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ENVIRONMENTAL VARIABLES, INCLUDING POLLUTANTS, AFFECTING LIVING BENTHONIC FORAMINIFERIDA

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ENVIRONMENTAL VARIABLES, INCLUDING POLLUTANTS, AFFECTING LIVING BENTHONIC FORAMINIFERIDA.

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Abstract.

Studies of living benthonic foraminiferal assemblages carried out by marine biologists are comparatively rare. This study of the changes in foraminiferal assemblages from three subtidal sites near Plymouth, U.K., has been carried out with the intention of determining the importance of various abiotic and biotic variables to the foraminiferal communities studied using statistical correlation. Temperature and salinity at depth and particle size characteristics together with organic content, bacterial abundance and type, and other meiofauna present were assessed monthly with samples taken for foraminiferal content, and for seasonal diatom analysis.

Deformed specimens were very rare in the examined samples of natural assemblages. Three different systems were used in an attempt to culture *Elphidium crispum* (Linné) for ecotoxicological studies, which failed. Ecotoxicological studies were carried out upon *Rotaliella elatiana* Pawlowski & Lee and adult *Ammonia batavus* (Hofker). The types of deformation produced by laboratory-maintained Foraminiferida were found not to be specific to the stressor used and, therefore, the use of this group of Protozoa as indicators of specific pollution is not possible.

The methods which *Elphidium crispum* utilises to remain epifaunal were investigated and found to be primarily controlled by phototaxis, together with geotaxis.

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"Ralph Nimmo had no college degree and was rather proud of it. 'A degree,' he once said to Jonas Foster, when both were considerably younger, 'is a first step down a ruinous highway. You don't want to waste it so you go on to graduate work and doctoral research. You end up a thoroughgoing ignoramus on everything in the world except for one subdivisional sliver of nothing.'"

Isaac Asimov, 1994.

DECLARATION

This is to certify that the work submitted for the Degree of Doctor of Philosophy under the title "Environmental variables, including pollutants, affecting living benthonic Foraminiferida" is the result of original work.

All authors and works consulted are fully acknowledged. No part of this work has been accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree.

Whilst carrying out this study a parallel study, concerning the distribution of live and dead Foraminiferida in Plymouth Sound, was undertaken by Paul Castignetti. Several samples were simultaneously taken by the author and P. Castignetti for their respective research, and the analysis of foraminiferidal content of cores was a collaborative venture. However, all the opinions and interpretations of data are entirely my own and my own responsibility.

During the course of this research the following papers have been published or submitted on the results obtained:

Manley, C.J., Shaw, S.R., 1997. Geotaxis and Phototaxis in *Elphidium crispum* (Protozoa: Foraminiferida). *Journal of the Marine Biological Association of the U.K.*, **77**.

Castignetti, P., Manley, C.J. The Correlation of Energy Levels and Vertical Distribution of Foraminiferida from Plymouth Sound; A Preliminary Study. Submitted to *Terra Nova*.

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CHAPTER 1.

FORAMINIFERIDA.

1.1. LIVING FORAMINIFERIDA.

Foraminiferida are members of the Phylum Protozoa: unicellular, eukaryotic, water-dependent organisms ranging in size from 2 μm-1000 μm (Clarholm, 1984). The basic constraint on the maximum size of unicellular organisms is the rate of diffusion (Fenchel, 1987). Fossil Foraminiferida have been found up to 7 cm in diameter, although most species of indigenous living Foraminiferida rarely exceed 1000 μm (1 mm). The Order Foraminiferida is a diverse group; most species are benthonic (Lee, 1990) and found at all latitudes (Leadbeater, 1991).

Representatives of this group are found in all marine waters ranging from hyposaline estuaries to hypersaline lagoons and salt marshes. Foraminiferida can be either planktonic (in suspension in the water column) or benthonic (living upon the sea bed). Only representatives of the benthonic taxa are found living in nearshore localities (Murray, 1979 {a}), whereas planktonic taxa are found in oceanic waters. Species of benthonic Foraminiferida can be further divided into those which are epifaunal (living at the sediment/water interface) or infaunal (living below the sediment/water interface).

1.2. THE TEST OF FORAMINIFERIDA.

The foraminiferid cytoplasm is enclosed by a test and classification is mainly based upon test morphology, although the production of granular and reticulose pseudopodia from the test have placed Foraminiferida in the Subclass Granuloreticulosia (Murray, 1979 {a}). The name Foraminiferida is derived from the Latin meaning "hole-bearers" and Foraminiferida have unilocular to

multilocular tests with at least one aperture. Some tests are simply composed of mucopolysaccharide but in others adventitious fragments are incorporated into the test, and in the best known forms the organic layer is reinforced with calcite, aragonite or occasionally silica spicules (Sleigh, 1991). Living Foraminiferida have tests composed of either arenaceous material (called arenaceous or agglutinated) or calcium carbonate and d'Orbigny was first to separate Foraminiferida into these two groups (Vinogradov, 1953). The common calcareous species can be subdivided into those having an imperforate test composed of small randomly arranged calcite crystals (called porcellaneous or imperforate) and those having pores and longer radial calcite crystals (called hyaline or perforate). The tests of calcareous species can be differentiated under a light-microscope; the tests of porcellaneous species are opaque and usually shiny in living forms, whilst the tests of hyaline species are translucent. Agglutinated, porcellaneous and hyaline tests form the three major suborders of extant Foraminiferida: Textulariina, Miliolina and Rotaliina respectively. The composition of the test, the number and arrangement of chambers and details of the aperture are used to classify to species level.

