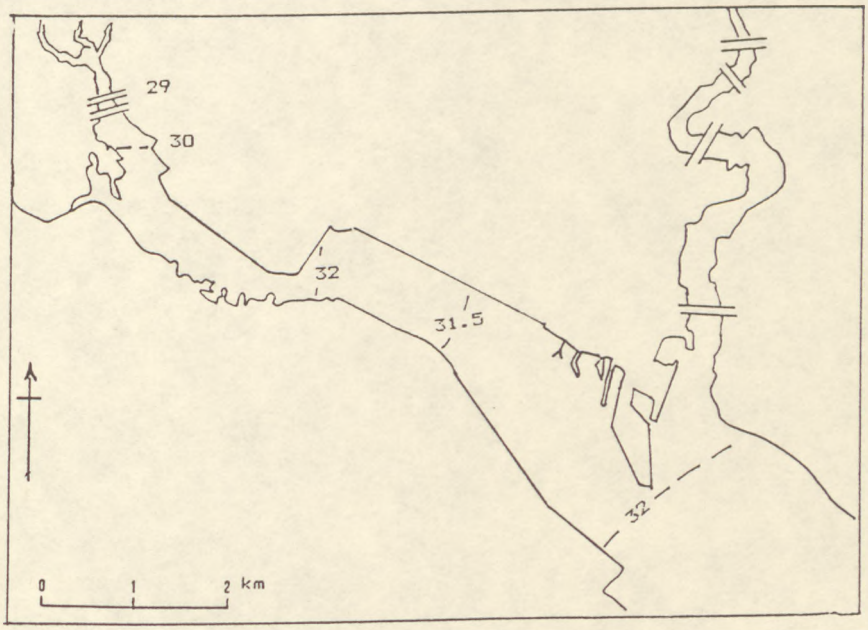


Figure 6.20.
Distribution of bottom-water salinity (%.) at high water (Spring tide) on 25/6/79 (after Romans, 1979).

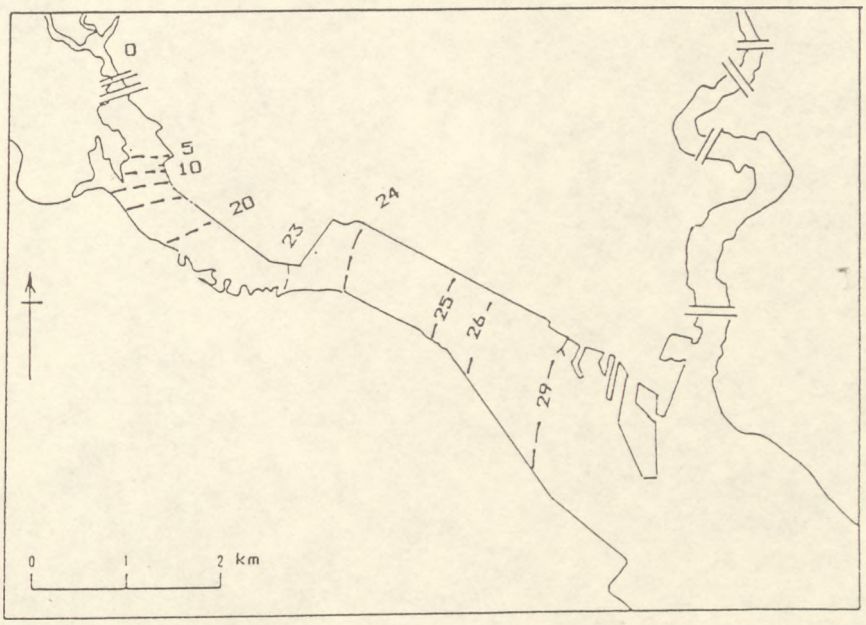


Figure 6.21.
Distribution of surface salinity (‰) at low water (spring tide) on 25/6/79. (after Romans, 1979).

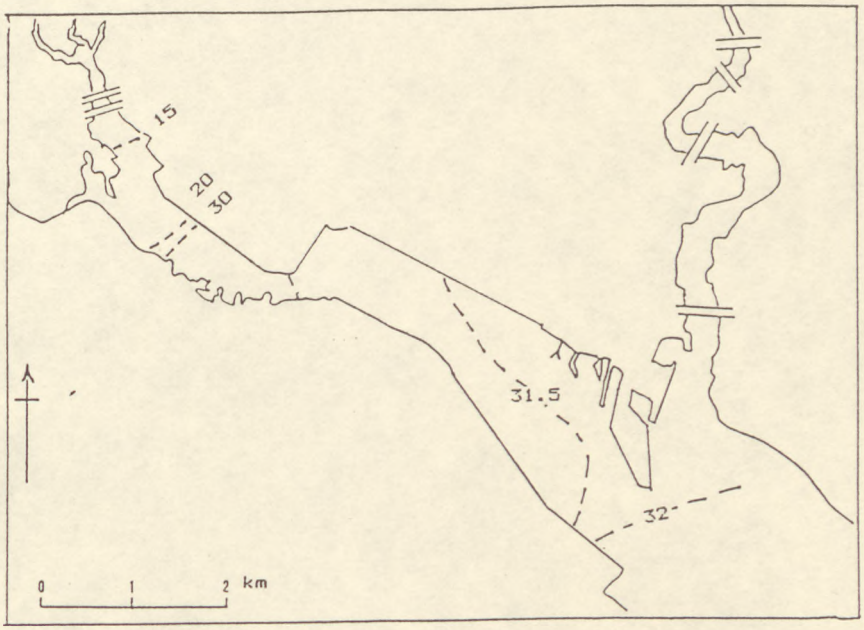


Figure 6.22.
Distribution of bottom-water salinity (‰) at low water (spring tide) on 25/6/79. (after Romans, 1979).

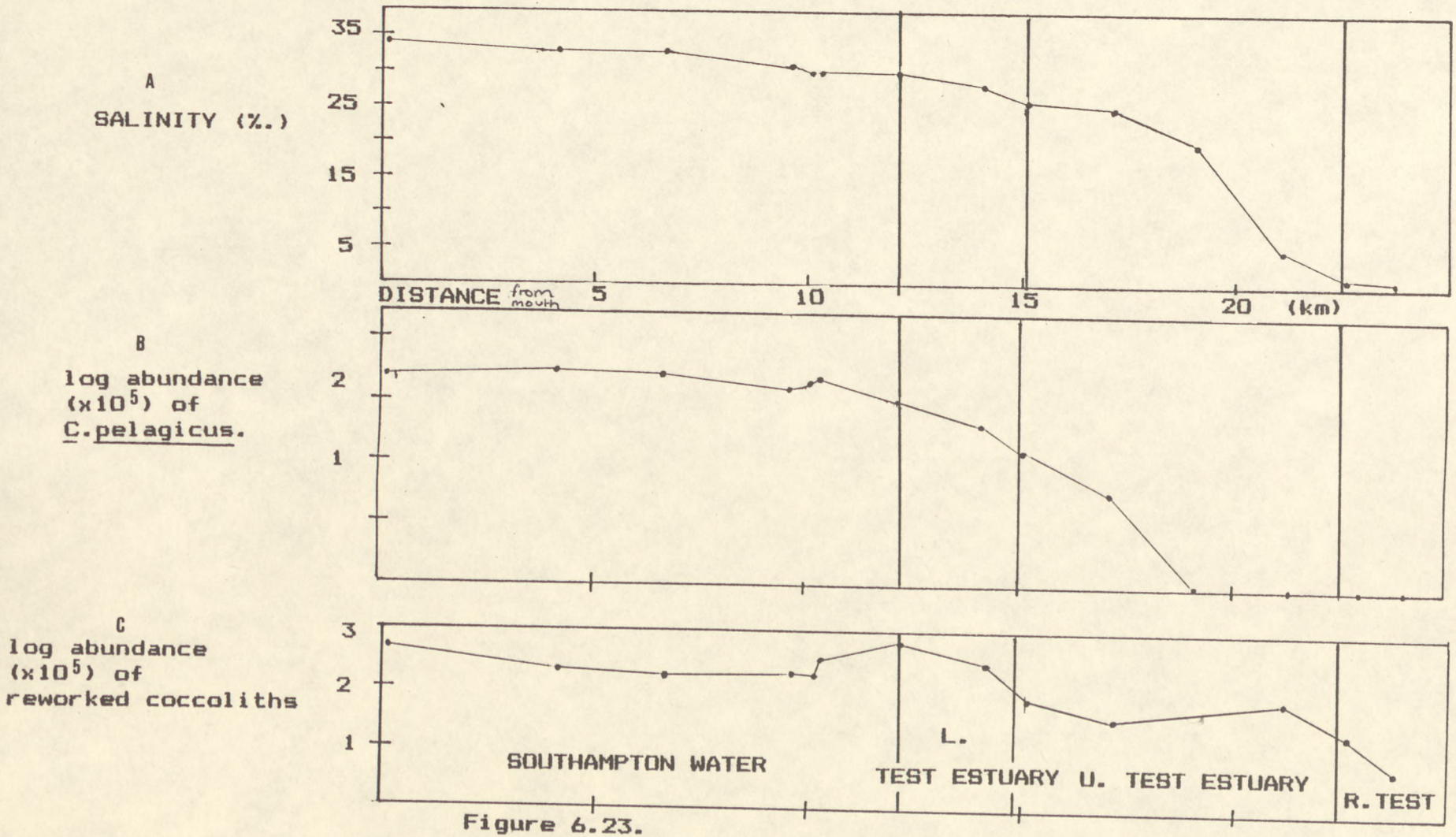


Figure 6.23.
Variations of A) surface salinity, B) abundance of C.pelagicus and C) abundance of reworked cocccoliths in Southampton Water and the Test Estuary.

flowing under the bridge is fresh and has no measurable salt concentration (Romans,1979).

On the 24 May 1975 the British Transport Docks Board carried out a current survey in the Bury swinging ground at the northern end of the western docks. This study showed that only in the period two and a half hours before first high water is there a small upstream flow, whilst between 3 and 5 hours after the first high water there is a strong surface current downstrem. These data indicate the dominant transport direction in this part of the Test Estuary is downstream. Further evidence of sediment transport directions within the Test Estuary was recorded by Romans (1979). At the mouth of the Test Estuary there is a broad area of upstream transport over the whole water column for the 4 hours before the first high water. For the remainder of the tidal cycle the flow is downstream with the highest currents occurring at low water.

Further up the Test the upstream transport becomes diffuse with a poorly defined region in which there is relatively low transport upstream in the 6 hours preceding high water. Within the upper Test the upstream flow is confined to a much smaller area. Romans recorded that there is no transport upstream in the surface waters. Upstream transport is confined to the bottom layer and only occurs just before the first and second high waters. The variations in the duration and magnitude of water movement within the Test Estuary are reflected in the number of coccoliths in the surface sediments. At the mouth of the estuary where up-estuary transport is occurring over a significant part of the tidal cycle moderately high coccolith numbers occur in the surface sediments (10^6 per gram). At Redbridge , where downstream transport is dominant coccolith abundances only reach 10^5 per gram. The scarce coccoliths found in the sediments at Redbridge were probably transported there by bottom currents during spring flood tides.

Although tidal influences extend into the southern part of the reed beds above Redbridge, no Recent coccoliths were observed in the sediments. It is doubtful whether any marine-derived silt is transported into these reed beds because of the overall predominance of downstream currents in this region. Therefore, above Redbridge in the Upper Test Estuary, the sediments are considered to be of fluviatile origin.

6.3.2.3. Itchen Estuary.

The transition from the open-waters of Southampton Water to the confined waters of the Itchen Estuary is marked by a decrease in Recent coccoliths in the surface sediments of the two area from ~ 50 to 38 $\times 10^5$ per gram. Surface salinities at the mouth of the Itchen average 30 ‰. or less. The highest abundances occur at the mouth of the estuary and in the deep-water area of the Princess Alexandra Dock and its dredged approach (> 20 $\times 10^5$ per gram). In the upper reaches of the Itchen Estuary coccolith abundances decline to 10^5 coccoliths per gram. Surface salinities at the head of the estuary at Woodmill range from 1 to 6 ‰. . Bottom salinities here however, attain 20 ‰. . The waters throughout the Itchen estuary are strongly stratified and the marine-derived silt is probably transported up the estuary in the saline bottom waters. Coccolith abundances at the head of the estuary , however, are only approximately 1/7 th their abundance value at the mouth of the estuary.

6.3.2.4. Hamble Estuary.

The abundance of Recent coccoliths in the surface sediments of the Hamble Estuary decrease upstream away from the influence of Southampton Water (Fig.6.24.). The transition from the open-water sediments of Southampton Water to the confined waters of the Hamble Channel is marked by a decline in coccolith numbers from > 50 to < 30 $\times 10^5$ per gram. However, their is no major decrease in the salinity at the mouth of the Hamble, where surface values

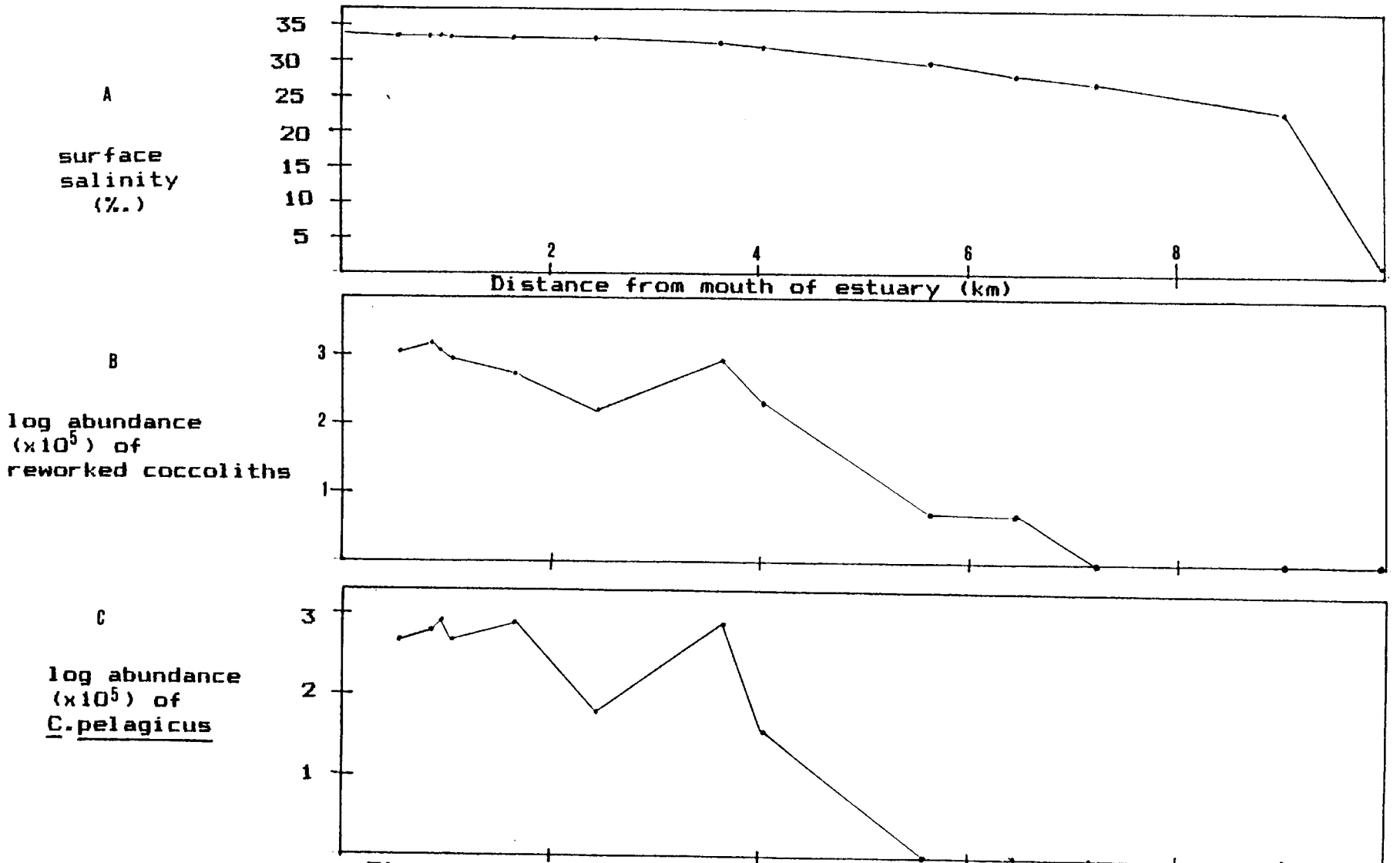


Figure 6.24.
Variations of A) surface salinity, B) abundance of reworked coccoliths and C) abundance of C.pelagicus in the Hamble Estuary.

average 33.5 ‰. on spring high tides (Collins,1967). Coccolith abundances are generally constant throughout the first 3km of the estuary, where surface salinities range 33.5 to 32.7 ‰. at high-water. This lower section of the estuary has a deep-water channel,in excess of 2m. Further up the estuary the channel shallows and salinity changes become more pronounced.

Coccolith abundances decline rapidly within the middle and upper reaches of the estuary. Sediments deposited at salinities of 32 ‰. or less contain less than 10^6/gram . At surface salinities of less than 30 ‰. < 10^5 coccoliths per gram occur in the sediments. No Recent coccoliths occur in the surface sediments deposited in the upper 3 km of the estuary, where surface salinities of the overlying waters fall below 25‰. . Further evidence of marine influence at the mouth of the Hamble is the common occurrence of marine-derived skeletal carbonate laths in the surface sediments. These occur in consistently high numbers throughout sediments deposited from waters with a surface salinity in excess of 32 ‰. . At salinities less than 28 ‰. they are scarce in the bottom sediments.

The siltation at the Port Hamble Marina, 2 km from the mouth of the estuary, has been studied by Tosswell (1984) . This study showed that the rate of siltation is in the order of 0.2 m/ annum with as much as 0.6m/ annum at the landward margin. Suspended solids in the waters at the Marina have a natural background level of 15 to 30 mg/l but peak values can be as high as 500 mg/l. These spasmodic bursts of high suspended sediment activity are of short duration, lasting only for a few hours, and occur predominantly on the flood tide rather than the ebb. Typically the second stage of the flood exhibits a higher concentration than the first, with very little sediment being in suspension during the near-stand. Tosswell concluded that there is a greater tendency for siltation during the periods of high suspended sediment concentrations. Highest concentrations of suspended

sediments occurred during April and September suggesting that the tidal range is significant factor.

Marine-derived silt is probably supplied in greatest volumes to the lower Hamble Estuary during the incursions of the high water spring tides. Marine sitation generally decreases in importance in the middle section of the estuary where the surface waters have salinities of 32 ‰. or less. The upper 3 km of the Hamble Estuary from Dock Copse to Botley Mill is considered to be a region of fluviatile sedimentation.

6.3.2.5. West Solent.

Recent coccolith abundances are lower in the estuaries of West Solent than those recorded from Southampton Water and in the open water sediments of East Solent. The highest abundance occurs in the Medina Estuary where 30 x 10^5 coccoliths per gram occur in the surface sediments. Coccoliths are also scarce in Wootton Creek a tidal inlet adjacent to West Solent (16 x10^5/g). Such low abundances in these estuaries cannot be explained simply by dilution from fluviatile sediments . Fresh water input from the Isle of Wight is low, particularly in Wootton Creek.

A possible cause for low abundances of Recent coccoliths along the north coast of the Isle of Wight is that currents transporting the coccoliths are mainly flowing northwards into Southampton Water, rather than flowing east into West Solent from East Solent. Coccolith abundances generally decrease in easterly direction in the sediments of West Solent. Low abundances of Recent coccoliths in West Solent sediments suggest that little marine-derived carbonate is being transported into the West Solent region through the Needles-Hurst Castle channel.

6.3.2.6. The Estuaries of the Beaulieu and Lymington.

Fine-grained carbonate is very scarce (1 % or less) in the Recent sediments of the Beaulieu and Lymington estuaries. Recent coccoliths are absent throughout the greater part of the Beaulieu and are seldom seen in the sediments of the Lymington. A possible reason for this scarcity of coccoliths may be that these inlets are sites of predominatly fluviatile sedimentation. This suggestion is not supported by the salinity distribution in these estuaries. The Lymington Estuary only has a short tidal length (2.3km), with high-water salinities at Lymington Quay averaging 30 %. in the surface waters. Therefore there is a strong marine influence throughout the estuary at high water. Additionally, sponge spicules abundant throughout the area of marine siltation in Southampton Water occur in large numbers in the Lymington sediments.

The Beaulieu has a much larger estuary (9km long) with a fairly continuous decrease in salinity in the surface waters from the mouth (34.5 %.) to the head of the estuary (18.5 %.). These salinity values show that there is a gradual decrease in marine influence from the mouth to the head of the Estuary. If fluviatile sedimentation was responsible for the scarcity of coccoliths upstream in the Beaulieu Estuary, one would expect a more gradual decrease in coccolith numbers in the surface sediments. However, coccoliths and fine-grained carbonate only occur at the mouth of the estuary and are not recorded further upstream.

A further indication in the gradual change in the degree of marine influence within the estuary is shown in the distribution of dissolved manganese and zinc in the waters (Holliday and Liss,1975). These workers showed that both Zn and Mn were supplied in concentrations of 50 ppm and 120 ppm respectively from fresh water at the head of the estuary. The concentrations of these metals in the surface waters were gradually diluted down the estuary as the fresh and marine waters mixed in the estuary. This

decrease in metal concentration forms a linear relationship with the increase in salinity of the water (Fig. 6.25.).

Another possible cause for the scarcity of fine-grained carbonate in these sediment may be the result of dissolution caused by acidic waters. The Beaulieu and Lymington both receive run-off from extensive areas of the New Forest. These streams drain a complex of leached, peaty and fertile alluvial soils, particularly the bogs and wet heaths in valleys and basins. The Beaulieu River drains a complex of heathland and grasslands (Fig.6.27), mainly on the Barton Sand Formation (Fig.6.28.), whereas there are gravel deposits in the shallow valley in the Beaulieu River itself. In general, both the plateau gravels and the 'Barton Sands' are strongly leached and dominated by heather. The extensive valley bogs in the area carry deep accumulations of peat. Tracts of alluvial soils also lie within the valleys of the Beaulieu.

The grasslands of the New Forest may be classified according to such criteria such as soil base status , soil moisture and soil fertility (Tubbs,1968). It is sufficient here to confine description to the broad categories of the bent/fescue stream-side lawns and the acid grasslands dominated by Bristle Bent (Agrostis curtisii) and Purple Moor-Grass (Molinia caerulea) .

The bent (Agrostis capillaris)/ fescue (Festuca ovina) lawns are confined in the New Forest to the base-rich, alluvial soils in valley bottoms. Putman et al. (1981) recorded the pH of several stream-side lawns in the Beaulieu catchment area and found that the average pH was only 4.7. These sites are generally wet and contain large amounts of organic matter which decomposes slowly releasing humic acids to the soils. Acid grassland occupies a considerable area of the New Forest (11,000 acres) (Tubbs, 1968). These grasslands have a large range in potential fertility. At the upper end are clay soils giving a pH value of 5.5 in the upper few cm of the soil

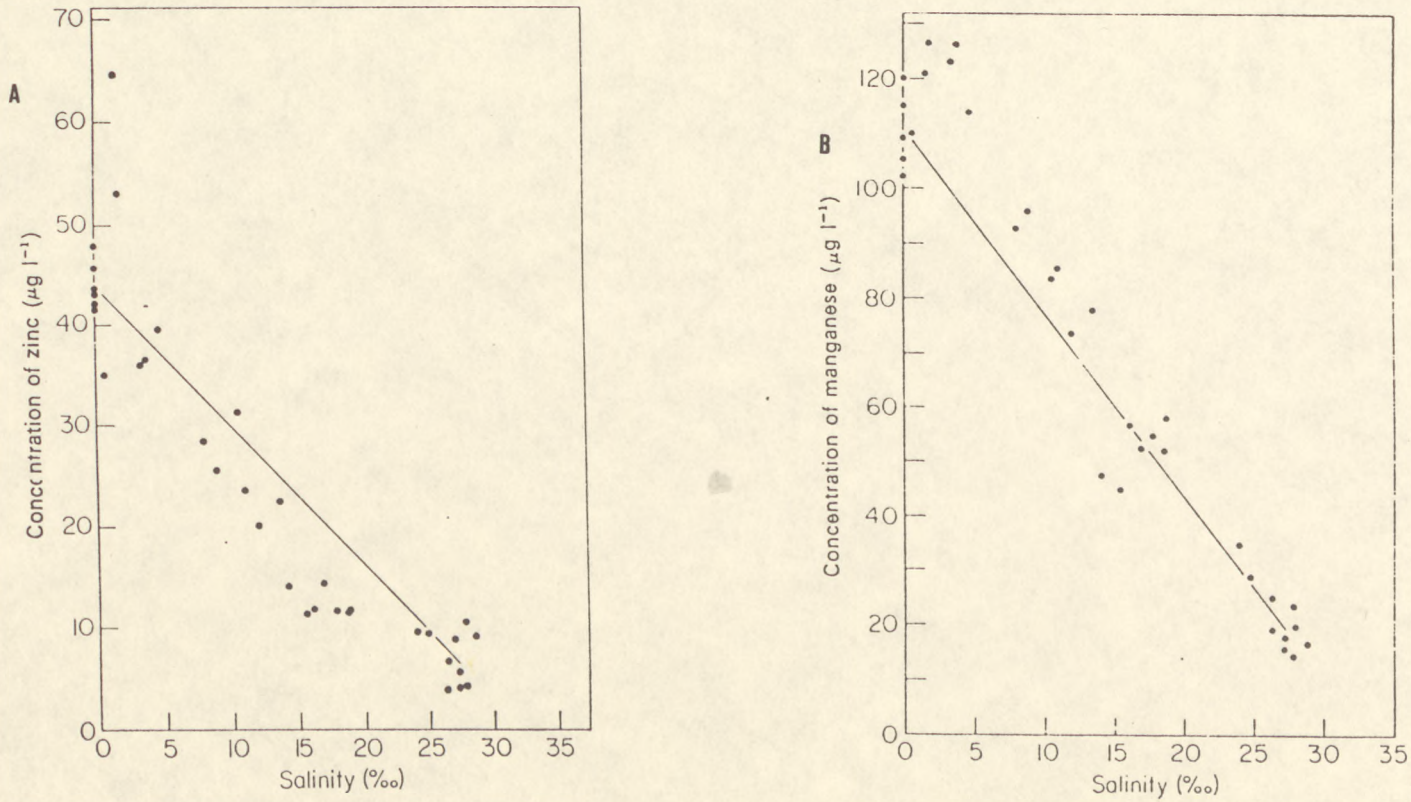


Figure 6.25.
Relationship between salinity and concentration of A) dissolved zinc,and B) dissolved manganese in the Beaulieu Estuary. (after Holliday and Liss, 1976).

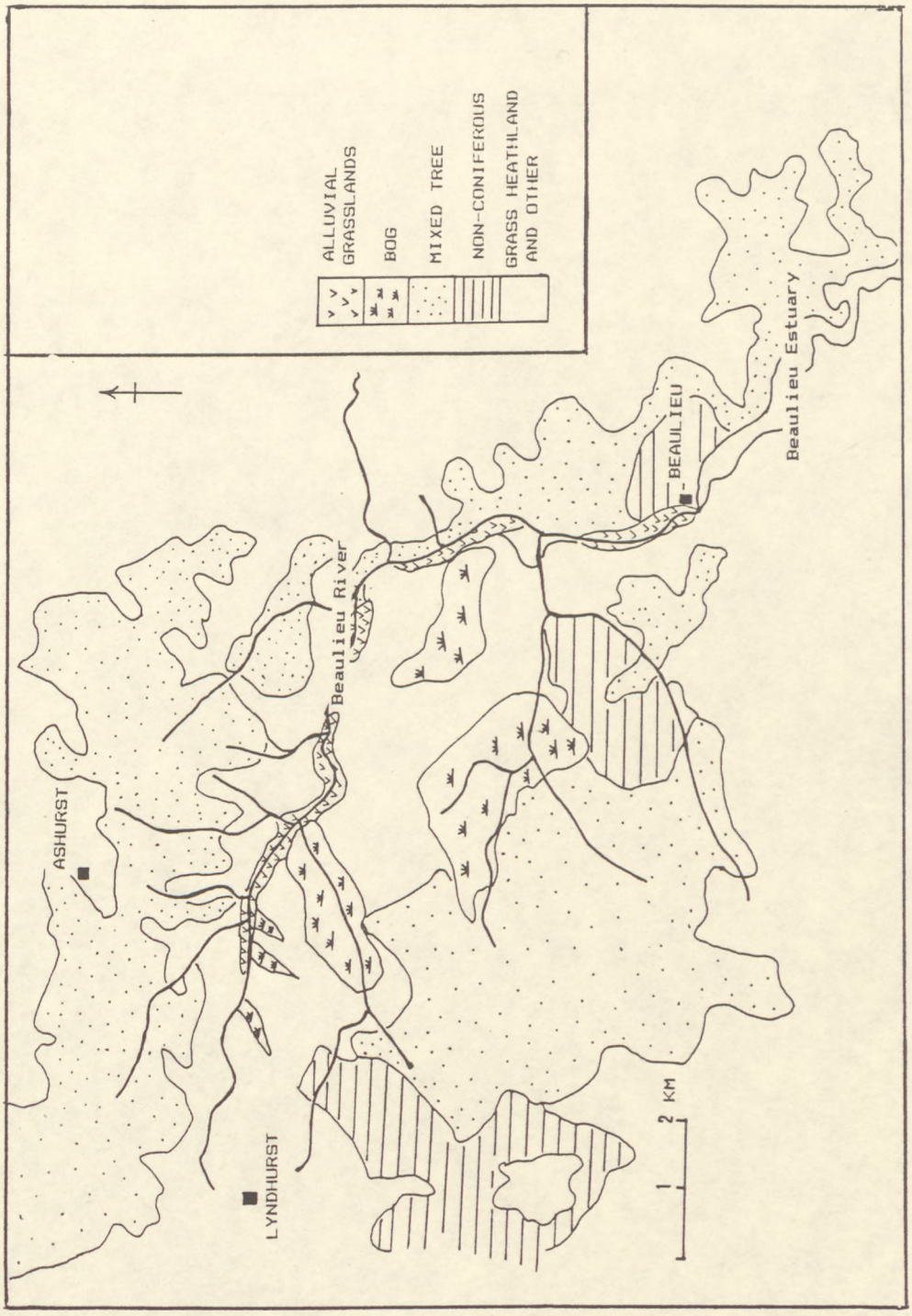


Figure 6.26.
Map showing the vegetation cover in the Beaulieu River catchment area (modified from Upstill-Goddard, 1980)

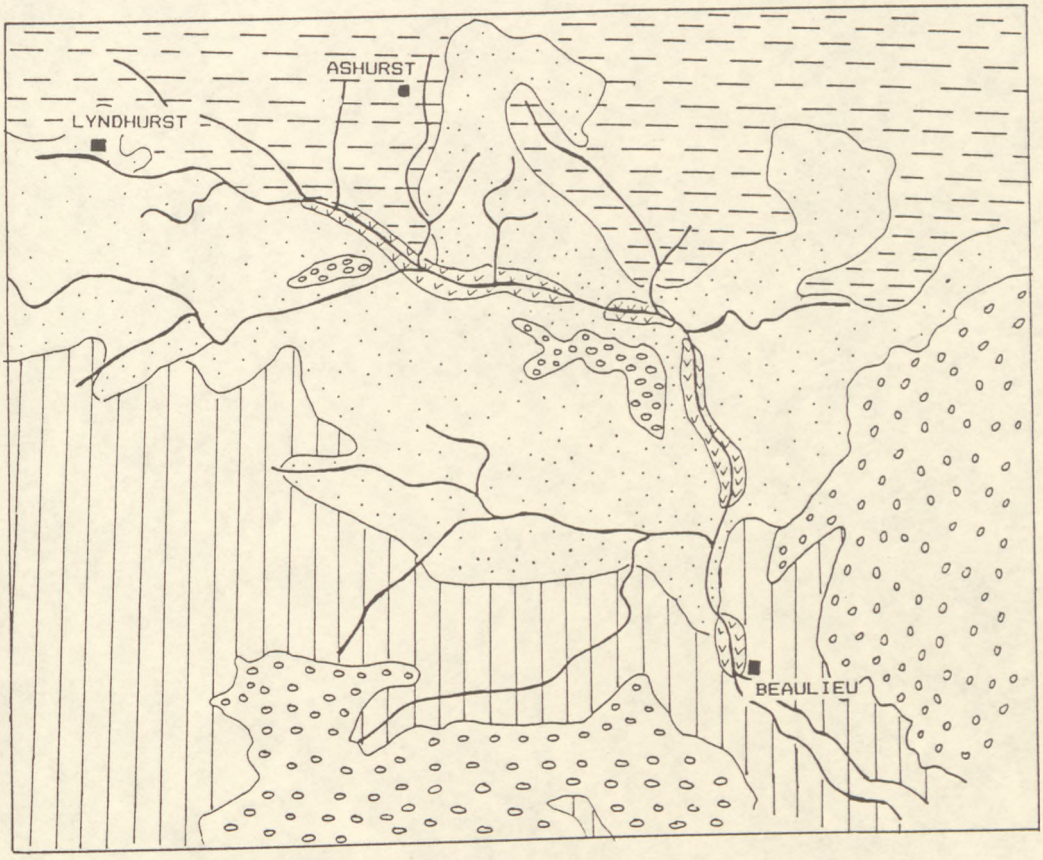


Figure 6.27.
Geological map of the Beaulieu River catchment area.

ALLUVIUM

PLATEAU GRAVEL

HEADON HILL FORMATION

'BARTON SAND'

'BARTON CLAY'

profile. At the lower end there are soils derived from coarser sediment, severely deficient in potash and phosphate , and acutely deficient in lime ; these give pH readings as low as 3.7.

Vegetation in which heather (ling) (Calluna vulgaris) is dominant extends over an area of approximately 18,000 acres of the New Forest. Calluna and other ericaceous heathland requires certain conditions to become established; the soil should be low in nutrients and have a low pH within the range 3.5 to 6.7 (Hazel,1983). Once established ling will exacerbrate soil deterioration thus providing the desired conditions.

Bogs and wet heaths occupy a total area of approximately 7,000 acres of the enclosed Forest (Tubbs, 1968) and are characterised by accumulations of peat in the valleys. When the peat is leached by waters deficient in base minerals it becomes increasingly acidic . Plant debris in the bogs decomposes slowly and releases quantities of humic acids to the soil.

The vegetation cover in the New Forest area is therefore suppling quantities of acidic run-off into the Beaulieu and Lymington drainage streams. Upstill-Goddard (1980) recorded the pH value of numerous streams flowing into the Beaulieu River. This study selected streams that had originated on the different geological units within the catchment area . The results are listed below.

Table 6.24. The pH of selected streams draining into the Beaulieu River.

Geological Unit	Number of observations	pH range	pH mean
Headon Hill Fm.	5	4.8- 6.4	5.9
Barton Sand Fm.	5	7.1- 7.6	7.2
Barton Clay Fm.	16	4.2- 7.6	6.2

The mean pH of the river water entering at the head of the Beaulieu Estuary is 6.5, whereas seawater at a salinity of 29 ‰ is 7.9 (Holliday and Liss , 1976). A similar range of pH values is recorded in the Lymington Estuary where river water has a pH value of 7.1 and seawater near the mouth of the estuary a value of 8.0. The influence of these acidic streams draining into the Beaulieu and Lymington estuaries will vary seasonally . Lowest pH values in the estuary waters are to be expected during periods of high rainfall and at low tidal levels.

The pH of normal marine water usually falls within the range of 7.8 to 8.2 because of the buffering action of bicarbonate ions which tend to resist changes in pH (Ollauson and Cato, 1980). Calcium carbonate is generally stable in shallow marine waters at a pH value of ~8. The river water of the Beaulieu and Lymington is not buffered and is consequently of lower pH. Calcium carbonate in contact with this river water will consequently start to dissolve.

The micron-sized skeletal carbonate deposited in the surface sediments would be most susceptable to dissolution from the acidic waters. Optical analysis of the Beaulieu sediments shows that carbonate generally only occurs as particles in the coarse silt and sand sized fractions. Carbonate forms 8% of the bulk sediment at the mouth of the Beaulieu but only 0.5 % in the fine silt fraction (2-20 um). A similar distribution of carbonate occurs in the Lymington sediments. Carbonate averages 4% in the bulk sediments as opposed to 1% or less in the fine fraction. An additional source of acidic waters in the estuaries of the Beaulieu and Lymington is supplied from the extensive areas of Spartina marsh, which occur at the mouth and lower reaches of both estuaries. This acidic influence would be most pronounced at low water when the interstitial marsh waters drain off the marsh into the numerous channels that cross the intertidal mudflats.

Fine-grained carbonate is certainly supplied to the

West Solent region. It was detected in XRD analysis of suspended sediments from the West Solent by Srisaengthong (1982). Carbonate also occurs within the Isle of Wight estuaries which lie almost directly opposite the Lymington and Beaulieu estuaries. These estuaries contain between 10% and 11 % carbonate in their fine fractions, but do not receive acidic run-off from heathland and bogs. Additionally, Dyer (1980) showed that the abundance of carbonate in the surface sediments of West Solent ranged from 20% near the coast of the Isle of Wight to less than 5% in the central channel and along the northern coastline.

It seems likely that fine-grained carbonate is supplied to the Beaulieu and Lymington estuaries from marine currents in amounts of approximately 10% . The individual micron-sized particles must be rapidly removed by acidic dissolution whilst they are resident at the sediment-water interface . The resulting sediment is therefore found to contain only relatively rare sand and coarse silt-sized carbonate but is barren of coccolith and other skeletal micron-sized debris. The slightly greater abundance of fine carbonate in the Lymington sediments may be attributed to the shorter ,more open tidal channel of the estuary.

6.3.3 The occurrence and derivation of reworked coccoliths in the Solent sediments.

Large numbers of reworked coccoliths are a consistent component in the fine fractions from the Solent sediments. Open-water sediments from East Solent and Spithead contain 339 to 740 $\times 10^5$ reworked coccoliths per gram. These are mainly Cretaceous forms with a minor component of Tertiary coccoliths . They represent between 86 and 93% of the total coccolith population in the sediments. High relative abundances of reworked coccoliths also occur in the central English Channel sediments (range 85 to 89%).

Reworked coccolith values in the sediments of Southampton Water are similar to those found in East Solent (range 78 to 91%) . The higher values being recorded from the deep-water areas near the mouth of Southampton Water and in the dredged approach to Dock Head. The quantitative abundance of reworked coccoliths in the sediments of Southampton Water remains high ranging from 184 to 748 $\times 10^5$ per gram. The first significant decline in reworked coccolith numbers occurs in the more confined waters of the Lower Test Estuary where abundances are reduced to 10 per gram. Surface salinities in this section of the estuary reach 26 ‰. at high water. Reworked coccoliths are scarce throughout the upper reaches of the Test Estuary (10^5 to 10^6 per gram). In the fluviatile sites in the River Test they are also scarce in the sediments (10^4 to 10^5). Reworked values in the fluviatile sediments therefore only represent 1% of the reworked values found in Southampton Water.

The reworked coccoliths have a very similar distribution to the Recent coccoliths in the sediments of Southampton Water and the Test Estuary, suggesting a similar derivation for both coccolith types. These data indicate that although the catchment area of the Test is

underlain by extensive areas of Chalk , no significant amounts of reworked coccoliths are being transported down the river and into the head of the estuary. The decreasing gradient of abundance of Recent and reworked coccoliths from Southampton Water and into the Test Estuary parallels the decrease in marine influence up the tidal inlet. This shows that both forms are being transported up the estuary and that they may be used as tracers of marine-derived silt in the sediments.

Reworked Tertiary coccoliths are subordinate to Cretaceous forms in Southampton Water. They occur most frequently at the mouth of Southampton Water but are very scarce in the Test Estuary. No Tertiary forms were recorded in the fluviatile sediments.

Cretaceous coccoliths also dominate the reworked component of the assemblages in the Itchen Estuary. Reworked coccoliths occur in numbers greater than 10^7 per gram throughout the sediments of the Itchen Estuary. Their numbers therefore do not decline as rapidly in an up-estuary direction as previously described for sediments in the Test Estuary. Abundances range from 287 $\times 10^5$ coccoliths per gram at the mouth of the estuary to 165 $\times 10^5$ at the tidal limits. The percentage reworked coccolith component in the sediments of the Itchen estuary is also high. It ranges from 88 % at the mouth to > 99% in the upper reaches and represent slightly higher values than those found in sediments from Southampton Water (range 78 to 91%). Such an increase in relative abundance of reworked coccoliths in the estuary may indicate an additional source of reworked coccoliths into the estuary system.

The source of these coccoliths could be from fresh water run-off from the catchment area, over half of which is underlain by Chalk strata. In fact, Chalk is found to outcrop less than 10 km from the tidal limits of the Itchen. Fluviatile sediments, sampled 1 km upstream from tidal influence, contain 18 $\times$ 10^5 reworked coccoliths per

gram. This figure only represents approximately 10% of the total number of reworked coccoliths found in sediments at the head of the estuary. These data indicate that although some coccolith detritus may be transported by the River Itchen into the Estuary system it is probably only a minor contributor.

Additionally, the waters of the Test and Itchen are noted for their clarity, a fact partly attributable to their lack of free-floating green algae (Doherty and Pilkington,1983). The algae are prevented from multiplying by the lack of two essential plant nutrients, nitrates and phosphates. In Chalk streams the excess of calcium effectively removes these compounds from the waters by binding onto them and depositing them in the bottom sediment. This silt can provide enough nutrients to support an extensive growth of rooted aquatic plants, which, in turn, benefit from the large amounts of light which are able to penetrate the waters. An extensive plant cover of the bottom silt may also provide an effective protection against erosion by currents. The clear water of Chalk rivers is also derived from the fact that they are mainly supplied by spring waters from the Chalk. Because the Chalk releases the water very slowly the supply remains constant throughout the year , as does its temperature. With little variation in the volume of water flowing down the river channels of Chalk streams, large quantities of suspended sediments associated with flood waters are seldom seen.

Another possible explanation for the higher relative abundance of reworked coccoliths in the Itchen is that they are derived from Chalk debris dumped in the estuary. Chalk is frequently used to strengthen the sides of many of the rivers and tidal inlets in Hampshire and has been observed by the author at various sites in the Itchen Estuary.

Reworked coccoliths have been recorded in sediments from the lower and middle sections of the Hamble Estuary.

They have their greatest abundance at the mouth of the estuary where 10^8 per gram occur. These sediments have the highest number of reworked coccoliths recorded in the Solent Estuarine System. A significant component of the reworked assemblage is composed of Eocene forms particularly Chiasmolithus bidens, Neochiastozygus dubius and Recticulofenestra spp. Both Cretaceous and Eocene derived coccoliths decrease in abundance up the estuary away from the influence of Southampton Water. Approximately 1 km from the mouth of the Estuary coccolith abundances have declined to $\times 10^7$ per gram. Within the middle and upper reaches of the Estuary reworked coccoliths average 10^6 per gram. At the tidal limits of the Hamble no reworked coccoliths are reported in the sediments.

High numbers of reworked Eocene coccoliths in the Solent estuarine sediments only occur at the mouth of the Hamble. This suggests a local derivation. A probable source for these Eocene coccoliths is from the Bracklesham Group exposed at the mouth of the Hamble and at Lee-on-Solent. These areas of the coast are being actively eroded at the present. Hodson and West (1970) have described a calcareous nannoflora from an upper Bracklesham horizon at Fawley; the same horizon is exposed at Lee-on-Solent (Fisher,1862). They recorded the presence of a diverse nannoflora which included Recticulofenestra spp., Neochiastozygus dubius and Traversopontis obliquipons ; all species found reworked in the Hamble sediments . Additionally Chiasmolithus sp. N.dubius, Recticulofenestra umbilica and Transversopontis obliquipons were also recorded in the Bracklesham Beds exposed at Whitecliff Bay on the Isle of Wight (Jones,1981). The variations in reworked coccolith numbers throughout the Hamble Estuary strongly indicate that large numbers of reworked coccoliths (both Cretaceous and Eocene forms) are being transported into the estuary by marine currents . Few, if any, reworked coccoliths are being brought down by the Hamble River draining a mainly Tertiary catchment area.

PLATE 6

Optical photomicrographs of calcite fibres in fine fractions (2-20 μm) from Southampton Water.

Fig.1 (x 400).

Fig.2 (x 600).



1



2

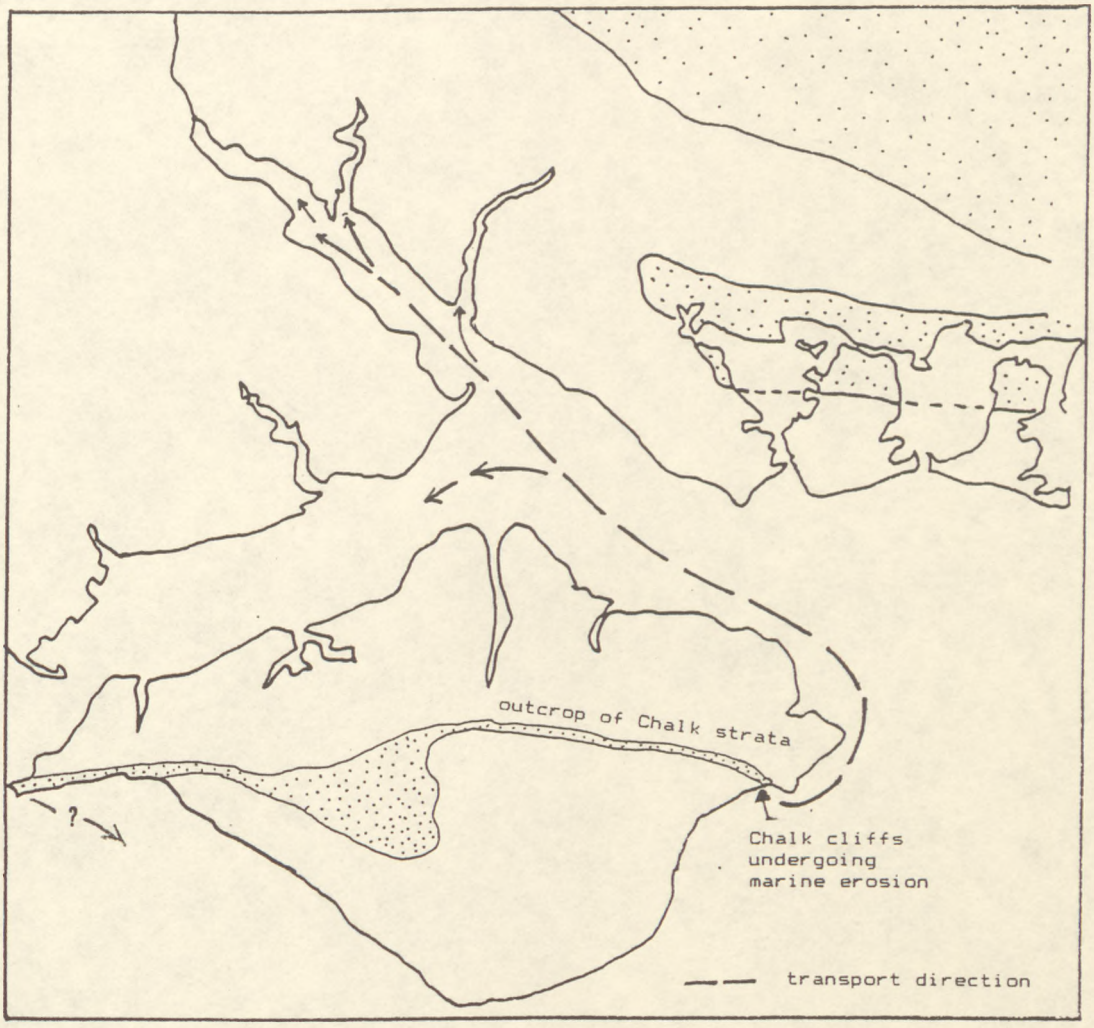


Figure **6.28.**
Proposed source and transport directions of reworked Cretaceous coccoliths found in the Solent surface sediments.

Table 6.25 Reworked Cretaceous coccoliths found in the Solent sediments.

Species	Range
Biscutum ellipticum	Sinemurian - U.Campanian
Cyclagelosphaera margerli	Bathonian - Campanian
Cylindralithus biarus	Cenomanium - Campanian
Eiffelithus eximus	Turonian - Campanian
Ellipsagelosphaera forbesii	Aptian - Campanian
E.keftalrempti	Bajocian - Campanian
Helicolithus trabeculatus	Albian - Campanian
Lithastrinus floralis	Aptian - Campanian
Manivetella pemmatoidea	Hauterivian- Campanian
Micula staurophora	Coniacian - Campanian
Markalius inversus	Hauterivian- Campanian
Prediscosphaera cretacea	Albian - Campanian
Prediscosphaera spinosa	Albian - Campanian
Phanolithus obscurus	Turonian - Campanian
Reinhardtites amthophorus	Santonian - Campanian
Tranolithus sallium	Albian - Turonian
Watznaueria barnesae	Bajocian - Campanian
Zygodiscus compactus	Barremian - Campanian
Zygodiscus elegans	Hauterivian- Cenomanian

As mentioned previously, the source of the reworked Cretaceous coccoliths in Southampton Water and its adjacent inlets is not thought to be from fluviatile input from the rivers Test and Itchen. These Cretaceous coccoliths are marine-derived in origin, most probably supplied from Chalk cliffs on the Isle of Wight.

The main outcrop of Chalk extends the length of the Isle of Wight from east to west. Impressive sea cliffs formed mainly of Upper Chalk occur at Culver Cliff at the eastern end of the Isle of Wight. These rise to height of over 100m, and at their base occurs a broad wave-cut platform which is revealed at low water. On the north side of the Culver Headland the Chalk dips steeply seawards. These cliffs are undergoing marine erosion and must supply a significant amount of Chalk detritus (ie., coccoliths) to the waters around the cliffs. The eroded Chalk coccoliths may then be transported around the Isle of Wight and into Southampton Water (Fig.6.28.). Dyer (1980) has also suggested a similar path for transport of sand and mud from East Solent and into Southampton Water.

There is little evidence to suggest that reworked Cretaceous coccoliths are being transported from the Needles, at the western end of the Isle of Wight, into the West Solent . Reworked coccoliths generally decline in numbers in a westerly direction in the West Solent sediments. Reworked coccoliths are either absent or very scarce ($< 10^5$ per gram) in the sediments of the Beaulieu and Lymington estuaries. Acidic run-off into these estuaries removes practically all fine carbonate from the sediments (see section 6.3.2.6.).

6.3.4 Species-composition and stratigraphical range of the reworked Cretaceous coccoliths found in the Solent sediments.

Reworked Cretaceous coccoliths recorded in the

surface sediments of the Solent are listed in Table 6.24. The reworked assemblages are dominated by one species, Watznaueria barnesae (Black) Perch-Neilson . This species is ubiquitous in sediments where reworked nannofossils are preserved. Watznaueria barnesae generally forms between 63 and 86% of the reworked coccolith component in the sediments from East Solent and Southampton water. W. barnesae has a placolith-type coccolith with strongly imbricated elements (Pl.8, Figs. 2 to 4). The species is sturdily built with a minimum of surface area exposed.

Hill (1975) conducted laboratory experiments to determine the selective dissolution of Upper Cretaceous (Cenomanian) coccoliths. The coccoliths were extracted at hourly intervals from an agitated acidic solution (pH 5.5) and the species-composition of the assemblages was determined. Hill found that W.barnesae was the most resistant to dissolution and its relative abundance was found to increase from 12 to 30 % over the period of the experiment. The species obviously has a sturdy, solution-resistant structure, which will survive the processes of erosion, transport and deposition. However, little direct information on sediment derivation is supplied by the occurrence of the species in the muds of Southampton Water. Although the species dominates Chalk assemblages it is also a consistent component of nannofossil assemblages in sediments ranging in age from Bajocian to Campanian. W.barnesae was also reported as a reworked component of Holocene sediments at Fawley (Hodson and West, 1972) and in Bracklesham Beds from Whitecliff Bay on the Isle of Wight (Jones, 1981).

Zygodiscus species and Prediscosphaera species are generally the next most dominant reworked taxa in the Solent sediments. These were also reported to be solution-resistant coccoliths by Hill (1975). Zygodiscus elegans and Z.compactus are composed of two strongly imbricate rims and a hollow central area spanned by a single bridge (Pl.8, Figs. 5 to 6). Prediscosphaera cretacea and P.spinosa are rhabdoliths composed of a

proximal and distal shield , the latter with an x-shaped structural support for the central spire. Many of the specimens of Prediscosphaera spp. have these stems preserved intact in the sediments (Pl.8, Fig.7). The Zygodiscus species range throughout most of the Cretaceous, but are common in the Chalk . Prediscosphaera spp. were probably derived from Chalk strata , as their occurrence in the Lower Cretaceous is limited to Albian sediments.

More direct evidence for the supply of reworked Chalk sediments in the Solent is supplied by the occurrence of Micula staurophora (Gardet) Stradner, Cylindralithus biarus Bukry, Eiffellithus eximius (Stover) Perch-Neilson , Phanolithus obscurus (Deflandre) Wind and Wise and Reinhardtites amthophorus (Deflandre) Perch-Nielson . All these species have occurrences limited to Chalk strata. M.staurophora (Pl.10, Fig.4.) and R.anthophorus (Pl. 10. Fig.8.) may be used as tracers of Upper Chalk imput into the Solent sediments. Both species are short ranging and are limited to the Upper Chalk. P.obscurus and E.exminius (Pl.10, Fig.7.) are common components of the Middle Chalk while Cylindralithus biarus (Pl.10., Fig.1.) is distributed throughout the three divisions of the Chalk.

The bulk of the other reworked Cretaceous species are long-ranging and provide less precise information on sediment derivation. All are common in Chalk strata. However, Ellipsagelosphaera forbesii Black (Pl.9,Fig.3). is probably supplied from Lower Cretaceous sediments as it becomes extinct in the lower Cenomanium.

6.3.5 Feldspar occurrence and derivation.

Feldspar/quartz XRD peak height ratios were calculated for the bulk samples and the fine fractions. Feldspar/quartz ratios for the fine fractions were generally low (0.01 or less) and showed little variation. However, there were significant variations of the ratio of

the minerals in the bulk samples. These will now be discussed.

Feldspar/quartz peak height ratios for the open-water sediments from the East Solent and Southampton Water are consistently very low (0.01 or less). Similar values were also recorded from the Itchen Estuary sediments. Significant changes in the feldspar/quartz peak height ratios occur in the Hamble Estuary. Low values , typical of those found in Southampton Water occur at the mouth of the Estuary (0.01). However, in the middle and upper sections of the Hamble where marine influence is reduced, values reach a maximum of 0.12. Similar large values typify sediments from the Upper Test Estuary (0.05 to 0.13) and in the fluviatile sediments from the River Blackwater (0.04). Feldspar/quartz peak height ratios also increase in an up-estuary direction in the Lymington and Beaulieu Estuaries. Values range from < 0.01 at the mouth of the Beaulieu to 0.10 in fluviatile sediments deposited above the estuary. Maximum values recorded in the Lymington tend to occur in the middle reaches of the estuary (0.04).

These variations in feldspar ratios strongly suggest that a fluviatile supply of sediments enriched in feldspar with respect to quartz is entering the upper regions of these estuaries. Additionally, marine-derived sediment entering the mouth of the estuaries throughout the Solent region is consistently rich in quartz but deficient in feldspar.

XRD analysis of the sediments showed that the feldspar component is dominated by potassic feldspar. Optical analysis confirmed that this feldspar was mainly the variety microcline. The feldspar source must lie in the catchment area of the estuaries. A most probable source of the feldspar is the Tertiary sediments which underlie extensive areas of the Hampshire Basin. The Beaulieu and Lymington estuaries drain a catchment area mainly supplied from the "Barton Sand", with smaller

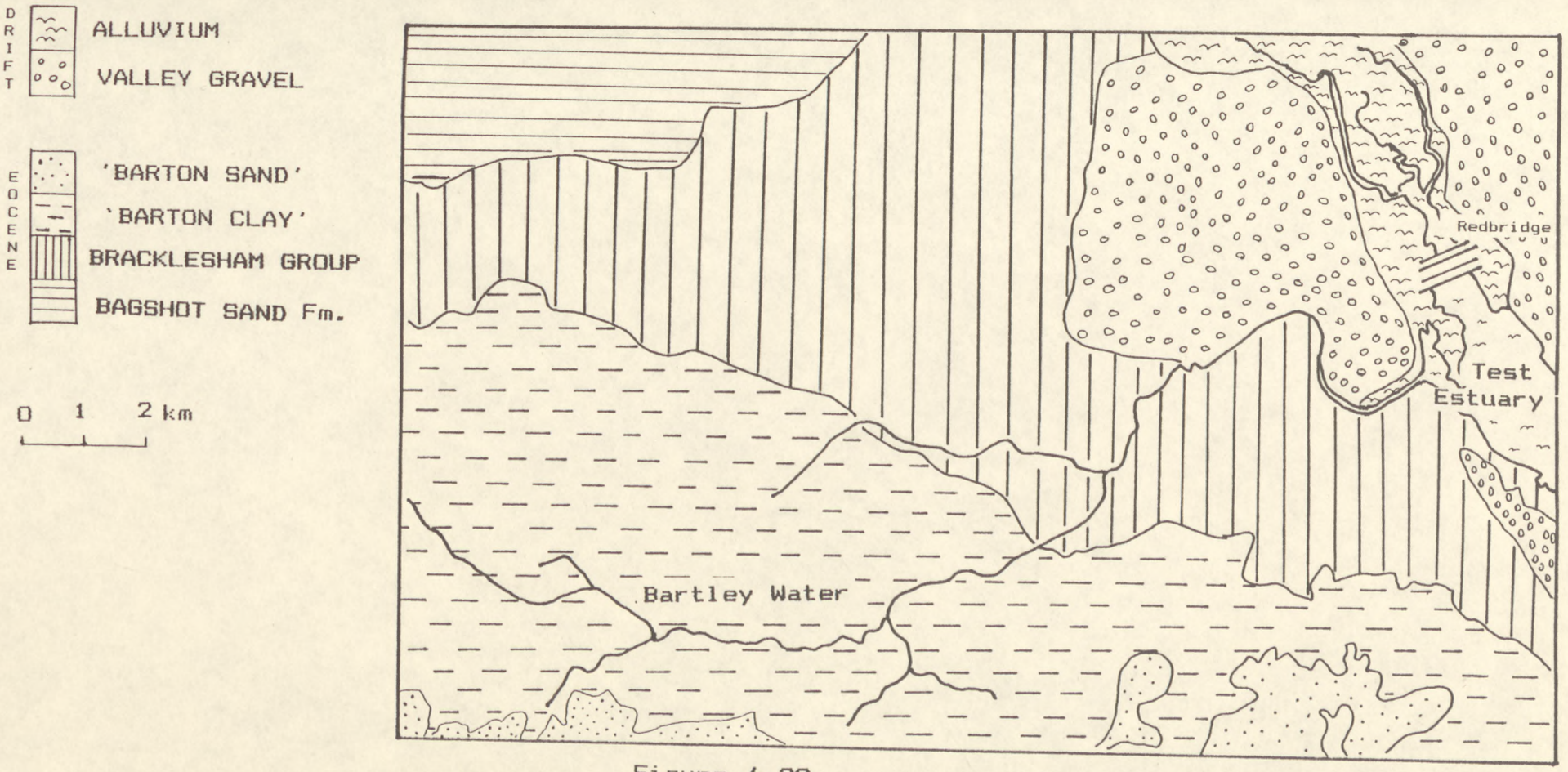


Figure 6.29
Geological Map of the Bartley Water catchment area.

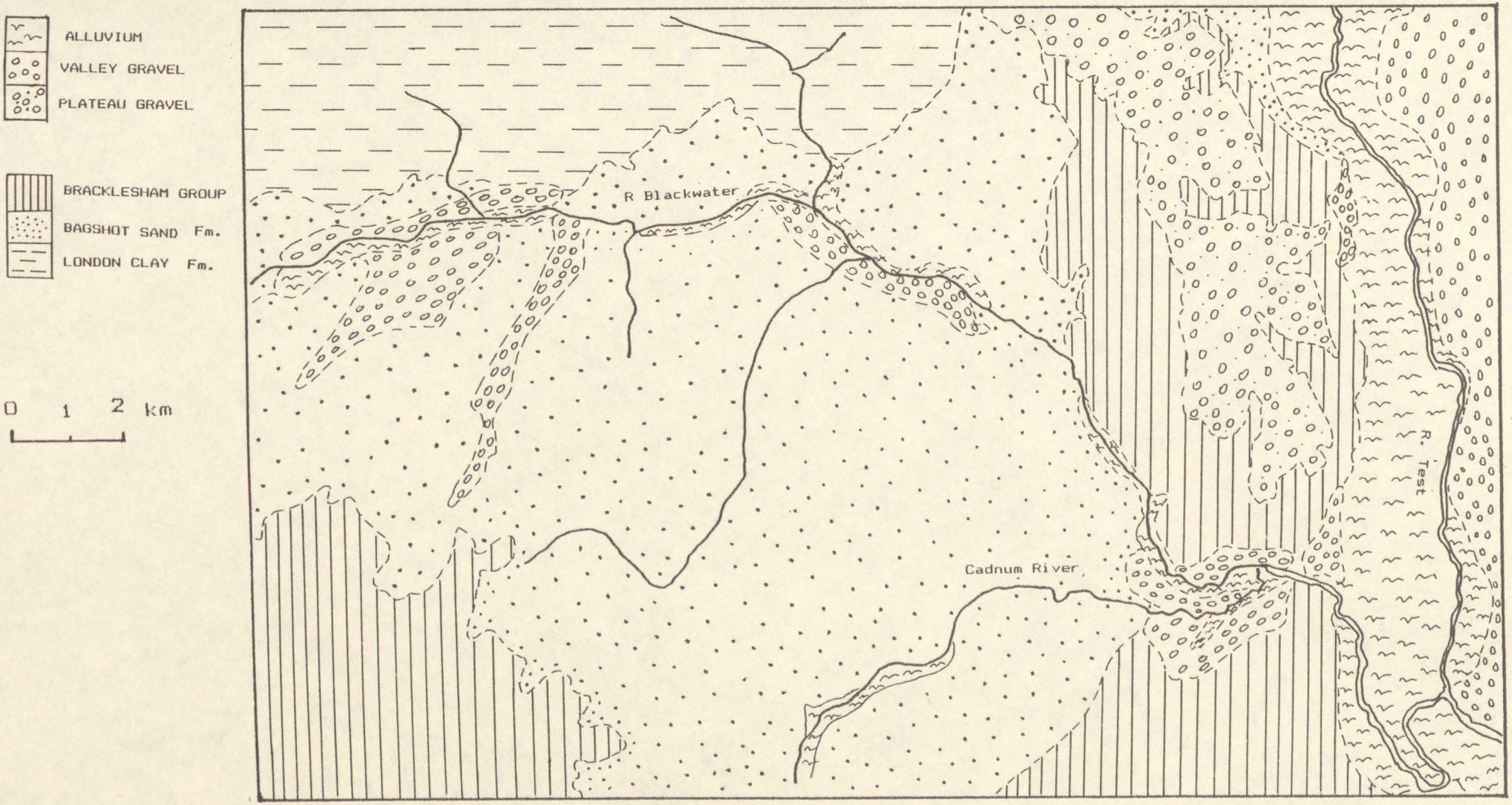


Figure 6.30
Geological Map of the River Blackwater catchment area.

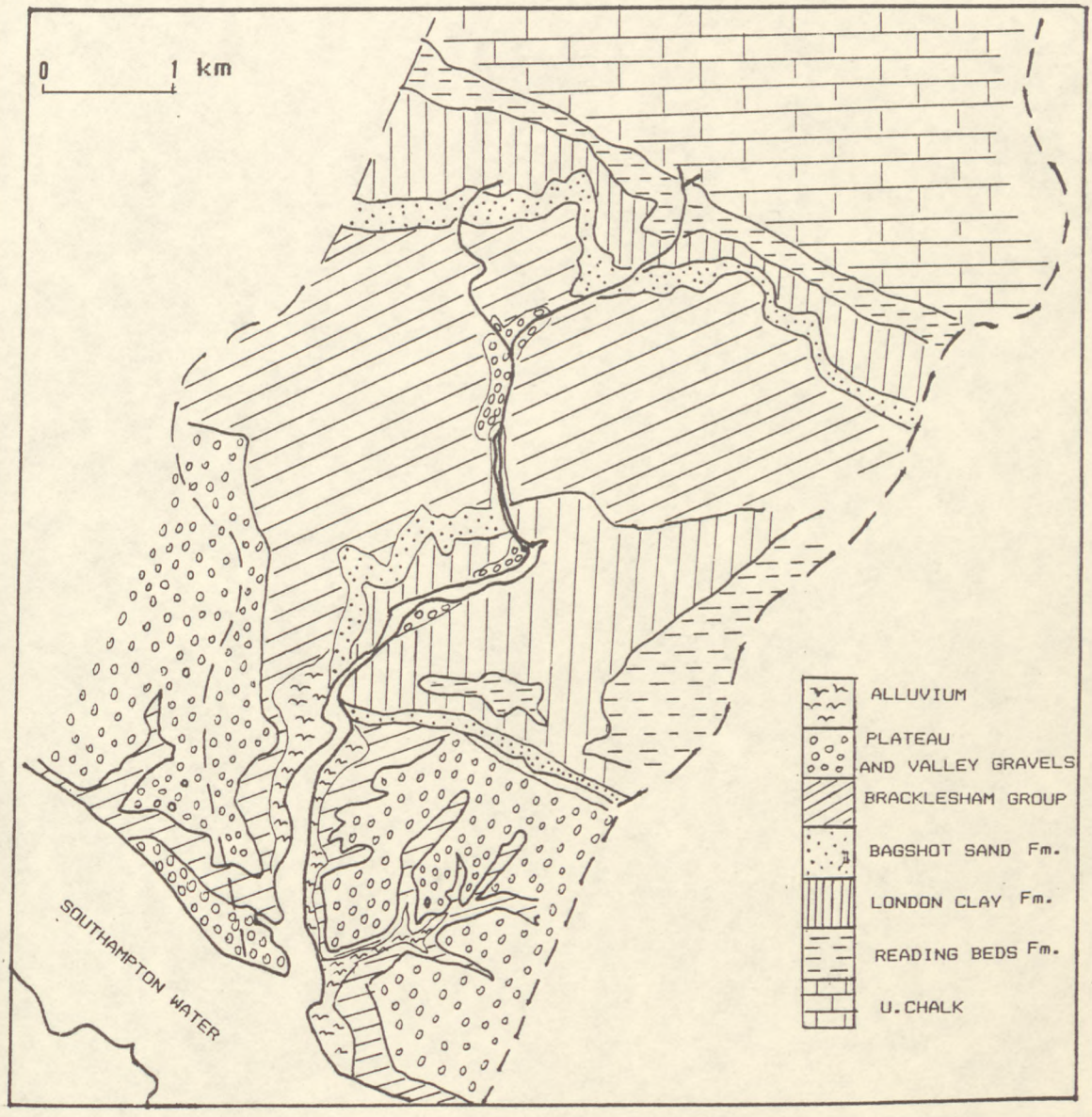


Figure 6.31.
Simplified geological map of the Hamble catchment area.

contributions from the "Barton Clay" and Headon Hill Formation (Fig.6.27.).

The mineral composition of the Upper Eocene sediments of the Hampshire Basin ('Barton Clay', 'Barton Sand' and 'Lower Headon Beds' has been extensively studied by Bale (1984). He found potassic feldspar (microcline) to constitute between 2 and 8% (mean 6%) of the clays and between 5 and 15 % (mean 8 %) of the sand deposits of the succession studied. Significantly, the "Barton sand" which supplies large amounts of run-off to the Beaulieu and Lymington Rivers tended to be richest in feldspar with values frequently exceeding 10 % . The bulk of the catchment area of the Test is underlain by Chalk strata. Potassic feldspar is unlikely to be supplied from such sediment. However, the catchment area of other streams which drain into the Test (e.g., the Bartley Water) comprises a predominantly wooded area extending across the northeast of the New Forest. This tract of woodland almost exclusively lies on the 'Barton Clay', although small sections also occur on the Bracklesham Group (Fig. 6.29).

Bale (1984) found potassic feldspar to vary between trace values to 10% of the bulk sediment from the Barton Clay. The River Blackwater which drains an area of mainly London Clay Formation and 'Bagshot Sand' also flows into the Test (see Fig. 6.30.). Fluviatile sediments from the Backwater have a feldspar/quartz ratio of 0.04 confirming that fresh water run-off from the river is an additional supplier of feldspar detritus.

The Hamble drains an Eocene catchment area mainly underlain by the Bracklesham Group, ' Bagshot Sand' and 'London Clay' (Fig.6.31.). The 'Bagshot Sand' and the 'London Clay' are thought to be the greater suppliers of reworked feldspar to the sediments of the Hamble, rather than the Bracklesham Group. Feldspar contents of the Bracklesham Group exposed at Whitecliff Bay on the Isle of Wight are consistently low (<5%) (Jones,1981).

Additionally, feldspar/quartz ratios are generally low (0.01) in sediments at the mouth of the Hamble where Bracklesham strata are actively being eroded.

The variations in feldspar/quartz ratios throughout the estuaries of the Solent Region show there is a varied source of potassic feldpsar in the Tertiary catchment area of the Hampshire Basin. Additionally, sediment transported by marine currents into the estuaries is consistently low in feldspar.

6.3.6 The occurrence and derivation of glaucony.

The general facies term 'glaucony' proposed by Odin and Matter (1981) is used here to describe green glauconitic grains and films, thus avoiding the specific mineralogical conotation of the term glauconite.

Dyer (1971,1976,1980) first recorded the widespread occurrence of glaucony in the Solent surface sediments. Glaucony occurs in the Solent sediments mainly as ovoidal or irregularly shaped fragments , ranging in size from coarse sand to fine silt. However, occasional clay-sized discrete particles and films of finely-disseminated glaucony are also observed. In smear slides most of the grains are green in transmitted light, with a range from pale green to dark olive green. The grains generally have a 'fresh' appearance with little evidence of peripheral oxidation. Most of the glaucony grains shows aggregate polarisation (a speckled birefringence) caused by the random intergrowth of microcrystalline mineral flakes (Humphreys and Balson, 1985).

In this study glaucony is found to be ubiquitous in the fine fractions from East Solent and the lower section of Southampton Water. It is most abundant at the mouth of Southampton Water, particularly so at the mouth of the Hamble. It generally decreases in abundance up Southampton Water and is scarce or absent throughout the

upper reaches of all the adjacent estuaries. Little variation in the abundance of glaucony occurs in the West Solent estuaries where it occurs in moderate amounts.

Glaucony is reported to be particularly common in the lower Barton Beds exposed in Christchurch Bay (Gilkes, 1966). Cliff sections here are subject to rapid erosion and have been receding at approximately 1m per year since 1897 (May, 1964). Reworked glaucony occurs abundantly in the surface sediments of Christchurch Bay, where it forms 1.5% of the shell-free sample by weight (Dyer,1970). Dyer believes that this area of glaucony-rich sediments is the source of much of the glaucony present in West Solent. The glaucony being transported into the West Solent through the Hurt Narrows. Glaucony was also recorded in Holocene deposits of Fawley (Hodson and West,1972) and was suggested to be derived from local glauconitic Bracklesham Beds, particularly from Lee-on-Solent. Hodson and West (1968) also report that glaucony is a common component in the Upper Bracklesham Beds exposed in the Fawley Transmission Tunnel. The scarcity of glaucony in the upper reaches of the estuaries of Southampton Water shows that little glaucony is being supplied by fluviatile input.

6.3.7. Variations in the carbonate content of the Solent sediments.

The carbonate content in the fine fractions (2 to 20 μm) of sediments from the East Solent and Southampton Water is consistent (range 15 to 21%) with the higher values occuring at the lower end of Southampton Water and in East Solent. XRD analysis shows that the fine-grained carbonate is predominantly composed of low-Mg calcite. Aragonite is rarely detected in the sediments. The skeletal carbonate consists mainly of fragments derived from the break-up of bivalve shells, foraminifera tests and modern and reworked coccoliths. Skeletal carbonate laths are particularly common in the sediments. This high abundance of skeletal carbonate laths in the fine fractions from Southampton Water is a diagnostic feature. They are most probably derived from the disintegration of Mytilus edulis valves (a common species living in Southampton Water). The calcite fibres are strongly birefringent in polarised light and have straight extinction (Pl.6). Rhombohedral cleavage may be observed in the fibres when they are observed with high magnification (x >1000).

Alexandersson (1979) described similar fibres derived from Mytilus edulis in the shallow-water sediments from the Skagerak. Mytilus edulis valves consist of fibrous or prismatic calcite, a blueish fabric , built of slender fibres in a parallel arrangement. The inner surface of the valves are built of white iridescent nacre in a sandwich-like arrangement of micrometer layers of aragonite, alternating with films of organic matter. During maceration of the mussel valves, the nacre breaks up into individual layers of aragonite and peels off in the form of irregular flakes. The fibrous calcite falls apart into free fibres. In the muds of Southampton Water

only the fibrous calcite fibres are common, aragonite flakes are seldom seen. The predominance of calcite in the fine fractions is also confirmed by XRD analysis. This suggests that the aragonite flakes are more suceptible to disintegration in the tidal inlets. The abundance of micro-skelatal units of shells in the Recent sediments of the Skagerak was suggested by Alexandersson to indicate that destructive diagenesis of carbonates was occurring in the surrounding waters. It is evident that similar processes are occurring in the Solent waters.

Carbonate abundances in the bulk sediments of the region range from 5% in the upper Southampton Water to over 20% in the open-water sediments of East Solent and Spithead (Dyer,1980).

High abundances of fine-grained carbonate occur in sediments from the Upper Test Estuary (29%) and in fluviatile sediments from the River Test (58%). A similar increasing abundance of fine-grained carbonate occurs in an up-estuary direction in the Itchen Estuary. Carbonate ranges from 18% at the mouth of the estuary to 62 % at the tidal limit at Woodmill. Fluviatile sediments from the Itchen contain 35 % fine grained carbonate. The increase in carbonate in these upper estuarine and fluviatile sites is not the result of an increased supply of biogenic skeletal debris. Coccoliths and skeletal laths are generally rare in the estuarine sediments and are either extremely rare or absent in the fluviatile sediments. The increase in carbonate must be supplied from a fluviatile source.

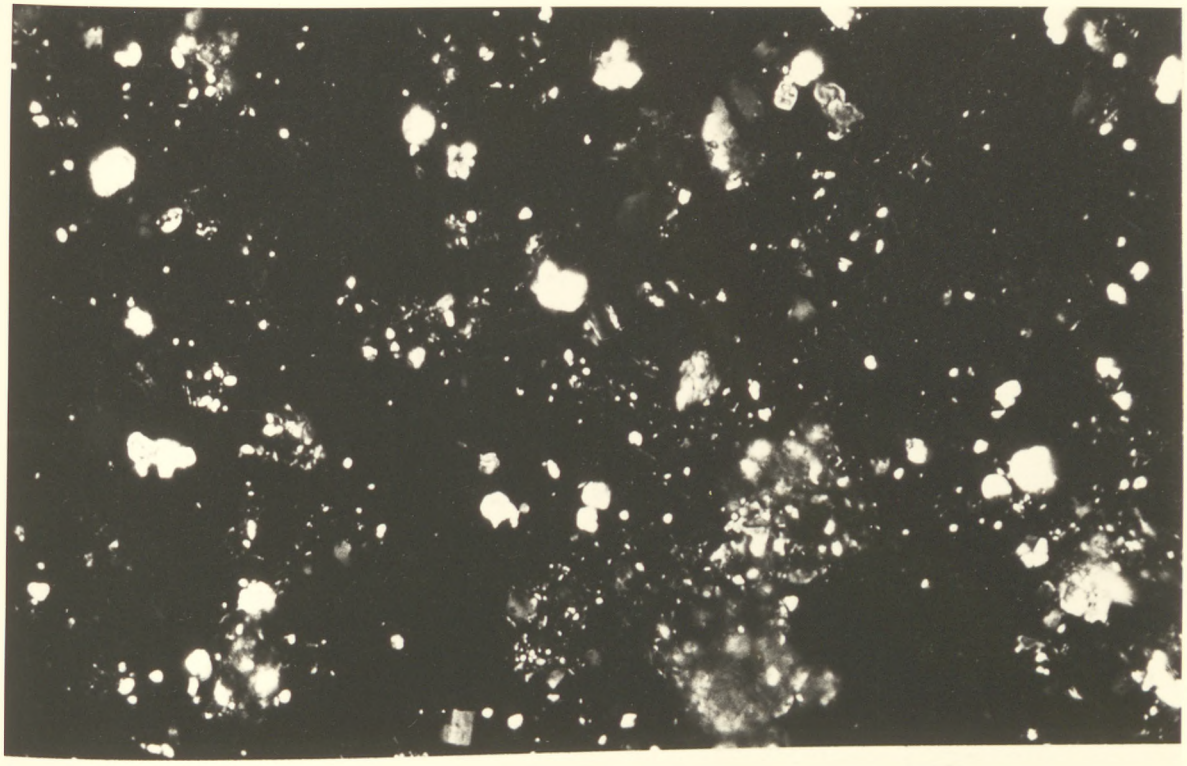
Smear-slide analysis of the fine-fractions reveals that the carbonate consists of a mass of micron-sized rhombs and other equidimensional anhedral grains of calcite (Pl.6,Fig.1). These fine-grained crystals are probably precipitated from the bicarbonate rich-waters that occur in the rivers Test and Itchen. Such precipitates have frequently been observed in marshes and other low-lying areas of the Test Valley (Kemp,1890). The

PLATE 7

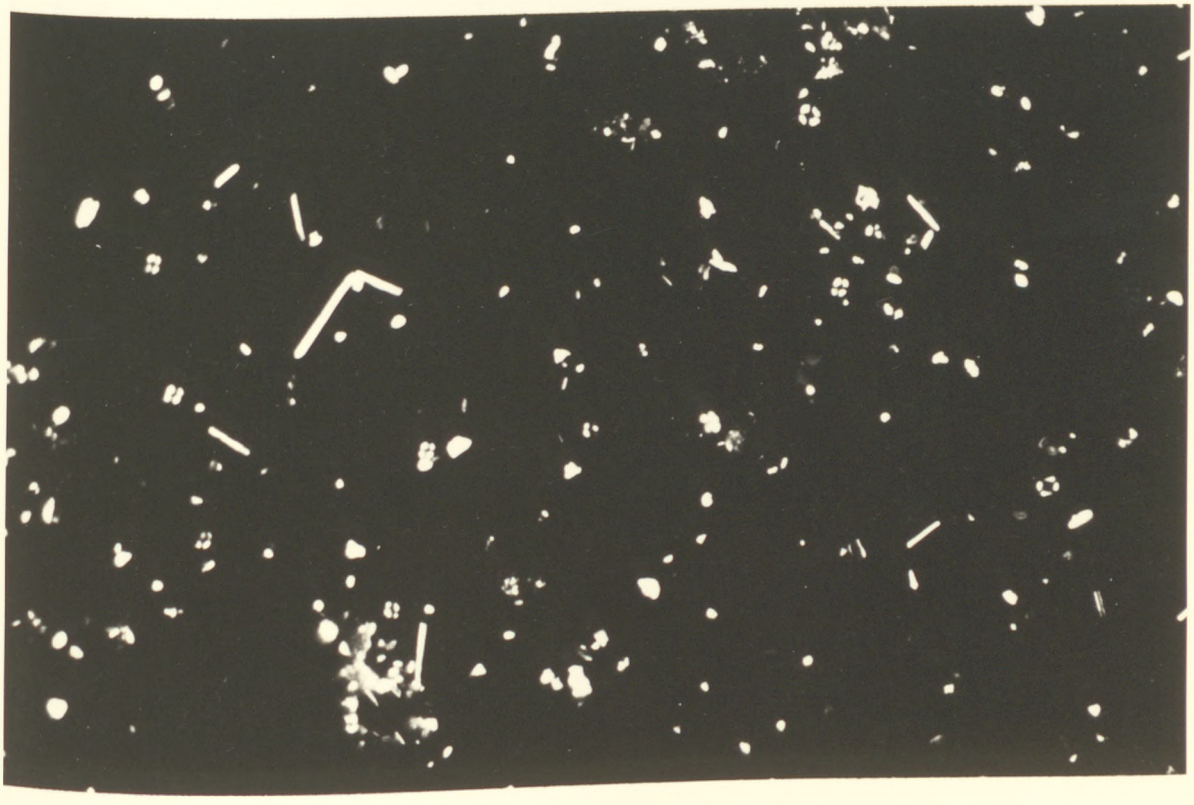
Optical photomicrographs of fine fractions from Southampton Water and the Test Estuary.

Fig.1 Fine fraction from the Upper Test estuary showing an abundance of calcite rhombs .

Fig.2 Fine fraction from the mouth of the Hamble Estuary showing abundant reworked Cretaceous coccoliths.



1



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same process but to a lesser extent may occur on the surface of the mudflats at the tidal limits of both the Itchen and Test estuaries. Inorganic precipitation would be most pronounced on drying mud-flats exposed at low tides during warm weather. However it is likely that that some of the fine-grained calcite crystals were precipitated as an indirect result of photosynthetic activity of algae. Tufa of algal origin has been recorded from the northern part of Southampton Water from Netley Shoal to Redbridge (Anderson, 1937). Tufa deposits also occur in the banks of the Itchen Estuary at Woodmill.

The increase in carbonate in the fine fractions of the upper estuarine and fluviatile sites in the Test and Itchen dramatically changes the calcite/quartz peak height ratios in the sediments. In the Upper Test and Upper Itchen values of 2.17 and 1.0 to 2.92 occur respectively. Only in these two areas do calcite/quartz ratios exceed 1.0. Values throughout the open waters of Southampton water only reach a maximum of 0.45.

Carbonate abundances in the Hamble Estuary decline in abundance from typical Southampton Water values at the mouth (~15%) to very low values in the upper reaches (~1%). These values indicate the decreasing marine supply of fine-grained carbonate up the estuary, and the lack of a carbonate source in the mainly Tertiary catchment area. The waters draining into the Hamble are not rich in bicarbonate ions and there are no records of tufa deposits in the upper estuary. The pH of the river water at Botley Mill ranges between 7.7 and 8.1 therefore dissolution effects due acidic run-off can be largely discounted in the Hamble sediments. The decrease in carbonate up the estuary merely reflects the increasing distance from its source.

Micron-sized siderite rhombs occur in sediments at the lower end of Southampton Water and in the lower Hamble estuary. A few of the siderite crystal have hollow centres. Similar siderite crystals were recorded from

upper Bracklesham Beds excavated in the Fawley Transmission Tunnel (Curry et al., 1968). The siderite crystals may have been derived from the Bracklesham Beds exposed at the mouth of the Hamble. This suggestion is consistent with the occurrence of reworked Eocene coccoliths found in large numbers at the mouth of the Hamble Estuary.

6.3.8. Source of the fine sediment in the Solent.

Suspended sediments in the Solent have been studied by Srisaengthong (1982) using Landsat MSS data. Most of this work concentrated along a 6.8 km transect between the Beaulieu and Lymington Estuaries. These results showed that relatively high suspended sediment concentrations occur in the winter months ranging from 20 mg/l to approximately 50 mg/l. Values were lower in the summer usually below 20 mg/l. The size distribution of the suspended solids was found to be a bimodal mixture of very fine silt (~8μm) and medium silt (~32μm).

These large seasonal fluctuations in suspended sediments are thought to be caused by suspended sediment being introduced from outside the Solent area. Biological production as measured by the percentage of organic carbon ranged from 20 to 30 % for the winter and summer respectively. Thus any extra amounts supplied from plankton and other organisms were not a major contributor to the variations in concentrations. Additionally, river run-off , a potential supply of suspended sediment is considered to be inconsequential when compared with the total volume of approximately 27×10^6 m^3 of the Solent (Srisoenthrong , 1982).

Marine-derived sediment may be supplied to the Solent via two transport paths;

1) through Hurst Narrows and into West Solent

2) around the eastern coast of The Isle of Wight.

Srisaengthong (1982) supports the idea first proposed by Dyer (1971) that sediment is being transported into West Solent through Hurst Narrows. Consequently, the principal source of suspended sediments to the Solent was suggested to be the Christchurch Bay area. The Barton Cliffs fronting the bay consist of a series of loosely cemented sands and clays and are undergoing rapid erosion. These cliffs are reported to have receded at at rate of 1m/year since 1895 (May,1964). The higher concentrations of suspended sediments in West Solent during the winter months would then correlate with the enhanced cliff erosion at Barton caused by increased wave action. Landsat imagery presented by Srisraethrong clearly showed turbid water entering into West Solent from Christchurch Bay on flood tides. Dyer (1980) has also presented evidence for the supply of sediment from the Barton Cliffs. He found glaucony to be a common component of the surface sediments of West Solent and suggested the mineral was derived from the glaucony-rich beds of the Lower Barton Beds exposed in Christchurch Bay. The distribution of glaucony in the estuarine sediments of West Solent studied in this report seem consistent with this supposition.

Reworked coccoliths are less abundant in the West Solent than in the East Solent and at the mouth of Southampton Water. Their abundance generally increases in an easterly direction away from Hurst Narrows. These variations in reworked coccolith numbers suggests that the suspended sediment entering West Solent is depleted in reworked coccoliths. This fact would be consistent with a derivation mainly from the Lower Barton Beds. The succession of the Lower Barton in Christchurch Bay contains few coccoliths (Hamilton and Hojjatzadeh, 1982). If suspended sediment entering West Solent contains few reworked nannofossils eroded Chalk detritus is unlikely to be a major component of the suspended load.

However, Srisaengthong (1983) has shown the occurrence of turbid water just to the south of the Needles. Such suspended sediment is likely to contain reworked Chalk coccoliths. These suspended sediments are therefore probably transported westwards into Christchurch Bay or eastwards along the south coast of the Isle of Wight. Dyer, in 1970, has suggested a predominatly westwards sediment transport direction of sediment from the Needles into Christchurch Bay. Coccoliths eroded from the Chalk outcrop of the Needles may therefore be transported into Christchurch Bay. Dyer (1980) and Srisaengthong (1982) have also suggested a sediment supply to East Solent from Channel waters. Dyer proposed that the sand fraction passes northwards into Hayling Bay with the majority of the remainder accumulating on Ryde Sandbank. This conclusion was based mainly on the distribution of limonite in the surface sediments. The limonite was thought to be derived from the erosion of Lower Cretaceous cliffs at Sandown Bay on the Isle of Wight. The mud fraction is deposited either in East Solent or is carried into the estuaries on the normal estuarine circulation and deposited during the long high-water stand.

The distribution of reworked and Recent coccoliths in the surface sediments strongly suggests a transport path from East Solent into Southampton Water. Reworked Cretaceous coccoliths are found in high numbers throughout East Solent and Southampton Water. Their abundances are only found to decrease in the adjacent tributary estuaries of Southampton Water. Some of the species of reworked coccolith (eg., Phanolithus obscurus) may be used as tracers of the movement of Chalk detritus. The gradual decline in the abundance of Cretaceous coccoliths up the estuaries indicates that these reworked forms are transported by marine currents into Southampton Water. There is very little evidence to suggest that the Cretaceous coccoliths are derived from fluviatle input into the estuaries. The bulk of the reworked Cretaceous coccoliths are thought to be supplied by marine erosion of the Chalk cliffs on the eastern coast of the Isle of Wight

(see section 6.3.3.). These eroded coccoliths are then transported by marine currents probably on flood tides in to Southampton Water and the adjacent inlets.

Recent coccoliths generally have a similar distribution to the reworked Cretaceous coccoliths in the surface sediments of the Solent. Abundances are high in East Solent and throughout Southampton Water but decline in the tributary inlets. The abundance of Coccolithus pelagicus in the sediments of East Solent, Spithead and Southampton Water is similar to abundances of the species in the English Channel sediments. This suggests that marine-derived siltation is occurring in these open-water areas where salinity reduction is slight. Both Recent and reworked coccoliths are probably supplied to Southampton water with the suspended sediment load on flood tides. Srisaethrong (1983) has shown that nearly all the suspended sediment supplied to Southampton Water is deposited in the high water stand. Turbid water supplied on flood tides from the West and East Solent returns clear on the ebb. A similar conclusion was reached by Tosswell (1984) for suspended sediments in the Hamble Estuary (see section 6.3.2.4). He recorded short-lived burst of suspended sediments associated with the flood tides with significantly lower concentrations on the ebb.