1.3. NUTRITION OF FORAMINIFERIDA.

Foraminiferida feed by their pseudopodia which gather unicellular algae, bacteria or organic detritus. Some species can utilise dissolved organic matter from the environment or from symbiotic algae held within the test. A review by Lipps (1983), shows that this group exhibits almost all known forms of feeding utilised by marine organisms and include herbivory, carnivory, suspension-feeding, detrital and bacterial scavenging, parasitism, cannibalism and symbiosis. The pseudopodia also allow Foraminiferida to move on, or through, substrata.

1.4. REPRODUCTION OF FORAMINIFERIDA.

Sexual and asexual reproduction generally occur in foraminiferid species, with only a few of the smaller species reproducing solely by binary fission, budding, fragmentation or cytogamy (Bock *et al.*, 1985). Sexual reproduction results in haploid gamonts which fuse to form a zygote, whereas asexual reproduction results in diploid agamonts. The utilisation of both types of reproduction is characteristic of plants (Murray, 1979 {a}) and the heterokont flagellation of gametes may indicate a link to an ancestral chrysophyte group; perhaps the Rhizochrysidales (Lee *et al.*, 1969). A strict alternation of generations may not occur and there may be several agamontic generations (schizogony) between gamontic phases (Murray, 1979 {a}). The reproductive cycle generally ranges from months to a year (dependent upon size of species and whether the environment is suitable) and the type of reproduction utilised may be nutritionally driven (Lee *et al.*, 1969). The first chamber formed is called the proloculus, and the size of the proloculus differs within species dependent upon the type of reproduction; sexual reproduction gives rise to offspring with relatively small prolocuIi (microspheric), whereas asexual reproduction gives rise to offspring with relatively large prolocuIi (megalospheric).

1.5. DEATH OF FORAMINIFERIDA.

Invertebrates typically suffer a high death rate both at the beginning and end of the life-cycle (Raup & Stanley, 1971). Foraminiferid mortality may occur as a result of reproduction, predation, disease, parasitic attack or unfavourable environmental factors. The offspring of reproduction are produced from the parental cytoplasm and, in calcareous species, much of the parental test becomes de-calcified to provide calcium carbonate for the tests of the offspring; this usually results in the death of the parent. Unselective predation of Foraminiferida may be carried out by many organisms, especially by deposit feeders and fish which ingest soft sediments.

Foraminiferid tests have been found in the digestive tract of the classes Polychaeta, Crustacea, Gastropoda, Asteroidea, Echinoidea and Holothuroidea (Mageau & Walker, 1976). Selective predation upon Foraminiferida is carried out by some decapods and shrimps, and predatory molluscs include various opisthobranch gastropods and scaphopods (Murray, 1973). Although Foraminiferida often pass through the gut of predators unharmed, some gastropods and scaphopods destroy the tests (Murray, 1973). The sand dollar *Mellita quinquiesperforata* selectively feeds on microeukaryotes and bacteria attached to silt and clay (Findley & White, 1983) and in the southwestern Pacific, penaeid prawns selectively prey upon Foraminiferida (Chong & Sasekumar, 1981; Moriarty & Barclay, 1981). Scaphopoda are also selective predators of Foraminiferida; Poon (1987) found that a species of Scaphopoda feeds preferentially on living Foraminiferida, especially *Uvigerina* species in British Columbia; and Bilyard (1974) observed that *Dentalium entale stimpsoni* preferentially selects *Quinqueloculina* species and *Islandiella islandica* (Nørvang), consuming 2.4% of the annual standing crop. Parasitism occurs between some foraminiferid species; and nematodes bore holes into foraminiferid tests and are probably parasitic upon them (Murray, 1973). Burial of Foraminiferida may be caused by the activities of fish, especially rays, leading to death. It is also possible that red tides, caused by dinoflagellate blooms, may asphyxiate Foraminiferida, because when these organisms die they produce an anoxic mucilaginous layer on the sea bed.