Local sources of fine sediment have also been identified for Southampton Water and the other tributary inlets. Large numbers of reworked Eocene coccoliths are found to occur in the Lower Hamble Estuary. These reworked coccoliths are most probably supplied from the Bracklesham Beds exposed at the mouth of the Hamble and at Lee on-Solent. Additional support for this is supplied from the occurrence of reworked glaucony and siderite , both common components of the Bracklesham Beds (Curry et al., 1968). Potassic feldspar (microcline) can be used as a tracer of fluviatile input to the estuaries of Southampton Water and also in the Lymington and Beaulieu estuaries (see Section 6.3.5). Marine-supplied sediment to East Solent, West Solent and Southampton water is

generally deficient in feldspar. Srisaengthong (1983) concluded that the source of suspended sediments in the Solent lies in West Solent and beyond in Christchurch Bay. This may be true for the sediments deposited in the estuaries of West Solent. However, the source of fine sediment deposited in Southampton Water and its tributary inlets is suggested from this study to originate mainly from East Solent and from outside Channel waters. The erosive action of Channel waters upon the Cretaceous succession exposed on the eastern coast of the Isle of Wight is thought to be a major supply of fine sediment to Southampton Water and its adjacent inlets.

6.4 CONCLUSIONS.

Four species of Recent coccolith occur in the surface sediments of the Solent Estuarine System; Coccolithus pelagicus, Emiliania huxleyi, Helicosphaera carteri and Braarudosphaera bigelowii. C.pelagicus is dominant and forms > 95% of the total assemblage. C.pelagicus occur in consistently high numbers (~ 50 $\times 10^5$ per gram) throughout the open-water sediments of East Solent and Southampton Water. Their numbers decline in the tributary estuaries of the Test, Itchen and Hamble (Fig.6.31.). This decrease in abundance of modern coccoliths reflects the declining marine influence in these tidal inlets. (Fig.6.33). Coccoliths and other fine-grained carbonate are either absent or very rare in estuarine and fluviatile sediments from the Beaulieu and Lymington. Fine-grained carbonate supplied to these estuaries is dissolved by acidic run-off from the New Forest catchment area, where extensive areas of acid grassland, heathland and bog occur.

Reworked coccoliths (mainly Cretaceous forms) occur in large numbers throughout the East Solent and Southampton Water sediments (>200 $\times 10^5$ per gram). Abundances of reworked coccoliths decline in an up-estuary direction in all the adjacent tidal inlets of Southampton Water (Figs. 6.32. and 6.33.). Their abundance in fluviatile sediments from the Test and Itchen decline to 6 and 18 $\times 10^5$ per gram respectively. These data strongly indicate that there is no significant fluviatile transport of reworked Chalk coccoliths into the estuaries of the Test and Itchen. It is therefore probable that although these Chalk rivers are rich in dissolved carbonate (as bicarbonate ions) they carry little particulate carbonate detritus .

The reworked Cretaceous coccoliths together with modern forms are transported into Southampton Water and the tributary estuaries by marine currents. They are carried in the suspended sediments load supplied on flood tides to Southampton Water. The Chalk cliffs on the eastern coast of the Isle of Wight are suggested to supply the bulk of the Cretaceous coccoliths . These cliffs are presently being eroded by marine currents and wave action. Most of the fine sediment in Southampton Water and its adjacent estuaries is probably supplied from suspended sediment transported from the East Solent and outside Channel waters.

Reworked coccolith values in the West Solent are generally lower than values found in the East Solent and Southampton Water. The source of the sediment in West Solent is thought to originate from Lower Barton Beds exposed in cliff sections in Christchurch Bay. Such sediment is relatively depleted in coccoliths.

Local sources of sediment have been identified in Southampton Water and the other tributary estuaries of the Solent. Large numbers of reworked Eocene coccoliths are found to occur in sediments from the Lower Hamble Estuary. These reworked coccoliths are most likely derived from Bracklesham Beds found exposed at the mouth of the Hamble and along the northern coast of Southampton Water.

Potassic feldspar (microcline) can be used as a tracer of fluviatile imput to the estuaries of Southampton Water and also in the Lymington and Beaulieu. The feldspar is supplied from Tertiary deposits which outcrop over extensive areas of the Hampshire Basin. Marine-derived sediment supplied to East Solent, West Solent and Southampton Water is generally quartz-rich but feldspar-poor.

Skeletal calcite fibres probably derived from the maceration of Mytilus edulis valves are a common component of the fine fractions. They are most abundant in

sediments deposited in Southampton Water and in the lower sections of the tributary inlets. The presence of such fibres indicates that destructive diagenesis of carbonates is occurring throughout much of the shallow waters of the Solent. However, constructive diagensis through the precipitation of carbonate is also reported to occur at the tidal limits of both the Test and Itchen estuaries. Here low-Mg, micron-sized rhombs are precipitated from the bicarbonate-rich Chalk streams.

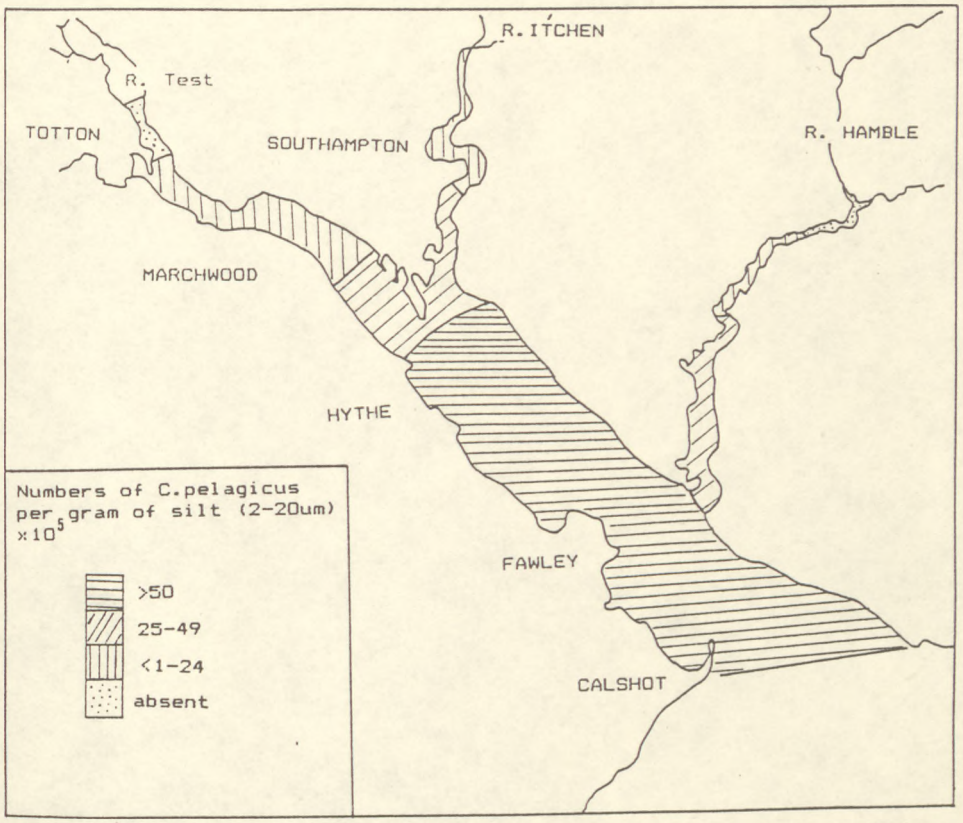


Figure 6.32.
Abundance of Coccolithus pelagicus in the surface sediments of Southampton Water and its tributary inlets.

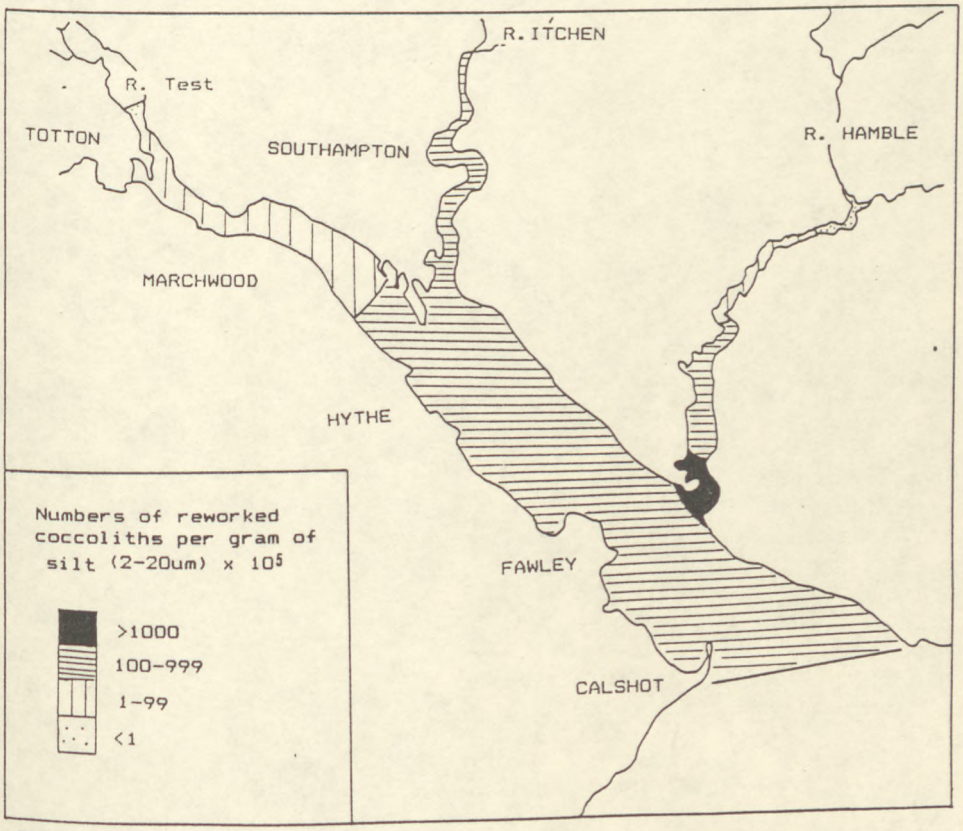


Figure 6.33.
Abundance of reworked coccoliths in the surface sediments of Southampton Water and its tributary inlets.

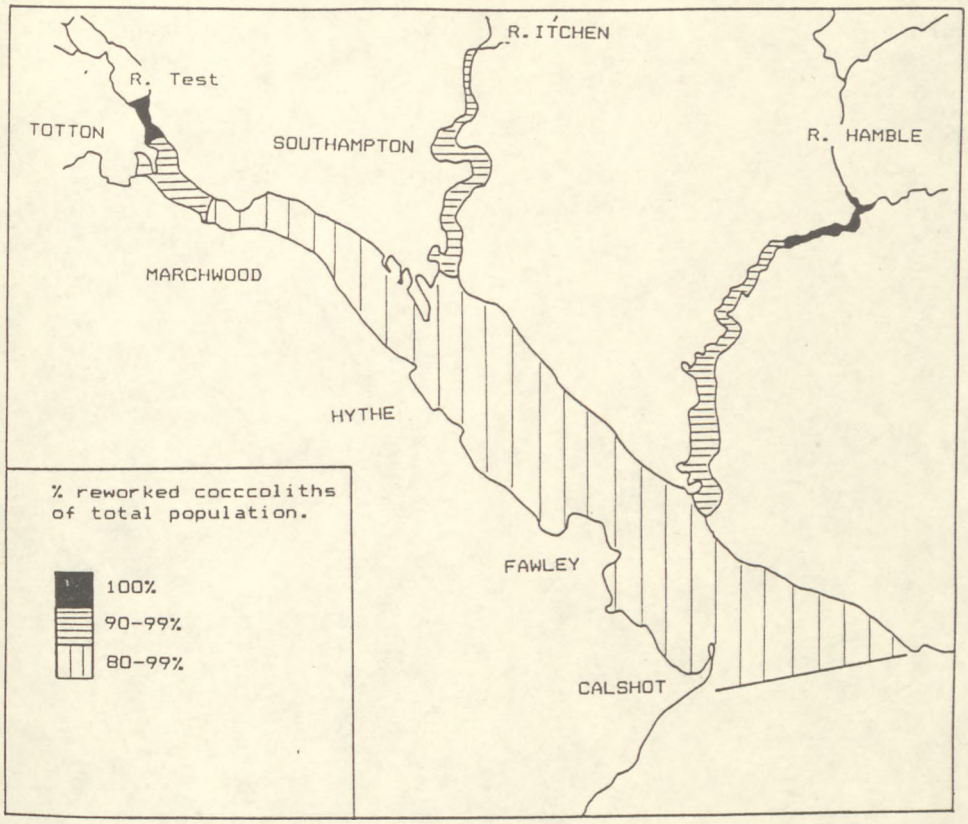


Figure 6.34.
% abundance of reworked coccoliths in the total coccolith flora in the surface sediments of Southampton Water and its tributary inlets.

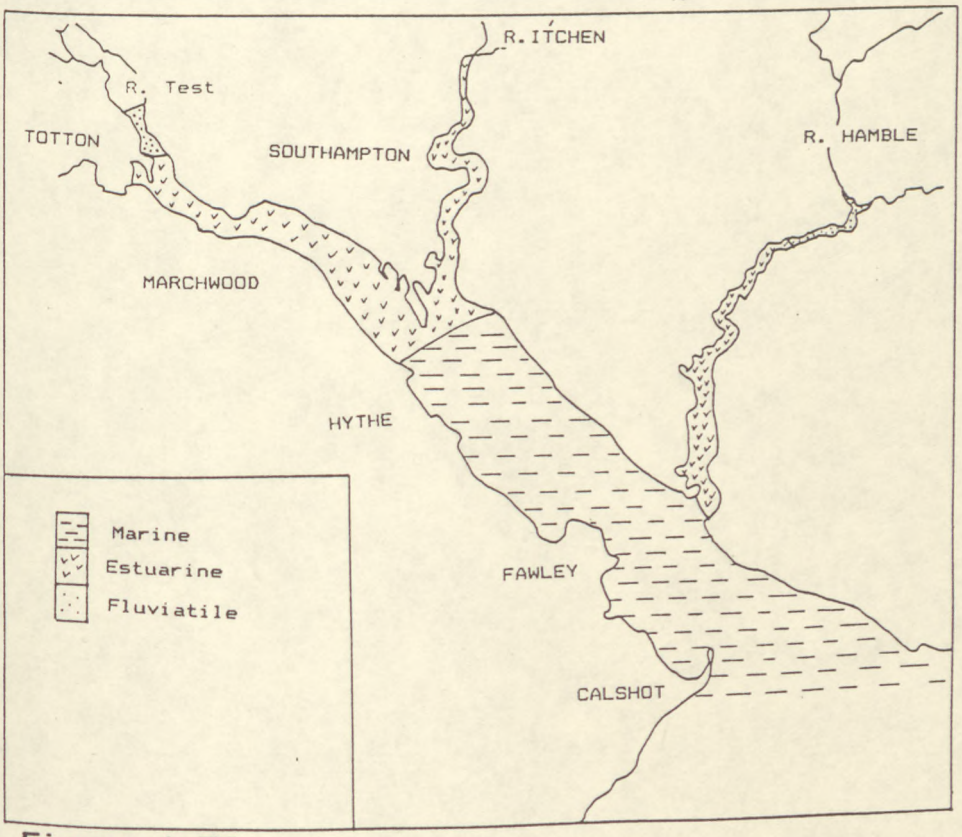


Figure 6.35.
Suggested areas of marine, estuarine and fluviatile sedimentation in Southampton Water and its tributary inlets.

PLATE 8

S.E.M. photomicrographs of coccoliths from the Solent sediments.

Fig.1 Coccolithus pelagicus, distal view (x 5,300). Neg. 284-6.

Fig.2 Watznaueria barnesae, proximal view (x 10,700). Neg. 504-3

Fig.3 W.barnesae, proximal view (x9,800). Neg. 295-5.

Fig.4 W.barnesae, distal view showing slight irregular thickening of shield elements (x 9,300). Neg. 295-5

Fig.5 Zygodiscus compactus, distal view (x 10,700). Neg. 504-2.

Fig.6 Zygodiscus elagans, distal view (x 7,400). Neg. 276-1.

Fig.7 Predicosphaera cretacea, distal view (x 10,500)). Neg. 504-5

Fig.8 P.cretacea, distal view (x 14,800). Neg 496-1.



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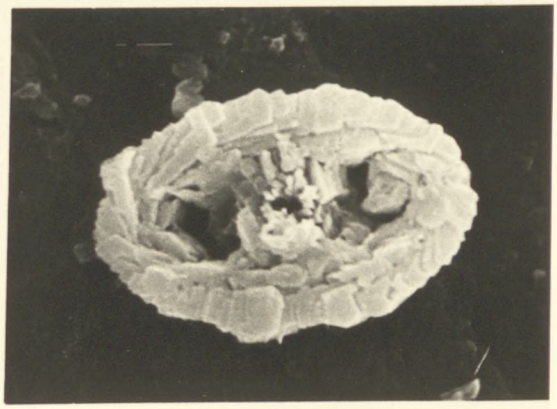
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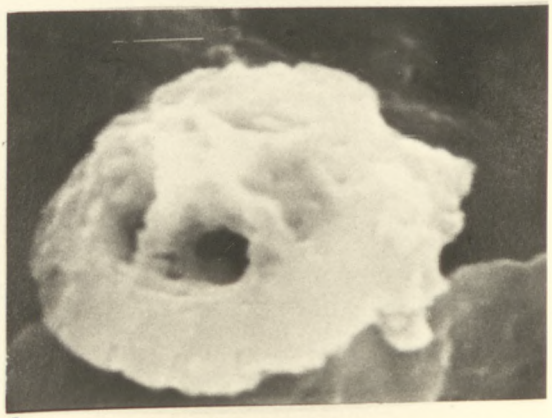
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PLATE 9

S.E.M. micrographs of reworked coccoliths from the Solent sediments.

Fig.1 Manivitella pemmatoidea, distal view (x 7,100). Neg. 376-3.

Fig.2 Lithastrinus floralis (x 5,200). Neg. 277-5.

Fig.3 Ellipsagelosphaera forbesii, distal view (x 4,400). Neg. 362-2.

Fig.4 Cyclagelosphaera margerli, proximal view (x 10,900). Neg. 362-7.

Fig.5 Recticulofenestra umbilica, proximal view (x 7,300) Neg. 496-2.

Fig.6 R. umbilica, proximal view (x 7,700). Neg. 362-6.

Fig.7 R. umbilica, distal view (x 6,100). Neg. 273-2.

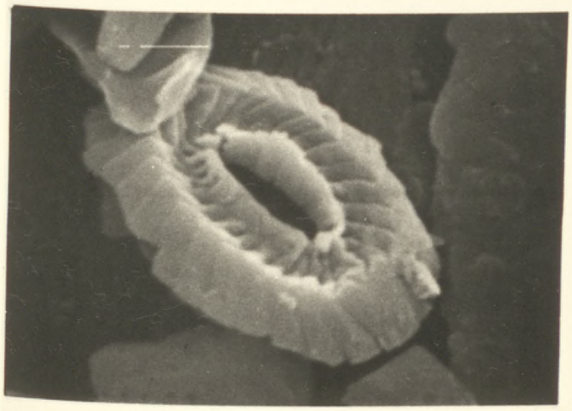
Fig.8 Neochiastozygus dubius, distal view (x 6,900). Neg. 390-1.



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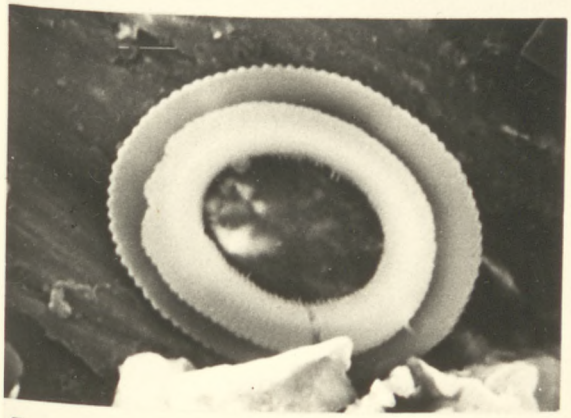
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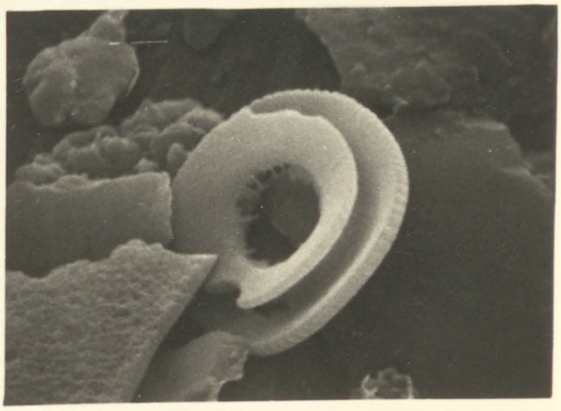
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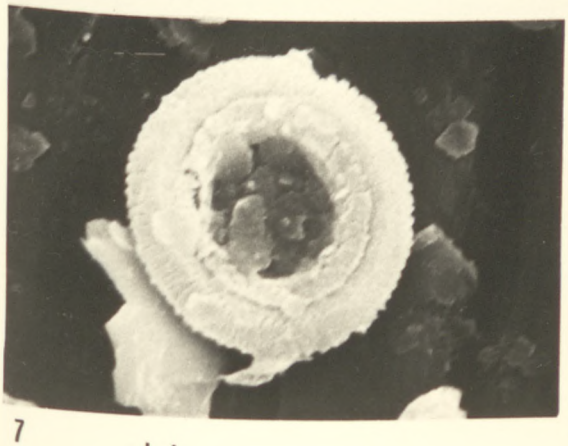
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PLATE 10

S.E.M. photomicrographs of reworked coccoliths from the Solent sediments.

Fig.1 Cylindralithus biarcus (x 7,300). Neg. 277-6.

Fig.2 Lithastrinus floralis (x 8,400). Neg. 274-3.

Fig.3 Markalius inversus, proximal view (x 6,900). Neg. 504-1.

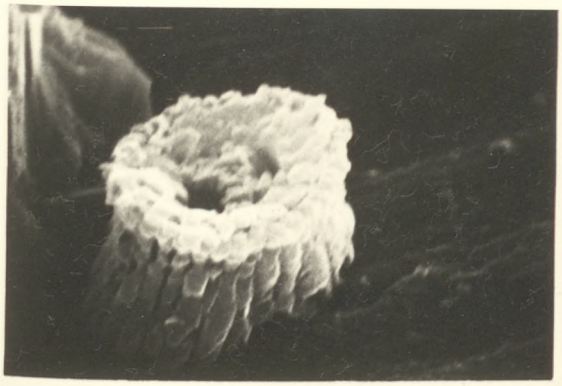
Fig.4 Micula staurophora , distal view (x 9,200). Neg. 279-5.

Fig.5 Helicolithus trabeculatus (x 9,800). Neg. 295-3.

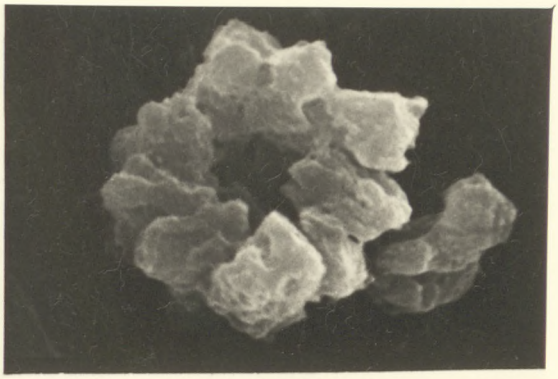
Fig.6 Phanulithus obscurus (x 10,000). Neg.

Fig.7 Eiffellithus eximius, distal view (x 11,800). Neg. 278-6.

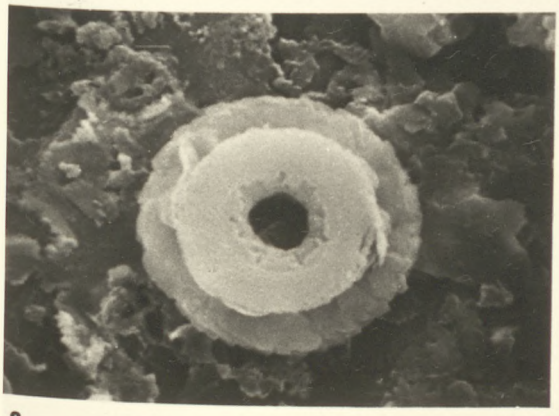
Fig.8 Reinhard tes anthophorus, distal view (x 9,100). Neg. 291-2.



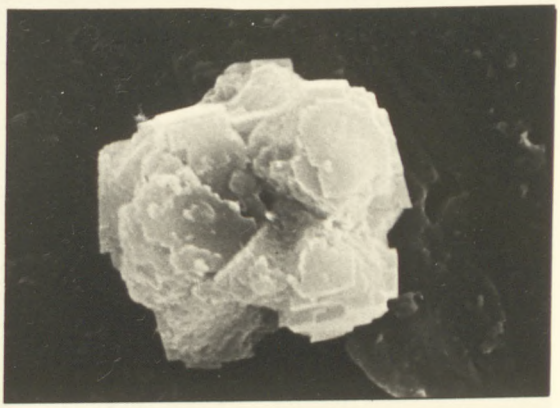
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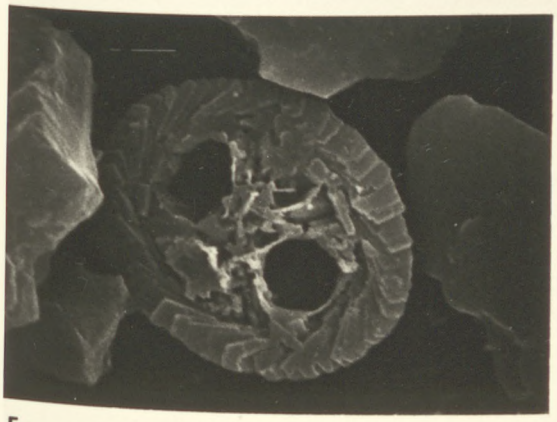
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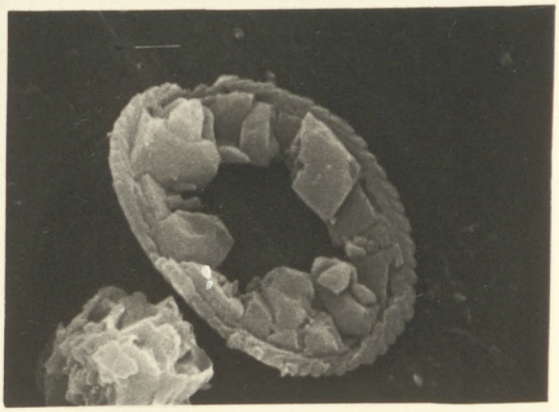
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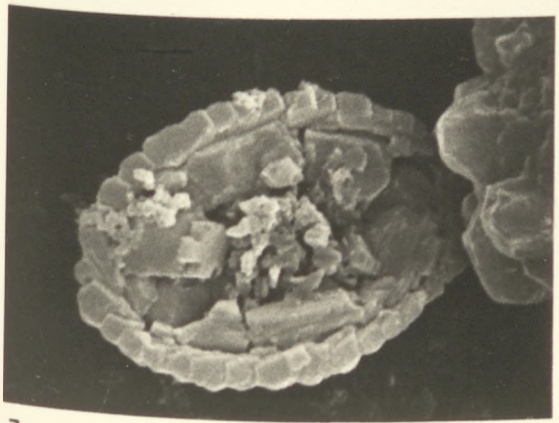
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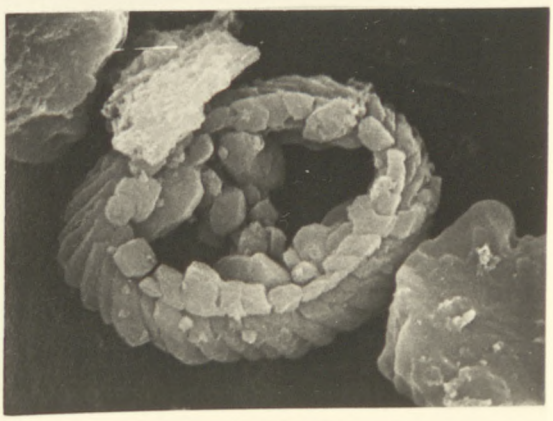
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CHAPTER 7

SYSTEMATIC PALAEONTOLOGY

CHAPTER 7

SYSTEMATIC PALAEONTOLOGY

7.1 INTRODUCTION.

The classification of the coccolithophores is more complex than most other algal Divisions. This is mainly caused by the different morphology of coccolithophores through different phases of the life cycle. Additionally, the classification of fossil genera and the bulk of the living taxa is based on the morphology of the coccoliths with little consideration for the character of the living cell (Tappan,1980). A further complication is caused by polymorphism, where different coccoliths are found on the same coccosphere.

The supragenetic classification used in this study is based on the extensive work of Okada and McIntyre (1977) and on the proposals of Tappan (1980). Okada and McIntyre tentatively classified 33 genera under previously proposed families. No further efforts were made by these workers to establish a more elaborate higher-level classification. The various coccolith species recorded in this study are listed in Table 7.1. The families in this classification scheme are listed in alphabetical order with genera and species listed in alphabetical order within each family. The nomenclature used in this study is based on the publications of Halldal and Markali (1955), Hay, Mohler and Wade (1966) and Okada and McIntyre (1977).

Table 7.1 Tentative systematics and list of taxa observed in the northwestern European sediments.

Kingdom PLANTAE
Division HAPTOPHYTA Hibberd, 1972
Class HAPTOPHYCEAE Parke and Dixon, 1964
Family BRAARUDOSPHAERACEAE Deflandre, 1947
Genus Braarudosphaera Deflandre, 1947
B.bigelowii (Gran and Braarud) Deflandre

Family CERATOLITHACEAE Norris, 1965
Genus Ceratolithus Kamptner, 1950
C.cristatus Kamptner

Family COCCOLITHACEAE Kamptner, 1928
Genus Calcidiscus Kamptner, 1952
C.leptoporus (Murray and Blackman) Loeblich and Tappan
Genus Coccolithus Schwartz, 1894
C.pelagicus (Wallich) Schiller
Genus Emiliania Hay and Mohler, 1967
E.huxleyi (Lohmann) Hay and Mohler
Genus Gephyrocapsa Kamptner, 1943
G.caribbeanica Boudreaux and Hay
G.ericsonii McIntyre and Be
G.oceanica Kamptner
Genus Umbilicosphaera Lohmann, 1902
U.hulburtiana Gaarder
U.sibogae (Weber-van Bosse) Gaarder
U.sibogae (weber-van Bosse) Gaarder var. foliosa (Kamptner) Okada and McIntyre.

Family HELICOSPHAERACEAE Black, 1971, emend. Jafar and Martini, 1975
Genus Helicosphaera Kamptner, 1954
H.carteri (Wallich) Kamptner

Family PONTOSPHAERACEAE Lemmermann in Brandt and Apstein, 1908

Genus Pontosphaera Lohmann, 1902

P.discopora Schiller

P.messinae Bartolini

Genus Scyphosphaera Lohmann, 1902

S.apsteinii Lohmann

Family RHABDOSPHAERACEAE Lemmermann in Brandt and Apstein, 1908

Genus Discosphaera Haeckel, 1894

D.tubifera (Murray and Blackman) Ostenfeld

Genus Rhabdosphaera Haeckel, 1894

R.clavigera Murray and Blackman

Genus Umbellosphaera Paasche, in Markali and Paasche, 1955

U.tenuis (Kamptner) Paasche

Family SYRACOSPHAERACEAE Lemmermann, in Brandt and Apstein, 1908

Genus Coronosphaera Gaarder, 1977

C.mediterranea (Lohmann) Gaarder

Genus Syracosphaera Lohmann, 1902

S.histrica Kamptner

S.nodosa Kamptner

S.pulchra Lohmann

Genera of uncertain position.

Genus Scapholithus Deflandre, 1954

S.fossilis

The list of synonyms for each species is restricted to the original description and to subsequent redefined descriptions employing electron microscopy. For a more extensive index and bibliography refer to the publications of Loeblich and Tappan (1963, 1966, 1968, 1969, 1970, 1972 and 1973).

Kingdom PLANTAE
Division HAPTOPHYTA Hibberd, 1972
Class HAPTOPHYCEAE Parke and Dixon, 1964
Family BRAARUDOSPHAERACEAE Deflandre, 1947
Genus BRAARUDOSPHAERA Deflandre, 1947

Braarudosphaera bigelowii (Gran and Braarud) Deflandre

Plate 15, Figs.5-8

1935 Pontosphaera bigelowii GRAN and BRAARUD, p.388, fig.67
1947 Braarudosphaera bigelowii (Gran and Braarud).-DEFLANDRE, p.439, figs. 1-5.
1970 Braarudosphaera bigelowii (Gran and Braarud) Deflandre.-BARTOLINI, p.152, fig.1.

Description:

Braarudosphaera has pentaliths with five elements each consisting of a single crystal orientated 72° apart. The cleavage plane of the crystals is in the plane of the pentalith, and perpendicular to the principal axis, to which the optical axes are oblique (Tappan, 1980). The calcite of the pentaliths is internally laminated parallel to the cleavage, as can be seen in Plate 17, Figs. 7-8. Isolated pentaliths and occasionally the individual elements of the pentaliths are all that is seen with the light and scanning electron microscope.

Dimensions:

The maximum width at the base of the pentaliths is 6.9 um, and at the upper face, 5.4 um. The height of the pentaliths is approximately 1/5 of the maximum width.

Family CERATOLITHACEAE Norris 1965
Genus CERATOLITHUS Kamptner 1950

Ceratolithus cristatus Kamptner

Plate 21 Figs. 15, 22.

1950 Ceratolithus cristatus KAMPTNER, p. 154.
1954 Ceratolithus cristatus Kamptner.-KAMPTNER, pp. 43-45, text-figs. 44-45.
1965 Ceratolithus cristatus Kamptner.-NORRIS, pp.19-21, pl.11, figs. 1-4; pl. 12, figs.1-4.

Remarks:

Single horseshoe-shaped coccoliths of this species were only scarcely recorded in sediments from the Celtic Sea.

Family COCCOLITHACEAE Kamptner 1928
Genus CALCIDISCUS Kamptner 1952

Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan

Plate 11, Figs.1-8, Pl.21, Figs. 4-6.

1898 Coccosphaera leptopora MURRAY and BLACKMAN. pp. 430, 439, pl. 15, figs. 1-7.
1902 Coccolithus leptoporus (Murray and Blackman). -LOHMANN, pp. 137-138, pl. 5, figs. 52, 61-64.
1930 Coccolithus leptoporus (Murray and Blackman) . - SCHILLER, pp. 245-247, text-figs. 9a-b, 10a-b, p. 121-122.
1954 Cyclococcolithus leptoporus (Murray and Blackman).-

Blackman).-KAMPTNER, pp. 23-24, text-fig. 20.

1967 Cyclococcolithus leptoporus (Murray and Blackman) Kamptner.-MCINTYRE and BE', p. 569, pl. 7, figs. a-c.

1970 Cyclococcolithina leptopora (Murray and Blackman).-WILCOXON, p. 82.

1974 Cyclococcolithus leptopora (Murray and Blackman) Kamptner.-JAFAR and MARTINI, p. 367-368.

1978 Calcidiscus leptoporus (Murray and Blackman).-Loeblich and Tappan, p. 1391.

Description:

Circular placolith with shields convex distally, concave proximally. The elements are petaloid with dextral imbrication in the distal shield and sinistral in the proximal shield. Both distal and proximal shields have sutures which curve sinistrally at the outer margin. The curved surfaces show a continous edge of rhombic crystal faces less than 1/10 µm in size (McIntyre and Bé , 1967). On the distal shield the central opening is usually open (1 to 2 µm diameter), but occasionally it is closed by rhombic crystals, forming a crater-like depression. The pore on the proximal side is covered by a thin plate of rhombic crystals. The element count for both shields is the same , since the elements are interconnected to form a U-shaped unit.

Remarks:

Calcidiscus leptoporus was previously thought to have 3 varieties based upon the number of elements found in the shields (McIntyre and Bé ,1967). This view has now been modified and the largest of these forms , var. A is referred to as C.macintyrei (McIntyre and McIntyre,1970). The remaining varieties are now grouped under C.leptoporus and are different only in the number of elements forming the placolith, and are probably ecophenotypes. The occurrence and morphology of these varieties are discussed in some detail in Chapter 3, Section 3.3.2.2.

Genus COCCOLITHUS Schwartz, 1894

Coccolithus pelagicus (Wallich) Schiller

Plate 14, Figs.6-8, Pl.15, Figs.1-8, Pl.21, Figs. 1-2.

1877 Coccosphaera pelagica WALLICH, p.348, pl. 17, figs. 1-2, 5, 8-11d.

1902 Coccolithophora pelagica (Wallich).-LOHMANN, pp. 138-139, pl. 5, figs. 58a,c.

1930 Coccolithus pelagicus (Wallich).-SCHILLER, pp. 246-247, text-figs. 123, 124a,c.

1960 Coccolithus pelagicus (Wallich) Schiller.-PARKE and ADAMS, pp. 263-274, pls.1-4.

1967 Coccolithus pelagicus (Wallich) Schiller -BARTOLINI, pp. 132-133, pl.1, figs.2-7, text-fig.4.

1970 Coccolithus pelagicus (Wallich) Schiller.-SEISSER p. 127, fig.6a-f.

Description:

Oval placolith, convex distally, concave proximally with a narrow central pore which may or may not be crossed by a small bridge. The bridge crosses the pore at its centre and at right angles to the long axis of the shield. The placolith has a large distal shield and a smaller proximal shield. The distal shield is composed of radially arranged elements which are dextrally imbricated. The elements have rounded off edges at the margins of the shield. On the distal side the central area is nearly covered by a number of flattened rhomboidal elements.

The smaller proximal shield has sutures which are inclined clockwise. In well-preserved specimens there is a bar of rhombic elements that crosses the pore at its centre.

Dimensions:

Table 7.2 Dimensions of Celtic Sea specimens.

	range	mean
Distal shield length (µm)	8.5 -14.5	11.7
Distal shield width (µm)	6.5 -12.6	9.8

Distal shield element no.	52 - 62	57
Proximal shield length (μm)	7.2 - 12.6	8.7
Proximal shield width (μm)	5.5 - 11.3	7.6

Remarks:

Most specimens recorded here are large with a high element count. Fig. 7.1 shows a graph of distal shield length plotted against element count for C.pelagicus measured in this study. The element count and length range data of C.pelagicus as reported by McIntyre et al. (1967) and McIntyre and Be' (1967) have been included in this graph. These figures add to the evidence for a comprehensive C.pelagicus rather than the existance of a separate smaller species termed Coccolithus sarsiae Black. C.sarsiae is now thought to represent a small variety of C.pelagicus.

Genus EMILIANIA Hay and Mohler 1967

Emiliania huxleyi (Lohmann) Hay and Mohler

Pl.12, figs 1-8, Pl.13, Figs 1-8, Pl.14, Figs.1-5, Pl.21 , Figs. 20-21.

1902 Pontosphaera huxleyi LOHMANN, p. 130, pl. 4, figs. 2-9, 69.

1930 Pontosphaera huxleyi Lohmann.-SCHILLER, pp.179-180, text-figs. 23, 29a-c, 59a-c.

1943 Coccolithus huxleyi (Lohmann).-KAMPTNER, pp. 43-49.

1967 Coccolithus huxleyi (Lohmann) Kamptner.-MCINTYRE and BE' pp. 568-569, pl. 5 fig. d; pl. 6, figs a-b.

1967 Emiliania huxleyi (Lohmann).-HAY and MOHLER in Hay et al., p. 447, pl. 10. figs. 1-2, pl. 11, figs. 1-2.

1971 Emiliania huxleyi (Lohmann) Hay and Mohler.-BARTOLINI, p. 136, pl. 4, figs 1-8.

1981 Emiliania huxleyi (Lohmann) Hay and Mohler.-HEIMDAL and GAARDER, p.51, pl.4, figs. 18, 19.

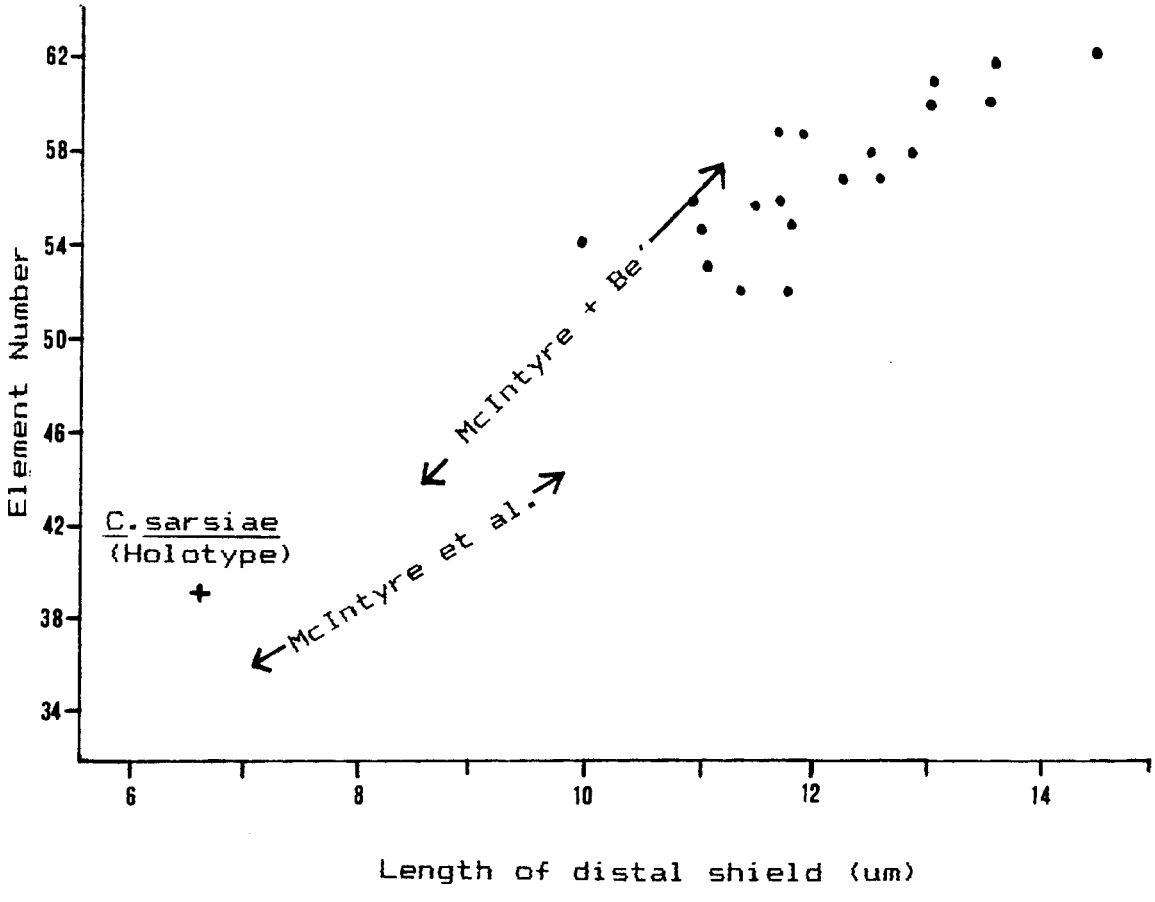


Figure 7.1
Lengths of Coccolithus pelagicus distal shields plotted versus the element numbers of the same shields. The range of these two variables as recorded by McIntyre and Be' (1967) and McIntyre et al. (1967) is also shown together with the position occupied by the holotype of Coccolithus sarsiae Black.

1984 Emiliania huxleyi (Lohmann) Hay and Mohler.- HALLEGRAEFF, p.233, figs. 8-12.

Description:

Elliptical placolith, shields of equal size, which are convex distally, concave proximally with a large central pore. The distal shield is formed of T-shaped elements and is oval to circular in cross-section. These elements are separated from each other except at the outer margin where the cross pieces are in contact and form a continuous margin (Pl. 13, Fig.1.). The whole structure resembles a spoked wheel. The elements of the proximal shield vary in shape and development depending on the environment. The elements in the warm-water variant resemble those previously described for the distal shield, whereas those in the cold-water variant form a solid shield of flattened elements with a blunt or slightly pointed margin (McIntyre and Bé , 1967). Between these two extremes a whole series of transitionary forms exist. The two shields are connected by a central column formed of elements that are a continuation of the shield elements.

A few coccoliths of E.huxleyi (~ 5%) recorded in sediments from the North Sea have a very unusual construction. Instead of having a fused distal shield and an 'open' proximal shield (as found in the typical cold-water variety) they have a fused proximal shield and an 'open'distal shield (Pl.14, Figs. 1-3). Such a construction for placoliths of E.huxleyi has not been previously reported , and is only reported for specimens from the North Sea in this study. Perhaps these forms are an ecophenotype of E.huxleyi limited to the waters of the North Sea. This scarce form of E.huxleyi is labelled the cold-water variety B, while the more common structure of E.huxleyi found in temperate latitudes is labelled the cold-water variety A. Other diagnostic features of the E.huxleyi cold-water var. B coccoliths are their large size (4.1 to 5.1 µm) and a partially fused central grill. The cold-water var. A coccoliths are generally much

smaller (range 2.7 to 3.9 μm).