1.6. GEOLOGICAL IMPORTANCE OF FORAMINIFERIDA.

Fossilised Foraminiferida have been found from the Cambrian period through to the Quaternary (Glaessner, 1963). The number of modern Foraminiferida occurring in earlier faunas decreases with increasing geological time and approaches zero in pre-Eocene sediments (Alve & Nagy, 1990). Most Recent species evolved in the middle or early Miocene and most Recent genera evolved in the late Cretaceous or early Tertiary (Douglas, 1979). Because of their extensive

variability, abundance and rapid evolution Foraminiferida are excellent biostratigraphic indicators (Boltovskoy & Wright, 1976) and they have become important in oil exploration and micro-palaeontology, as well as in biostratigraphy and palaeoecology (Lee, 1990). Foraminiferida are used for the biostratigraphical correlation of borehole successions and have also been used to interpret ancient depositional environments (Phleger, 1964; Murray, 1980). Calcareous tests are well-preserved in sediments unless they become dissolved at the Carbonate Compensation Depth. Calcareous tests are universally distributed in marine sediments and may demonstrate test variabilty due to slight environmental differences (Myers, 1943). They have also been used to interpret the circulatory currents of oceans through time, ecological and zoogeographic problems and palaeoclimatic problems (Boltovskoy & Wright, 1976). Due to the small size of Foraminiferida, the interest from the oil industry, and because they date from the Cambrian, this has resulted in more foraminiferid species being described than within any other group of Protozoa. Approximately 34,000 species have been described, of which 4,000 species are living today (Bock *et al.*, 1985).

1.7. IMPORTANCE OF FORAMINIFERIDA TO THE MARINE ECOSYSTEM.

On the ocean floor benthonic invertebrates are the primary consumers. Meiofauna (organisms less than 500 μm) are generally interstitial and are composed of diverse animal phyla. Protists are important consumers of bacteria, and heterotrophic Protista have a ubiquitous distribution, ingesting a wide range of food types, and so at times, controlling algal and bacterial production (Capriulo, 1991). Marine Protozoa, by grazing on bacteria, phytoplankton and zooplankton form a critical link in the food web (Atlas & Bartha, 1981); and as members of many food chains they play a role in the ecology of a vast number of species (Mageau & Walker, 1976; Atlas & Bartha, 1981). Protozoa are small organisms which have the potential for rapid growth, have a high metabolic rate and, therefore, a relatively

small protozoan biomass may have a relatively large effect on element cycling (Fenchel, 1987). The heterotrophic utilisation of amino acids, lipids, glucose, silicate, phosphate and bicarbonate may put dissolved organic matter into a particulate form for other organisms (Newell, 1979). It appears that each meiofaunal species is specialised for food type, allowing large numbers of meiofauna to exploit the different nutrients available within an area. Detritivores are known to utilise different parts of the microbial community and may co-exist in high densities (Newell, 1979).

Benthonic Foraminiferida are important members of the meiofauna, converting bacterial and unicellular algal nutrients into a form which can be preyed upon by many phyla of other marine organisms and regenerate nutrients within the system. Benthonic Foraminiferida have been found to play a very important role in the cycling of organic matter in marine benthonic environments; Altenbach (1992) found that approximately 6-10% of the total organic flux arriving at the sediment surface (Kiel Bight and Norwegian Sea) was ingested by benthonic Foraminiferida. Foraminiferida are generally recognised as the major producers of calcium carbonate sediments in the world's oceans (Muller, 1974). Calcitic "oozes" are found as sediments within the large oceans and are formed from the calcareous tests of Foraminiferida and coccolithophores. The incorporation of carbon dioxide into the calcium carbonate tests of Foraminiferida is an important sink for this gas.

1.8. HISTORY OF FORAMINIFERAL STUDIES.

According to Haynes (1981), Herodotus was the first person to describe fossil Foraminiferida from the pyramids of Egypt in the fifth century B.C. and, until d'Orbigny in 1826, the Foraminiferida were believed to be inorganic (Boltovskoy & Wright, 1976). Since d'Orbigny's initial classification many workers have collected and described species, and Loeblich & Tappan (1987) provide the most up-to date classification of this Order. Geologists recognised the importance of

Foraminiferida for micropalaeontology, but until Murray's work (1965 {a}) linking the distribution of living Foraminiferida with environmental variables no work was carried out upon the quantitative distribution of living Foraminiferida. Following Murray's work many fellow geologists have linked the distribution of living Foraminiferida with the abiotic variables of the environment: with water depth, temperature, salinity and substratum characteristics; and, more recently, organic content being recorded. There has been no biological interest in living Foraminiferida until recently because, unlike most Protozoa, Foraminiferida are not medically important; nor are they pathogens or parasites of commercially important fish or crustaceans. Biological interest is mainly centred on the culture of species in laboratories to understand the life-cycle of Foraminiferida. Although marine Foraminiferida show only a very small proportion of the population to be abnormal, some fossilised Foraminiferida show abnormalities in test morphology (Arnal, 1955). Some living specimens produce test aberrances which have been correlated with salinity extremes (Almogi-Labin *et al.*, 1992) and to the presence of heavy metals (Alve, 1991; Sharifi *et al.*, 1991).

1.9. AIMS OF THE STUDY.

The aims of this investigation are to study the changes in foraminiferid abundance at three sites throughout an annual cycle and to correlate these changes not only with the abiotic variables (temperature, salinity and sedimentary factors) but also with biotic factors (organic, bacterial and diatom content of the sediment and other meiofauna present). In order to investigate whether abnormalities of the test are caused by pollutants it is intended to culture Foraminiferida in the laboratory and expose the offspring to heavy metals in solution, and to extremes of salinity. The number of abnormal specimens in sediments from the three sites sampled will also be recorded. In addition a small study upon *Elphidium crispum* (Linné) will be undertaken to try to establish the mechanism by which this species remains epifaunal.

CHAPTER 2.

SAMPLING & TAXONOMY.

2.1. INTRODUCTION.

The quantitative sampling of Foraminiferida in each of three sites each month for a period of a year was undertaken. This section of the study describes the sampling technique, sampling sites and the processing of samples. The taxonomy of the foraminiferid fauna is also provided.

2.2. SAMPLING DEVICE.

The type of sampling device for any study must be carefully chosen to meet the requirements of the investigation. Many grabs have been designed to sample the marine benthos, but few are suitable for the quantitative recovery of Foraminiferida. For this investigation a replica of a grab designed by W. G. Murray & J. W. Murray (1987) (referred to as the "Murray Grab"), specifically constructed for the quantitative recovery of subtidal marine benthonic Foraminiferida, was used.

The flocculent layer at the sediment/water interface often contains a rich and delicate meiofaunal assemblage (Gooday, 1986; Murray, 1987) and most sampling devices disturb or lose part of this layer (Douglas *et al.*, 1980; Thiel, 1983; Eleftheriou & Holme, 1984; Gooday, 1986). The Murray Grab takes samples with minimal disruption and allows no winnowing of fine sediment by sealing the sample with a water-tight rubber seal. The grab collects the upper 1 cm of the sea bed in most sedimentary facies, although in soft muddy sediments a deeper section may be removed.

A copy of the Murray Grab (constructed by Adrian Matthews; University of Plymouth Workshop) was slightly modified in that a twenty pound weight was added to aid triggering the device in rough weather. Samples were retrieved in

depths of water ranging from 1 m to 11 m in all weather conditions. The grab has been designed to sample only the upper 1 cm of substratum within a 10 cm by 10 cm container, providing a good quantitative sample in most sediment types of 100 cm^3, excluding only pebbly sediments where foraminiferal abundance would be negligible due to high wave energy. The sample recovery varied slightly, however, with generally more sediment being recovered from the Drake's Island site (probably due to the extra weight added to the grab to aid triggering), resulting in more than 100 cm^3 of sediment being taken from this substratum.

This method of sampling allows direct comparison of foraminiferal abundance both temporally and geographically. The design of the grab is such that the fine proportion of the sediment is not lost, or "winnowed", from the sample container as it is winched up through the water column, unlike other grabs. This characteristic is invaluable to foraminiferal sampling, as particle sizes of 63 µm and above are analysed for foraminiferal content. It also allows a more accurate determination of sediment organic content, bacterial enumeration and identification, particle size and diatom identification than could be assessed using other grabs.

Although Foraminiferida are more abundant within sediments than attached to plants (Lee, 1974) the proportions of the assemblage which are epiphytic or epilithic would be under-represented using the grab (Lutze & Thiel, 1989). Hedley (1958) reports that the stalked *Haliphysema tumanowiczii* is common in the Plymouth area, but due to the nature of sampling for this study this epiphytic/epilithic taxa has not been encountered, although the collection of *Miliolinella subrotunda* (Montagu) which is elevated above the sediment surface by producing a tube (Altenbach *et al.*, 1993) was collected. Also, due to the drying of the sediment, fragile organic testate forms would not be recognisable. The possible misidentification of soft-bodied "squatter" Foraminiferida in tests of other species (Moodley, 1990 {b}) may also over-represent some species, but as

identification of Foraminiferida is carried out only with reference to the morphology of the test, this would be impossible to quantify.

2.2.1. Testing the sampling device.

The purpose of this part of the study was to examine the efficiency of the Murray Grab and to verify that sampling the upper 1 cm of sediment provides a representative sample of the foraminiferal assemblage as well as collecting the portion of the sediment which contains the highest numbers of living Foraminiferida. Species which may not be present, or under-represented, in such a sampling programme are identified. This part of the study was collaborative work carried out by Paul Castignetti and the author, and only the live taxa separated from the sediment will be discussed in this Chapter. Appendix I contains the raw data.

Various authors have determined from core data that foraminiferid species have well-defined depth habitats (see Kitazato, 1981, 1994; Gooday, 1986; Moodley, 1990 {a}; Buzas *et al.*, 1993; Corliss & van Weering, 1993; Hunt & Corliss, 1993; Jorissen *et al.*, 1992; Rathburn & Corliss, 1994). To ascertain the depth to which Foraminiferida were living in the sample area nine cores were taken by diver (Rod Jones: Institute of Marine Studies, University of Plymouth). Different sedimentary facies often contain different foraminiferal assemblages (Boltovskoy & Wright, 1976) and, therefore, six areas of different sedimentary facies were cored for analysis. The positions of the core localities are shown in Figure 2.1. The samples ranged from low-energy areas characterised by muddy sediments, to areas of high-energy characterised by shell gravels. It is believed that sediment particle size is a very important factor influencing foraminiferal species distribution on and in the sediment, as it may influence chemical parameters within the habitat, such

as oxygen, organic content, pH and Eh (Boltovskoy & Wright, 1976; Murray, 1991).