Remarks:

The delicate structure of E.huxleyi is easily damaged , and fragments in all stages of disintegration are commonly seen. The central tube appears to be most resistant and these oval rings may be preserved alone (Pl. 13, Fig.8.).

Genus GEPHYROCAPSA Kamptner, 1943

Gephyrocapsa caribbeanica Boudreaux and Hay

Plate 16, figures 3-6, Pl.21, Figs. 13-14, 16.

1967 Gephyrocapsa oceanica Kamptner.-MCINTYRE and BE', pl.9, fig. A.

1967 Gephyrocapsa caribbeanica BOUDREAUX and HAY in Hay et al., p.447, pl.12, figs. 1-4; pl.13, figs. 1-4.

1970 Gephyrocapsa caribbeanica Boudreaux and Hay.-MCINTYRE and BE' text-fig. 5d.

Desription:

Elliptical placolith with a small central opening. Distal and proximal shields have the same element count. A bridge crosses the central area on the distal side and lies within an angle of 45° from the long axis of the coccolith. This bridge is strongly built and is formed of several elements from the central collar. The central opening varies from 1/3 to 2/5 of the total diameter of the shield.

Remarks:

This is the earliest gephyrocapsid to develop a diagonal bridge. G.caribbeanica may be distinguished from G.oceanica by a smaller element count, by a narrow central area which lacks a grill, by a wider rim, and by the bridge which makes an angle of less than 45° with the

maximum diameter of the coccolith (Roth and Coulbourne, 1982). However, Bukry (1973), believes the angle of the bridge is partially latitude-controlled and cites the central area proportions as the most distinctive feature. Roth and Coulbourne (1982) included gephyrocaspids resembling Gephyrocapsa lumina Bukry, 1973 and G. muellerae Breheret, 1978 in this species because they seem to fall within the intraspecific variations of G.caribbeanica. This classification scheme is adopted here.

Gephyrocapsa ericsonii McIntyre and Bé

Plate 16, Figures 7-8.

1967 Gephyrocapsa ericsonii MCINTYRE and BÉ , p. 571, pl. 10; pl. 12, fig. b.

1976 Gephyrocapsa ericsonii McIntyre and Bé .-SEISSER, p. 134, figs. 10a-b.

1977 G. ericsonii McIntyre and Bé.-OKADA and MCINTYRE, p.10, pl.2, fig.9 (part).

1979 G. ericsonii McIntyre and Bé.-CONLEY p. 28, pl. 1, fig. 16; pl. 2, fig. 16.

1984 G. ericsonii McIntyre and Bé.-HALLEGRAEFF, p. 233, figs. 13-14.

Description:

Very small (~ 2um) elliptical placolith with a large central opening spanned by a distinct, highly arched bridge.

Remarks:

This species is similar in construction to G.caribbeanica and G.oceanica with the exception of the bridge whose two elements are thinner, blade-like and highly arched. The last mentioned feature is not apparent in the illustration of G.kamptneri Déflandre and Fert 1954. Therefore, Roth and Coulbourne (1982) disagree with the recommendations of Pierce and Hart (1979), and do not consider G.ericsonii a junior synonym of G.kamptneri.

This terminology is adopted here. This placolith is the smallest of all the gephyrocapsids, and was scarcely recorded in this study.

Gephyrocapsa oceanica Kamptner

Plate 16, Figs. 1-2, Pl.21, Fig. 12

1902 Pontosphaera huxleyi LOHMANN, (in part) p.130, pl.4, fig.1

1943 Gephyrocapsa oceanica KAMPTNER, p.45.

1955 Gephyrocapsa oceanica Kamptner.-HALLDAL and MARKALI, p. 18, pl. 24, figs. 1-2.

1960 G.oceanica Kamptner.-HASLE, pl. 2, figs. 4a-b.

1969 Gephyrocapsa oceanica Kamptner.-BOUDREAUX and HAY, pp.258,261, pl.1, figs. 18-25.

1977 G.oceanica Kamptner.-OKADA and MCINTYRE, pp 10-11, pl. 3, figs. 3-9.

Desciption:

Elliptical placolith with a moderately large central opening, convex distally, concave proximally. Bukry (1973) states that the central opening is approximately equal to the rim width measured along the short axis. The elements of the distal shield are slightly imbricate, sinistral in the proximal and dextral in the distal shield. In the proximal view the central pore is covered by a delicate grill of interconnecting rods radiating from the central line. This grill may be missing or severely corroded (Pl.16, Fig.1.).

Remarks:

Roth and Coulbourne (1982) report that this species shows great variability in relative size of the central area and thickness of the bridge. This species is very scarce in the shelf sediments studied.

Genus UMBILICOSPHAERA Lohmann, 1902

Umbilicosphaera hulburtiania Gaarder

Plate 19, Fig. 6 (in part).

1970 Umbilicosphaera hulburtiana GAARDER, pp. 121-126.
1977 Umbilicosphaera hulburtiana Gaarder.-OKADA and MCINTYRE, p.12, pl.3, fig. 12.

Description:

Elliptical placolith, convex distally with a large central tube bordered by a generally narrow collar. The suture lines between the collar elements are straight but not imbricate.

Remarks:

Coccoliths of this species show much variation in size and the relative width of the collar and the central tube. The specimen shown in Pl.19, Fig.6 has a large central opening 2/3 the diameter of the shield. The main difference between this species and U. sibogae is that the former has oval placoliths and the latter has circular coccoliths.

U. hulburtiana is only recorded from sediments in the Celtic Sea, where it is very scarce.

Umbilicosphaera sibogae (Weber-van Bosse) Gaarder 1970

Plate 19 Figs. 4-5, Pl.21, Fig.10.

1901 Coccosphaera sibogae WEBER-VAN BOSSE, pp. 137, 140, pl. 17, figs. 1-2.
1902 Umbilicosphaera mirabilis LOHMANN, pp. 139-140, pl. 5, figs. 66, 66a.
1954 Cyclococcolithus mirabilis (Lohmann).-KAMPTNER pp. 24-25, text-figs. 21-23.
1961 Umbilicosphaera mirabilis (Lohmann).-BLACK and BARNES, pp. 140-141, pl. 25.
1967 Umbilicosphaera mirabilis (Lohmann).-MCINTYRE and BE', pp. 571-572, pl. 11, fig. c.
1970 Umbilicosphaera sibogae (Weber-van Bosse)- GAARDER,

pp. 122-126, figs. 9c-d.

1975 Umbilicosphaera sibogae (Weber-van Bosse) Gaarder.-KLING, p. 10, pl.1, fig. 2.

1977 Umbilicosphaera sibogae (Weber-van Bosse) Gaarder.-OKADA and MCINTYRE, p.13,pl.4, fig. 2.

Description:

Circular placolith with a convex distal shield equal in length to or smaller than the flat proximal shield. The upper shield consists of a ring of a varying number of stout crystals surrounding a wide circular pore, which lies at the bottom of a crater-like depression. The rim of the crater is sharply angular and is formed from the intersection of clean-cut crystal faces which dip away steeply on either side.

The elements of the distal shield are sinistrally imbricate. The element sutures radiate in straight lines from the central pore, covering the inner one-third of the distal shield. The outer half of the distal shield is characterised by curving anti-clockwise element sutures.

Remarks:

McIntyre and Be' (1967) reported the occurrence of two distinctly different forms within this species. Okada and McIntyre have documented these differences between the two forms. The form first described as Coccosphaera sibogae by Weber-van Bosse (1901) differs from the other form first described by Kamptner (1963) as Cycloplacolithus foliosa by having;

1) a larger coccosphere with a greater number of coccoliths,

2) coccoliths with with a proportionally larger central area without spines,

3) coccoliths with a smooth continuation of the suture line instead of sharply offset suture lines on the distal shield.

Coccospheres bearing both types of coccoliths were very occasionally reported by Okada and McIntyre (1977). However, as most individuals of this species can be clearly designated to one of the two forms, Okada and McIntyre justified taxonomic discrimination at variety level. They proposed a new combination Umbilicosphaera sibogae var. foliosa for the form with coccoliths first described by Kamptner.

Dimensions:

The distal shield ranges in size from 4.0 to 5.8 µm and contains 32 to 34 elements.

Umbilicosphaera sibogae (Weber-van Bosse) Gaarder var. foliosa (Kamptner) Okada and McIntyre

Plate 19, Figs 1-3, Pl.21, Fig. 11.

1963 Cycloplacolithus foliosus KAMPTNER, pp. 167-168, pl. 7, fig. 38

1964 Cyclococcolithus mirabilis (Lohmann) Kamptner.-COHEN, p. 237, pl. 2, figs. 3a-f.

1967 Umbilicosphaera mirabilis Lohmann.-MCINTYRE and BÉ, pp. 571-572.

1977 Umbilicosphaera sibogae (Weber-van Bosse) Gaarder var. foliosa (Kamptner).-OKADA and MCINTYRE, p.13, pl. 4, fig. 1.

1980 Umbilicosphaera sibogae (Weber-van Bosse) Gaarder var. foliosa (Kamptner) Okada and McIntyre.-REID, pp.155-156, pl.2 figs. 3-4.

Description:

Circular placolith, convex distally, concave proximally, with a small central pore area. The distal shield is constructed of a variable number of sinistrally imbricate elements. Inner portion of suture line on distal shield straight and sharpely offset from zigzag-patterned, slightly curving line of outer section of the shield. Spines may protrude from the inner margin

of the proximal shield through the central opening.

Remarks:

Kamptner (1963) was t' first to describe this form , which he named Cycloplacolithus foliosus. Since this form is considered a variety of Umbilicosphaera sibogae as explained in the remarks on the typical form of the species, a new combination U.sibogae var. foliosa was proposed by Okada and McIntyre (1977).

Dimensions:

Distal shield contains between 32 and 36 elements and ranges in size from 5.1 to 6.9 µm.

Family HELICOSPHAERACEAE Black, 1971, emend. Jafar and Martini

Genus HELICOSPHAERA Kamptner, 1954

Helicosphaera carteri (Wallich) Kamptner 1954

Plate 17, Figs 1-4, Pl.21, Figs. 3,7.

1877 "Coccosphaera carteri" WALLICH, pp. 347-348, pl. 17, figs. 3-4, 7, 7a, 12s, 17.

1902 Coccolithophora pelagica (Wallich).-LOHMANN, pp. 138-139, pl. 5, fig. 5a.

1930 Coccolithus pelagicus (Wallich).-SCHILLER, pp. 246-247, text-fig. 124a.

1941 Coccolithus carteri (Wallich).-KAMPTNER, pp.93-94, 111, Pl.12, fig. 134, pl. 13, figs. 135-136.

1954 Helicosphaera carteri (Wallich).-KAMPTNER, pp. 21-32, text-figs. 17-19.

1961 Helicosphaera carteri (Wallich) Kamptner.-BLACK and BARNES, pp. 139-140, pls. 22-23.

1967 Helicopontosphaera kamptneri HAY and MOHLER in Hay et al., p.448, pls. 10-11, fig. 5.

1969 Helicopontosphaera wallichi (Lohmann).-BOUDREUX and HAY, 1969, pp. 272-273, pl.6, fig.9.

1977 Helicosphaera wallichii (Lohmann).- Okada and McIntyre pp. 14-15, pl.4, fig.8.

Decription:

This species exhibits wide variation in size and form. The centre of the proximal surface is covered by a large flat elliptical shield , construded of elongated plates disposed approximately at right angles to the periphery of the shield (Black and Barnes, 1961). The plates at each of the rounded ends of the shields meet at a focal point and tend to be wedge-shaped. Between these two points the plates on either side of the shield lie in two roughly parallel series separated by a major suture. This suture varies considerably in shape and size. It may be deeply incised and give rise to a thin open slit (Plate 17,fig 2), while in other examples it may have the same definition as the suture boundaries (plate 17, fig 3). Most of the specimens recorded in this study have linear sutures rather than obliquely arranged sutures.

Surrounding the central part of the shield is a distinct flange of narrow radiating plates. These wind around the shield in a clockwise direction when viewed proximally, making a spiral of approximately one and a quarter turns before flaring out to form a wing-like expansion. The flange passes beneath and never above the penultimate whorl. The distal surface has a very different appearance, it is covered by a shield of tangentially arranged crystals concealing all the structures seen on the proximal surface, except the wing and the last half-turn of the flange.

Dimensions:

Range of coccolith lengths 9.4 to 10.0 μm, mean 9.6 μm; widths 3.5 to 3.2 μm, mean 3.3 μm.

Remarks:

Refer to Jafar and Martini (1975) for the retention of the generic name Helicosphaera and rejection of the generic name Helicopontosphaera.

Jafar and Martini suggested the inclusion of

Helicosphaera wallichii, a species having coccoliths with obliquely arranged central openings within Helicosphaera carteri which has two elongated openings. Okada and McIntyre (1977) reported that the size and shape of the central openings are important factors for the separation of the fossil species belonging to the genus Helicosphaera. Therefore they concluded that Helicosphaera wallichii (Lohmann) Okada and McIntyre n. comb. should distinguish those species which have coccoliths with obliquely arranged central openings. However, Okada and McIntyre have observed specimens which exhibit transitional forms between the two types and stated "their separation at species level is tentative". Hallegraeff (1984) recorded cells that carried both Helicosphaera carteri- and Helicosphaera wallichii-type coccoliths on the same coccosphere.

There seems insufficient evidence to justify separation of these two types at species level. Therefore in this study both types are included under Helicosphaera carteri as suggested by Jafar and Martini in 1975.

Family PONTOSPHAERACEAE Lemmerman, 1908
Genus Pontosphaera Lohmann 1902

Pontosphaera discopora Schiller

1925 Pontosphaera discopora SCHILLER, p.11, pl.X, fig.4
1955 Pontopshaera discopora Schiller.-HALLDAL and MARKALI, p.19, pl.27, figs. 1-3.
1969 Pontosphaera discopora Schiller.-BOUDREAUX and HAY, p.271, pl. IV, figs. 1-7.

Description:

Cribolith with pores in the central region 0.2 to 0.3 um in diametre and arranged more or less regularly in lines concentric with the elliptical outline of the coccolith (Halldal and Markali,1955). The pores of this species are visible with the light microscope.

Remarks:

This species was only recorded by optical microscopy.

Pontosphaera messinae Bartolini

Plate 19, Fig. 8.

1970 Pontosphaera messinae BARTOLINI, p.150-151, pl.7, figs. 1-2.

1973 Pontosphaera messinae Bartolini.-BURNS, pp. 153-154, pl.2, figs. 4-7.

Description:

Elliptical concavo-convex cribilith. The proximal surface is shown in Pl.17, fig.8 and is slightly concave with a prominent central area suture line and a variable number of central pores in random spatial arrangement.

Genus SCYPHOSPHAERA Lohmann, 1902

Scyphosphaera apsteinii Lohmann

Plate 19, Fig.7.

1902 Scyphosphaera apsteinii LOHMANN, p. 132, pl.4, figs. 26-30

1930 Scyphosphaera apsteinii Lohmann.-SCHILLER, pp. 194-195, text-figs. 36, 75.

1970 S. apsteinii Lohmann.-GAARDER, pp. 119-121 text-figs. 4e-f, 6a-b.

1979 S. apsteinii Lohmann.-CONLEY, p. 30, pl. 3, fig. 20.

Decription:

Discolith with distal surface showing a smooth border surrounding a central area covered with small pores.

Remarks:

The species is very scarce in the sediments. The

specimen shown in Pl. 19, Fig.7. is badly corroded.

Family RHABDOSPHAERACEAE Lemmermann, 1908
Genus DISCOSPHAERA Haeckel, 1894

Discosphaera tubifera (Murray and Blackman Ostenfeld

1898 Rhabdosphaera tubifer MURRAY and BLACKMAN, pp. 438-439, pl. 15, figs. 8-10.
1900 Discosphaera tubifer (Murray and Blackman) .- OSTENFELD, p. 200.
1902 Discosphaera tubifer (Murray and Blackmann) Ostenfeld.-LOHMANN, pp. 141-142, pl.5, figs. 47-48, 48a, 50.
1944 Discosphaera tubifera (Murray and Blackman) Ostenfeld.-KAMPTNER, p. 139.
1955 Discosphaera tubifera (Murray and Blackman) Ostenfeld.-HALLDAL and MARKALI, p. 17, pl. 22. figs. 1-3.
1967 Discosphaera tubifera (Murray and Blackman) Ostenfeld.-MCINTYRE and BE', p.566, pl.1, figs. a-c.

Description:

Crytolith coccolith with a large trumpet-shaped appendix attached to a small, slightly convex, round to oval base plate. This species was only recorded with the light microscope so no **description is provided.**

Genus RHABDOSPHAERA Haeckel, 1894

Rhabdosphaera clavigera Murray and Blackman

Plate 18, Figs. 1-3.

1898 Rhabdosphaera claviger MURRAY and BLACKMAN, p. 438, pl. 15, figs. 13-15.
1902 Rhabdosphaera stylifera LOHMANN, p. 143, pl. 5, fig. 65.
1967 Rhabdosphaera stylifera Lohmann.-MCINTYRE and BÉ .

p. 567, pl. 4.

1971 Rhabdosphaera clavigera Murray and Blackman .- GAARDER and HASLE, p. 536, text-fig. 11.

1983 Rhabdosphaera clavigera Murray and Blackman . -NORRIS, p.31-33, figs. 1a-c, 2-5.

1984 Rhabdosphaera clavigera Murray and Blackman .- HALLEGRAEFF, p.236, figs. 32-33.

Description:

Mushroom-like (helatoform) crytolith, convex distally, from which rises a long hollow stem constructed of elongate calcite fibres. The basal plate has a central area composed of overlapping rhombic crystals which rise towards the centre, forming the spinal base. The stem is composed of elongated crystals in a spiral construction (Pl.18, Fig.3.). The distal end of the spine is reported to have two distinct forms. It may swell to be club-like in shape, or terminate in four vanes at right angles to each other around the stem. Only club-like stems are recorded from specimens in this study.

Dimensions:

Table 7.3 Dimensions of Rhabdosphaera clavigera.

Basal Plate		stem		Reference	Locality
range	mean	ange	mean		
4.2-6.0	4.8	7.6-9.4	8.8	1	Celtic Sea
3.5-5.4	4.6	4.8-9.3	8.2	2	Med. Sea
2.7-3.4	3.2	3.6-5.0	4.3	3	Atlantic

1- This study, 2- Bartolini (1970), 3- McIntyre and Bé (1967)

Remarks:

Previously Rhabdosphaera clavigera and R. stylifera have been distinguished mainly on the construction of the spine, the former being club-like, the latter ending in arrow tail-like vanes (Cohen,1965). However, in 1965 Cohen, while retaining R.clavigera and R.stylifera as separate species stated that "there are also intermediate

forms between R. clavigera and R.stylifera". Borsetti and Cati (1972) have reported coccospheres that bear both claviform and styliform coccoliths. McIntyre and Bé reported no systematic or biogeographical differences between the two types and grouped all individuals under the name R. stylifera. They used R. stylifera as the comprehensive name for both forms mainly because the "stylifera"-type form was more commonly found than the "clavigera"- type form. However Bartolini (1970) and Siesser (1975) consider R.stylifera Lohmann (1902) as a junior synonym of R. clavigera Murray and Blackman 1898. This terminology is also used in this study.

Genus UMBELLOSPHAERA Paasche, 1955 emend. Gaarder,1981.

Umbellosphaera tenuis (Kamptner) Paasche

Plate 20, Fig. 3.

1937 Coccolithus tenuis KAMPTNER, p.311, pl. 17, figs. 41-42.
1955 Umbellosphaera tenuis (Kamptner).-PAASCHE in Markali and Paasche, p. 97, pls. 3-6.
1967 U.tenuis (Kamptner) Paasche.-BARTOLINI, p. 146 , pl.2, figs. 2-3.
1984 U.tenuis (Kamptner) Paasche.-HALLEGRAEFF, p. 236, fig. 30.

Description:

Plate 20, Fig.3 shows what appears to be an elliptical shield with a small central opening. In fact it is a broad funnel-shaped macro-coccolith, with the central tubular part gradually widening into the convex, umbrella-like outer rim (Paasche, 1955 p.97). 25 ridges situated between the central opening and the outer edge are spaced at generally regular intervals around the plate. These ridges are wedge-shaped with minor ridges branching off when the outer edge is approached.

Dimensions:

The specimen figured is 6 μm long, 4.5 μm wide.

Family SYRACOSPHAERACEAE Lemmermann, 1908

Genus CORONOSPHAERA Gaarder, 1977

Coronosphaera mediterranea (Lohmann) Gaarder

Plate 18, Figs. 4, 6.

1902 Syracosphaera mediterranea LOHMANN, p.133-134, pl.4, figs. 31, 31a, 32.

1954 Syracosphaera pulchra (Lohmann).-HALLDAL and MARKALI, P.332, text-fig.4.

1955 Syracosphaera pulchroides HALLDAL and MARKALI pp. 10 -11.

1977 Coronosphaera mediterranea (Lohmann) GAARDER in Gaarder and Heimdal, p.60-62, pl.14, figs. 21-26.

Description:

Oval incomplete caneolith with a thick wall and a large central area. The top of the wall slopes sharply inwards and is covered by very fine suture lines. Central area consists of radially arranged lamellae and a solid central field of variable development. The stomatal coccoliths bear a central rod with a pointed end (Pl.18, Fig.4). The peripheral ring wall ends in a crown-shaped top. This is a regular feature, from which the name of the genus is derived (Gaarder and Heimdal,1977).

Dimensions:

Coccolith length 4.5 to 2.6 um
coccolith width 2.1 to 3.2um
length/width ratio 1.3 to 1.6

Genus SYRACOSPHAERA Lohmann, 1902

Syracosphaera histrica Kamptner

1941 Plate 21 Fig. 23.

1914 Syracosphaera histrica KAMPTNER, pp.84, 104, pl. 6, figs. 65-68.

1970 Syracosphaera nodosa (Kamptner).-OKADA and HONJO, p. 21, pl. 1, figs. 1-2.

1977 Syracosphaera histrica Kamptner.-GAARDER and HEIMDAL, pp. 55-56, pl.2, figs. 9-15.

1980 Syracosphaera histrica Kamptner.-REID, p. 160-162, pl. 5, figs. 7-8.

Description:

When observed with the light microscope these coccoliths display a characteristic hourglass-shaped extinction cross (see Pl.21, Fig.23).

Remarks:

This species is very scarce in the sediments.

Syracosphaera nodosa Kamptner

1941 Syracosphaera nodosa KAMPTNER, pp. 84-85, 104, pl.7, figs. 73-76.

1955 Syracosphaera nodosa Kamptner.-HALLDAL and MARKALI, pp. 13-14, pl.14.

1982 Syracosphaera nodosa Kamptner.-CHEN and SHEIH, p. 266, pl.16, figs. 1-2.

Remarks:

Because this species was only scarcely observed with the light microscope no photomicrographs are presented.

Syracosphaera pulchra Lohmann

Plate 18, Figs.5, 7-8, Pl.21, Figs 17-19.

1902 Syracosphaera pulchra LOHMANN, p. 134, pl. 4, figs.

33, 36-37.

1930 Syracosphaera pulchra Lohmann.- SCHILLER, pp. 207-209, text-figs. 11, 30, 90a-b.

1955 Syracosphaera pulchra Lohmann.-HALLDAL and MARKALI, p. 12, pl. 11.

1977 Syracosphaera pulchra Lohmann.-OKADA and MCINTYRE, p.27, pl. 10, figs. 11-12.

1977 Syracosphaera pulchra Lohmann.-GAARDER and HEIMDAL, p. 55, pl.1, figs. 1-8.

Description:

Elliptical **caneolith** with a narrow raised rim (0.5 to 1.0 µm wide) constructed of imbricate elements. In distal view the caneolith has a large central area composed of narrow lath-shaped radially arranged elements which converge towards the centre. The radial ribs are arranged in bundles or sheaves, and overlap to some extent at the centre. The ribs themselves consist of calcite crystals arranged end to end but out of line and joined with an oblique suture (Black and Barnes,1961). This gives rise to the characteristic broken or bent appearance of the ribs.

Dimensions:

Table 7.4 Dimensions of Syracosphaera pulchra.

Length		Width		Reference	Locality
range	mean	range	mean		
4.7-9.8µ	6.6µ	3.0-7.5µ	4.8µ	1	Mediter. Sea
4.5-7.1µ	7.1µ	3.0-6.0µ	4.9µ	2	Atlantic.
4.9-6.0µ	5.4µ	3.6-4.2µ	3.8µ	3	Celtic Sea.

1- Bartolini (1970) 2- Seisser (1977) 3- this study.

Genera of uncertain position.

Genus SCAPHOLITHUS Deflandre 1954

Scapholithus fossilis Deflandre

Plate 20, Figs. 1-2.

1954 Scapholithus fossilis DEFLANDRE, pl. 16, figs. 6-9.
1969 Scapholithus fossilis Deflandre.-BOUDREAUX and HAY, p. 281, pl. 7, figs. 16-20.
1982 Scapholithus fossilis Deflandre.-CHEN and SHIEH, pl.16, figs. 6-9.

Description:

Isolated scapholiths are occasionally recorded in the sediments.

Remarks:

Because only isolated poorly preserved scapholiths rather than whole coccospheres are found in the sediments, a separation of the genera Calsiolena Gran and Anoplosolenia Deflandre is not possible. Therefore the genus Scapholithus is used for all scapholiths.

PLATE 11

S.E.M. photomicrographs of Calcidiscus leptoporus

Fig.1 Oblique distal view (x 9,100). Neg. 453-2, sample BM50, Celtic Sea.

Fig.2 Oblique proximal view (x 15,500). Note slight etching on suture boundaries. Neg. 384-6, sample ES 129, Lough Hyne.

Fig.3 Proximal view of distal shield with proximal shield absent. Note the range in size and shape of the distal elements. (x 14,100). Neg. 452-5, sample BM 50, Celtic Sea.

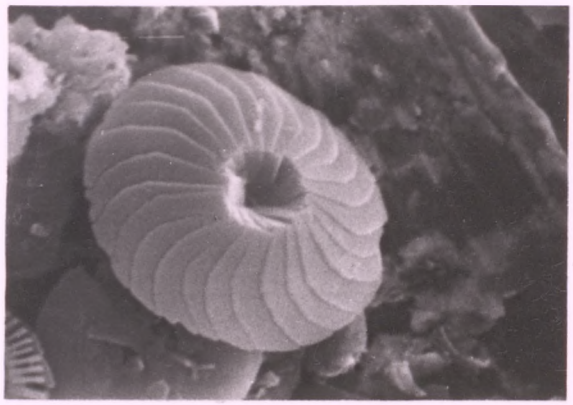
Fig.4 Oblique distal view (x 14,100). Neg. 452-7, sample BM 50.

Fig.5 Oblique side view (x 10,300). Neg. 453-6, sample BM 50.

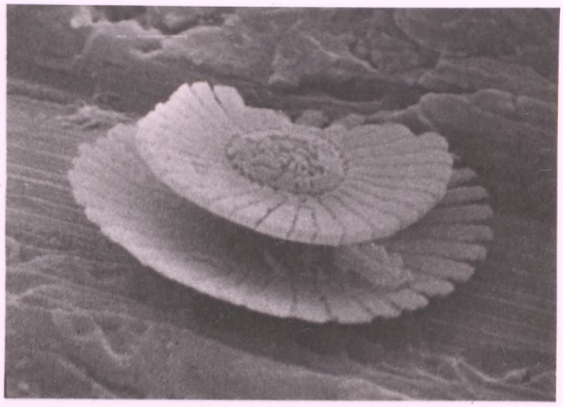
Fig.6 Distal view (x 9,100). Neg. 452-2, sample BM50.

Fig.7 Aggregate of shields (x 6,600). Neg. 452-8, sample BM 50.

Fig.8 Coccolith showing dissolution features, note etching on suture boundaries and in central region (x19,000). Neg. 389-8, sample ES 129, Lough Hyne.



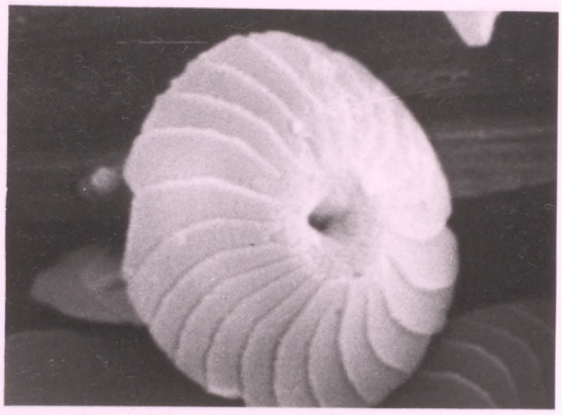
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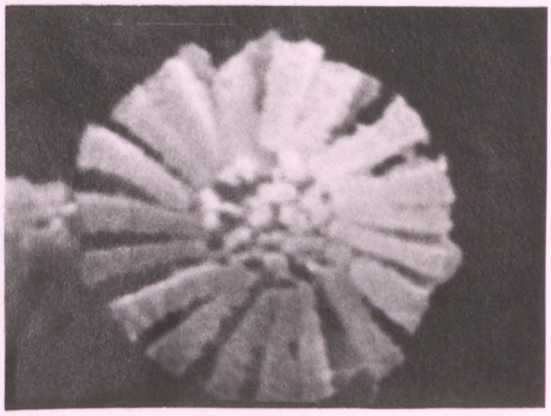
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PLATE 12.

S.E.M. photomicrographs of Emiliania huxleyi.

(Figs.3 to 8 from sample 200, filter 1)

Fig.1 Coccosphere (x 9,700). Note the dissolution of the T-shaped ends of the elements and the wide separation of the elements of the distal shield. Neg. 454-6, sample BM 50, Celtic Sea.

Fig.2 Magnified view of coccosphere shown in Figure 1. (x 14,000). Neg.454-7, BM 50, Celtic Sea.

Fig.3 Coccosphere (x 11,000). Neg. 489-7

Fig.4 Coccosphere (x 5,000). Neg. 489-8.

Fig.5 Collapsed coccosphere (x 9,600) Neg. 490-2,

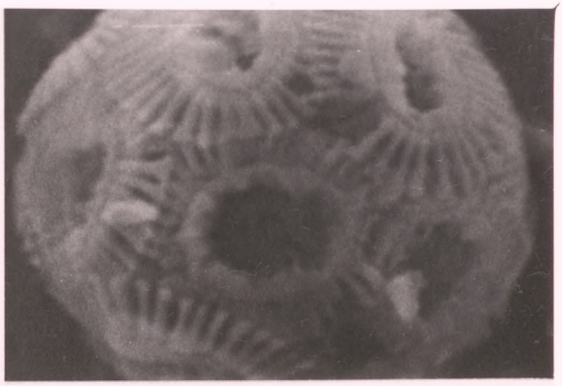
Fig.6 General view of coccolith debris (x 2,800). Neg. 489-2.

Fig.7 General view of coccolith debris (x 10,000). Note that the fragments of the shields still retain their T-shaped elements suggesting that simple breakage rather than dissolution is responsible for the disaggregation. Neg.490-7.

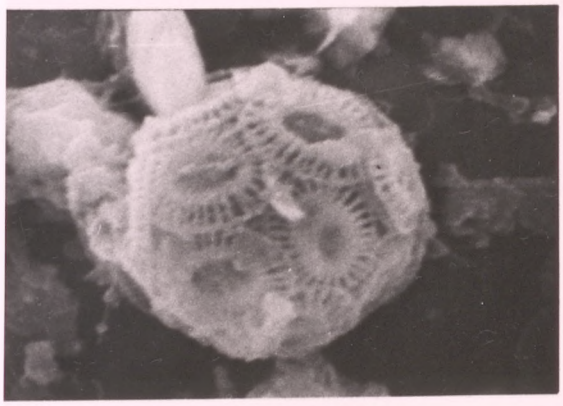
Fig.8 General view of coccolith debris (x 10,000). Neg.490-5.



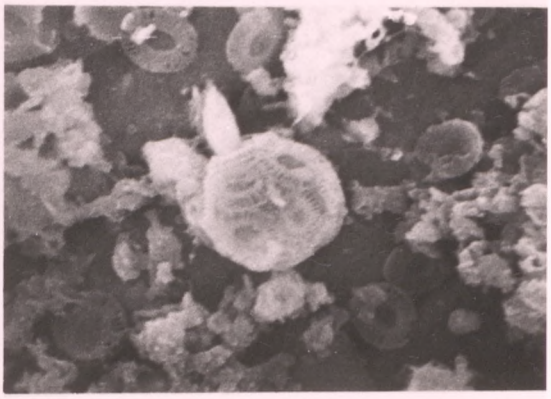
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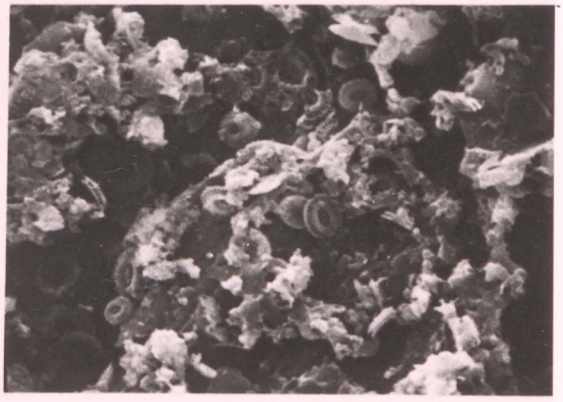
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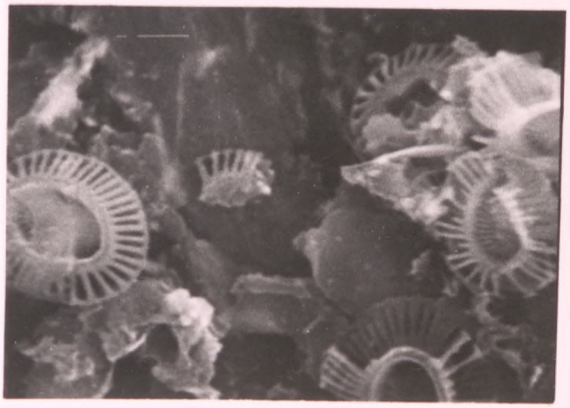
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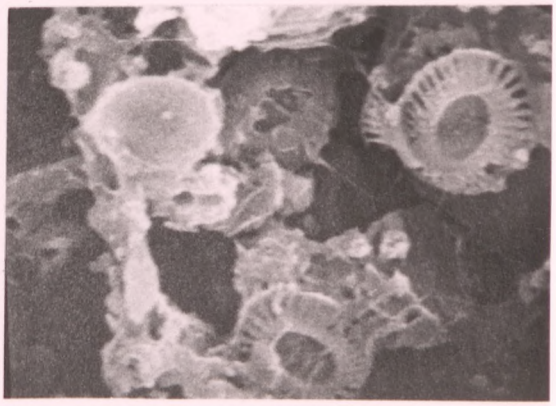
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Plate 13.

S.E.M. photomicrographs of *Emiliania huxleyi*.

(Figs. 4 to 8 all from sample WF 202, Northern North Sea)

Fig.1 Distal view of a warm-water variety showing well-preserved T-shaped elements and central grill (x 33,000). Neg. 432-6, sample ES 130, Clonakilty Bay.

Fig.2 Distal view of warm-water variety showing dissolution of the central grill and of the T-shaped ends of the elements. (x 21,000). Neg. 431-6, sample ES 130, Clonakilty Bay.

Fig.3 Distal view (x 20,700). Neg. 384-7, sample ES 129, Lough Hyne.

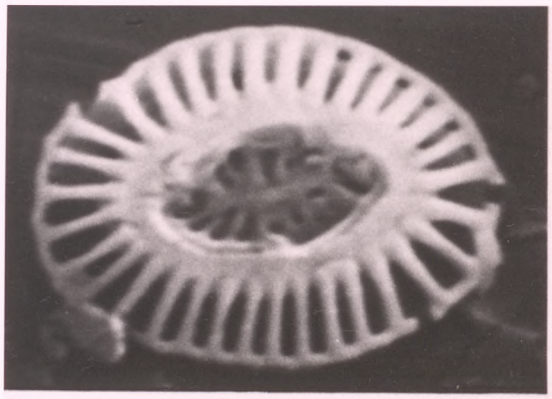
Fig.4 Distal view showing broken distal elements and damaged 'solid' proximal shield, (cold-water var.A coccolith), (x 15,9000). Neg. 502-8.

Fig.5 Distal view of badly corroded coccolith, (warm-water var.) (x 32,000). Neg. 502-8.

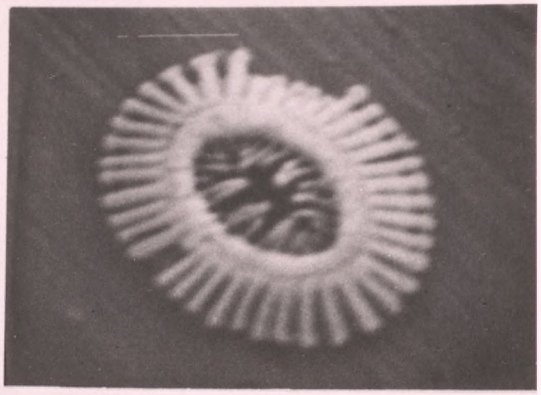
Fig.6 Proximal shield with remnants of distal shield elements (warm-water var.) (x 17,000). Neg.503-3.

Fig.7 Proximal shield and central ring structure but with distal elements absent (x 17,000). Neg. 503-8.

Fig.8 Both proximal and distal shields absent , remnant central ring preserved alone.Distal view remnant (x 13,000). Neg. 503-7.



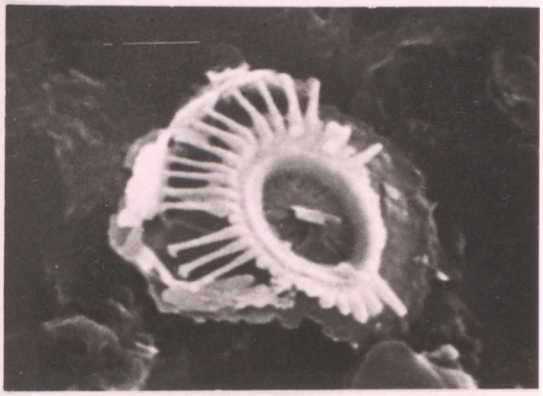
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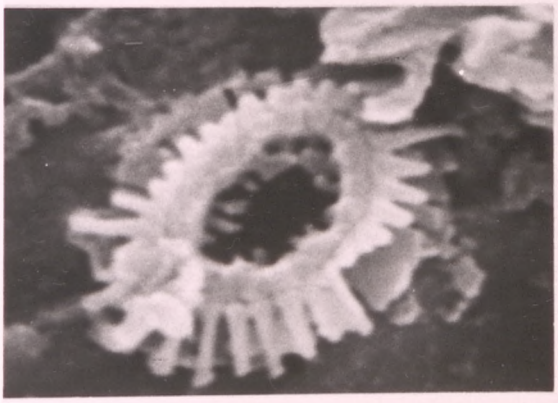
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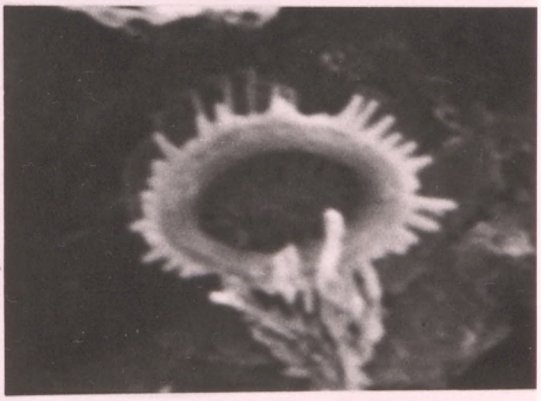
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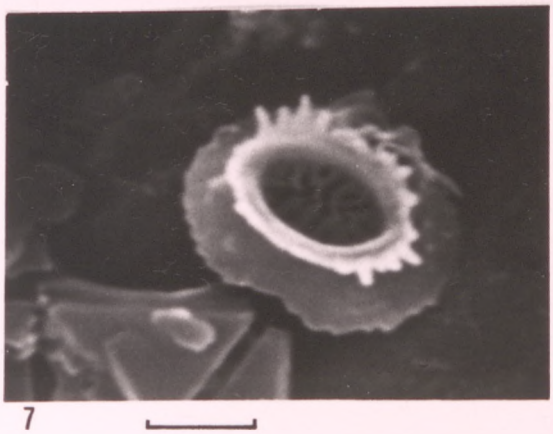
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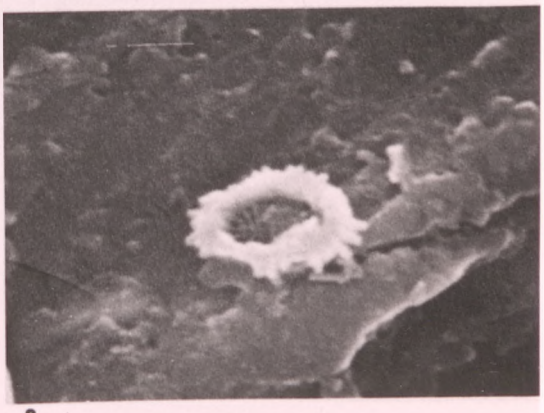
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PLATE 14

S.E.M. photomicrographs of E.huxleyi and C.pelagicus.

Fig.1 E.huxleyi with solid distal shield (cold-water var. B) (x 16,000). Neg. 503-1, sample WF 200, North Sea.

Fig.2 E.huxleyi, small specimen (warm-water var.), large specimen (cold-water var.B) (x 10,900). Neg. 491-1, filter sample 200-4, North Sea.

Fig.3 E.huxleyi, view showing a warm-water var. lying on top of a cold-water var. (x 14,900). Neg. 594-4, filter sample 200-1, North Sea .

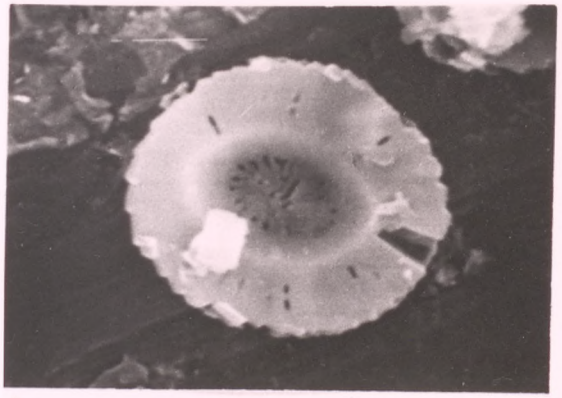
Fig.4 E.huxleyi, with solid proximal shield (cold-water form var.B) (x 20,000). Neg. 494-4, sample ES 129, Lough Hyne.

Fig.5 E.huxleyi, broken cold-water form var.A (x16,000). Neg 432-5, ES 130, Clonakilty Bay.

Fig.6 Coccolithus pelagicus, proximal view (x 7,200). Neg. 384-8, ES 129, Lough Hyne.

Fig.7 Coccolithus pelagicus, side view (x 6,700). Neg. 384-4, ES 129, Lough Hyne.

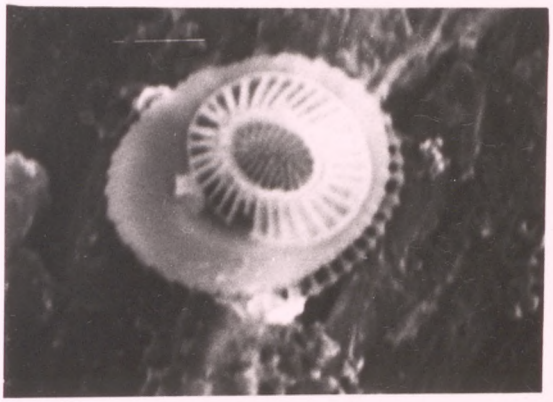
Fig.8 C.pelagicus, side view (x 4,900). Neg. 454-8, BM 50, Celtic Sea.