2.2.2. Materials & Methods.

Staining of previously-frozen Foraminiferida with the protoplasmic stain Rose Bengal was tested by freezing Foraminiferida for 48 hours, thawing and staining, after which the foraminiferal protoplasm was found to accept the stain in the way characteristic for each species.

Nine cores were taken on six sites, although the data from three cores were not used due to very low abundance of stained Foraminiferida. This study comprised a relatively small number of samples as it was designed to evaluate the Murray grab within different sedimentary facies. Four cores of 48 cm length and 4.4 cm diameter were taken by diver (Rod Jones; Institute of Marine Studies, University of Plymouth) in June, 1994 from the areas of Withyhedge Beacon, Drake's Island, Barn Pool and Queen's Ground (Fig. 2.1.). Five cores of 48 cm length and 4.4 cm diameter were taken by diver (Rod Jones; Institute of Marine Studies, University of Plymouth) in April 1995 in the areas of Withyhedge Beacon, Drake's Island, Barn Pool, Melampus Beacon and the Breakwater. Because of poor weather conditions, the Queen's Ground core could not be repeated and was replaced by the core from Melampus Beacon and an additional sample was taken inside the Breakwater. The first set of cores was taken in 1994 and the second set in 1995 to allow for inter-annual variations within the foraminiferal assemblages. Core recovery was variable ranging between 18 cm and 48 cm of sediment. The cores were sealed on the sea bed and kept in an upright position until freezing in the laboratory. The frozen cores were then sectioned. The topmost 1 cm of the core formed section 1, the next 2 cm section 2, three further lengths, each of 5 cm, became sections 5a, 5b, and 5c.

The remainder of each core was divided into 10 cm lengths, as sections 10a, 10b, and 10c. Cores were taken from the sediment/water interface downwards; in cases of poor recovery the lower part of the sediment column was not retrieved.

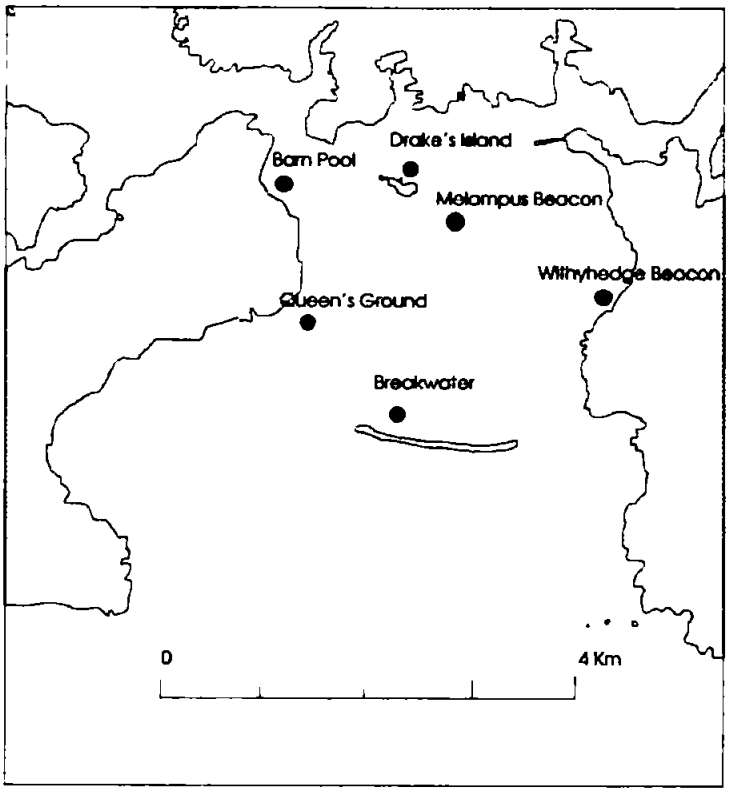


Figure 2.1: Localities of sample sites for cores.

When thawed, the separated fractions were individually wet-sieved over a 63 μm sieve and flooded with Rose Bengal at a concentration of 1g per litre of distilled water (Walton, 1952) for a period of 20 minutes. The excess Rose Bengal solution was rinsed from the samples which were then dried thoroughly in an oven at 60°C. Foraminiferida were separated from the sediment by flotation with carbon tetrachloride (specific gravity 1.56). Each fraction from each core was then analysed for Foraminiferida. Foraminiferal protoplasm stains in a manner characteristic to each species (for example, the ultimate and penultimate chambers of *Ammonia batavus* {Hofker}) and those specimens which accepted the stain in the typical way were assumed to be living at the time of sampling. Tests which did not accept the stain were

presumed to be dead at the time of sampling. All stained/living specimens were picked from the core fractions and form the data set.