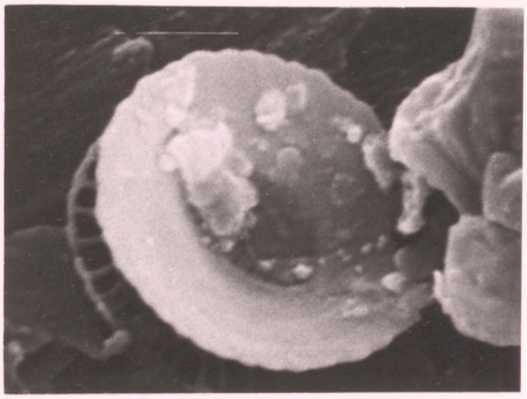
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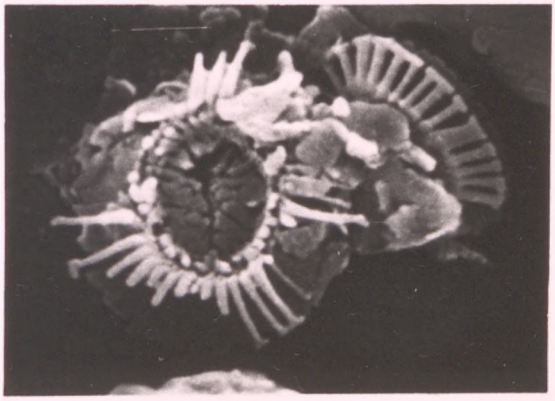
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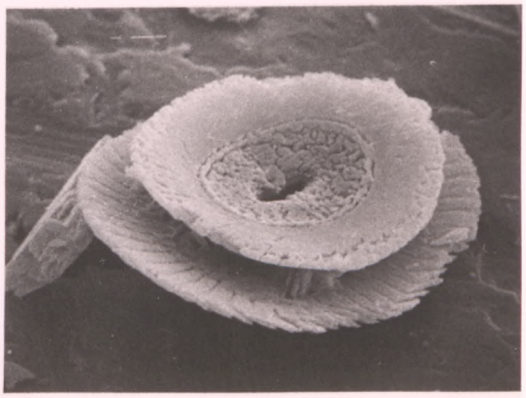
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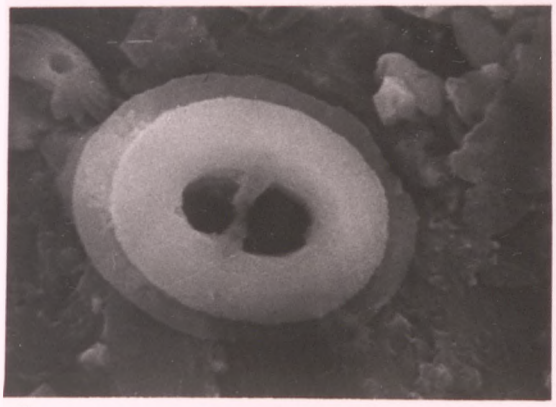
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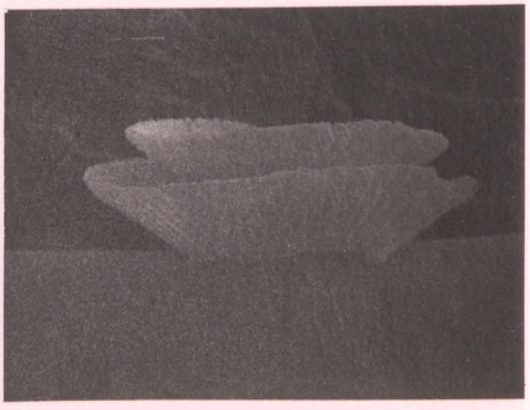
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PLATE 15

S.E.M. photomicrographs of Cocccolithus pelagicus.

Fig.1 Coccosphere (x 2,600). Neg.451-1, sample BM 50, Celtic Sea.

Fig.2 Magnified view of coccosphere shown in Fig.1. Note the difference in size of the placoliths of C.pelagicus and Gephyrocapsa ericsonii (centre) (x 6,300). Neg. 452-2, sample BM 50.

Fig.3 Oblique distal view (x 6,700). Neg. 378-1, sample ES 126, Lougher Estuary.

Fig.4 Distal view (x 6,900). Neg. 389-3, sample ES 129, Lough Hyne.

Fig.5 Distal view (x 4,800). Neg. 376-1, sample ES 126, Lougher Estuary.

Fig.6 Magnified view of central area shown if fig.5 (x 9,400). Neg. 376-2, sample ES 126, Lougher Estuary.

Fig.7 Oblique distal view (x 6,900). Neg. 389-5, sample ES 129, Lough Hyne.

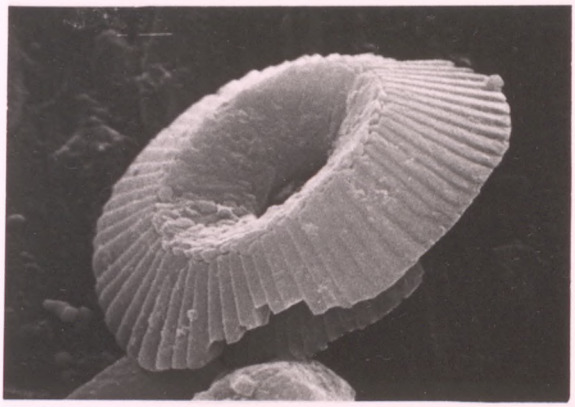
Fig.8 Distal view of overgrown specimen (x 5,200). Neg. 502-4, sample WF 202, North Sea.



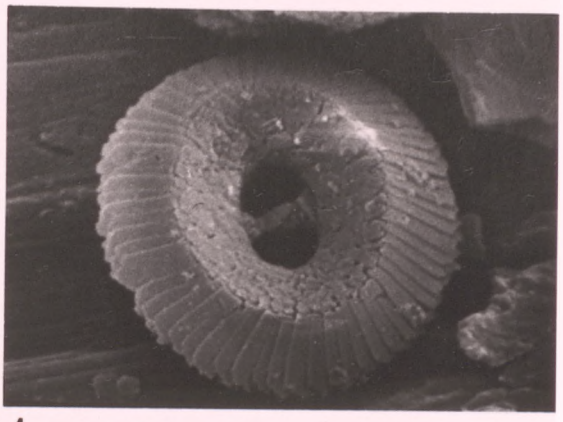
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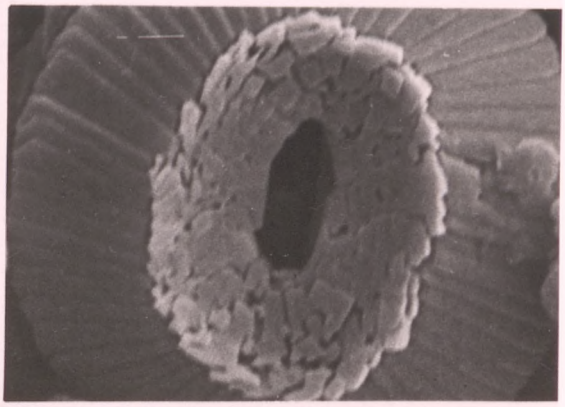
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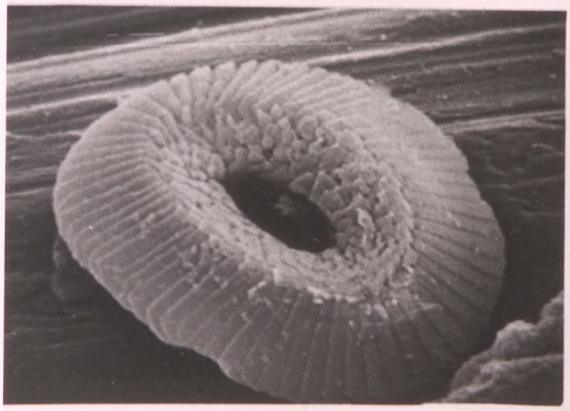
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PLATE 16

S.E.M. Photomicrographs of *Gephyrocapsa* species.

(All Figs. from sample BM50, Celtic Sea).

Fig.1 *Gephyrocapsa oceanica* oblique distal and side views (x 9,100). Neg. 453-2,

Fig.2 *Gephyrocapsa oceanica*, oblique distal view (x 15,500). Neg. 384-6.

Fig.3 *Gephyrocapsa caribbeanica*, distal view (x 18,500). The bridge crossing the central pore is composed of several elements. Neg.453-1.

Fig.4 *G.caribbeanica*, distal view (x 14,800). 472-6.

Fig.5 *G.caribbeanica*, distal view (x 15,000). Neg. 472-3

Fig.6 *G.caribbeanica*, distal view (x 14,000). Neg. 453-2

Fig.7 *G.ericsonii*, distal view (x 20,000). Neg. 453-2.

Fig.8 *G.ericsonii*, distal view (x 13,900). Neg.451-5.



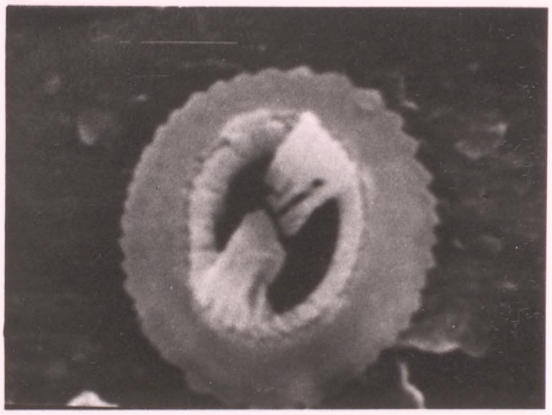
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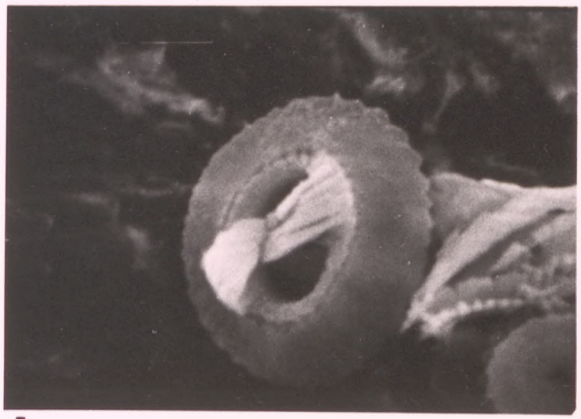
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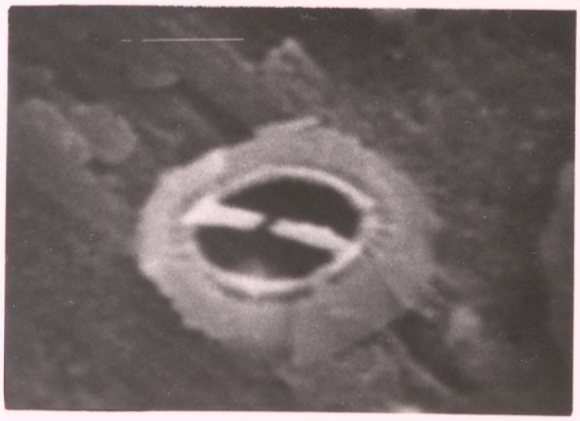
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PLATE 17

S.E.M. photomicrographs of Helicosphaera carteri and Braarudosphaera bigelowii.

Fig.1 Helicosphaera carteri, proximal view x 7,400). Neg. 432-2, sample ES130, Clonakilty Bay.

Fig.2 H.carteri, proximal view. Note central pores elongate and arranged in a straight line. (x 9,800) Neg. 472-8, sample BM51, Celtic Sea.

Fig.3 H.carteri, proximal view (x 7,400). Neg. 431-7, sample ES130, Clonakilty Bay.

Fig.4 H.carteri, distal view (x 21,500). Neg. 503-5, WF202, North Sea.

Fig.5 Braarudosphaera bigelowii, distal view (x 21,500). Neg. 447-7, BM11, Celtic Sea.

Fig.6 B.bigelowii, proximal view (x 10,500). Neg. 446-5, sample BM11.

Fig.7 B.bigelowii, proximal view (x 10,400). Neg. 446-7, sample BM11.

Fig.8 B.bigelowii, magnified view of the proximal surface shown in fig.7. Note the lamellar structure of the pentalith. (x 21,000). Neg. 446-8, sample BM11.



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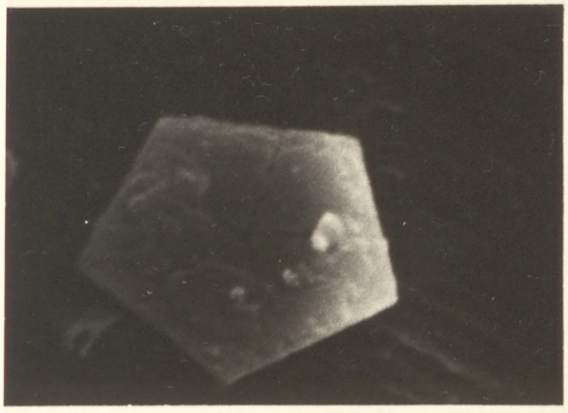
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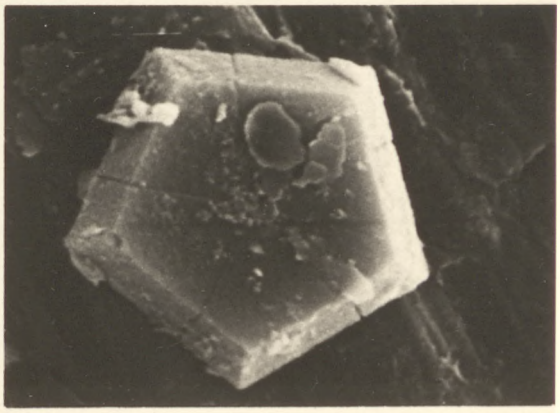
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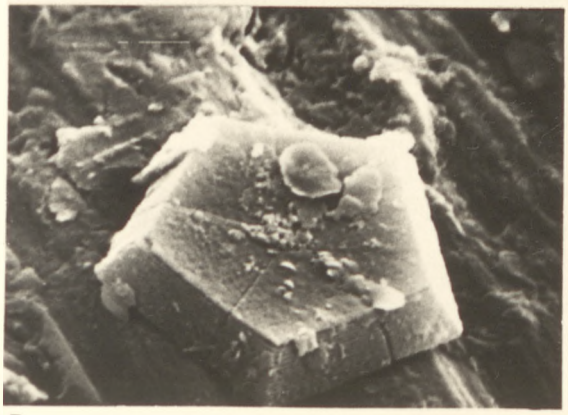
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PLATE 18

S.E.M. photomicrographs of Rhabdosphaera clavigera, Coronosphaera mediterranea and Syracosphaera pulchra.

Fig.1 Rhabdosphaera clavigera, side view (x 9,300). Neg. 488-1, sample BM 51, Celtic Sea.

Fig.2 Rhabdosphaera clavigera, side view (x 9,400). Neg. 452-4, sample BM 50, Celtic Sea.

Fig.3 R.clavigera, side view (x 11,000). Neg. 450-6, sample BM 50, Celtic Sea.

Fig.4 Coronosphaera mediterranea, oblique side view of helatoform caneolith. Note the large spine protruding from the base of the distal surface. (x 19,000). Neg. 447-1, sample BM 27, western English Channel.

Fig.5 Syracosphaera pulchra, distal view (x 14,800). Neg. 437-5, sample BM 50, Celtic Sea.

Fig.6 Coronosphaera mediterranea proximal view (x14,800). Neg. 504-4 sample WF 202, North Sea.

Fig.7 Syracosphaera pulchra, proximal view (x 9,600). Neg. 488-4, sample BM 51, Celtic Sea.

Fig.8 S.pulchra, proximal view, (x 14,800). Neg. 473-5, BM 51, Celtic Sea.



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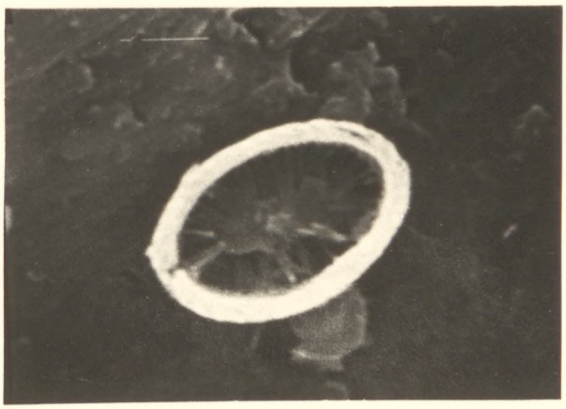
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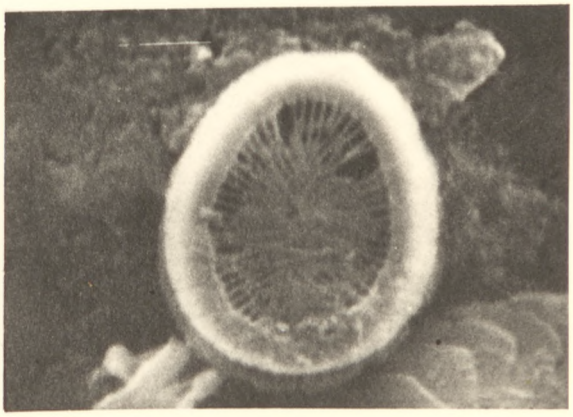
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PLATE 19

S.E.M. Photomicrographs of Umbilicosphaera spp., Scyphosphaera apsteinii and Pontosphaera messinae.

Fig.1 Umbilicosphaera sibogae var. foliosa, oblique distal view (x 9,600). Neg. 488-2, sample BM 51, Celtic Sea.

Fig.2 U.sibogae var. foliosa , distal view (x 11,000). Neg. 450-2, sample BM 50, Celtic Sea.

Fig.3 U.sibogae var. foliosa, oblique distal view (x 9,900). Small spines protrude into the central pore. Neg. 454-4, sample BM 51.

Fig.4 U.sibogae, distal view (x 14,000). Neg. 451-7, sample BM 50.

Fig.5 U.sibogae, distal view (x 14,800). Neg. 473-4, sample BM 51.

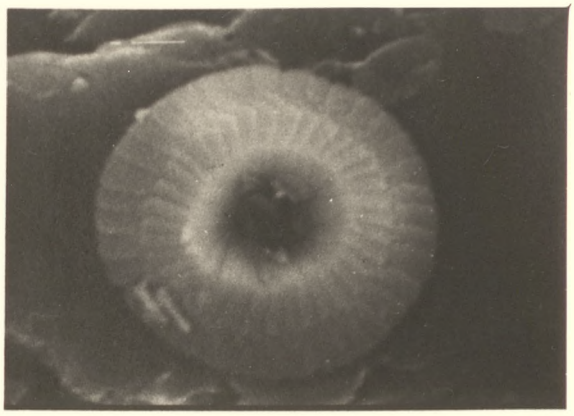
Fig.6 U.hulburtiana oblique distal view (x 15,000). Neg. 478-3, OC 40 , Rockall Bank.

Fig.7 Scyphosphaera apsteinii, proximal view (x 6,700). Neg. 488-7, sample BM 51.

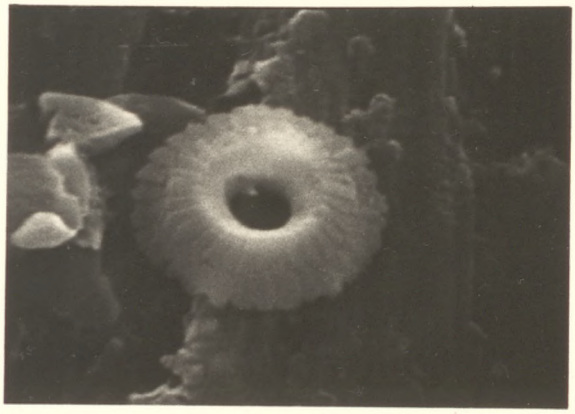
Fig.8 P.messinae proximal view (x 6,700). Neg. 451-8 sample BM 50.



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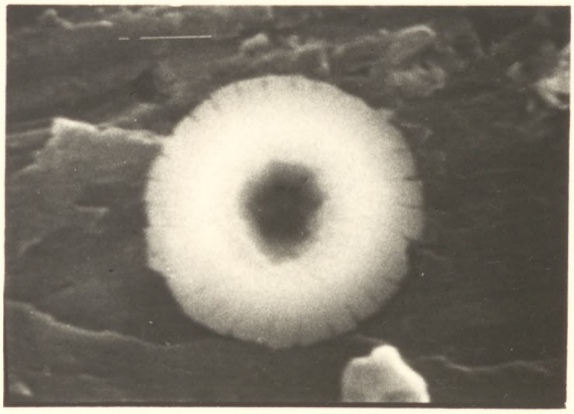
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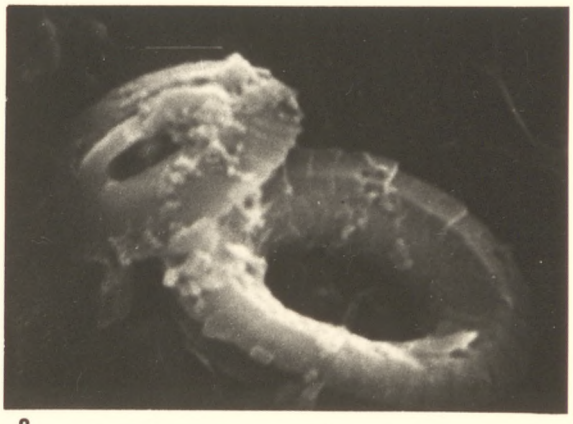
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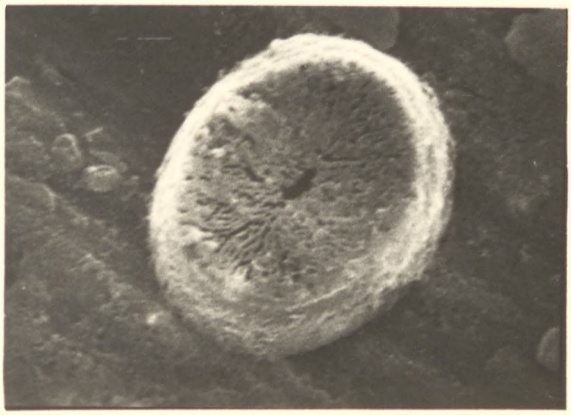
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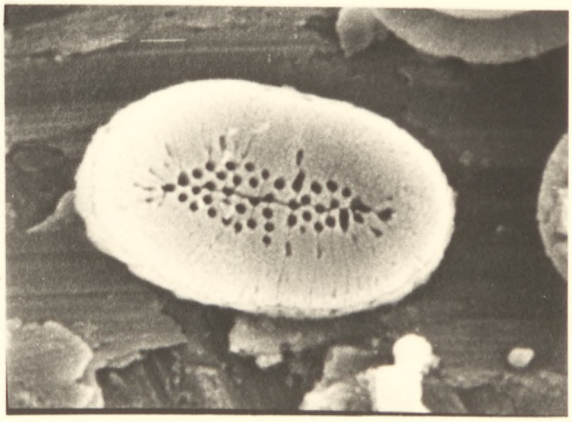
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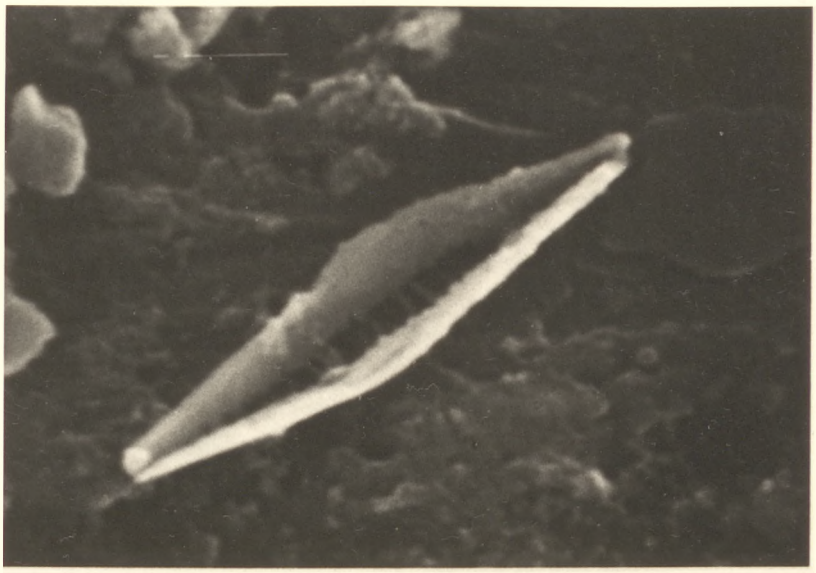
PLATE 20

S.E.M. photomicrographs of Scapholithus fossilis and Umbellosphaera tenuis. (All from sample BM 51, Celtic Sea).

Fig.1 Scapholithus fossilis, proximal view (x 14,900). Neg. 473-3.

Fig.2 Scapholithus fossilis, proximal view (x 14,900). Neg. 473-8.

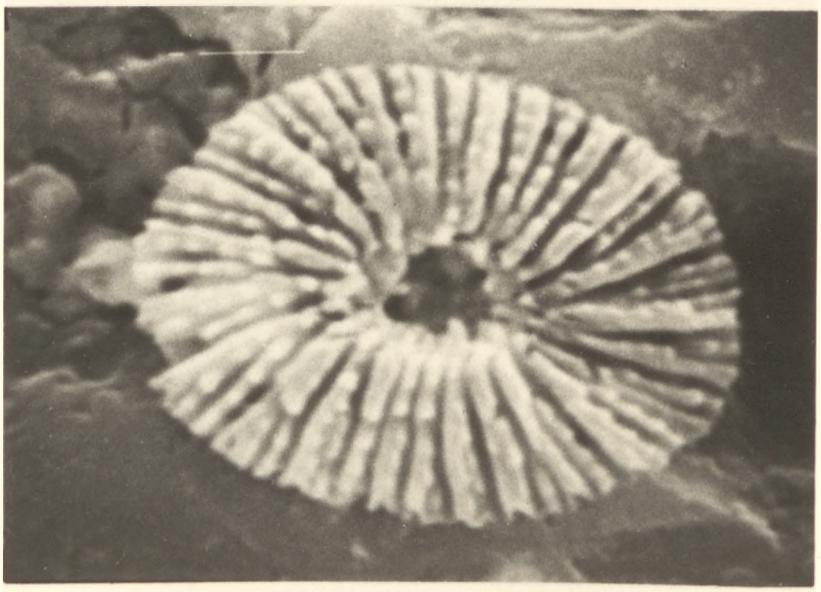
Fig.3 Umbellosphaera tenius, distal view (x 14,900). Neg. 473-8.



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PLATE 21.

Optical photomicrographs of Recent coccoliths from sample BM 51, western Celtic Sea. (All Figs. x1,600).

Figs. 1-2 *Coccolithus pelagicus*

Figs. 3,7 *Helicosphaera carteri*

Figs. 4-6 *Calcidiscus leptoporus*

Figs. 8-9 *Umbellosphaera tenuis*

Fig. 10 *Umbilicosphaera sibogae*

Fig. 11 *Umbilicosphaera sibogae* var. *foliosa*.

Fig. 12 *Gephyrocapsa oceanica*

Fig. 13-14,16 *Gephyrocapsa caribbeanica*

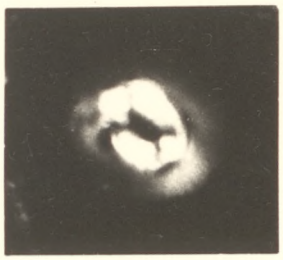
Fig. 15. *Ceratolithus cristatus*

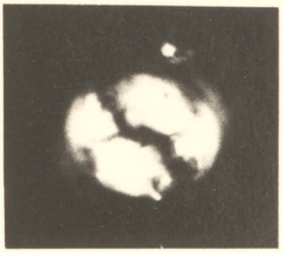
Figs. 17-19 *Syracosphaera pulchra*

Figs. 20-21 *Emiliania huxleyi*

Fig. 22 General view of coccolith debris.

Fig. 23 *Syracosphaera histrica*.


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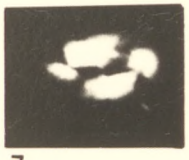

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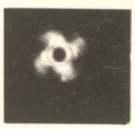

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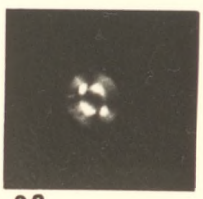

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PLATE. 22

S.E.M. photomicrographs of motile dinoflagellate thecae from filter sample 200-3, North Sea.

Fig.1 *Dinophysis acuta* Ehrenberg (x 720). Neg.496-5.

Fig.2 *D.acuta* (x 1,100). Neg. 496-4.

Fig.3 Oblique view of a *Protoperidinium* sp. (x 1,400). Neg.497-5.

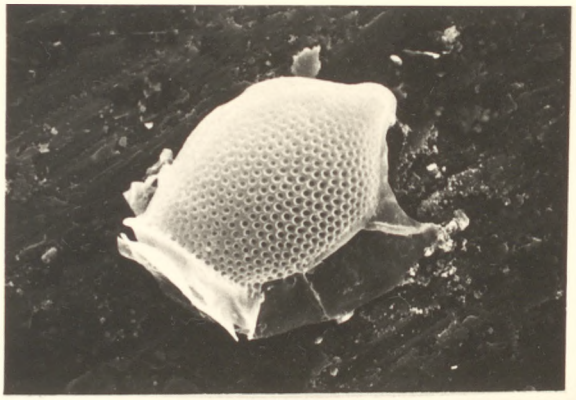
Fig.4 View of a *Protoperidinium* sp. showing an apical horn, crenulated girdle margin and recticulate ornament of plates (x 730). Neg. 497-8.

Fig.5 *Ceratium tripos* (Muller) Nitzch, theca with long spines (x 350). Neg. 497-5.

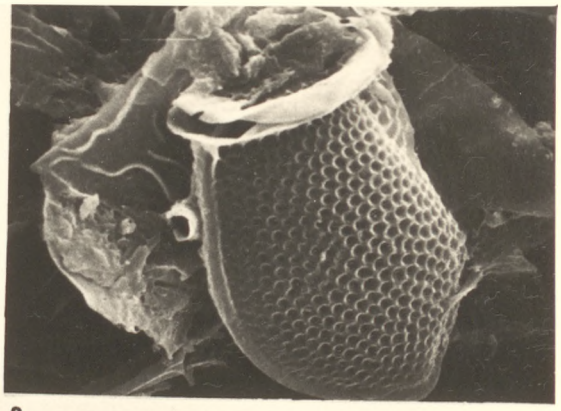
Fig.6 Broken spined-theca of *Ceratium tripos* (x 490). Neg. 496-6.

Fig.7 View of *Ceratium tripos* thecae and a *Protoperidinium* sp. (x 200). Neg. 496-8.

Fig.8 Aggregate of *Ceratium* spp. spines (x 200). Neg. 497-7.



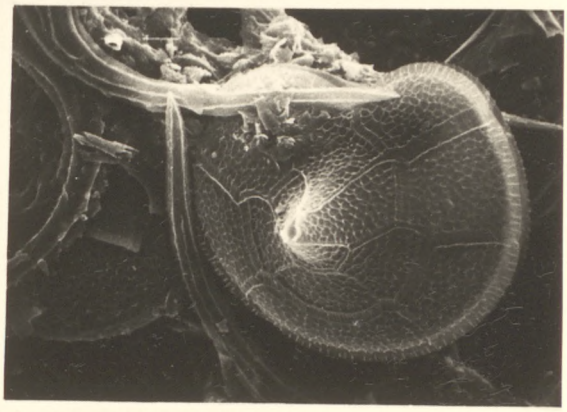
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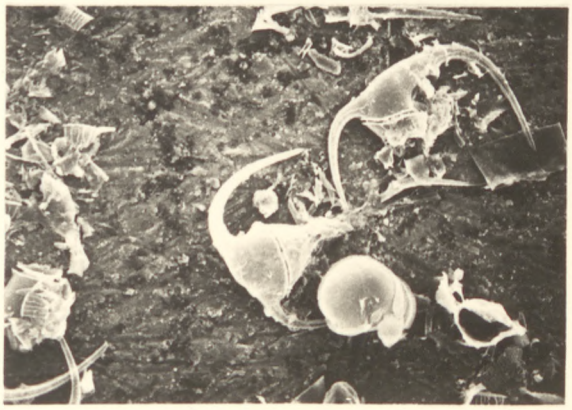
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PLATE 23.

S.E.M. photomicrographs of various plankton groups.

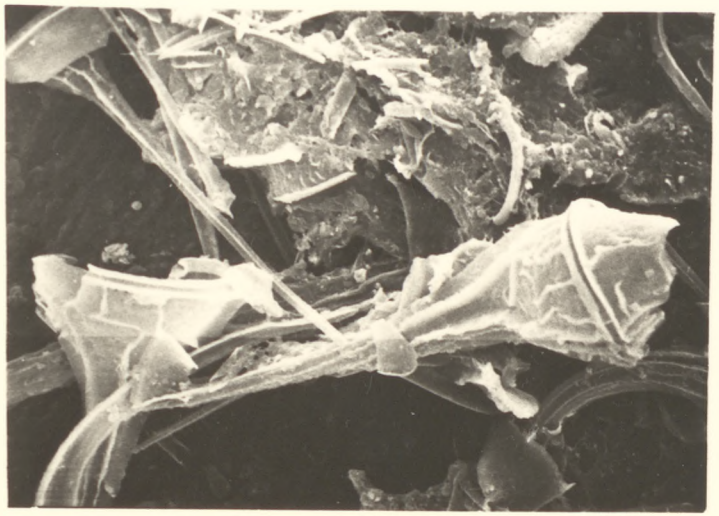
Scale bar = 10 um.

Fig.1 Ceratium furca (Ehrenberg) Claparede and Lachmann (x500). Neg. 497-6, filter sample 200-3, North Sea.

Fig.2 Aggregate of Ceratium spines (x 730). Neg. 496-4, filter sample 200-3, North Sea.

Fig.3 Actinoptychus senarius Ehrenberg (x 1,300). Neg.278-7, ES 169, Barmouth Estuary.

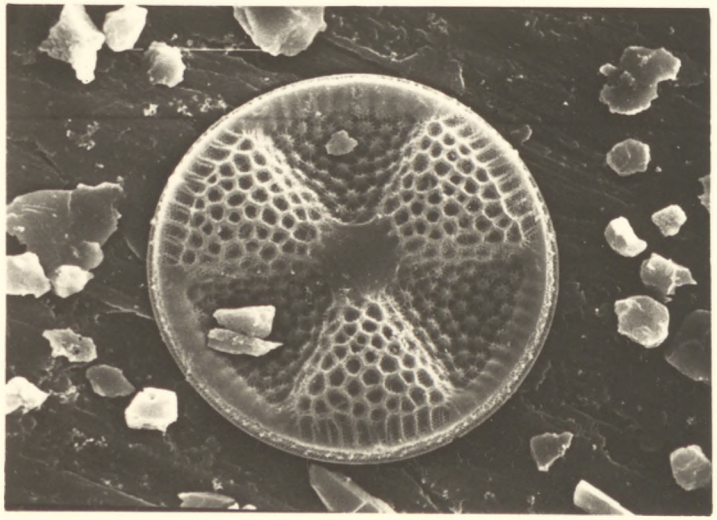
Fig.4 Skeleton of the silicoflagellate Distephanus speculum (Ehrenberg) Haeckel (x 2900). Neg. 447-4, JM 29, Forties Field (North Sea).



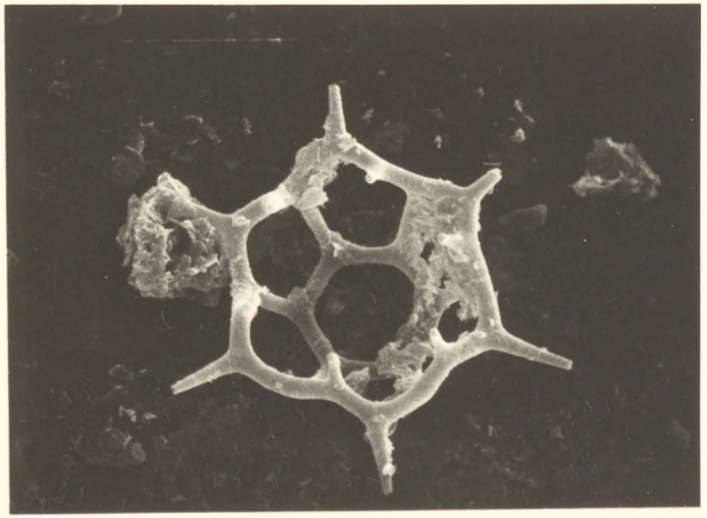
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CHAPTER 8

DISCUSSION

8.1 Comparison with Atlantic Ocean and other described coccolithophore assemblages.

The ecology and distribution of coccolithophores in the Atlantic Ocean have been the subject of extensive qualitative studies. There is less data describing the quantitative abundance of coccoliths, particularly in the bottom-sediments. Coccolithophore abundances in plankton samples are usually given as cells per unit volume of filtered seawater or as relative percentages (Hulburt,1964; McIntyre and Be',1967). This data is often difficult to interpret because of seasonal variations in the phytoplankton communities.

The first extensive biogeographical survey of coccoliths in the waters and sediments of the Atlantic was recorded by McIntyre and Be' (1967). These authors delineated five floral zones, based on the coccolith assemblages, termed tropical, subtropical, transitional, subarctic and subantarctic (Fig.8.1). Boundaries of these zones in the sediments paralleled those of living coccolithophore assemblages although warm-water species tended to have a wider distribution in the waters, than in the sediments. The Celtic Sea and the other shelf waters of northwest Europe lie in the transitional zone of McIntyre and Be' (1967). This zone should have coccolith assemblages marked by an increase in dominance of the placoliths Gephyrocapsa ericsonii, Emiliania huxleyi, Calcidiscus leptoporus, and in the colder waters of Coccolithus pelagicus. These general charactertistics of the transitional zone are reflected in the coccolith assemblages of the European shelf, although G.ericsonii is scarce (<0.5%) and Emiliania huxleyi is particularly dominant.

Geitzenauer et al. (1977) recorded the coccolith assemblages in North Atlantic and Pacific

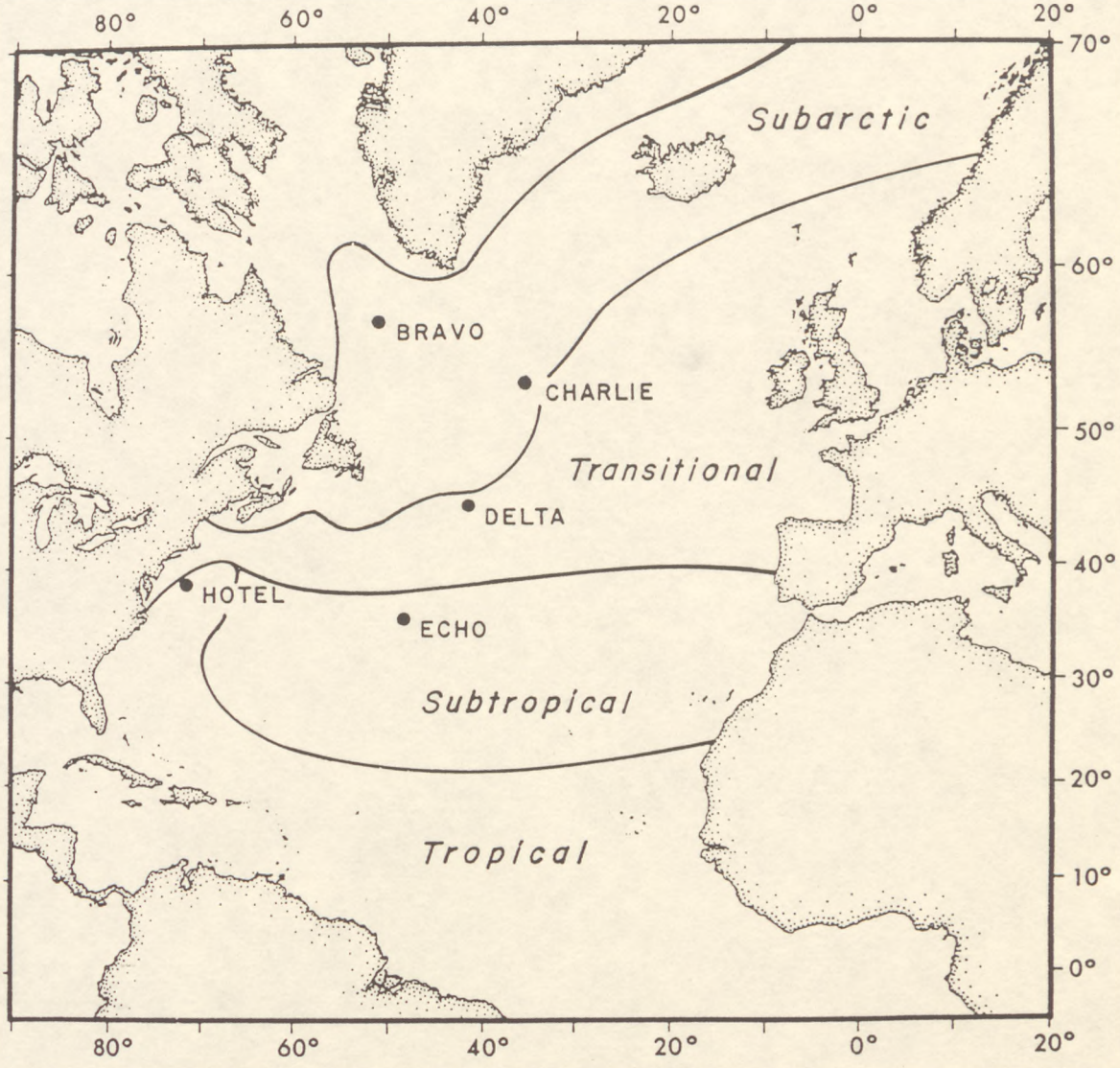


Figure 8.1
Map showing sample localities of Okada and McIntyre (1977) and distribution of coccolithophore floral zones in the North Atlantic (after McIntyre and Be', 1967).

bottom-sediments. These authors did not list the species composition of individual samples, but presented contour maps showing the variations in relative abundance of the more common species in both oceans. Many of the species had distributions extending throughout wide areas of the North Atlantic, but peak abundances were limited to much smaller domains. Okada and McIntyre (1979) studied the seasonal distribution of coccolithophores in the western North Atlantic. They recorded the standing crop and floral assemblages at five weather stations (Fig.8.1). Stations Delta in the transitional zone and Charlie in the subarctic zone occur in waters that have annual temperature ranges similar to those found in the northwest European shelf seas.

The annual mean composition of the coccolithophore assemblages at the stations were presented by Okada and McIntyre for surface (surface and 20m levels combined) and 100m levels. Both 'surface water' and 100m level coccolithophore assemblages are combined here. Such values should be more representative of coccolith assemblages present in the bottom-sediments, rather than a mean value for a specific level in the water column. The data recorded by Okada and McIntyre, together with the mean relative abundance of coccolith species in the slope and shelf sediments from the Celtic Sea and western English Channel and the North Sea are listed in Table 8.1.

The distribution and the abundance of coccolith species in the Atlantic and the other oceans, and their relation to the coccolith assemblages in the Recent sediments of northwest Europe will now be discussed. Particular emphasis will be placed on the correlation of the assemblages recorded here with those present in the North Atlantic. If a species is scarce or absent in the North Atlantic, reference to its occurrence in other waters will be discussed in more detail.

Table 8.1 Average composition (% of total flora) in shelf and slope sediments from northwest Europe and plankton assemblages at the weather stations Charlie and Delta.

			CELTIC SEA		
	CHARLIE	DELTA	SLOPE	SHELF	NORTH SEA
B. bigelowii	-	-	-	0.4	0.1
C. cristatus	-	-	P	-	-
C. pelagicus	14.5	R	0.4	3.1	2.0
C. mediterranea	7.1	0.5	P	P	P
C. leptoporus	1.6	1.7	11.9	0.4	0.7
D. tubifera	-	R	P	0.1	P
E. huxleyi	67.9	69.7	67.0	91.5	93.5
G. caribbeanica	R	2.5	20.0	0.9	1.1
G. oceanica	R	1.1	P	P	-
G. ericsonii	-	2.6	P	P	-
H. carteri	0.2	0.6	P	0.2	0.1
P. discopora	-	-	-	P	P
P. messinae	-	-	P	-	-
R. clavigera	0.5	R	P	0.1	0.2
S. histrica	-	-	P	P	-
S. nodosa	0.4	R	P	P	-
S. pulchra	R	0.7	0.7	3.3	2.2
Sc. fossilis	-	-	P	-	-
S. apsteinii	-	-	P	P	-
U. tenuis	-	-	P	-	-
U. hulburtiana	-	1.2	P	P	-
U. sibogae	-	R	P	P	-
Floral zone	S.art.	Tran.	Tran.	Tran.	Tran.
Temperature°C	5-13	13-22	6-18	6-17	6-14
Sample	Plank.	Plank.	Sed.	Sed.	Sed.

P = <0.1% R = 0.5%
S. art = subarctic Tran. = transitional Plank. = plankton
Sed. = sediment.

Data from weather stations compiled from Okada and McIntyre (1979).

Braarudosphaera bigelowii

Gaarder (1954) has described the occurrence of B.bigelowii within plankton samples from the North Atlantic. She found the species distributed along the southwest coast of Ireland, off the Azores and on the border of the Sargasso Sea. Lecal-Schlauder (1949) also recorded B.bigelowii in plankton samples from the coast off Morocco. She thought the species to be a typical Atlantic form (1949,p.162). The species is reported to be limited to the transitional zone of the Pacific (Okada and McIntyre,1979).