The upper 1 cm section in all cores provided a volume of 15.2 cm^3. Foraminiferal numbers in all sections of each core were divided by the length of the section to standardise living abundance with volume. Cores of low living abundance (*i.e.* less than 20 individuals per core) were discounted.

2.2.3. Results.

Description of the cores

The mean particle size of each sample through each core remained reasonably constant (Appendix I).

The Breakwater core was dominated by silt and clay, with only minor amounts of very fine sand. The core was structureless with little change in colour or sediment type observed throughout its length. The Breakwater site represented possibly the lowest-energy environment within Plymouth Sound.

The Barn Pool cores exhibited a distinctive medium-brown silt and clay portion in the upper 1 cm, representing the depth of the oxidised sediment. Below this, the remainder of the core was of black fine sand, silt, clay, and to a lesser extent, pebbles and shell fragments. It is thought that the Barn Pool site was subject to low current activity interspersed by brief periods of tidal scour.

The Withyhedge Beacon cores were characterised by poorly-sorted medium-grained sand, silt and clay, representative of low to moderate energy levels. The cores displayed a light brown silty section in the upper 1 cm, representing the oxidised sediment. Below the uppermost 1 cm, the sediment

of sand, silt and clay became very dark brown to charcoal-grey. The section between 17 cm and 29 cm of the core retrieved on the 30th June 1994 exhibited sediment of a slightly lighter colour than that above or below it. Both cores from this site exhibited subtle variability (slightly mottled appearance) of sediment type and colour throughout their length.

The Drake's Island cores consisted of medium-grained well-sorted sands. The upper 2 cm consisted of fine/medium clean grey sand, followed by light brown sand with small amounts of silt, grading into a sand which contained a greater proportion of silt and became dark grey. This well-sorted sediment is thought to be representative of moderate to high energy conditions.

The Melampus Beacon core consisted of medium to coarse well-sorted sands; pale grey at the surface and gradually becoming darker down the core. This deposit is believed to represent high-energy conditions.

The Queen's Ground core consisted of medium/coarse sand to fine shell gravel. The core was very uniform in composition, except for a slight fining in particle size down the core. It is thought to be representative of a very high-energy environment.

Abundance of Foraminiferida

All the cores with the exception of Withyhedge Beacon contained disappointingly low numbers of live Foraminiferida. Six cores contained sufficient live Foraminiferida for analysis: three from the 30th June 1994 and three from 6th April 1995. Figure 2.2 and Figure 2.3 show that all but one of the cores (Withyhedge Beacon; April, 1995) yielded the highest living foraminiferal densities within the top 1 cm.

The cores of relatively low-energy muds (Barn Pool) showed a sharp decline of live foraminiferal densities down the core; 61% and 67% of all Foraminiferida occurred within the top 1 cm; 84% and 67% within the uppermost 3 cm. The cores from higher-energy environments (Drake's Island and Queen's Ground) showed a more gradual reduction in foraminiferal densities: 25% and 29% of all stained Foraminiferida occurred within the top 1 cm, and 63% and 64% occurred within the upper 3 cm. Cores of low to moderate energy (Withyhedge Beacon) showed a foraminiferal density of 56% (June, 1994) and 6% (April, 1995) within the top 1 cm. Both cores from Withyhedge Beacon exhibited unusually high densities (33% and 73% respectively) of live Foraminiferida in the combined 5c and 10a sections of the core (which correspond to 13 cm to 28 cm depth).

Test type

Foraminiferida were sub-divided into categories on the basis of test type. Figures 2.2 and 2.3 show that hyaline taxa were most abundant dominating all sections of all cores except the Queen's Ground core, which was dominated by agglutinated taxa in the upper 1 cm and by porcellaneous taxa in section 2 (2 cm and 3 cm). The hyaline taxa described the pattern of distribution of stained Foraminiferida in all other cores except that from Drake's Island (Figure 2.3), where agglutinated taxa were significant from section 2 (2 cm and 3 cm) onwards. The Barn Pool core of 1994 had a low abundance of porcellaneous specimens compared to that sampled in 1995, whilst Withyhedge cores from both years were dominated by hyaline taxa (especially amongst the separate group of live specimens at depth). The total live assemblages in the cores examined ranged from 4 to 236 specimens per core and were composed of 59 species.