Other records of the species occurrence in the southern hemisphere are in the Great Barrier Reef-Coral Sea region (Conley,1979), East China Sea (Wang and Sambtleban,1983), South China Sea (Chen and Sheih,1982), and in the Bay of Bengal (Guptha,1981). All these occurrences were reported from shallow waters from marginal seas, and shelf environments (subtropical to transitional zone sediments). B.bigelowii is consistently recorded from the shelf sediments of the Celtic Sea and English Channel (mean 0.5%). Its adaption to near-shore environments is reflected by the species occurrence in waters at the eastern margin of the English Channel.

Calcidiscus leptoporus

Calcidiscus leptoporus is distributed throughout the North Atlantic, the Caribbean and the Gulf of Mexico (Gietzenauer et al.,1977). The species is found from the subantarctic through to the subarctic, an area encompassed by the 2°C isotherm (McIntyre and Be',1967). The species is therefore eurythermal, although Hasle (1960) and Geitzenauer et al. (1977) have reported it to be more abundant in equatorial assemblages.

Abundances of the species in North Atlantic sediments between latitudes 43°and 50°N, range 7 to 13,5% (McIntyre et al., 1967). Similar values occur in the

slope sediments studied here. A sharp decline in the species abundance occurs across the shelf-break, as abundances in shelf assemblages average only 0.5% . This distribution is further confirmed in the subordinate species counts. Wang and Samtleban (1982) have documented a similar depth-controlled abundance of C.leptoporus (var. A+B) in sediments from the East China Sea. The species formed 1 to 5% of assemblages deposited at depths between 115 and 1500m, but was scarce (<1.0%) or absent in shallow-water assemblages (<100m).

Ceratolithus cristatus

The biogeographical distribution of this species in the Atlantic is not well documented. In the Pacific, however, the species is most common in temperate waters of moderate phosphate content off the Southern California coast and on the East Pacific Rise (at about latitude 10° S) (Roth and Coulbourne, 1982). C.cristatus is reported to be occasional to common at the weather stations Delta, Echo, and Hotel in the North Atlantic (Okada and McIntyre,1977). Its occurrence in slope sediments at the western margin of the Celtic Sea is the most northerly reported for the species in the Atlantic. Although the species is thought to occur more frequently in coastal waters than in deeper waters, the species is not recorded in the shelf sediments studied here.

Coccolithus pelagicus.

Coccolithus pelagicus is commonly regarded to be a cold-water species. It was originally thought to be restricted to the North Atlantic and North Pacific at temperatures between 6°and 14°C, with maximum abundances between 9°and 12°C (McIntyre and Be',1967; McIntyre et al.,1970). Braarud (1979) however, extended the temperature range of the species to include sub-zero temperatures. Braarud found C.pelagicus in an area of pack-ice in the East Greenland Polar Current in the Denmar Strait, between Iceland and Greenland, at temperatures as

low as -1.7°C.

In the North Atlantic the maximum southerly distribution of the species is drawn at the position of the 14°C isotherm, lying at about 40°N during the winter (McIntyre and Be',1967). There is little quantitative data describing the species occurrence in sediments from the North Atlantic. Geitzenauer et al. (1977) found the species restricted to the subarctic zone, but absent from the transitional zone. It occurred in the southern Labrador Sea, across the southern border of the Norwegian Sea and along the coast of Norway. These abundances, to the northwest of Britain, generally varied between 0 and 35% . C.pelagicus was reported in plankton samples from the Delta weather station (<0.2%). Similar low abundances (<1.0%) were also reported from several plankton samples in the North Atlantic by McIntyre and Be'. Further occurrences of the species have been found in the cold waters off Newfoundland and Shetland (Gaarder,1954). Its distribution was mainly limited to coastal waters.

Milliman (1980) found that coccospheres of C.pelagicus dominated plankton samples of surface and near-surface waters on Rockall Bank (Lat. 57° N). Adjacent water samples from the Rockall trough, however, contained almost exclusively diatom frustules; coccolithophores were extremely scarce. Abundances of C.pelagicus in the bank waters exceeded 10^6 coccoliths per litre of water; such values are 1 to 3 orders of magnitude greater than normally expected in the North Atlantic.

Two sediment samples have been studied from Rockall Bank, OC 35 (57°46.09'N, 13°49.69'W) and OC 40 (57°36.6'N, 14° 29.1'W). The coccolith assemblages from the Bank are dominated by C.pelagicus (42 to 47%) and E.huxleyi (49 to 55%). Sample 40, contains 5,500 $\times 10^5$ coccoliths per gram of coccolithus pelagicus. This abundance reflects an order of magnitude greater than the mean abundance of the species in the Celtic Sea. These large quantitative and

relative abundances of the species, though, are not typical for the northeastern Atlantic; they reflect the favourable conditions for coccolith growth produced by upwelling on the shallower portions of the Bank (Milliman,1980).

C.pelagicus is recorded to be either absent or scarce in the deep, warmer waters of the transitional zone. The species is also scarce at the western margin of the Celtic Sea (mean 0.8%). The abundance of the species increases across the shelf-break, reaching a maximum of 6% in the Celtic Sea. C.pelagicus is one of the few species to occur in higher numbers in near-shore waters. The species thrives in the cold, shallow-water environments of the eastern North Atlantic, such as the Celtic Sea and, in particular, the Rockall Bank. In deeper waters at the same latitude, however, the species is scarce or absent.

Coronosphaera mediterranea

The biogeographical distribution of this species in the Atlantic and Pacific oceans is poorly known. Coronosphaera mediterranea has a reported temperature range of between 2°and 29°C in the Atlantic (Okada and McIntyre,1977), so it should be widely distributed.

The species is reported as a minor component (<1.0%) of coccolith assemblages deposited in the marginal sea environments of the Red Sea (Winter,1982), the Great Barrier Reef-Coral Sea region (Conley,1979) and in the East China Sea (Chen and Sheih,1982). Hallegraeff (1984) reported the species to have a cosmopolitan distribution in Australian coastal waters; it occurred in the Coral Sea, the Gulf of Carpentaria and in the East Australian Current. The species only formed a minor component of the assemblages in the Australian waters and accounted for less than 10^4 cells per litre. C.mediterranea is also scarce (<1.0%)in the shelf assemblages of the Celtic Sea, western English Channel and in the North Sea.

Coronosphaera mediterranea is a eurythermal species

and is probably a widespread, but minor component in oceanic and shelf sediments. The species shows no preference for either environment.

Discosphaera tubifera

D.tubifera has low abundances throughout the North Atlantic, occurring in the central North Atlantic as far north as 60°N. Peak abundances of the species occur in the region east of the Greater Antilles (2 to 2.5%) (Geitzenauer et al.,1977). The temperature range of the species is reported to be between 14°and 30°C, although it is rare in transitional zone waters (<0.2%) (Okada and McIntyre,1979). D.tubifera is also scarce in the shelf sediments of the Celtic Sea and North Sea (<0.5%). The area lies near the northern limit of the species distribution in the North Atlantic

Emiliania huxleyi.

E.huxleyi is ubiquitous in sediments from the Celtic Sea, western English Channel, Irish Sea and from the northern North Sea. It dominates the assemblages and forms up to 97.5% of the total flora. McIntyre and Be' (1967) reported that E.huxleyi has the greatest biogeographical range of all coccoliths in the North Atlantic. Except in tropical waters, the species averages 50% ; this rises to 100% in subpolar seas. The species has an unusually wide temperature and salinity tolerance. According to Paasche (1968), E.huxleyi grew in laboratory cultures at temperatures ranging between 7°and 27°C, while optimum growth occurred at 20 to 23° C. In the North Atlantic, however, the species has been found in waters at temperatures as low as 1°C (Okada and McIntyre,1979). The species reproduces at all seasons in temperate and warm seas, but at high latitudes populations are probably replenished yearly, from warmer waters.

As mentioned in section 3.3.2.2 E.huxleyi has two distinct ecophenotypes, a cold-water form and a warm-water

form, although a series of transitional forms also occur. The cold-water form usually dominates in assemblages north of 30°N latitude. E.huxleyi assemblages in sediments from northwest Europe, as expected from the northern latitude of the shelf (48° to 61° N), are dominated by the cold-water form and transitional forms. The warm-water form is always subordinate and only occurs in sediments from the Celtic Sea. Geitzenauer et al. (1977) reported that the warm-water form occurred in assemblages in the Atlantic as far north as 43°N. The occurrence of this form in the Celtic Sea therefore extends the reported distribution of this ecophenotype in the Atlantic.

E.huxleyi comprised 40.0 to 66.6% of coccolith assemblages deposited in the transitional zone of the North Atlantic (Geitzenauer et al.,1977). Similar concentrations of the species also occurred in plankton samples from the weather stations Delta and Charlie (Okada and McIntyre,1979). The abundance of the species in continental slope sediments at the western margin of the Celtic Sea averages 67%, a typical transitional zone value. A sharp increase in the species abundance occurs across the shelf-break. In shallower shelf waters (<200m), E.huxleyi usually forms over 90% of the nannoflora. E.huxleyi is therefore the species that is best adapted to the shelf environments of northwest Europe.

Gephyrocapsa caribbeanica.

Gephyrocapsa caribbeanica is a cold-water species, with highest abundances recorded from the transitional zone (McIntyre and Be',1967). It is the most cosmopolitan of the Gephyrocapsa species, ranging from tropical to subpolar seas (5° to 21° C) (Okada and McIntyre, 1979). Typical abundances of G.caribbeanica in the transitional zone were reported to range between 8 and 28% (Gietzenauer et al., 1977). Similar abundances occur in slope sediments at the western margin of the Celtic Sea (20%). The species abundance, however declines to around 1.0% (range 0 to 4%) throughout the shelf of northwest Europe.

G.caribbeanica prefers the cool, deeper waters of the northeast Atlantic and has no significant adaption to shelf seas.

Gephyrocapsa ericsonii.

Little quantitative data has been published on the distribution of this species in the North Atlantic. The species is thought by McIntyre and Be' (1967) to be characteristic of the transitional zone , south of latitude 55°N. The maximum abundance of this species in the North Atlantic sediments is reported to be 16% (Geitzenauer et al.,1977). The species ,though, was generally so scarce in the sediments that no biogeographical range could be determined. Okada and McIntyre (1979) reported the species formed 2.6% of the annual coccolith flora at the Delta weather station. They also showed that the temperature range of the species was between 12°and 30°C.

G.ericsonii is a wide-ranging species, occurring throughout tropical to transitional waters in the Atlantic. Because of its scarcity, no environmental preference has been determined. G.ericsonii is also very scarce in the Celtic Sea; this suggests no preference of the species for shelf environments.

Gephyrocapsa oceanica

Gephyrocapsa oceanica is a warm-water species with a maximum temperature range in the Atlantic of between 12° and 30°C (Okada and McIntyre, 1979). In the Pacific, the species is reported to be a common component of coccolith assemblages deposited by warm waters of high to moderate fertility (Roth and Coulbourne,1982), being most abundant in the tropical Pacific, between latitudes 10°S and 10° N (>35%). Highest abundances in the Atlantic occur in the equatorial region (20 to 43 %) (Geitzenauer et al.,1977). The species was scarce or missing from transitional zone

sediments. Okada and McIntyre , however, have recorded G.oceanica in plankton samples at the Delta weather station in the transitional zone, where it formed 1.2% of the mean coccolithophore flora.

Gephyrocapsa oceanica is scarce (<1.0%) in slope and shelf sediments studied here. It was only reported from the Celtic Sea. The scarcity of G.oceanica is a reflection of the northern latitude of the study area

Helicosphaera carteri

According to Geitzenauer et al. (1977) , the distribution of Helicosphaera carteri extended across the equatorial Atlantic into the Caribbean, the Sargasso Sea and in low numbers in the northern central Atlantic. The species was generally absent from transitional zone sediments. H.carteri formed 0.6% of the annual, mean coccolithophore flora at the Delta weather station (Okada and McIntyre,1979). The species was also consistently recorded in low numbers from Holocene sediments, cored by the D.S.D.P. in the transitional zone. It occurred at sites 401, 548, and 549 on the Goban Spur, the northern margin of the Rockall Bank, and also near the Mid-Atlantic Ridge (45° N latitude) (Muller,1985; Pujois,1985; Steinmetz, 1985).

The scarcity of this species in the eastern North Atlantic is reflected in its abundance in slope and shelf sediments from the Celtic Sea and North Sea (mean 0.5%).

Pontosphaera discopora

Pontosphaera discopora was not recorded in plankton samples from the Pacific Ocean and was a scarce component of samples from the Delta weather station in the transitional zone of the North Atlantic (Okada and McInyre,1977). The species was found to be a minor component ($<10^4$cells/l) in the warm-core eddies of the East Australian Current in the Tasman Sea

(Hallegraeff,1984). P.discopora was also a minor component (<0.3%) in the shelf assemblages from northwest Europe, occurring in the Celtic Sea and the North Sea area. The environmental prference of this species has not been determined.

Pontosphaera messinae

The biogeographical distribution of Pontosphaera messinae is not well documented. The species was not recorded in the coccolithophore survey of Okada and McIntyre (1977) from the North Atlantic and the Pacific. P.messinae is reported to be very scarce in the surface sediments of the Pacific (Roth and Coulbourn,1982). The species occurs in the Alboran Sea, the western part of the Mediterranean Sea (Bartolini,1970). P.messinae was only recorded from slope sediments at the western margin of the Celtic Sea in this report. The environmental preference of P.messinae has not been determined.

Rhabdosphaera clavigera

Geitzenauer et al. (1977) report that R.clavigera is not found in significant numbers north of 45°N in the North Atlantic. Its range is recorded to extend from the central equatorial Atlantic into the Caribbean and across the North Atlantic south of 50 N. The species has been found living in waters at temperatures between 3°and 29°C, but the species was very scarce in transitional and subtropical plankton samples (0.2%) (Okada and McIntyre, 1979). R.clavigera is scarce (<0.5%) from the area studied, as expected from the northern latitude of the shelf.

Scapholithus fossilis

Because only isolated scapholiths rather than coccospheres are found in the sediments, separation of these scapholiths into the genera Calciosolenia Gran and Anoploselenia Deflandre is not possible. The genus

Scapholithus is used for all scapholiths here.

The scapholiths may represent Calciosolenia sinuosa Schlauder, as this is the most common scapholith in the North Atlantic

Scyphosphaera apsteinii

Scyphosphaera apsteinii is reported to be very scarce in Recent Pacific sediments (Roth and Coulbourne,1982). In the Atlantic, the species has only been commonly recorded from the tropical zone. S.apsteinii occurs in submarex cores from the Nicaragua Rise in the Caribbean Sea (Boudreaux and Hay, 1969). It was reported to be common in green faecal pellets caught in a sediment trap array deployed in the Sargasso Sea (Honjo,1978). The species also occurred in the Gulf of Mexico and in the Bahamas (Gaarder and Hasle ,1971; Wood,1968). In the eastern tropical Atlantic, the species occurs in sediments from the inner Cape Verde Basin (Muller and Roth, 1975). No occurrence of the species in either the plankton or sediments, has been noted further north in the Atlantic. S.apsteinii occurs in sediements from the Celtic Sea and also in filter samples from the northern North Sea. Its biogeographical distribution is extended to about 60° N latitude; the species therefore occurs in tropical to transitional zone sediments from the North Atlantic.

Syracosphaera histrica

The distribution of Syracosphaera histrica is poorly known in the North Atlantic. Boudreaux and Hay (1969) found the species occurred in deep-sea cores from the Caribbean. It has been reported living in the Adriatic (Cohen,1965). The distribution of the species is better documented in the Pacific Ocean. It is most abundant (>3.0%) in coccolith assemblages deposited by the warm and nutrient-poor waters of the Central Water Mass (Roth and Coulbourne, 1982). S.histrica has also been reported in

shelf sediments from the South China Sea (Chen and Sheih,1982). The species is absent from plankton samples recorded at the Delta weather station and its occurrence in the Celtic Sea (<0.5%) is the most northerly record of the species in the Atlantic.

Syracosphaera nodosa

S.nodosa has a reported temperature range of 2° to 26° C (Okada and McIntyre,1979). It is a scarce constituent of coccolithophore assemblages at the Delta weather station (<0.2%). There are no other reported occurrences of the species in the Atlantic in either plankton or sediment samples. Small numbers of the species (<1.0%) occur in sediments from the Sundra shelf, South China Sea (Chen and Sheih,1982). S.nodosa is very scarce in the Celtic Sea sediments (<0.3%) and is not recorded from the North Sea or Irish Sea.

Syracosphaera pulchra.

Syracosphaera pulchra occurs in low numbers throughout the North Atlantic basin. Typical transitional zone abundances range from 0.2 to 2.5% (Gietzenauer et al., 1977). Peak values (5.4 to 8.0%) occur along the mid-Atlantic Ridge. S.pulchra was also reported to be scarce in the Pacific (<4.0%), prefering tropical and nutrient-poor subtropical waters (Roth and Coulbourn,1982). The greatest abundances of the species were observed in an arc across the western and central Pacific Rise, between latitudes 10°and 22°N, and on the East Pacific Rise at 10°S . The mean abundance of the species in sediments from the Celtic Sea and Western English Channel is 3.8%, whereas it averages 2.2% in northern North Sea sediments. No pronounced increase or decrease in the species abundance occurs in the shelf sediments of northwest Europe when compared with oceanic sediments.

Umbellosphaera tenuis

Umbellosphaera tenuis occurs in sediments from the equatorial Atlantic , Caribbean Sea, Gulf of Mexico and throughout the central North Atlantic as far north as 51° N latitude (Geitzenauer et al.,1977). The species is scarce and limited to nutrient-poor waters of the tropical west and central North Pacific (Roth and Coulbourne,1982). According to Okada and McIntyre (1979), the species is found in waters at temperatures of between 13° and 28° C. In the transitional zone of the North Atlantic U.tenuis is scarce (0.4 to 1.4%). McIntyre and Be' (1967) also reported similar values (1% or less) for the species in temperate latitudes of the North Atlantic (43°to 49°N).

U.tenuis occurs at the southwestern margin of the Celtic Sea (<0.5%) and is absent from the shelf regions. The Celtic Sea lies near the northern biogeographical limit of the species in the Atlantic.

Umbilicosphaera hulburtina

U.hulburtiana has low abundances in the equatorial Atlantic, the Caribbean Sea, Gulf of Mexico and in the central North Atlantic as far north as as 53° N (Geitzenauer et al.,1977). Peak abundances of the species occurred in the tropical and subtropical zones of the North Atlantic (1.8 to 2.2 %). Lower abundances (<0.8%) characterise sediments from the transitional zone. Okada and McIntyre (1979) reported that the temperature range of the species is between 13°and 30°C and that it comprised 1.2% of the nannoflora at the Delta weather station. The scarcity of the species throughout the northeast Atlantic is reflected by its abundance in sediments from the Celtic Sea (<0.25%)

Umbilicosphaera sibogae

Umbilicosphaera sibogae occurs throughout the North Atlantic and in adjacent basins. Geitzenauer et al. (1977) recorded a cold-water variety with peak abundances

in the Sargasso Sea, and a warm-water variety with highest abundances in the equatorial Atlantic, southeastern North Atlantic and in the Caribbean Sea. In the Pacific , U.sibogae prefers moderately nutrient-rich, tropical waters, between latitudes 10° S and 20° N (Roth and Coulbourne,1982). North of 35°N the species is scarce, but, it is still recorded from samples at 50°N latitude.

Low abundances of U.sibogae (<3.5%) characterise transitional zone sediments of the North Atlantic (McIntyre and Be',1967; Geitzenauer et al., 1977). These authors, however, did not distinguish between U.sibogae var. sibogae and U.sibogae var. foliosa. Both forms have a temperature range of between 13° and 30° C and comprise <0.2% of the coccolithophore flora at the Delta weather station (Okada and McIntyre, 1979). Both forms are also recorded from shelf and slope sediments from the Celtic Sea. U.sibogae is more abundant in the slope sediments, where it forms up to 0.5% of the nannoflora. It is either very scarce (<0.25%) or absent in the shelf. The scarcity of the species in the study area may be explained by the species preference for warmer waters.

8.2. Characteristic features of continental shelf and marginal sea coccolith assemblages.

Okada and Honjo (1975) and Honjo (1977) have investigated the coccolithophore distribution in plankton samples from the Asian marginal seas such as the East China Sea, South China Sea, and the Sundra Shelf area of the Java Sea. These marginal sea floras differed greatly from the pelagic floras at the equivalent latitude in the Pacific (Okada,1973). From these studies it was concluded that coccolithophore assemblages in marginal seas are characterised by the following features:

1) a lower species diversity of coccolithophores occurs than is observed in the open-ocean,

2) placolith-bearing coccolithophores are dominant,

3) most coccolithophores bear malformed coccoliths,

4) the standing crop is considerably more aggregated in marginal sea facies than the open-ocean,

5) a sharp biological boundary exists between the open-ocean and the marginal sea,

6) E.huxleyi is generally scarce,

7) G.oceanica is dominant,

The extent to which these points are relevant for coccolith assemblages deposited in sediments from the continental shelf of northwest Europe and in other marginal sea environments will now be discussed.

Marginal seas are generally thought to be characterised by a lower species diversity of coccolithophores than in the open ocean. These differences between marginal seas and the open-oceans are not universally apparent when the number of species recorded in the surface sediments is used as a index of

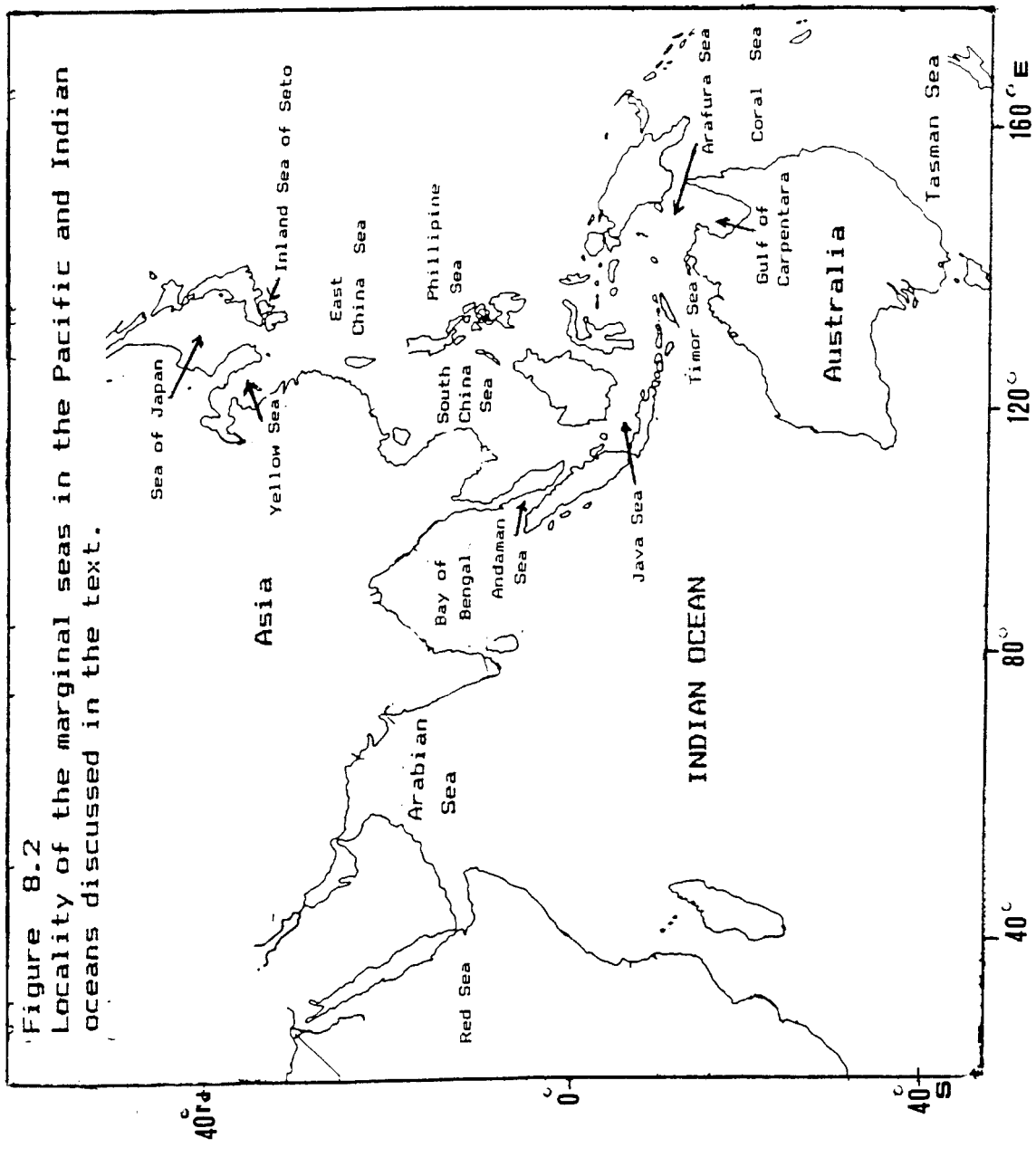


Figure 8.2
Locality of the marginal seas in the Pacific and Indian oceans discussed in the text.

species diversity. Eight or fewer species occur in the shelf sediments of the North Sea, Irish Sea and the Eastern English Channel, whereas eighteen species occur in sediments from the Celtic Sea and western English Channel. Such numbers of species are fairly typical of those found in oceanic sediments. Twenty-two species of coccolith are commonly found in the surface sediments of the North Atlantic and Pacific (Geitzenauer et al.,1977).

Higher numbers of species occur in shelf sediments in the marginal seas from the west Pacific: 28 to 35 species in the East China Sea (Chen, 1979; Wang and Samtleban, 1983), 38 species in the South China Sea (Chen and Shieh, 1982), 32 species in the Taiwan offshore region (Chen, 1980) and 59 species in the Great Barrier Reef-Coral Sea region (Conley, 1979). All the assemblages containing high numbers of coccolith species were deposited at low latitudes, generally north of 30°S. This increase in species number, when compared with the shelf of northwest Europe, is probably a reflection of the higher water temperatures (generally >20°C) that occur in these shallow Asian seas.

Shelf and marginal sea coccolith assemblages deposited at higher latitudes, contain fewer coccolith species: twelve species in the Tasman Sea (35°to 37°S latitude) (Burns,1975), eighteen species in the western Mediterranean (35°N) (Bartolini, 1970) and fifteen species from continental slope sediments off South Africa (33°to 35°N) (Seisser,1976). A similar decrease in numbers of species also occurs with latitude in the open-oceans (McIntyre and Be',1967; Burns, 1972). Marginal sea and shelf sediments, therefore, do not necessarily contain lower numbers of coccolith species when compared with oceanic deposits of a similar latitude. Despite the high species number in some marginal coccolith assemblages, these environments may be distinguished from the open ocean by a high dominance of one or two species generally the forms E.huxleyi and G.oceanica. Dominance values in surface sediments for the two most abundant species are

(<80%) in the North Atlantic (McIntyre and Be', 1967) and (40 to 80%) in the Western Pacific (Gietzenauer et al.,1977). Higher dominance values, however, may occur in subpolar and polar seas (Gietzenauer and Huddlestun,1973).

Dominance values of the two most abundant species are always high throughout marginal seas; >90% in the shelf of northwest Europe, >95% in the Great Barrier Reef region (Heckel,1973), >90% in the East China Sea (Wang and Samtleban,1983), and >80% in the shelf of the Tasman Sea and in the Gulf of Mexico (Burns,1975; Pierce and Hart,1979). High dominance values for the two most abundant species may therefore be regarded as a reliable indicator of a marginal sea environment.

The dominance of placolith-bearing coccolithophores in the living flora has been considered by Honjo (1977) as a characteristic feature of marginal seas. The mean placolith components for the shelf sediments recorded in this study are 97.4% for the Celtic Sea and western English Channel, 96.8% for the Irish Sea and 92.5% for the northern North Sea. A high dominance of placoliths therefore certainly characterises the shelf of northwest Europe.

Wang and Samtleban (1983) however, have pointed out that placoliths always predominate in coccolith assemblages deposited in the open oceans as well as in marginal seas. They suggest that the dominance of placoliths is not an indicator of shallow-water assemblages. More than 98% of placoliths occur in coccolith assemblages deposited at latitudes north of 40°N (McIntyre and Be',1967). Placoliths are the most resistant of all types of coccolith structure and their relative abundances are usually found to be greater in bottom sediments than in the overlying waters. Lower mean placolith values are found in plankton samples from the weather stations Charlie (84.0%) and Delta (79.5%) in the subarctic and transitional zones respectively of the North Atlantic (Okada and McIntyre, 1979). The dominance of

placoliths in coccolith assemblages decreases at lower latitudes. In bottom sediments from the Atlantic, deposited between 40° N and 2° S latitude, placoliths generally form between 80% and 98% of the assemblage. This decrease is caused by the increasing abundance of the forms Rhabdosphaera clavigera, Umbellosphaera tenuis and U.regularis in tropical and sub-tropical regions.

Similar dominance values occur in marginal sea sediments deposited at low latitudes: 88% in the Gulf of Mexico (Pierce and Hart, 1979), 75 to 95% in the South China Sea (Chen and Sheih, 1983), >85% in the Great Barrier Reef and >70 in the Coral Sea (Conley, 1979). The consistent dominance of placoliths in the shelf assemblages of northwest Europe is not a diagnostic feature of such assemblages, but is a general characteristic of coccolith assemblages preserved in bottom sediments .

Okada and Honjo (1975) regard the extensive occurrence of malformed coccoliths as one of the most significant features of assemblages in marginal seas. Malformation occurred in all species and took several different forms. High numbers of cells having malformed coccoliths (90-100 %) occurred in stations from the South and East China Seas. Coccoliths of Gephyrocapsa oceanica which made up 95% of the flora (sampled during October,1968) had an irregular bar, or lacked the central structure completely. Additionally, these coccoliths lacked a floor in the central opening and the elements of the shield were narrow and barely flush, rather than imbricated as in normal coccoliths. Similar malformed coccoliths of E.huxleyi cells had twisted elements of the distal shield and grill. Wang and Samtleban (1983), however, have pointed out that the nannoflora recorded by Okada and McIntyre is not typical for the East China Sea.

Nishida (1977) analysed another surface plankton sample (taken during the winter) and found E.huxleyi was more dominant (64%) and G.oceanica (21%) to be

subordinate in the assemblages. Additionally, no occurrence of malformed coccoliths was noted by Nishida. Malformed coccoliths are either extremely scarce or absent in the surface sediments of the East China Sea and South China Sea (Wang and Samtleban, 1983; Chen and Sheih, 1982). This general absence of malformed coccoliths in bottom sediments from an area where reported malformation is extensive in the overlying waters suggests that these coccoliths are susceptable to rapid dissolution and disintegration.

No malformed coccoliths were observed in any of the coccolith species preserved in the shelf sediments of northwest Europe. Some varations in the structure of certain coccoliths were noted (eg., E.huxleyi and C.leptoporus). These variations,however, were merely the occurrence of different ecophenotypes of the same species in the assemblages, or were related to dissolution effects. Malformed coccoliths have not been reported in surface sediment from other near-shore areas ; the suggestion of Wang and Samtleban (1983, p.257) therefore that malformation of coccoliths is not of palaeoecological significance is well-justified. The conclusion of Okada and McIntyre (1977) that most coccolithophores observed from marginal seas bear malformed coccoliths should therefore be rejected; it is probably only a local, seasonal feature.

One possible reason for the malformation of coccoliths is that very low concentrations of nutrient salts, caused by overcrowding, occurred during the coccolithophore blooms (Okada and Honjo,1975). No significant correlation of the malformation was observed with dissolved oxygen, ammonia and phosphate, but some relationship was suggested with nitrate levels less than 0.1 ug-atom/l, although the authors stated this was not conclusive.

Similar low nitrate levels (<0.1 uM/l) also occur in the northern Celtic Sea after spring diatom blooms

(Pingree, 1980). During these periods, coccolithophores are known to occur in the plankton. Malformation of coccoliths , however, has not been recorded in either plankton or sediments samples from the area. Coccolithophores require an exogenous source of one or more vitamins, particularly vitamin B1 (thiamin) and vitamin B12 (Cobalimin) (Tappan,1980). Perhaps a deficiency in one of these vitamins caused the malformation of the coccoliths in the Asian marginal seas.

Honjo (1977) concluded that the standing crop of coccolithophores is considerably more aggregated (ie., concentrated in small areas) in marginal sea facies than the open-sea facies. Similar results were obtained by Okada and Honjo (1975) who concluded that the coccolithophores in these marginal seas of the Western Pacific were highly concentrated compared to that of the open-ocean environment. Both horizontal and vertical distributions of the neritic populations were very sporadic. In the South China Sea, the distribution varied according to the distance from the mainland; the closer to the western and northern shores, the larger the population of the coccolithophores.

Wang and Samtleban (1983) suggest that any initial aggregated, sporadic distribution must be averaged with time, as no such results are recorded in the bottom sediments of the South China Sea. Additionally, the larger populations of coccolithophores close to the shore were not reflected in the sediments, because terriginous sediments dilute the coccoliths, causing a reduction in coccolith numbers towards the coast.

Little evidence of aggregated coccolith populations can be found in the surface sediments from the shelf of northwest Europe. One of the most notable features of these coccolith assemblages is their homogeneity, particularly in the outer shelf environments of the Celtic Sea and northern North Sea. In these outer shelf regions, coccolithophore populations have been reported over a

large area between 45°and 60°N latitude. Additionally, large populations of E.huxleyi were consistently recorded by Braarud et al., (1953) from a wide area of the northern and central North Sea.

Burns (1975) , however, found that within several adjacent slope and shelf sediments from the western Tasman Sea, the relative contributions of each species to the assemblages varied considerably, both in the number of specimens present and in the presence or absence of a particular species. Such variations in the consistency of coccolith assemblages from different shelf regions is probably a reflection of the differing environmental parameters of the regions. These variations, however, preclude the use of aggregated coccolith assemblages, as indicators of shelf and marginal sea sediments.

Apart from the results obtained from the plankton study of Okada and McIntyre (1975), coccolith abundances have been reported to decrease across shelf regions towards land. Coccolith abundance and numbers of species decrease in both plankton (Murray et al.,1983) and sediment samples, northwards and eastwards away from the open-oceanic conditions present in the southwest Celtic Sea. The landward decrease is most notable in the shallow waters of the English Channel. A similar decrease of coccolith numbers is also noted in the North Sea, where numbers decrease southwards away from the open-oceanic conditions found at the northern margin of the North Sea.

Marshall (1968) in a study of the nannoflora of the Sargasso Sea, found that the coccolithophores, together with dinoflagellates, dominated in waters of high salinity, whereas diatoms however, were more plentiful in coastal waters. The number of species of coccolithophores increased with distance offshore, with fewer dominant forms.

Burns (1975) recorded the abundance and species composition of nannofossil assemblages from continental

shelf to offshore, basinal sediments in the western Tasman Sea. Shelf sediments had extremely low numbers and few species Slope sediments had low coccolith numbers , which were slightly more diverse than shelf assemblages. Basinal sediments, however, contained abundant, diverse coccolith assemblages. Wang and Samtleban (1983) found that coccolith assemblages deposited at depths greater than 500 m in the East China Sea contained ten or more species; sediments deposited in shallower waters close to the coast, however, contained seven or fewer species.

Heckel (1973) found that the coccolith component in the fine fractions increased with distance from the coast in the Capricorn Basin of the Great Barrier Reef. Less than 2% coccoliths occurred in the coastal regions, where water depths were less than 40m. An area of more than 10% coccoliths occurred in sediments at depths in excess of 100m.

Futterer (1980) produced similar results in his study of sediments from the continental margin off northwest Africa (16° to 28°N lat.). He found that the greatest coccolith content of the silt fractions (10 to 20%) occurred in offshore sediments at depths in excess of 2000m. Lower values occurred along the inner shelf region (<5%) close to the continent. The decrease in coccolith abundance and numbers of species towards land may be regarded as one of the most characterisitic features of shelf and marginal sea sediments.

Honjo (1977) concluded that a sharp biological boundary exists between the open-ocean and marginal seas. This biological boundary was marked in the marginal seas of the Asian shelf by a sudden increase in the dominance of G.oceanica. Although no basinal sediments were analysed here , suitable data describing oceanic coccolith assemblages from the northeastern Atlantic may be compiled from the work of McIntyre and Be' (1967) and Geitzenauer et al. (1977). From these results it is apparent that oceanic assemblages typical of the eastern North Atlantic

are deposited in continental slope sediments (depth ~1200m) at the western margin of the Celtic Sea. Such oceanic sediments contain coccolith assemblages with a high species diversity; three species are dominant, E.huxleyi (66 to 68%), G.caribbeanica (20%) C.leptoporus (11.1 to 12.7%). A sharp biological boundary must occur near the break of slope at the 200m of water depth, as shelf assemblages throughout the Celtic Sea (<200m water depth) are distinctly different from the oceanic floras. These differences are mainly reflected in the abrupt increase in the dominance of E.huxleyi, which forms over 90% of the assemblages. Similar E.huxleyi-dominated assemblages also characterise sediments from the shelf regions west of Scotland and throughout the northern North Sea.

Satellite studies on coccolithophore production along the continental shelf-edge have also determined a sharp biological boundary (Holligan et al.,1983). Large blooms of E.huxleyi were recorded on the Celtic and Armorican shelf regions during April and May (1979) close to and inshore of the 200m contour; the outer limit of these blooms generally marks out the shelf-break boundary. Evidence from both plankton and sediment samples has shown that a biological boundary occurs in coccolith populations at the break of slope at the western margin of the continental shelf. Such a boundary, however, is not universal for shelf-slope environments.

Burns (1977) found that nannofossil abundance and species diversity increased considerably from shelf to basinal sediments in the Tasman Sea, although it is only in the outer rise sediments that the content and composition of coccolith species approaches that found in basinal sediments. Burns concluded that the nannofossil assemblages of the continental shelf and upper slope represented a sediment formed in and below a vastly different hydrological regime to that of the oceanic basins. The Tasman Sea, therefore, has a distinct biological boundary in the middle slope region.

Burns also noted that the large nannofossil species component (such as Coccolithus pelagicus, Calcidiscus leptoporus and Umbilicosphaera sibogae) increased considerably from shelf to basin. Shelf assemblages contained low proportions of these species (5 to 18%), slope sediments contained higher proportions (20 to 30%), whereas continental rise and oceanic basinal sediments contained the highest numbers (20 to 40%). A similar trend of increasing abundance of larger species occurs towards open oceanic conditions in the Celtic Sea. Shelf assemblages contain a mean of 3.1% large species whereas slope sediments contain a mean of 11.3% . Much larger values,however, are also found in the near-shore sediments of the English Channel where the coccolith assemblages are dominated by the species Coccolithus pelagicus (generally >25%). A low percentage of large coccolith species is not necessarily characteristic of all shelf assemblages, although it may be a feature characteristic of outer shelf regions.

Okada and Honjo (1975) concluded that the extremely rare occurrence of E.huxleyi was characteristic of coccolithophorid populations in marginal seas, whereas G.oceanica dominated these floras. G.oceanica was most dominant in the plankton samples from the South China Sea where it formed 95-100 % of the assemblages. A general trend of increasing dominance was also noted from the open ocean to the coast.

Wang and Samtleben (1983), although recording E.huxleyi as one of the more dominant species in bottom sediments from the South China Sea, also found a trend of increased relative abundance of G.oceanica towards the land. G.oceanica however, became dominant over E.huxleyi in the middle shelf region. A similar increase in abundance of G.oceanica and decrease in E.huxleyi from the open-ocean to the coast has also been reported in other areas from the western Pacific, including the Great Barrier Reef region (Conley, 1979) , western Tasman Sea

(Burns,1975) and in the East China Sea (Wang and Samtleban,1983).

The dominance of G.oceanica over E.huxleyi in the assemblages studied by Conley (1979), however, was not a universal feature. In the southern Great Barrier region E.huxleyi was dominant (41 to 71%) and G.oceanica was subordinate (15 to 39%). G.oceanica is also the most abundant species in sediments from the Bay of Bengal and in the Andaman Sea in the northern Indian Ocean (Guptha, 1981). This dominance of G.oceanica in some of the marginal seas of the Asian shelf is certainly not typical of shelf waters and sediments from the Atlantic Ocean. Throughout the shelf sediments of northwest Europe, E.huxleyi is by far the most dominant species (>90%) whereas G.oceanica is only a very sparse component (<0.1%).

Numerous plankton studies on coccolithophores in samples from the shelf and marginal sea regions of the Atlantic have been made, eg., in the Norwegian coastal waters (Braarud et al.,1958), the North Sea (Braarud et al.,1953), the coast of southern Europe and North Africa (Gaarder,1954), the coast of the USA (Hulburt,1967; Wood,1968; Marshall 1971) and in the Gulf of Mexico (Gaarder and Hasle, 1971). All these studies reported that E.huxleyi was the dominant species (often forming 100% of the population), whereas G.oceanica was either rare or absent.

The dominance of E.huxleyi in shelf environments is certainly the most charactistic feature of coccolith assemblages from the Atlantic Ocean.

G.oceanica is a warm-water species, with a maximum temperature range in the Atlantic of between 12° and 30° C. (Okada and McIntyre,1979). The species is therefore not expected to be a major component of shelf sediments at high latitudes. G.oceanica, however, is replaced at high latitudes by G.caribbeanica, the cold-water form of the genus. G.caribbeanica forms a major component of North

Atlantic assemblages (up to 49.3%) (Geitzenauer et al.,1977). This species is a sparse component of shelf assemblages studied here and is generally absent from plankton samples of neritic waters in the Atlantic.

Although E.huxleyi has been acknowledged as the most dominant species in the investigations of the neritic regions of the Atlantic, it is also common over a wide range of oceanic plankton communities. The dominance of this species alone cannot therefore be regarded as a reliable indicator of shelf sea environments. However, a very high dominance of E.huxleyi (~90%), coupled with a general scarcity of Gephyrocapsa species in bottom sediments, may be regarded as a reliable indicator of shelf assemblages in the Atlantic Ocean. This dominance of E.huxleyi over Gephyrocapsa spp. is reversed in coccolith assemblages in some of the Asian marginal seas, where water temperature and salinity values are all within a range suitable for good growth of E.huxleyi . The dominance of G.oceanica in these regions suggests that the species has taken over the niche filled by E.huxleyi in the shelf regions of the Atlantic.

The dominance of G.oceanica has been shown not to be a universal feature of marginal seas as suggested by Honjo and Okada (1975). Such a dominance is feature mainly limited to the marginal Asian seas of the West Pacific. The dominance of E.huxleyi is a consistent feature of shelf sediments in the North Atlantic.

8.3 The origin of reworked coccoliths in shelf and marginal sea sediments.

Reworked coccoliths have a widespread occurrence in the continental shelf assemblages from northwest Europe. Reworked forms are either rare (<1.0%) or absent throughout the shelf sediments from the northern North Sea and the Celtic Sea. These low values reflect the general

absence of coccolith-bearing strata in the mainly Palaeozoic lands that border the shelf regions. Larger numbers of reworked coccoliths occur in the sediments from the inner shelf regions of the southern North Sea and the English Channel. Reworked abundances may exceed 90% of the total flora in these regions. A notable feature of these reworked assemblages is the dominance of reworked Cretaceous forms , particularly Watznaueria barnesae, Zygolithus species and Prediscosphaera species. These Cretaceous taxa are most likely to have been supplied from the Chalk strata, which outcrops on both sides of the English Channel and along the eastern coast of England.

Detailed studies on Chalk rivers which drain into the Solent (see Chapter 6) show that little, if any fine-grained Chalk detritus (ie., coccoliths) is deposited by these rivers. Reworked Cretaceous coccoliths are either rare or absent within fluviatile and upper estuarine sediments deposited by these rivers. Reworked coccoliths are abundant at the mouths of the estuaries and decline in numbers in an up-estuary direction. Reworked Cretaceous coccoliths are therefore suggested to be supplied from marine currents into the estuaries. The Chalk rivers of southern England are noted for their clarity and rarely carry large quantities of suspended sediment. This lack of sediment is partly attributed to the fact that Chalk releases water slowly, with the supply remaining fairly constant all year round. Chalk rivers do contain high quantities calcium carbonate, but this is mainly in the form of dissolved carbonate (as the bicarbonate ion), rather than particulate chalk detritus.

The reworked nannofossils present throughout the surface sediments of the English Channel are therefore most probably supplied by marine and submarine erosion of Chalk cliffs, such as those found on the Isle of Wight, the Dorset coast and along the Dover coast. Plumes of white suspended sediment have been seen by the author in waters bordering the Chalk cliffs on the Isle of Wight after periods of heavy seas. Reworked coccolith

concentrations must be very high in such clouded water and would be redistributed and deposited in the bottom sediments by the prevailing hydrological conditions.