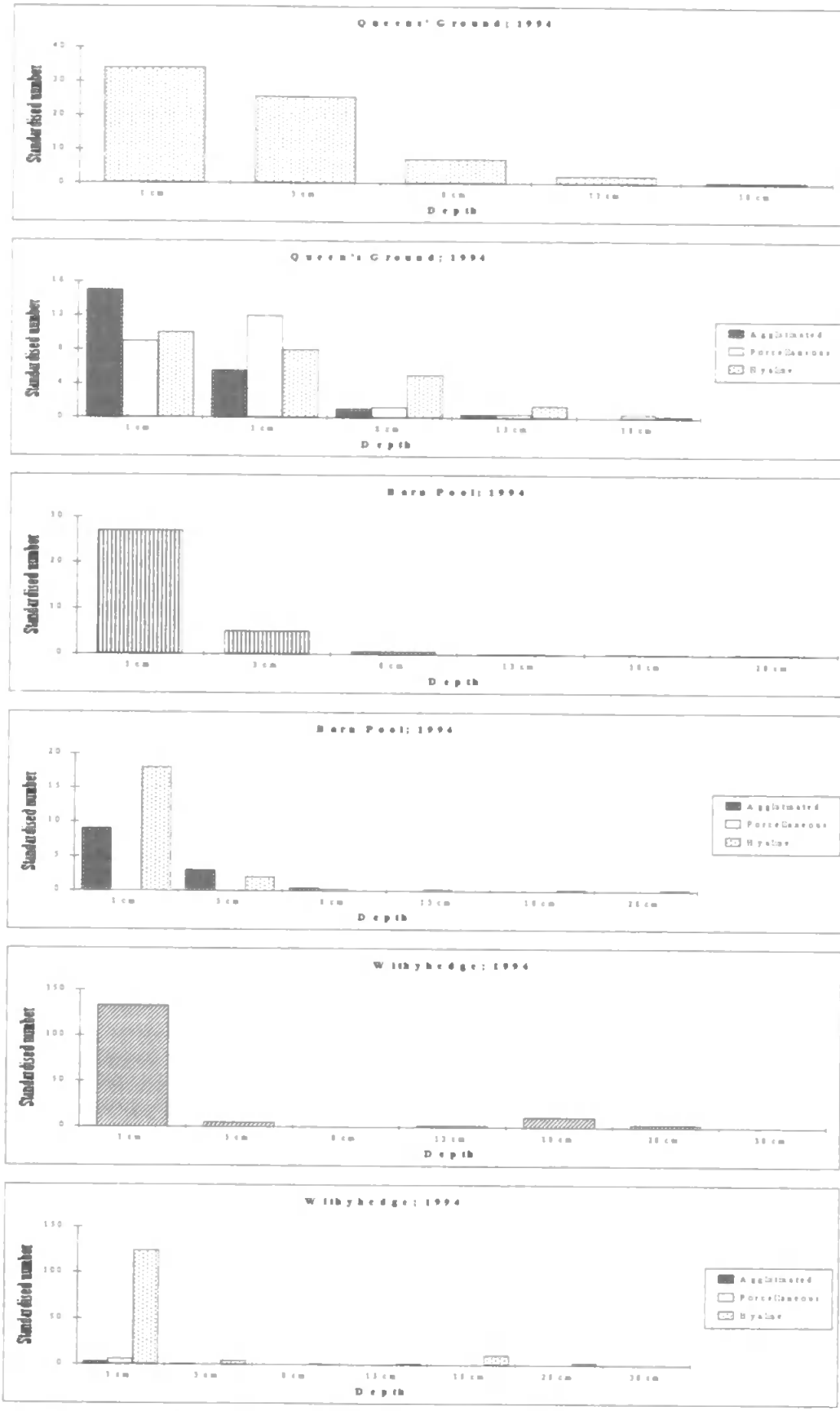


Figure 2.2: Abundance and test type of live Foraminiferida (adjusted for volume) from cores in 1994.