Cohen (1965) came to a different conclusion regarding reworked nannofossils in bottom sediments from the Adriatic. He found a decrease in 'land-derived' forms and an increase in Recent forms in the sediments at increasing distances from the Italian coast. These reworked forms were suggested to have originated from the mountains of the Italian Peninsula and were brought down to the coast by rivers. These forms were Upper Cretaceous and Tertiary in age and were in a recrystallised state. Cohen based his conclusions mainly on investigations using optical microscopy. S.E.M analysis of these samples failed to record a single Cretaceous coccolith. Cohen concluded that identification using the electron microscope was hindered by a secondary layer of calcite covering the nannofossil specimens. Such a layer was suggested to obscure every structural detail, making the forms indistinguishable from mineral particles.

Diagenetic overgrowths on calcareous nannofossils do not aid species identification, but rarely obscure every structural detail. Such overgrowths, instead of covering the nannofossils with a 'blanket' of calcite, selectively pick-out individual skeletal elements. The overall basic shape of the nannofossil is retained and individual elements may become irregularly thickened with secondary overgrowths (Pl.8, Fig.4).

Cohen's failure to record reworked Cretaceous nannofossils in samples analysed by S.E.M. may be the result of the general scarcity of such nannofossils in the original sediment. Samples prepared for S.E.M. are small and have to be examined slowly at high magnification (~ x5000) to ensure that every particle may be identified correctly. Slides prepared for optical analysis, however, may be much larger and can be rapidly scanned at low

magnification (~ x800). Cohen is unlikely to have mis-identified the Cretaceous forms under optical microscopy, but possibly overestimated their quantitative abundance in the samples. Such an overestimation of reworked values may have been caused by the general scarcity of Recent forms in the assemblages.

Analysis of fluviatile and estuarine sediments at the margins of the Adriatic should confirm whether Cohen's suggestion of a fluviatile source is correct, and also determine quantitatively the number of nannofossils transported by the rivers.

Chen (1980) has documented the abundance of redeposited Neogene coccoliths in the surface sediments, offshore of Taiwan, in the region between the South and East China seas. The source of these Neogene coccoliths was suggested to be the various rivers (eg., the Pachang, Tsengwen and Hsiatamschui) that drain the outcrop area on Taiwan and flow into the Taiwan Strait or the Philippine Sea. Highest concentrations (>50%) occurred along the shore line, especially in the vicinity of the mouths of the main estuaries. Reworked values on the outer shelf dropped below 0.05%. Chen found a very good correlation of high reworked coccolith values in sediments where land-derived detrital sediments were most abundant. The redeposited forms consisted of Sphenolithus spp., Discoasterids, Pseudoelimania spp., Calcidiscus spp., Ceratolithus spp. and Gephyrocapsa spp.

These reworked coccoliths showed the same characteristics as those of Cretaceous forms found within the shelf sediments studied in this report ie., higher birefringence colours, broken shape and overgrowths on the skeletal elements.

A further example of the fluviatile supply of nannofossils to a marginal sea was recorded by Pierce and Hart (1979) from bottom sediments in the Gulf of Mexico. The most abundant occurrence of reworked nannofossils in

sediments delineated three distinct geographical areas that correlated with the known position of freshwater influx into the Gulf System. The presence of reworked coccoliths, only in areas adjacent to the Mississippi River, Rio Grande and rivers flowing into Campeche Bay, map-out transport directions of terriginous sediments into the Gulf. Reworked forms included Chiastozgus sp., Discoasterids, Micula staurophora, Watznaueria sp., Zygodiscus sp., Sphenolithus sp. and Prediscosphaera sp.

Redeposited Miocene and Pliocene coccoliths were also recorded by Chen (1979) in bottom sediments from the southern Okinawa Trough; a marginal basin behind the Ryukyu Island Arc. It is bounded by the Arc to the south and east, and by Taiwan to the west. Reworked species, including discoasterids and Sphenolithus species, were thought to be have been transported from northeastern Taiwan by turbidity currents. Submarine erosion of Neogene strata, outcropping along the southern and northern margins of the trough, was also thought to supply nannofossils to the sediments. The redeposited Pliocene coccoliths were thought to have been derived from the thick Pliocene Shimarjiri Group sediments, which outcrop on Southern Ryukyu Island.

Reworked nannofossils have been reported by Guptha (1976) in Arabian Sea sediments occurring in the slope region off Bombay. Cretaceous and Tertiary forms , mixed with Recent sediments, are being deposited by the Indus River in the Arabian Sea. Reworked nannofossils also occur in the Gulf of Kutch and in the south eastern Arabian Sea (Guptha,1979). Mixing of nannofossils is caused by very strong tidal currents in the Gulf of Kutch. It was suggested that the Gulf is a large contributor of reworked fossils to the western slope sediment off India.

Guptha (1981) has also recorded the nannofossils from Recent sediments off the Andaman Islands; the Andaman Islands separate the Bay of Bengal from the Andaman Sea. Twenty-four species of reworked coccoliths were recorded

ranging in age from Eocene to Pliocene , with Miocene forms dominating. The source of these nannofossils was thought to be mainly from the submarine outcrops of late Neogene strata in the Bay of Bengal and the Adaman Sea regions. An additional source of reworked forms was suggested to be the Adaman Islands where there are Tertiary sediments , but this supply could not be fluviatile; the islands have only a poor drainage system. Turbidity currents and submarine slumping were thought to play a major role in the redistribution of the nannofossils.

Shafiq (1978) has recorded the nannofossil assemblages in the surface sediments of the Scott Plateau and Java Trench, off the northwest coast of Australia. Late Cretaceous nannofossils occur among Quaternary cores in the northern Scott Plateau and the Java Trench. The reworked Cretaceous forms were derived from the Lower Campanian Chalk outcropping in the central Scott plateau. The occurrence of these reworked taxa was suggested by Shafiq to indicate that bottom currents are actively stripping away and redistributing older sediments exposed on the seafloor.

Nannofossil assemblages in Recent sediments from the deep-sea areas adjacent to the Canary Islands were reported to contain abundant reworked Cretaceous forms by Muller and Roth (1975). These reworked taxa included Eiffellithus turriseiffeli, Micula stauropora, Watznaueria barnesae and Zygodisus species, all forms recorded in the shelf sediments studied here. The reworked forms were suggested by Muller and Rothe to be derived from shallow-water sediments, either from the African coast or from the broad shelf off Morocco.

Reworked coccolith taxa are a commonly reported component of marginal seas and continental shelf assemblages. A feature of these assemblages is their uniformity in species-composition; they are generally limited to a few solution-resistant , robust taxa.

From the examples discussed above, three main sources of reworked coccoliths are suggested to supply calcareous nannofossils to marginal sea and continental shelf sediments:

1) Coastal erosion of cliff sections, eg., Chalk cliffs along the English Channel.

2) Fluviatile imput, eg., the Mississippi in the Gulf of Mexico (Pierce and Hart,1979), the Indus to the Arabian Sea (Guptha, 1975), the Pachang to the offshore region of Taiwan (Chen, 1980).

3) Submarine erosion caused by strong tidal currents and/or turbidity currents, eg., the Gulf of Kutch (Guptha, 1979), Okinawa Trough (Chen, 1979), Scott Plateau and Java Trench (Shafiq, 1978).

8.4 Controls on the distribution of coccolithophores and other phytoplankton on the northwest European continental shelf.

8.4.1 Introduction.

At temperate latitudes the classic pattern of annual phytoplankton change is a spring bloom, consequent on increased radiation , followed by a variable but usually lower phytoplankton crop during the summer. Frequently there is a brief autumn bloom, but a very low level of plankton crop occurs during the winter (Raymont,1963).

Phytoplankton crop (standing crop) is defined as the biomass of phytoplankton and may be measured in various ways. The weight of matter (wet or dry) per unit volume may be determined, or the weight measured beneath a unit of surface (usually 1m squared) throughout the length of the euphotic column. One of the most common techniques used in assessing standing crop is the estimation of the concentration of cell pigment, usually chlorophyll-a, since this is universally present in marine algae.

8.4.2 Temporal changes in phytoplankton growth in the shelf waters.

Phytoplankton growth in temperate shelf seas is generally insignificant between December and March . During this period, although there are large quantities of nutrients in the water, unfavourable conditions for algal growth occur because of reduced light intensities and by wind and tidal mixing, which removes the cells from the photic zone before large populations can build up.

Pingree (1975,1980) has summarised the main features

of phytoplankton growth in the Celtic Sea and western English Channel. These general features described from the Celtic Sea are also applicable to the other deeper waters (~ 100m) around the British Isles.

Phytoplankton growth in the Celtic Sea in early spring is triggered by the stabilisation of the water column and the development of the thermocline. As the temperature of the surface layer increases there is lessened interchange between the near-surface and deep waters and algae in the upper 15 to 20 m multiply rapidly in the improved light regime.

Pingree (1975) noted that the thermocline first developed to the south of Ireland in early April (Fig.3.9) and spread across the Celtic Sea to penetrate the English Channel less than a month later. Stratification was established first in the area of weak tidal streams (<0.5 kts), near Nmyphe Bank (6° to 7°W). During the spring bloom temperature differences between surface and bottom waters were >0.6°C; cholorophyll-a concentrations reached 10 mg/cubic metre and surface nutrient levels were dramatically reduced (nitrate by 98%, silicate by 85% and phosphate by 70%) (Fig.8.3). This depletion of nutrients was confined to the area of water stratification, but did not occur in the well-mixed regions where phytoplankton crops were low.

The spring phytoplankton bloom followed a gradual extension of the thermocline throughout the Celtic Sea and eventually penetrated the western English Channel to approximately 4° W by May. Stabilisation of the water column was the essential factor in algal-multiplication; the process of the flowering could not be attributed to advection. After the spring bloom, the plant crop declined rapidly and summer growth was suggested by Pingree to depend upon the rate of supply of nutrients by vertical mixing from the bottom, mixed layer.

Throughout the summer the phytoplankton crops were

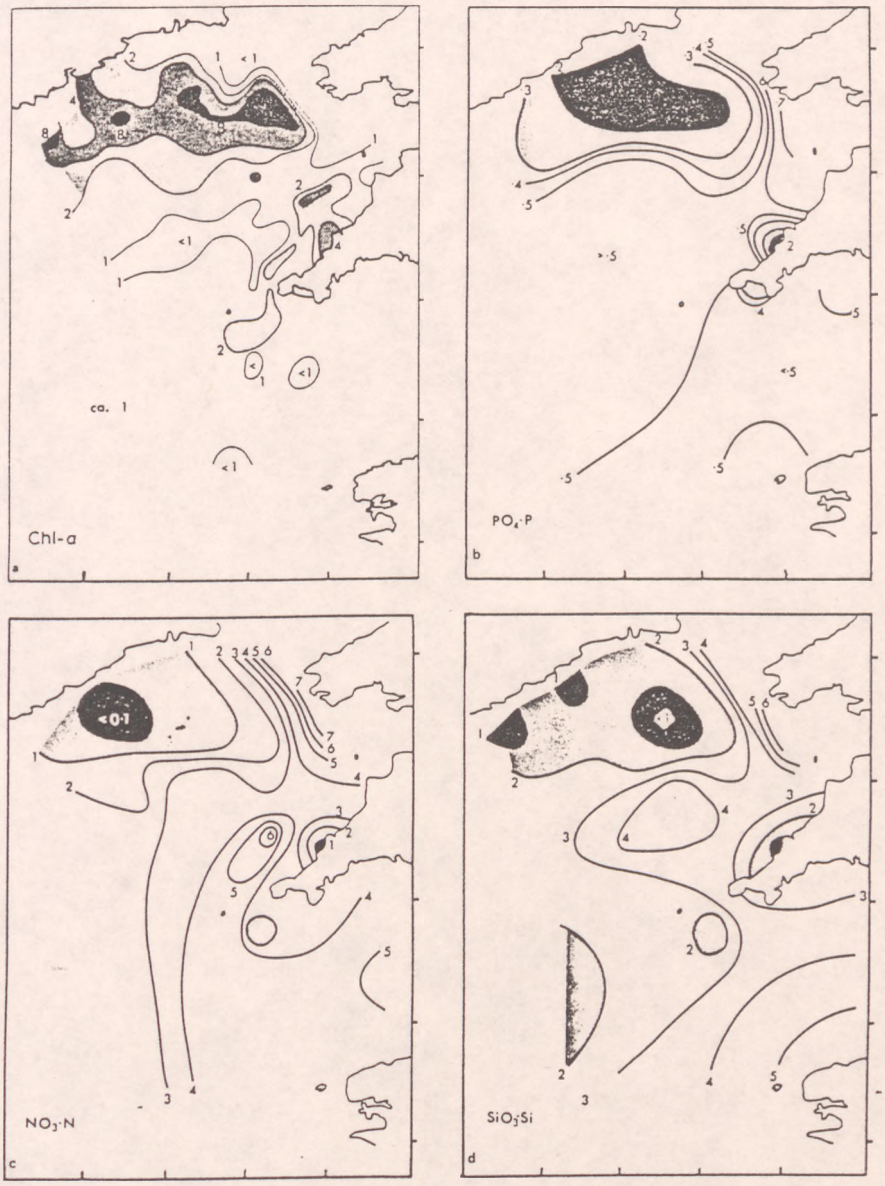


Figure 8.3
Surface distribution of properties in the Celtic Sea during the spring phytoplankton outburst (9-21st April,1975). a. Chlorophyll-a (mg/cubic metre). b. Phosphate (uM/l). c. Nitrate. (um/l). d. Silicate (uM/l). (After Pingree, 1980).

generally poor. In the deep, well-mixed regions of the English Channel, although there were abundant nutrients the mean light level experienced by the algae was low. Thus, close to Land's End and to the French Coast where there was considerable mixing, the waters contained a sparse flora. In the stratified region, the surface nutrients were depleted to minimal values after the spring blooms. Consequently, west of the Scilly Isles well stratified water also contained a sparse flora. The thermocline region itself was rich in cholorphyll where plant growth was enhanced by the extra degree of stability of the water column and extra nutrients.

During autumn the thermocline retreated towards Nymphe Bank from the Channel. Although greater mixing allowed enrichment of the surface layers, surface light intensity was low and phytoplankton crops were reduced. The surface light by October was 50% of that in April.

Pingree (1975,1980) has shown that the stability of the water column, related to thermocline formation and breakdown and to tidal bottom movements, exerts a profund influence on algal growth in the Celtic Sea.

8.4.3 Seasonal succession of phytoplankton growth in the shelf waters.

The growth of phytoplankton in the shelf waters of northwest Europe occurs as a seasonal succession of different phytoplankton communities (Holligan and Harbour, 1977). Early spring (April) plankton growth is dominated by large algal cells; diatoms bloom as they are able to utilize the large concentrations of nutrients which have built up in the waters over the winter months. The dominant species include Nitzchia, Rhizosolenia, Chaetoceros and Thalassiosira. The colonial flagellate Phaeocystis poucheti may also be a major component of the plankton under these conditions.

Early spring blooms of diatoms are quickly replaced by mixed communities of diatoms and dinoflagellates, and from May onwards the latter usually dominate. This community is associated with lower levels of inorganic nutrients in the surface waters. However, conditions of intermediate vertical stability (~1° to 3° C temperature difference between surface and bottom waters) allows some upward mixing of nutrients, so that some growth of large algal cells can continue. In regions of a very shallow thermocline,a diatom-dominated population is likely to persist in the surface waters until well into June, (e.g. station E1 in the western English Channel) (Fig.8.6).

The mid-summer period is dominated by dinoflagellates and flagellates (including coccolithophores), which occur in the thermocline and surface layers respectively. Continued warming of the surface layer leads to a further reduction in turbulence across the thermal gradient (temperature differences are greater than 3° C). The physical stability of the water column together with sufficent light energy from above and a supply of inorganic nutrients from below permit dinoflagellate populations to become established in the thermocline. High levels of dissolved organic phosphorus and reduced nitrogen ,in particular urea and ammonia, (Butler in Holligan and Harbour, 1977) occur within the thermocline. These concentrations were presumed to be caused by the aggregation of zooplankton, and may be important controls on the growth of the dinoflagellate species Gyrodinium aureolum which is abundant during August.

During mid-summer inorganic nutrients fall to minimum concentrations, as upward transport from the bottom-mixed layer is strongly inhibited by the physical and biological properties of the thermocline. Small flagellates dominate the phytoplankton in the surface waters ; the few dinoflagellates that occur are merely indicative of the subsurface populations.

During autumn as the thermocline is slowly eroded, the small flagellate/dinoflagellate communities are replaced by dinoflagellate/ diatom communities. These are later replaced by diatom communities. With the breakdown of the thermocline large quantities of nutrients are transported to the surface layers as mixing increases. Diatom growth, however, becomes limited by the general reduction in illumination.

Halldal (1953) has recorded the seasonal fluctuation in cell number and species composition at a weather ship station in the Norwegian Sea (66° N, 2° E). Between December and March phytoplankton growth was insignificant because of low light intensities. A fairly early spring growth commenced with increased light penetration in the Norwegian Sea. Considerable mixing of the water column, however, prevented a significant increase in phytoplankton until May, when stability was established. The onset of spring growth was therefore later and less abrupt than that recorded from the Celtic Sea. The growth peaks (Fig.8.4) occurred late in the year; diatoms in July and August, coccolithophores and dinoflagellates in June and July and again in September and October. The decrease of plankton in mid-summer and subsequent recovery in the early autumn, was suggested by Halldal to be the result of a partial depletion of nutrients in the waters , followed by replenishment as autumnal mixing occurred coincident with the depression of the thermocline.

Pingree et al., (1978) has studied the effects of vertical stability on phytoplankton distribution in waters from the northwest European Shelf. They divided phytoplankton populations in the thermocline into three groups according to differences in temperature between the surface and bottom waters;

1) temperature differences $<3^{\circ}C$; a mixed community of dinoflagellates and diatoms,

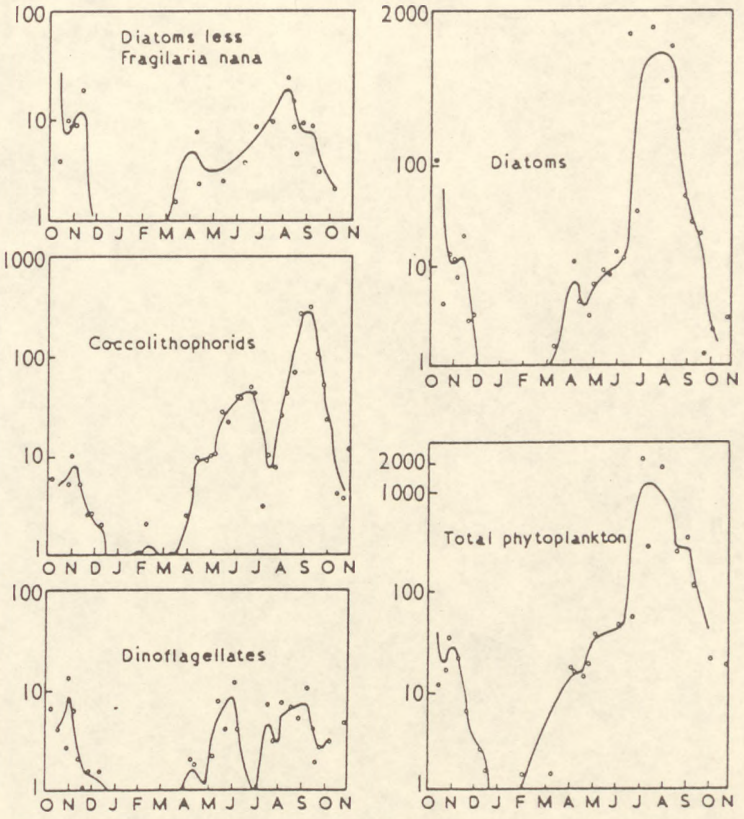


Figure 8.4
Seasonal growth of phytoplankton in the Norwegian Sea (after Halldal,1953).

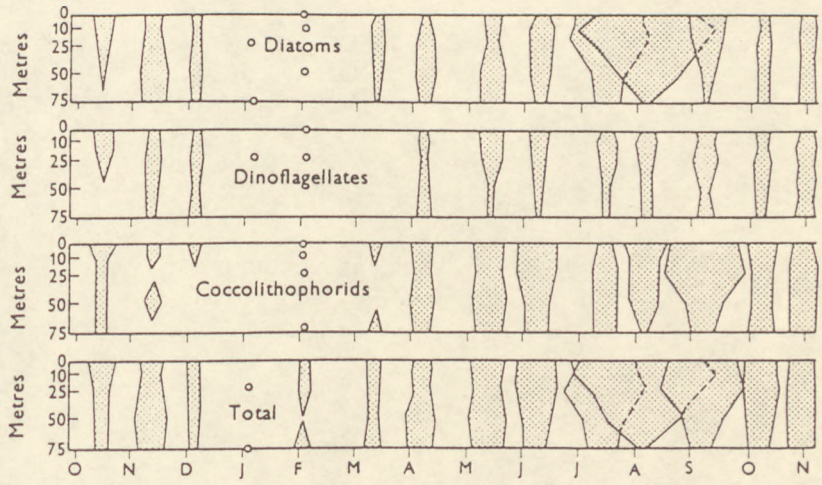


Figure 8.5
The vertical distribution of the phytoplankton in the Norwegian Sea during one year's sampling (after, Halldal,1953).

2) 3° to 6° C; dinoflagellates,

3) >6° C; small flagellates.

These population types represent the successional series of phytoplankton communities described by Holligan and Harbour (1977) which occur after the establishment of the thermocline in spring, and then also occur in reverse order as the thermocline is eroded in early autumn.

From the work of Pingree et al. (1978) the following generalisations may be made about plankton populations in the shelf waters of northwest Europe.

1) In weakly-stratified and well-mixed waters diatoms are the most abundant photosynthetic organisms. These populations in terms of species-composition may vary from benthic types (Paralia, Pleurosigma) to more oceanic communities, depending on the strength of oceanic influence in the area.

2) In surface waters overlying a well-developed thermocline, chlorophyll-a levels are generally low and small flagellates dominant.

3) Mixed populations of dinoflagellates and diatoms form the high chlorophyll concentrations in frontal regions.

From the points discussed above it is suggested that small flagellates (including coccolithophores) are most common in well-stratified waters, particularly where surface-to-bottom temperature differences of the water mass exceed 6° C. Temporal and spatial variations in the degree of stratification and differences in the surface to bottom temperature of the waters should therefore be important controls on coccolithophore distribution in the surface waters. Highest surface-to-bottom temperature differences and greatest stratification of the water column occur during mid and late summer. Coccolithophore

growth should therefore be most concentrated during this period.

Coccolithophores have been reported in plankton samples from the shelf of the Celtic Sea and western English Channel during the period May to August (Holligan,1978; Holligan et al.,1983; Murray et al.,1983). They have also been reported in large numbers from the North Sea in May; >125,000 cells/l by Braarud et al., (1953), 14.5 million cells/cubic metre recorded by Cadee (1985). Further north, in the Norwegian Sea, coccolithophores reached maximum abundance during August and September (Halldal, 1953). A similar trend of increasing coccolith abundance during the summer was also noted in filter samples taken from the northern North Sea (lat. 58°N). Highest numbers of coccoliths (20 to 25% of the fine fraction) were filtered from the water column in July (sampling time 48 hours). Lower numbers (10 to 15%) occurred during an earlier sampling period over the months of April and May.

The above records of coccolithophore occurrence were reported from stratified shelf waters with well-developed thermoclines. There are no records of significant coccolithophore growth in the tidally mixed waters of the northwest European shelf, e.g. southern North Sea, central and eastern English Channel. The distribution of coccolithophores in plankton samples is therefore largely restricted to regions of well-stratified waters.

8.4.4 Spatial changes in phytoplankton composition and abundance across frontal regions.

Holligan (1978) has recorded the quantitative abundance of plankton, including coccolithophores, in a series of plankton samples, across the frontal region in the western English Channel. Table 8.2 lists the species composition of the plankton across the Ushant Front. At station E5 (49°06' N, 06°32' W) in the Western Approaches to the Channel, coccolithophores dominated the plankton

Table 8.2.
Differences in the composition of the phytoplankton across the frontal region in the western English Channel shown in Fig.8.7. (modified from Holligan, 1978).

Position		48 45'N 04 40'W	49 51'N 05 20'W	49 06'N 06 32'W
Sample		(A)	(B)	(E5)
Date		(27/7/76)	(28/7/76)	(2/8/76)
Sample depth		2 m	2 m	25 m
		Mixed	Mixed	Stratified
Chlorophyll a	(mg/m)	1.2	46	58
Diatoms	(cells/ml)	27.9 (27)	0.1 (1)	0.1 (3)
Dinoflagellates	(cells/ml)	2.1 (15)	2760 (9)	0.1 (3)
Flagellates	(cells/ml)	410	no count	760
Coccolithophores	(cells/ml)	0	0	800 (1)

Numbers in parentheses represent number of species recorded.

Table 8.3
Changes in the phytoplankton populations in the thermocline at stations E1 and E5, July to August 1976, showing coccolithophores dominant at station E5. (after Holligan,1978).

	Date	Maximum chlorophyll a concentration (mg/m)	Dominant phytoplankton species
E1	14 July	2.5	Dinophysis acuta Gyrodinium aureolum Heterocapsa triquetra
	20 July	5	D. acuminata, D.acuta
	4 July	26	Ceratium lineatum G. aureolum
	12 July	17	G. aureolum
E5	21 July	5	Flagellates
	2 August	~80	Coccolithophores
	11 August	~80	G. aureolum Coccolithophores

community forming up to 8000 cells/l. However, plankton samples taken from the frontal region of the western English Channel did not contain any coccolithophores. Sample A east of the frontal boundary off the north Brittany coast was dominated by dinoflagellates whereas sample B, off the Lizard,contained a mixed community of diatoms and dinoflagellates.

Additionally, Holligan (1978) found that coccolithophores dominated the plankton communities in the thermocline, at station E5, throughout August (1976), where maximum chlorophyll-a concentrations reached 80 mg/cubic metre of seawater (Table 8.3). At station E1, off the south coast of Cornwall near the eastern margin of stratified waters in the western English Channel, coccolithophores never dominated the plankton during August. Here the plankton was mainly composed of dinoflagellates such as Dinophysis acuta, Gyrodinium aureolum and Ceratium lineatum. It is therefore evident that across transitional regions (frontal regions) between stratified and tidally mixed regions large spatial changes in abundance of coccolithophores and other phytoplankton occur.

In the frontal region of the western English Channel concentrated dinoflagellate blooms (red tides) may occur in the summer. These red tides are composed mainly of the species Gyrodinium aureolum . In the frontal region, large amounts of nutrients are transferred across the thermocline boundary by mixing processes. The eastern boundary of the more persistent part of the dinoflagellate bloom is marked by the position of the front at spring tides (Pingree, 1980). The western limit of the red-tide blooms is controlled by a deeper and more stable thermocline, through which there is little or no exchange of water properties between the surface and the bottom mixed layer.

In the well-mixed region of water, east of the frontal boundary in the English Channel , no red-tides occur, although both adequate light and nutrients for

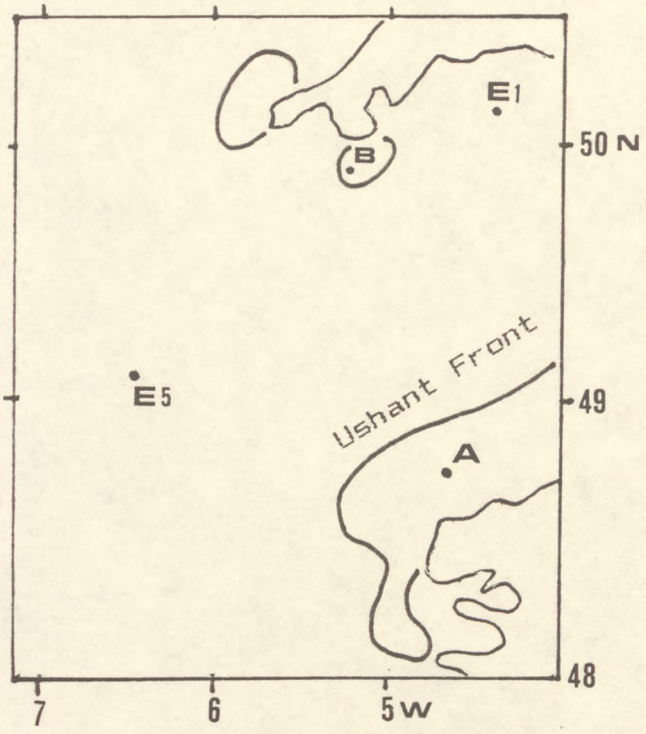


Figure 8.6
Location of plankton sampling points of Holligan (1978) and position of the frontal boundary in the western English Channel.

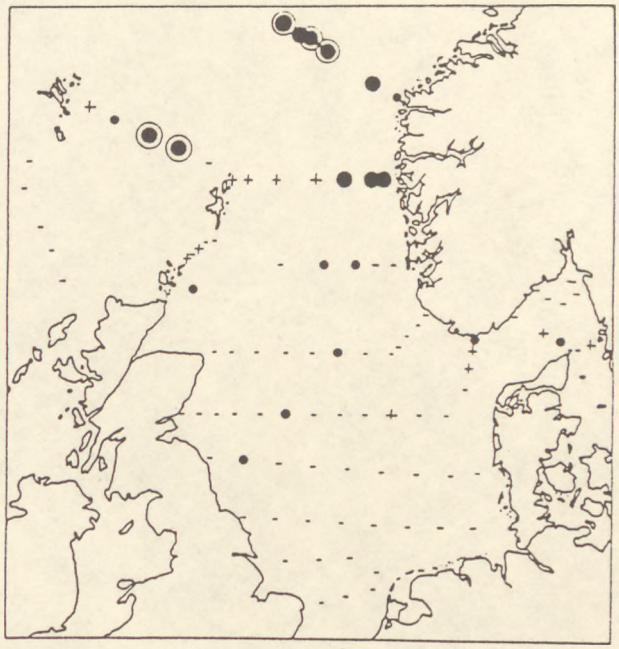


Figure 8.7
Distribution of Anthosphaera robusta in plankton samples during May 1948 (after Braarud et al., 1953).
Maximum numbers at each station (cells per litre).

+ 0—1,000
• 1,001—5,000
● 5,001—25,000
⊙ 25,001—

growth occur at the surface. The thoroughness of the mixing, however, does not allow the plant cells sufficent time in the surface layers to produce any marked degree of surface phytoplankton. Similar controls would also limit coccolithophore growth in the tidal-mixed waters of the central and eastern Channel regions. These frontal regions, however, are not favoured by coccolithophores. Abundances of coccolithophores usually increase away from the frontal boundary within stratified waters.

Braarud et al. (1953) have documented the abundance of coccolithophores in plankton samples in the region of the Orkney- Shetland Isles front. Abundances of E.huxlevi ranged from >125,000 cells per litre in stratified waters to the northeast of the Shetland Isles, to less than 25,000 cells per litre in well-mixed water (St=1.0) between the Isles . A similar decrease in abundance of the other common coccolithophore species in the plankton (Anthosphaera robusta) occurred (Fig.8.7). This species was either scarce (<1,000 cells/l) or absent from the well-mixed waters, but formed over 25,000 cells per litre in the stratified waters northeast of Shetland.

8.4.5 Hydrological controls on coccolith abundance in the Recent sediments.

8.4.5.1 Stratification and thermocline development.

The spatial distribution of coccolithophoresin the plankton samples, largely restricted to well-stratified waters with a pronouced thermocline, is also reflected in the bottom sediments of the shelf regions. Highest numbers of coccoliths (10^8 to 10^9 coccoliths per gram) occur in sediments deposited beneath a pronounced thermocline, (e.g., in the Celtic Sea, western English Channel and in the northern North Sea). In the Irish Sea maximum abundance of coccoliths (>2000 $\times 10^5$ coccoliths/g) occurs in assemblages deposited to the southwest of the Isle of Man. This area corresponds to a region of weak tidal currents (<1 kt.) . In these deep waters a pronounced thermocline occurs at a depth of about 20m. Throughout the tidally mixed waters of the central and eastern English Channel and in the southern North Sea coccoliths are either rare [(<1%) (<10^7 per gram)] or absent.

As mentioned in Chapter 3 the degree of stratification in the water column is quantified by the parameter;

$$St = \log 10 \left[H / Cd\ U^3 \right]$$

where Cd is the stratification parameter,
H is the water-depth and
U is the maximum tidal stream velocity.

The stratification parameter is then easily calculated for a coastal region and contours of St = 1, 1.5 and 2 from the shelf waters of northwest Europe are shown in Fig. 8.8. High values of the parameter (>2) reflect stratification ; low values (<1) are associated



Figure 8.8.
Predicted contours of the stratification parameter (St), for St = 1, 1.5 and 2 from the numerical model. The continuous heavy line represents the predicted frontal boundary for which S = 1.5. All these frontal regions can be identified from hydrographic studies and satellite images and represent important physical, biological and chemical boundaries. Sediments from stratified areas are associated with high numbers of coccoliths; sediments from mixed areas have low numbers of coccoliths. (After Pingree,1978).



Figure 8.8.
Predicted contours of the stratification parameter (St), for St = 1, 1.5 and 2 from the numerical model. The continuous heavy line represents the predicted frontal boundary for which S = 1.5. All these frontal regions can be identified from hydrographic studies and satellite images and represent important physical, biological and chemical boundaries. Sediments from stratified areas are associated with high numbers of coccoliths; sediments from mixed areas have low numbers of coccoliths. (After Pingree,1978).

with tidally mixed waters.

These contours reflect the distribution of the tidal stream velocities since they are raised to the cube power. Water-depth varies less over the region and consequently is not such an important control on the degree of stratification. The transition from stratified waters to well-mixed waters occurs at a critical value (St=1.5). The St= 1.5 contour marks out the occurrence of frontal regions in the surface waters of the shelf.

Bottom sediments have been sampled across a number of these frontal boundaries shown in Fig. 8.8. These include:

1) The Ushant front in the Celtic Sea and western English Channel.

2) The northern Celtic Sea front.

3) Orkney-Shetlands front in the northwestern North Sea.

4) Flamborough Head front in the southern North Sea.

5) Irish Sea front in the northern Irish Sea.

Abrupt changes in coccolith abundance and species diversity occur across these frontal regions, although these changes are not so well-defined across the Orkney-Shetland Isles Front. In the western English Channel the frontal region marks the eastern limit of coccolith assemblages deposited in the bottom sediments containing eight or more species, with a total of 18 different species being recorded from the assemblages. East of the frontal boundary in the central English Channel coccolith assemblages are restricted to 6 or fewer species. The frontal region also divides bottom sediments containing 10^8 to 10^9 coccoliths per gram (which represents between 2 and 20% of the fine fraction) in the western English Channel from bottom sediments containing 10^7 coccolith per gram in the central Channel (<1% of the fine fraction). Similar decreases in species-number and in the quantitative abundance of coccoliths in the bottom sediments occurs

across the frontal region in the northern Celtic Sea.

The frontal region off Flamborough Head, which extends across the southern North Sea at a latitude of approximately 54° N, delineates the the most southerly distribution of coccoliths in the bottom sediments of the North Sea (with the exception of a small area off the French coast). Coccolith assemblages deposited just to the north of the frontal boundary (~55°N) contain 5 or more species which contribute 10^7 coccoliths per gram.

Coccolith abundances in bottom sediments across the frontal region of the Orkney- Shetland Isles decline from 10^9 coccoliths per gram deposited from stratified waters (east and west of the Islands) to 10^8 coccoliths per gram deposited from well-mixed waters in the vicinity of the Islands. This represents a decline in coccolith-component in the fine fractions from >15% to <5% . However, there is no corresponding decrease in the number of coccolith species contained in the assemblages across the frontal region. Five or more species occur in the assemblages throughout the region regardless of the degree of stratification of the water column. The coccolith species present in the bottom sediments are probably transported into the region by Atlantic currents. Pingree et al., (1978) regard that the advection of Atlantic Water across the shelf edge and through the Orkney-Shetland passage plays an important role in the distribution of water properties in the region.

The degree of stratification of the water column has been shown to exert a strong control on the distribution of coccoliths in the Recent sediments of the shelf. High numbers of coccoliths are deposited from stratified waters; low numbers are associated with well-mixed waters.

5.4.5.2 Tidal stream velocities.

As mentioned above,tidal stream velocities strongly

control the degree of stratification of the water column and provide most of the energy for mixing processes in the shelf waters. From the correlation of coccolith abundance with water stratification it is clearly evident that tidal stream velocities must also have a strong control on the distribution of coccoliths in the sediments. Maximum tidal stream velocities are strongly negatively correlated with coccolith abundances in the sediments.

Highest abundances of C.pelagicus and S.pulchra occur in assemblages deposited from waters in the central Northern Celtic Sea, where tidal streams are ~0.5 kts (0.3 m/s) or less. A gradient of increasing tidal stream velocity occurs northwards and eastwards throughout the Celtic Sea and is parallelled by a gradient of decreasing coccolith abundance in the surface sediments. In the Celtic Sea and English Channel mixing of the water column occurs where tidal streams exceed 2 kts (1.2 m/s) . The changes documented across frontal boundaries in the Celtic Sea and Irish Sea in the previous section are also applicable to the 2 kts boundary.

In the northern North Sea maximum coccolith abundances (10^9 per gram) occur in the regions of weak tidal streams (~<0.75 kts). In the southern North Sea where tidal currents exceed 1 kt, no Recent coccoliths occur in the sediments, apart from an isolated occurrence along the Continental coast.

Tidal stream velocities have been shown to have a strong control on the distribution of coccoliths in the shelf sediments. The distribution of coccoliths in the sediments parallels the reported distribution of coccolithophores in the surface waters. Both samples record high numbers from environments of weak tidal influence and low numbers of coccoliths from tidally mixed environments. Tidal mixing of surface waters removes populations of coccolithophores from the well-illuminated surface waters before large populations can build-up.

Estuarine environments characterised by strong tidal currents, however, may contain fairly abundant diverse coccolith assemblages (e.g., tidal sediments from the Bristol Channel and Severn Estuary). Coccoliths are transported into the estuary from offshore assemblages deposited from stratified waters. Such examples are likely to occur where estuaries,in which there is a strong tidal influence,lie adjacent to offshore waters which are well-stratified. The recognition of such tidally influenced environments should be established by recognition of derived stenohaline, size-sorted, benthic foraminifera (cf., Murray and Hawkins, 1976).

5.4.5.3 Surface salinity.

The distribution of surface salinity values varies from 35.5 ‰. at the western margin of the Celtic Sea to <30 ‰. in the Skagerak, at the eastern margin of the North Sea. Throughout the largest part of the shelf region, however, fairly typical marine salinities occur in the surface waters (~34 to 35‰.) (e.g., in the Celtic Sea, English Channel, west of Scotland and northern North Sea.) Such relatively small variations of salinity are unlikely to control the quantitative abundance of coccolithophore assemblages which are dominated by the species Emiliania huxleyi. This species frequently forms over 90% of the total coccolith assemblage.

Histograms of the abundance of E.huxleyi plotted against surface salinity values in the Celtic Sea and English Channel and in the northern North Sea showed no significant relationship. Abundances of the species varied little over the salinity range 35.5 to 34.0 ‰.

Emiliania huxleyi has an sually wide salinity range (16 to 45 ‰.) (Paasche, 1968). In the polluted Oslo Fjord the species occurs in large numbers at salinities as low 18‰. (Tappan,1980). E.huxleyi is particularly abundant in the coastal and fjord waters of north Norway, which are typically of low salinity, but highly

stratified.

Pingree et al. (1982) recorded the distribution of plankton in the Skagerak (late August, 1982) where a shallow thermocline (10 to 15m depth) occurred,and where the surface salinity values were 27 ‰. An intense sub-surface chlorophyll-a maximum occurred (up to 30 ug/l). This maximum was associated with a large growth of coccolithophores, particularly E.huxleyi. Large populations of E.huxleyi have been reported from the Oslo Fjord (75 million cells/l) and on the Norwegian west coast at 11° C and 33 ‰ salinity (115 million cells/litre) (Berge,1962). E.huxleyi was also recorded in numbers of >20,000 cells /litre over the salinity range 26-33 ‰ in the Skjomen Fjord (north Norway) (Schei,1975).

Salinity values are therefore suitable for growth of E.huxleyi in the tidally mixed waters of the English Channel, southern Celtic Sea and Irish Sea where the species is either absent or scarce in the surface sediments. Changes in salinity do not therefore significantly control the distribution of E.huxleyi in the surface sediments.

The other coccolith species present in the assemblages do not have such a well-documented salinity tolerance. Therefore the effects of salinity change on these species throughout the shelf waters is less predictable.

Abundances of the species C.pelagicus and S.pulchra , however,were plotted against changes in surface salinity of the North Sea, Celtic Sea and English Channel. Both species showed no significant correlation with salinity,

All the species found in the shelf sediments of northwest Europe are also found in bottom sediments deposited in other marginal seas at lower salinities. They occur in the Southern Okinawa Trough, East China Sea

, deposited from waters with a surface salinity range of 34.4-34.0‰. (Chen, 1979), and in the East China Sea deposited from the Kuroshio Current with a salinity of ~ 34.0 ‰. (Wang and Samtleban,1983). Additionally, many of the coccolith species are deposited in a lagoonal coccolith flora recorded from Belize (British Honduras) by Kling (1975) where the surface salinity averages 34.0 ‰. or less.

The relatively small changes in the surface salinity across the shelf waters are therefore not a significant control on the distribution of coccoliths in the Recent shelf sediments.

8.5.4.4 Surface water temperature.

The maximum range of summer temperatures in the regions of the shelf studied are given below:

Celtic Sea	15° to 17° C
North Sea	12° to 18° C
Irish Sea	13° to 16° C

Such small variations in surface temperature are unlikely to affect the distribution and abundance of E.huxleyi, a eurythermal species. This species has a maximum temperature range of between 2° and 30° C in the Atlantic Ocean (Okada and McIntyre,1979). These variations in surface temperature, however, control the type of coccolith structure secreted by E.huxleyi. The ecophenotypes of E.huxleyi present in the assemblages have been discussed in Chapters 3,4 and 5. Variations in surface temperature are unlikely to exert a significant control the total coccolith numbers in the sediments because of the high dominance of E.huxleyi.

Surface temperature, however,is thought to control the distribution of the minor, warm-water, species-component in the assemblages. The reduced species

diversity of coccolith assemblages found in the North Sea (10 species) as apposed to 18 species occurring in Celtic Sea assmblages , is attributed to differences in the temperature of the inflowing Atlantic Water into the two basins. Atlantic water entering the North Sea from a latitude of ca. 61° N, has spring/summer temperatures usually ~ 12°C. Surface water entering the Celtic Sea from a latitude of ca. 48° N has a temperature >16° C in the summer. These differences in summer temperatures reflect differences in the strength of the Gulf Stream at the western margins of the two basins. Many of the scarce warm-water coccolith species supplied from the Gulf Stream into the Celtic Sea are not supplied to the northern North Sea. These include the species Umbilicosphaera sibogae, U.hulburtiana and U.tenuis, which all have a reported lower temperature limit of 13°C in the Atlantic. Such species are therefore absent from North Atlantic inflow to the northern North Sea.

8.4.5.5 Nutrient salt concentrations

Coccolithophores have been reported in large numbers mainly during the mid-summer and late summer periods throughout the shelf waters of northwest Europe. The waters during this period generally contain minimal concentrations of nutrients. This temporal distribution suggests an association between coccolithophore occurrence and low nutrient concentrations in the water column.

Figure 8.3 shows the surface distribution of nutrient concentrations in the Celtic Sea after spring phytoplankton blooms. With reference to Figs. 3.13 to 3.15 it is apparent that maximum coccolith abundance (10^9 per gram) in the Recent sediments occurs below waters of lowest nutrient concentrations(< 2 uM/l nitrate, <3 uM/l silicate) in the Celtic Sea.

In the North Sea, the main sources of free phosphate and nitrate and of soluble silicate are the rivers of

England and northern Europe which drain into the southern North Sea, and the northern Atlantic inflow (Lee,1980) . Nutrient concentrations of the English and Continental Coastal water masses range 35 to 45 uM/l (nitrate) and 0.7 to 3.0 uM/l (phosphate). Whereas in the North Atlantic inflow these nutrients range from 10 uM/l and 0.6 to 0.8 uM/l respectively. The phosphate and nitrate contents of the inflow from the Baltic are very low, (<7 uM/l nitrate and <0.4 uM/l phosphate) (Lee,1980). There is an annual cycle of the various nutrient concentrations and this varies from place to place, depending on the timing of the spring phtoplankton production cycle and the extent to which the water column is stratified. In general, the nutrient salt levels are at a minimum in July and August, the period of maximum coccolithophore growth in the surface waters.

Very low levels of nutrients occur in the Skagerak during the summer months (<0.2 uM/l, nitrate, <0.1 uM/l phosphate, < 1.0 uM/l silicate). At such nutrient levels large populations of coccolithphores have been reported in the surface waters of the Skagerak (Pingree et al., 1982).

An important feature of many nannoplankton species is that their optimal rate of multiplication is generally higher than that of the larger net phytoplankton, following the broad generalization that rate of uptake, growth and division is higher with reduced cell size (Raymont,1963). It is often suggested that oceanic nannoplankton have an advantage over the larger-celled species in competition for nutrients at low concentrations, because smaller-sized species and usually faster growing oceanic species frequently have lower Ks values (Friebele, Correl and Faust,1978). The constant Ks defines the minimum concentration at which a species can grow (Parsons et al., 1984). Ks values therefore describe the ability of a species to use low concentrations of a nutrient.

Coastal phytoplankton communities generally have Ks values of >1μ mole for nitrate uptake, while oceanic communities have lower Ks values of ~0.2 μM = (0.2 μg at/l) (MacIsaac and Dungdale, 1969). Emiliania huxleyi, which has a small diameter(~6 μm),has been shown by Eppely et al. (1969) to have a Ks value of 0.1 μM nitrate/l, while Gonyaulax polyedra which is a large dinoflagellate cell (~ 45μm diameter), had a Ks value of > 5μM nitrate /l.

Differences in Ks values coupled with differences in the ability of a species to reach their maximum growth rate at different light intensities, have been suggested as being important factors in controlling species succession in phytoplankton blooms (Eppley et al.,1969). From Fig. 8.9,A it is evident that E.huxleyi reaches its maximum growth rate at low light intensities using ammonium ions, and that its growth was approximately double that of the other recorded species at a concentration of 0.5 μM NH /l. However, Figure 8.9, B at a higher light intensity, the larger celled species Skeletonema costatum and Ditcylum brightwelli grew faster than E.huxleyi at concentrations above 2 μM (NO.)./l.

The preference of E.huxleyi for low nutrient levels, particularly, at lower light intensities may explain why the species is so common in stratified waters in temperate and high latitude shelf and oceanic waters. However, the species is also common in low nutrient environments at low latitudes. The species along with G.ericsonii dominates the coccolithophore communities in the Gulf of Elat (Aqaba) where the surface nutrients are extremely low (phosphate 0.03-0.25 μM/l, nitrate 0.07-2.0 μM/l) (Winter et al., 1979).

The efficiency of utilization of light energy is one factor which may modify the effects of nutrient level. Parsons and Takahashi (1973) computed growth rates for a comparatively large-celled species (Ditylum brightwellii) and a small-celled species (E.huxleyi), applying average values for incident radiation, average light intensity in

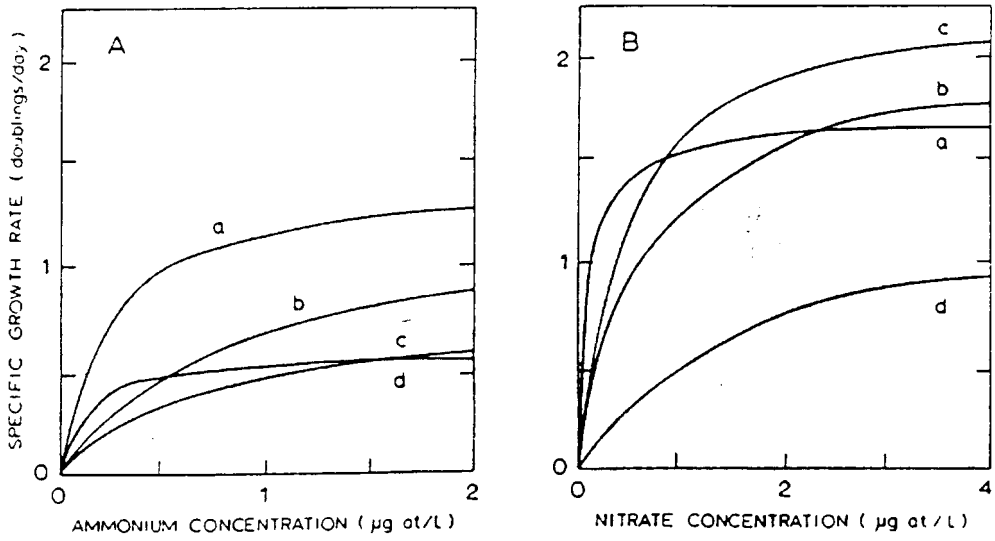


Figure 8.9
Growth rate versus ammonium and nitrate concentrations at two light intensities, (B) approx. 4 times (A). (a) E.huxleyi, (b) Ditylum brightwellii (c) Skeletonema costatum (d) Dunaliella tertiolecta (after Eppeley et al., 1969).

the water column, mixed-layer depth, nitrate concentration and upwelling intensity. The growth rate for E.huxleyi was highest in regions of water stability; the larger celled algae grew faster in upwelling and coastal regions. Some nannoplankton species may divide rapidly (e.g. every 5 or 6 hours. Dense populations of coccolithophores may, therefore, accumulate even more rapidly than populations of the larger diatoms and dinoflagellates.

E.huxleyi and many and other nannoplankton species are small algal cells (<20 μm) and are therefore well-adapted to the nutrient deficient waters that are associated with a thermocline during mid-summer periods. Such small cells are able to efficiently extract the low levels of nutrients, which are typical of the surface waters.

A similar conclusion was reached by Hulburt and Corwin (1970) who described phytoplankton populations from Casco Bay in the Gulf of Maine. The waters in the Bay are characterised by strong mixing and by high nutrient levels. Diatoms dominated the phytoplankton through the growth season, and the crop diversity was relatively high, varying from 100-300 cells/ml. In contrast in the Gulf of Maine waters outside the Bay, there was considerable nutrient depletion in the euphotic zone during the summer. E.huxleyi dominated the plankton populations in the Gulf waters although the standing crop was much reduced. Gran and Braarud (1935) also consider that low nutrient levels may favour coccolithophores in the Gulf of Maine.

E.huxleyi has been reported to use uric acid, as a source of nitrogen and, interestingly, this species has been found in polluted waters (Tappan,1980). High levels of reduced nitrogen (in particular urea and ammonia) have also been reported to occur in large quantities during summer within the thermocline of the western English Channel. These concentrations were thought to be caused by aggregation of zooplankton (E.I. Butler in Holligan and Harbour, 1977). Such a source of nitrate might be

used by E.huxleyi when nitrate concentrations are low and may explain why monospecific blooms of the species occcur during mid-summer when nutrient levels are minimal.

Although photosynthetic, the Haptophyta require an exogenous source of one or more vitamins particulary vitamin B1, thiamin and vitamin B12, cobalamin. All species of Haptophyta require a source of either thiamin or cobalamin or both. However, E.huxleyi does not require vitamin B12 and may therefore be abundant at times and in places where this may be lacking whereas other phytoplankton may be absent. Such conditions may occur in the nutrient deficient waters above a well-developed thermocline.

From the points discussed above a strong negative association seems to occur between nutrient salt-levels and abundance of coccoliths in the Recent shelf sediments. Coccolith abundance is highest in sediments where surface-water nutrient concentrations are depleted in the summer months.

8.4.5.6 Water-depth.

As mentioned in section 8.5.4.1, the water-depth influences the degree of stratification of the water column, although to a lesser degree than the tidal stream velocities.

Water-depth is strongly positively correlated with coccolith abundance in open-water sediments from the Celtic Sea, English Channel and in the North Sea. Additionally, high coccolith numbers are also associated with the axial deep-water channel of the Irish Sea. The decline in coccolith numbers with water-depth, though, is less apparent in some very shallow-water environments. Large numbers of coccoliths (10^8 per gram) occur in intertidal sediments from estuaries in southwest Ireland and Cornwall. Such values reflect the transport of large numbers of coccoliths into the estuaries from offshore

stratified waters. Varol (1985) also recorded calcareous nannofossils from intertidal sediments in Jason Bay, South China Sea.

Large numbers of coccoliths in ancient sediments should therfore not preclude the interpretation of very shallow-water,or even estuarine environment of deposition.

8.4.5.7 Turbidity.

In general the distribution of turbidity in the shelf waters is similar to the distribution of salinity. High salinity Atlantic water has low turbidity levels; coastal waters have higher turbidity levels (Lee,1980).

Turbidity is generally low throughout most of the Celtic Sea and English Channel. In the eastern English Channel, however, turbidity is much higher. Here, the suspended matter concentrations are greater than in the adjacent Atlantic waters; the sediment is supplied by sources within the Channel (coastal run-off, coastal erosion and seafloor erosion). Suspended sediment concentrations in Channel water entering the Dover-Calais Strait are 1.2 to 2.7 mg/l at salinities above 35%. (Eisma and Kalf, 1976). Coastal waters along the Strait may be much higher, however, attaining 11 mg/l. Turbidity remains high throughout the southern North Sea, particularly along the coasts.

Atlantic inflow to the northern North Sea has low turbidity and carries suspended matter concentrations of the order of 0.1 to 0.2 mg/l (Eisma and Kalf, 1978). The inflow from the Baltic, through the Skagerak, although of low salinity (<35%.), has low turbidity and low suspended sediment concentrations ca. 1mg/l. Large numbers of coccoliths occur in both plankton (Pingree et al.,1982) and sediment samples (Mikkelson,1985) from the Skagerak.

The distribution of Recent coccoliths in the bottom

sediments of the shelf can be broadly correlated with variations in the turbidity and suspended sediment concentrations. Highest coccolith numbers occur in sediments deposited from low turbidity Atlantic waters; coccoliths are either scarce (10^5 per gram) or absent in sediments deposited from highly turbid waters (e.g., southern North Sea and eastern English Channel). Reworked coccolith abundances, however, are higher in sediments deposited from waters containing high levels of suspended sediments.

8.4.6 Phytoplankton growth in other temperate latitude shelf environments

The controls on coccolithophore distribution and abundance described from the shelf waters of northwest Europe should also be applicable to other temperate tidal-influenced shelves. One such environment is the Bay of Fundy and Gulf of Maine off the coast of Maine, USA and New Brunswick, Canada . Gran and Braarud (1935) described the plankton distribution in relation to the hydrography of this region. In the Gulf of Maine stratification of the water column occurred during the summer months, however along the coast the tidal currents between the islands and the shoals caused turbulance, making the waters more uniform than in the central part of the Gulf.

The Bay of Fundy, a slightly funnel-shaped side branch of the Gulf, is associated with very strong tidal currents. These currents ensure that throughout the greater part of the Bay the waters are well-mixed. However, in the summer (August) some degree of stratification occurs at the mouth and central region of the Bay. Coccolithophores were found to be most abundant in August. Greatest numbers occurred in offshore waters of the Gulf and at the mouth of and in the central region of the Bay of Fundy (>10,000 cells/l). However, in the tidally mixed waters along the coast of Maine coccolithophores were either rare (<1,000 cells/l) or absent. Coccolithophores were also rare along the borders

of the Bay of Fundy (<6,000 cells/l).

Therefore in the Gulf of Maine and Bay of Fundy coccolithophores were only abundant in the plankton where there was some degree of stratification in the water column.

8.4.7 Water stratification and coccolith abundance in low latitude marginal seas.

The association of water stratification and tidal-mixing with coccolithophore abundance in low latitude marginal sea and shelf environments is not well-documented. Most previous reports have concentrated on the correlation of coccolithophore abundance with salinity, depth and also nutrient concentrations ,although the latter two points are associated in general with the degree of stratification of the water column.

Winter et al. (1978), however, concluded that the most important hydrological control on coccolithophore occurrence in the Gulf of Elat was the breakdown of the upperwater stratification, resulting in the near uniform (21°C) temperature structure. Following this event many of the summer coccolithophore species disappeared, species diversity decreased dramatically and a rapid increase in the dominance of G.ericsonii G.oceanica and U.sibogae occurred. Conley (1979) noted that strong tidal currents in the Torres Strait, between Australia and Papua New Guinea, were associated with bottom sediments containing a very low diversity coccolith assemblage dominated by G.oceanica.

Okada and Honjo (1977) showed that coccolithophore distribution in the Arafara Sea and Gulf of Carpentaria off the northwest coast of Australia was controlled by a well-defined thermocline in these shallow waters (<65m). Generally, a small standing crop occurred in the surface waters while a larger population occurred in the bottom

layer. The presence of coccolithophores below the thermocline in the Gulf is in contrast to shelf waters from northwest Europe , where coccolithophores largely occur above the thermocline. Higher light intensities present at low latitudes mean that coccolithophore production in the bottom waters is not limited as at temperate latitudes.

The exact controls imposed by stratification and mixing processes have on coccolithophore assemblages in low latitude shelf and marginal seas have yet to be determined. However, it seems likely that even at low latitudes coccolithophore assemblages of low diversity are associated with well-mixed waters.

8.5 Some comments on ancient shelf and marginal sea coccolith assemblages.

Coccoliths and other calcareous nannofossils are generally abundant in marine strata of Jurassic to the present age , and occur sparsely in marine Triassic beds . The appearance of calcareous nannofossils in the Mesozoic was suggested by Twenhofel (1939, p.327) to have changed the location of the major sites of carbonate deposition. Paleozoic limestones accumulated in shallow epicontinental seas where the calcium carbonate could later be recycled, but since the Mesozoic, oceanic basins have been the major sites of calcium deposition as planktonic oozes. However, during the Mesozoic there were still some notable accumulations of coccolith-rich sediments in relatively shallow, epicontinental seas. Such deposits are generally thought to be associated with a marine transgression which submerges large areas of land, reduces the supply of detrital sediment and allows the accumulation of a near pelagic ooze. The reasons for the preferential accumulation of nannofossil oozes in some of these sites of deposition and the general palaeoceanography of these sites is now discussed.

The Lower Tithonian, Solnhofen lithographic limestones (Bavaria, Germany) have long been known to contain abundant coccoliths (Gumbel,1891). The fine fractions of these limestones contain approximately 500,000 coccoliths per cubic millimetre (Flugel and Franz,(1967). These laminated sediments consist of alternating limestones and thin marly intercalations in laminae averaging 2cm thick. The coccolith laminae were dominated by Watznaueria barnesae and Ellipsagelosphaera lucasi Noel with smaller contributions from other species.

Barthel (1970) has studied the depositional environment of the Solnhofen basin. He described a moderate relief terriginous coast in the north, a barrier reef in the south and numerous relatively deep (30 to 60m) lagoonal basins surounding isolated partly inactive, sponge, patch reefs. Water nutrients and some sediment were derived from the open sea to the south. A hot climate associated by strong evaporation was indicated by the presence of reptiles, corals, plants and carbonate-rich sediments. Stratification occurred in the lagoonal waters, with heavy salt-brines sinking to the lagoon floor. Bottom waters were stagnant, preventing the occurrence of benthos and preserving the finely-laminated sediments. The correlation of evenly and thinly-laminated beds over several miles, absences of evaporites and of algal growth on bedding planes, lack of tidal-channels, all indicated a continous cover of water in the lagoon. Occasional freshwater influences in the near-shore region were not excluded in Barthel's reconstruction.

The origin of the coccoliths in the Solnhofen Limestone has been the subject of much debate. Gumbel (1891) thought that the coccolith ooze was laid down in quiet bays by in-situ growth. Flugel and Franz suggested the lime-mud originated from drifting masses of plankton entering the Solnhofen basin. Van-Straaten (1971) believed the lime-mud was deposited from suspensions, the suspensions being caused by storms stirring-up carbonate mud which had been deposited in a very shallow sea, north of the present Solnhofen basin.

Busonje' (1972,a;b) has rejected the lagoonal environment of deposition suggested by Barthel. The abundance of coccoliths in the limestone was suggested by Buisonje' to be the result of accumulative coccolith blooms.

These blooms occurred in an open-water shelf environment at depths between 150 to 200m. Buisonje'

suggested that upwelling conditions bringing large quanties of nutrients to the surface caused the blooms , similar to modern red tides. Macro-organisms were thought to have been poisoned by toxins released from the intense coccolithophore blooms. The macro-organisms then rapidly fell to the sea bed. According to Buisonje' immediately after the deposition of these organisms, "a thick jelly-like mass of dead coccolithophorida reached the bottom too". Benthic invertebrates were restricted from the sediments by the lack of oxygen which occurred as the organic matter settled and decayed, thus preserving the finely-laminated structure of the sediments.

The dominance of one or two opportunist species in populations of high standing crop, but with a generally low species diversity, is certainly a feature of bloom conditions. However, the the Solnhofen Limestone is unlikely to have resulted from the accumulation of recurrent red tides. In modern seas, red tides are associated with much larger algal cells than nannoplankton, being dominated by large dinoflagellate cells. Additionally, intense blooms of coccolithophores have never been reported to release toxins, poisonous to macro-organisms. Such toxins have been reported to be excreted by twenty species of dinoflagellates (Tappan,1980).

Red tides occur with greatest frequency in tropical and subtropical regions, although they are also common in temperate climates. In all cases red tides are correlated with with regions of upwelling water in coastal regions, e.g., off the Pacific coast of North America, off Chile and off southwest Africa. These regions are characterised by large concentrations of nutrients caused by increasing turbulence and mixing. Red tides generally occur in late summer when water temperatures are high and the products of the decay of previous plankton crops are at a maximum. They also depend on temperature and salinity stratification effects, which increase the concentration of the cells in a small area. In such areas, large algal

cells will have adequate concentrations of nutrient to stimulate their rapid growth. Nannoplankton species with small Ks values are not Qbundant in upwelling areas.

Coccolithophores in laboratory experiments (Leadbeater, 1971) have been reported to move an average of 5 to 8 mm per minute at 18°C. This is probably less than the rate of current movement and they are regarded as relatively passive plankton. Thus in upwelling areas , populations of coccolithophores would be quickly dispersed. Dinoflagellates however, have much greater control on their movements. It is well known that they can migrate vertically in the sea in a diurnal pattern. In turbid eutrophic waters Ceratium fuscus descends during the night and rises to the surface during the day (Hasle, 1954). Therefore, dinoflagellates have the ability to migrate towards area of favoured growth ie., nutrient-rich waters.

The rapid deposition of coccoliths , in aggregates, from in-situ growth described by Buisonje' is not reflected in the mode of preservation of the coccoliths. The results of Flugel and Franz (1967) confirmed that the Solnhofen limestone is a micrite, with a mean grain size of 1 μm. Only 2% of the grains are >6 μm. The limestone consists almost exclusively of fragments of coccoliths and complete coccoliths are scarce. The coccoliths are not recrystallised and their fragments clearly show their boundaries and form the euhedral components of the limestones. The presence of delicately preserved insects and jelly-fish together with disaggregated coccoliths in the Solnhofen Limestone cannot be explained by the environment of deposition proposed by Buisonje'. Insects are not a reported constituent of continental shelf sediments deposited from areas of upwelling water. Forms such as the giant moth Kalligramma with a wing span of more than 21 cm are unlikely to have survived settling through 150 to 200 m in an open-shelf environment.

Fossil insects (including dragonflies and beetles)

have been reported from the Lower Lias of Charmouth, Dorset (Zeuner,1962). The environment of deposition of the Lias has been compared by Zeuner with that of the present-day Bombay coast. Here there are numerous islands and inlets and mud sedimentation occurs under quiet tidal conditions.

Fossil insects have also been reported from the lithographic limestones of Montsech (late Jurassic to early Cretaceous) Ledrida Province, Spain (Walley and Jarzembowski,1985). The limestone was deposited in a lagoonal-lacustrine environment which became stagnant at times (Sachairer and Janicke,1970). The insects occur in a fine-grained, well-cemented brown limestone. The limestones are are finely-laminated with no evidence of bioturbation and only a little of current activity. The incoporation of the insects was visualised by Whalley and Jarzembowski (1985, p.140) "as a gently 'rain' of water-logged material" and were not thought to have been deposited from storms or flash floods. Tranquil conditions of deposition are generally associated with the occurrence of insects in sediments.

The lagoonal environment of deposition proposed by Barthel (1970) is thought here to be the most likely origin of the Solnhofen Limestone. The coccolith detritus was probably transported into the Solnhofen Basin from offshore waters. The nannoflora of the sediments is dominated by Watznaueria barnesae and Ellipsagelosphaera lucasi Noel, both species with sturdy, placolith-type coccoliths. Yet,in the lagoonal sediments these coccoliths are generally disaggregated, being preserved as micron-sized crystals. The occurrence of such coccolith detritus, in an environment characterised by stratified, stagnant waters and by an absence of bioturbators in the bottom sediment, is most likely explained by the coccoliths being broken-up outside the Solnhofen basin. Once washed into the lagoonal waters the coccolith detritus settled slowly and was preserved in the thinly laminated sediments.

Abundant coccoliths occur in bands in the Upper Jurassic, Kimmeridge Clay of southern England and consist mainly of Ellipsagelosphaera brittanica (Gallois,1976). Tyson et al. (1979) also proposed a stratified model for the deposition of the Kimmerige Clay coccolith limestones. These bands are associated with the following lithological succession:

coccolith limestones
oil shales
bituminous shales
fine-grained clastics

This succession was attributed to the vertical movement of the oxygen: hydrogen sulphide interface in a temporarily stratified water column. This model was based on the modern analogue of the Black Sea. Microlaminated surface sediments occur in the Black Sea and consist of alternaing layers of dark laminae and coccolith oozes. The dark laminae have been interpreted as the products of seasonal mass mortality of the photosythetic bacteria that live just below the oxygen: hydrogen sulphide interface in the Black Sea. Cooling of the surface waters during the winter decreases the stability of the low salinity surface layer and enables turbulent mixing processes to descend to the oxygen - hydrogen sulphide interface. The subsequent oxygenation of these lower waters ensures mass mortality of the anaerobic bacteria. As the dead bacteria settle through the water column the contained elemental sulphur acts as a nucleus for the formation of pyrite framboids.

The clays at the base of the cycles described by Tyson et al. (1979) were suggested to be deposited under oxygenated bottom condition below normal wave base, partly by hemipelagic setting and partly from low density currents. The bituminous shales were believed to be formed during periods of fluctuating anaerobic conditions with a consequent preservation of greater amounts of organic matter. The oil shales represent predominantly

anerobic bottom conditions with only very weak current action and minimal clastic sedimentation. The high proportion of miospores in the oil shales and the sparsity of dinocysts were thought to represent a low-level of plankton productivity. The coccolith limestones marked the maximum distribution of anerobic bottom waters in the kimmeridge Clay basin . At this time the top of the H_2S zone had migrated to a level where it could supply nutrients by seasonal convective processes to the euphotic zone. This, was suggested, stimulated the coccolith blooms.

However, under such conditions in marine waters where large amount of nutrients are transferred to the surface waters coccoliths do not dominate plankton populations. Wangersky (1977) has shown that dinoflagellates become dominant when the major source of utilisable nutrients (ie., phosphorus and nitrogen) is organic matter regenerated from the degradation of dissolved organic compounds by bacteria.

An alternative explanation for origin of the Kimmmeridge Clay coccolith bands is that they originated from a highly stratified stagnant water column which was nutrient deficient. Very quiet water conditions of deposition are indicated by the abundant occurrence of well-preserved coccospheres in the bands. Settling through a very stable water column allowing an entirely pelagic mode of deposition is not consistent with waters where convective processes mix nutrients to the surface waters.

Tidal currents must have been remarkably weak in the Kimmeridge shelf seas. Comparisons with the modern shelf of the Celtic Sea show that even in the deepest waters of the shelf where the maximum tidal streams are 0.3m/s or less coccospheres form <0.01% of the total nannoplankton fraction. The Kimmeridge shelf, at least at the time of deposition of the coccolith bands, must have had very stagnant bottom waters conditions and was probably much

wider than modern counterparts.

The occurrence of coccolith-rich bands interlaminated with oil shales (kerogen-rich mudstones) has been suggested to represent alternating coccolith and dinoflagelate blooms (Gallois, 1976). Laminations are particularly distinct in the Freshwater Steps Stone Band in Dorset. Such an alteration of blooms might represent alternating periods of waters stratification and low-nutrient concentrations which would favour nannoplankton, whereas periods of upwelling nutrient-rich waters would be associated with dinoflagellate blooms.

The most widesread occurrence of coccolith-rich limestones were deposited across northwest Europe during the late Cretaceous. During this period, northwest Europe lay at the margin of the European Continent which was submerged below a widespread epicontinetal sea. (Hancock,1975) The Chalk sea in Europe was of normal marine salinity (~35%.) as shown by the widespread occurrence of echinoderms and brachiopods which cannot flourish in lower salinities . Most estimates of palaeodepth suggest that the Chalk was deposited between 50 and 200 m in an outer shelf environment (Hakasson et al., Kennedy and Garrison,1975). The marine transgresion of the Upper Cretaceous submerged large areas of land, thus reducing the supply of detrital sediment (Hancock,1975). This lack of detritus allowed a near-pelagic deposit of low-magnesium calcite to be laid down in the warm,shelf,chalk seas. The lack of seasonal supply of detritus in the Chalk sea would also cause a lack of seasonal variation in nutrient supply from the land.

Current action in at least part of the Chalk sea is strongly indicated by the mode of preservation of the coccoliths. Hancock (1975) describes the Chalk as being predominantly composed of two particle size ranges, 0.5-4 μm and 10-100 μm. The fine fraction is composed of individual coccoliths, and their skeletal fragments which

account for the sub-micron sized particles. Coccospheres are generally not observed in the Chalk. This general absence of coccospheres and predominance of coccolith detritus suggests that most of the coccolith debris is broken up during sedimentation. Such processes occur in the shelf seas of northwest Europe even at current speeds of the order of 0.3 m/s.

Other evidence for the occurrence of bottom currents on the Chalk sea floor is provided by the occurrence of beds of pebbles which may be bored or encrusted with oysters. Such pebbbles are on or within hard-grounds but even in soft white-chalk there are concentrations of small shell-fragments (e.g., in M.cortestudinarium zone of the Sussex coast (Kennedy and Garrison,1975)). Intraformational conglomerates also occur in the Chalk. These are current reworked accumulates of nodules derived from the sedimentary reworking of nodular chalks. Some of the special adaptions of animals to cope with a soft bottom were also useful in coping with currents. rhynchonellids occur with wing-like extensions of the deltidial plates which implies strengthening of the pedicle (Owen,1965).

The presence of hard-grounds and other such features such as ommission surfaces, winnowed horizons and nodular chalk indicate that the slow pelagic type of sedimentaion in the Chalk Seas was not continuous without breaks in supply of carbonate. Kennedy and Garrison (1975) attributed cyclicity in Upper Cretaceous chalks of southern England to sea-level change. Arthur et al. (1986): suggest that cyclic variation in the strength of bottom-current agitation may be the cause of these Chalk cycles. Varations in bottom current strength might be effected by periodic changes in the frequency and intensity of storms pasing over the shelf, by rates of evaporation and sinking and mixing related to wind intensities. During such periods of storms, the water column would have been disturbed and the pelagic mode of settling halted. Additionally, surface production of

coccolithophores would have been be reduced because of increased turbulence and decreased illumination.

The reported absence of coccospheres from the upper Cretaceous Chalk distinguishes these sediments from similar coccolith-rich thin limestones bands in the Jurassic, Kimmeridge Clay. These differences probably reflect variations in the bottom water conditions. The Chalk bottom waters were oxygenated and influenced at least periodically by currents , whereas the Jurassic limestones were deposited under quiet, stagnant, bottom waters. Such differences in bottom water conditions also are reflected in the amount of organic matter preserved in the different successions. Chalk is low in organic matter whereas the Jurassic limestones are associated with bituminous rich shales.

Further documentation of the mode of preservation of coccoliths and the occurence of coccospheres in sediments should be carried out. Such studies may provide valuble palaeoceanographic information on the mode of settling and deposition of sediments.

CHAPTER 9

CONCLUSIONS

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Coccoliths have been recorded from many estuarine and marginal marine environments from the shelf of northwest Europe. Coccoliths are particularly abundant (10^8 per gram) in intertidal sediments from estuaries in southern Ireland and Cornwall. Such values reflect the transport of large numbers of coccoliths into the estuaries from offshore stratified waters. These estuaries are therefore acting as silt-traps for marine-derived sediments.

The occurrence of large numbers of coccoliths in ancient sediments should therefore not preclude the interpretation of a very shallow water, or even estuarine environment of deposition.

The transport and deposition of coccoliths and other fine-grained sediments have been described in some detail in the Solent Estuarine System. Coccolithus pelagicus dominates the coccolith assemblages in the Solent sediments, forming >95% of the total assemblage. Coccolithus pelagicus occurs in consistent numbers (~50 x 10^5 per gram) throughout the open-water sediments of East Solent and Southampton Water. Numbers decline in the tributary inlets of the Hamble, Itchen and Test. This decrease in coccolith number reflects the declining marine-influence in these tidal inlets. Coccoliths and other micron-sized carbonate grains are either absent or very scarce in the estuarine and fluviatile sediments from the Beaulieu and Lymington. Carbonate supplied to these estuaries is dissolved by acidic run-off from the New Forest, where extensive areas of acid grassland, heathland and bog occur.

Reworked coccoliths (mainly Cretaceous forms) occur in large numbers throughout the sediments of the East Solent and Southampton Water (>200 $\times 10^5$ per gram). Abundances of the reworked forms decrease in an up-estuary direction in all the adjacent tributary estuaries of Southampton Water. Few reworked Cretaceous coccoliths are therefore supplied by the Chalk rivers of the Test and Itchen. This suggests that although these Chalk rivers are rich in dissolved carbonate (as bicarbonate ions), they carry little particulate Chalk detritus.

Reworked Cretaceous coccoliths together with Recent forms are transported into Southampton Water and its adjacent tributary inlets by marine currents. They are supplied as suspended sediments during flood tides. The Chalk cliffs on the Isle of Wight are considered to be the main source of the Cretaceous coccoliths found in the Solent. Large numbers of Eocene coccoliths are only found in sediments from the lower Hamble Estuary. These forms are thought to be derived from the Bracklesham Group which are exposed at the mouth of the Hamble and at Lee-on-Solent. Potassic feldspar (microcline) can be used as a tracer of fluviatile input to the estuaries of Southampton Water and also in the Lymington and the Beaulieu. The feldspar is supplied from Tertiary deposits which outcrop over extensive areas of the Hampshire Basin.

Two sediments were examined from the continental slope, at the western margin of the Celtic Sea. These sediments contain twenty species of Recent coccolith. High numbers of coccoliths (10^{10}per gram) occur in these sediments, accounting for 62 to 68% of the fine fractions and up to 82% of the carbonate fine fraction. The assemblages contain three dominant species: E.huxleyi (66 to 68%), G.caribbeanica (20%) and C.leptoporus (11.1 to 12.7%). This species-composition is typical for the northeastern North Atlantic.

Two distinct coccolith assemblages are delineated within sediments from the continental shelf of the Celtic Sea and English Channel:

1) outer shelf assemblages (Celtic Sea and western English Channel),

2) inner shelf assemblages (central and eastern English Channel.

Eighteen coccolith species are recorded from the outer shelf assemblages. Eight or more of these species occur from any one site. Abundances range from 10^9 coccoliths per gram in the central and southern Celtic Sea to 10^8 per gram in the northern Celtic Sea and western English Channel. All coccolith species decline in abundance in these general directions. A characteristic feature of the assembalges in this region is their homogeneity. E.huxleyi dominates the assemblages, particularly in open-water sites , where it forms over 90% . C.pelagicus and S.pulchra are the only other ubiquitous species. These species usually form <5% of the assemblages. Gephyrocapsa caribbeanica occurs in most of the samples and averages 2.0% of the assemblages.

Minor species found in the assemblages (2.0 to 0.1%) include Helicosphaera carteri, Rhabdosphaera clavigera, U.sibogae, B.bigelowii, D.tubifera, Syracosphaera nodosa, and Calcidiscus leptoporus. Trace amounts (<0.1%) of Umbilicosphaera hulburtiana, Syracosphaera histrica, Coronosphaeara mediterranea, Sycosphaera apsteinii and Pontosphaera discopora also occur in the assemblages. Coccoliths are rare (10^7 or less) in the Recent sediments of the inner shelf of the central and eastern English Channel and account for less than 1% of the fine fraction. Species-diversity is low in the region ranging from four to six species in the central Channel to three or fewer in the eastern Channel. Greatest numbers of coccoliths are transported northwards and northeastwards in the Celtic

Sea, rather than eastwards into the English Channel. The variations in coccolith abundance and species diversity are attributed to the hydrological factors which distinguish the Celtic Sea waters from those of the central and eastern English Channel. The degree of tidal influence is considered the most important control on coccolith distribution in Recent sediments of the two regions. In areas of weak tidal currents (<2 kts) in the Celtic Sea and in the western English Channel, sediments deposited beneath a pronounced thermocline contain abundant coccoliths. In the central and eastern English Channel, where tidally mixed waters prevail all year round, a sparse nannoflora is deposited. Reworked nannofossil assemblages occur frequently in the sediments, particularly in the central and eastern English Channel. Here because of reduced primary productivity and because of the proximity of Chalk and Tertiary outcrops, the reworked nannofossil component exceeds 90% of the total flora.

Eight species of Recent coccolith occur in the sediments of the Irish Sea: E.huxleyi, C.pelagicus, S.pulchra, H.carteri, G.caribbeanica, C.leptoporus, R.clavigera and B.bigelowii. The assemblages are dominated by E.huxleyi which forms up to 94.0% of the total nannoflora. Coccolithus pelagicus is subordinate in the assemblages although its abundance increases in coastal sediments.

The distribution and abundance of coccoliths in the Recent sediments of the Irish Sea are controlled by water-currents and the water column conditions. Highest numbers of coccoliths occur in sediments at the mouth of St. George's Channel and in an isolated area of weak-tidal currents to the southwest of the Isle of Man. The bulk of the coccolith assemblages in the sediments of the Irish Sea are supplied from Atlantic water flowing north through St. George's Channel. Southwards currents through the North Channel are thought to be of little importance in the transport of coccolith species into the

Irish Sea. Large tidal currents at the mouth of St. George's Channel may act as an ecological filter barrier for many of the pelagic species found in the Celtic Sea but missing from the Irish Sea.

Ten species of Recent coccolith occur in the sediments of the North Sea; E.huxleyi, C.pelagicus, S.pulchra, C.leptoporus, G.caribbeanica, C.mediterranea, R.clavigera, D.tubifera and B.bigelowii. The coccolith assemblages are dominated by E.huxleyi which averages 93.5% of the flora in the northern North Sea sediments. Subordinate species (1 to 2.5 %) include C.pelagicus, S.pulchra and G.caribbeanica. The other species only form a minor component (<1.0%). Filter samples analysed from the northern North Sea also showed a dominance of E.huxleyi (97.3%) in the overlying waters. A comparison between the coccoliths in the filter and in the sediment samples delineated differences in the state of preservation between the two sample types. Coccoliths present in the surface sediments frequently showed signs of dissolution on their skeletal elements, whereas coccoliths filtered from the water column generally had a more pristine condition.

The distribution of coccoliths in the surface sediments of the North Sea are controlled by currents and the varying hydrographic conditions present in the overlying waters. Highest coccolith numbers (10^9 per gram) are deposited at the northern and northwestern margins of the North sea, where Atlantic influences are pronounced. These waters are stratified in the summer and have surface salinities varying from 34.0 to 35.2%. . Coccolith assemblages deposited in this region contain five or more species. Coccolith abundance and species-diversity decrease steadily from north to south over the region, reflecting the decreasing component of Atlantic water and in the increasingly mixed character of the water mass. Recent coccoliths are generally absent in the southern North Sea, south of 54° S. The waters of this region are tidally-mixed and have medium to low salinities (<35.0%.),

The coccolith assemblages found in the Recent sediments are mainly supplied from North Atlantic inflow between Shetland and the Norwegian coast. Smaller numbers of coccoliths are also transported through the Fair Isle Channel. Northward flowing Channel water from the Dover Strait is not a major supplier of coccoliths to the central and northern North Sea. The main difference between the North Sea and Celtic Sea assemblages is the absence in the North Sea sediments of the warm-water species-component of the Celtic Sea assemblages. These difference are thought to reflect the lower temperature (~12 or less) of the Atlantic inflow to the North Sea. The described distribution and abundance of coccoliths in the Recent shelf sediments of Northwest Europe reflects the overlying hydrographic conditions of the water column. The degree of vertical mixing which largely determines the availability of light energy and nutrients for phytoplankton growth is thought to be the most important control on coccolith abundance .

In stratified waters with a well-developed thermocline large populations of coccolithophores occur in the surface waters, particularly during mid and late summer. Coccolithophore growth is enhanced in this good light regime and is also favoured by low nutrient levels as nannoplankton cells have low Ks values. Low nutrient levels occur in the surface waters overlying a thermocline as there is little exchange of water properties across the thermocline boundary. In tidally mixed waters, associated with strong tidal currents, coccolithophores are either rare or absent. Although there are sufficient nutrients for algal growth, coccolithophores present within the water column are removed from the surface waters before any significant growth can occur. Additionally, well-mixed waters because of their associated high nutrient levels are generally favoured by large-celled species with high Ks values (ie., diatoms).

The environmental preference of coccolithophores for

low concentrations of nutrients and well-stratified waters explains the spatial variations of coccolith abundance recorded in the sediments. The spatial variations in coccolith abundance across a frontal region between stratified waters and tidally mixed waters are shown schematically in Fig. 9.1 Highest coccolith abundances and numbers of species are found in assemblages deposited from a well-defined thermocline, ie., in the Celtic Sea and western English Channel and in the northern North Sea. Coccoliths are either rare or absent in sediments deposited from tidally mixed waters, ie., in the central and eastern English Channel and in the southern North Sea.

Similar controls on coccolith abundance are likely to have occurred in ancient shelf and marginal sea environments, at mid to high latitudes. The presence of coccoliths in such environments and their mode of preservation should provide information on the degree of tidal influence within the water column. The occurrence of well-preserved coccospheres in shelf sediments is a good indicator of a weak tidal current system and an entirely pelagic mode of settling. Ancient shelf sediments barren of coccoliths but deposited from near-marine salinities (~34 ‰ or greater) may be interpreted as representing deposition from a well-mixed water column.

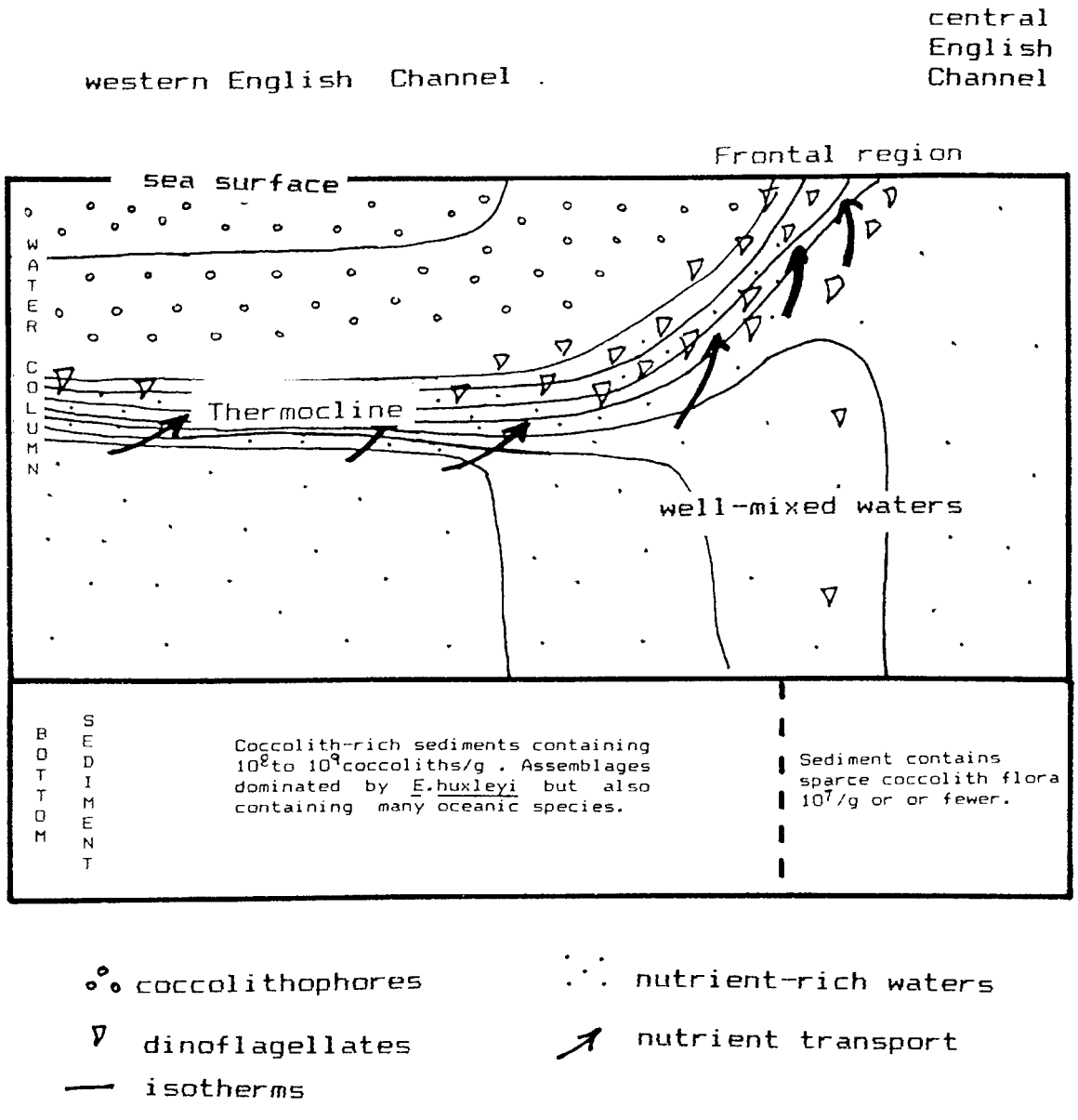


Figure 9.1
Spatial changes in coccolith abundance across the frontal region in the western English Channel. Water-column conditions represent the period from May to September when a thermocline is developed in the western English Channel. Large populations of coccolithophores, dominated by Emiliania huxleyi, occur in the nutrient-deficient, well-illuminated waters above the thermocline. Coccolithophores are scarce in the well-mixed waters of the central English Channel. Dinoflagellates are more abundant within the thermocline itself and at the frontal boundary, where nutrient renewal across the thermocline stimulates their growth. Coccolith abundance in the bottom sediments mirrors the distribution in the overlying waters with greatest numbers being deposited below the region of thermocline development

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APPENDICES

APPENDIX 1

Carbonate (CO_2) determination by infrared analysis.

CO_2 was detected and measured by infrared absorption using a BINOS (Ley Bold-Haraeus) infrared photometer set to the appropriate wavelength. In this study 100% Analar $CaCO_3$ was used as a standard. Carbonate CO_2 was determined by treating 0.02g of sample, weighed into a glass boat, with phosphoric acid. The acid treatments were carried out in an enclosure at an elevated temperature at 125° C, in order to facilitate faster reaction and prevent rentention of evolved CO_2 in the solution.

With the aid of oxygen gas-flow (a flow rate of ~200 cc/min was used) the evolved CO_2 was fed into a 1 litre volumeter. The CO_2 and O_2 mixture was expelled through the infrared analyser and the output was visually displayed by meter and displayed on a chart recorder. 0.02g of sample was weighed and processed in the same way, as the standard and the measured concentration compared to the Analar standard concentration.

Repeat measurements of standard Analar $CaCO_3$ showed that the infrared gas analyser posessed a precision of $\pm$ 4% .

APPENDIX 2

X-ray diffraction techniques.

In the present study all samples were run on a Phillips (PW1010) X-Ray diffractometer with Ni-filtered

Cu/Kα radiation generated at 36 KV and 24 mA.

Previously ground bulk samples (<40 μm) and fine-silt fractions (2 to 20 μm) of selected samples were placed in a holder using a glass slide to smooth the target area and then directly X-rayed over the required 2θ range. The diffraction traces were recorded at an angular velocity of $2^{\circ}2\theta$ per minute using 1° aperture slits, at a time constant of 1 second and, depending on intensity, count rates of 1×10^{3} to 4×10^{4} counts per second.

XRD analysis was used here to dectect variations in the ratio of minerals in samples rather than to determine absolute mineral abundances. Calcite/quartz and potassic feldspar/quart peak height ratios were measured from the diffraction traces. The reflections used for mesuring the ratios were quartz (101) at 3.34 Å, calcite (104) at 3.03 Å, and potassic feldspar (002) at 3.24 Å.

Each sample was run twice and the average value taken. Repeat measurements showed that the technique had a precision of $\pm$ 12% .