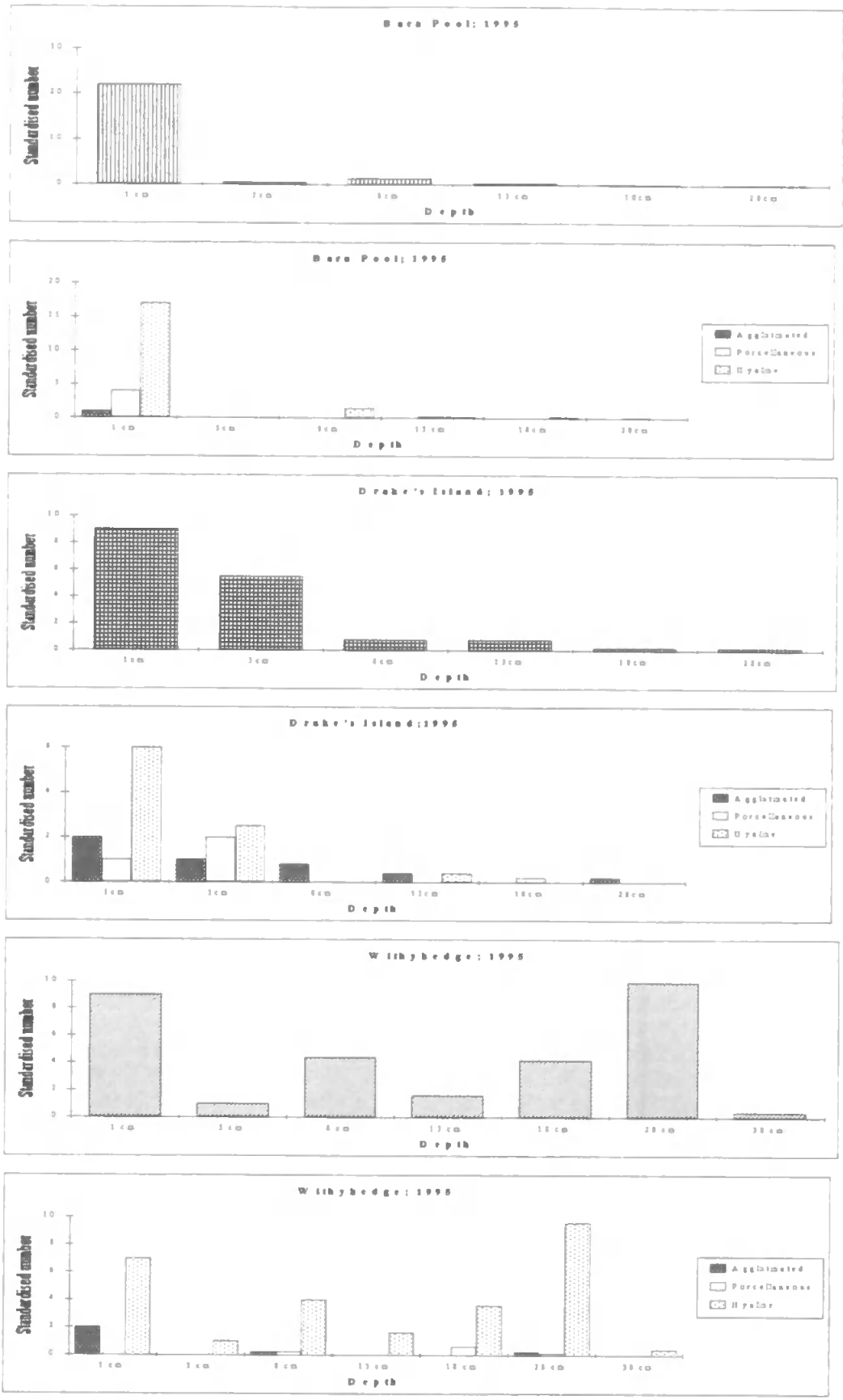


Figure 2.3: Abundance and test type of live Foraminiferida (adjusted for volume) from cores in 1995.

Species at depth

The Withyhedge cores of both years revealed a group of live Foraminiferida living at depth at this site. The live/stained Foraminiferida were mostly composed of hyaline taxa. In 1994 the species living at depth, in decreasing order, were *Elphidium crispum*, *Ammonia batavus*, *Nonion depressulus*, *Globulina gibba*, *Brizalina spathulata*, *Bulimina elegantissima*, *Eggerelloides scabrum*, *Quinqueloculina oblonga* and *Fissurina lucida*, whilst those in 1995 were *Ammonia batavus*, *Nonion depressulus*, *Elphidium crispum*, *Fissurina lucida*, *Eggerelloides scabrum*, *Lagena clavata*, *Bulimina elegantissima* and *Quinqueloculina oblonga*. The *Elphidium crispum* at 1 cm depth and at 18 and 28 cm depth were analysed for size to examine if these groups living at different depths were ontogenetically dissimilar.

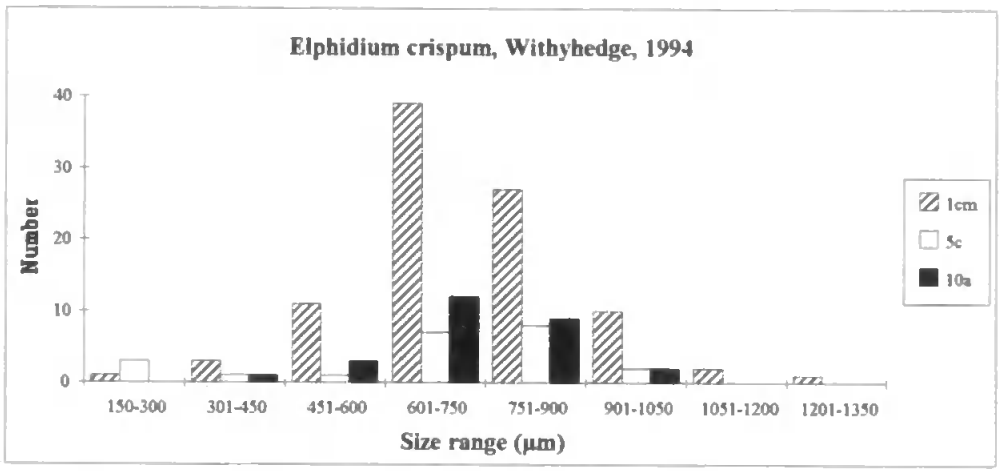


Figure 2.4: Comparison of size ranges of *Elphidium crispum* from Withyhedge core 1994 living at different depths.

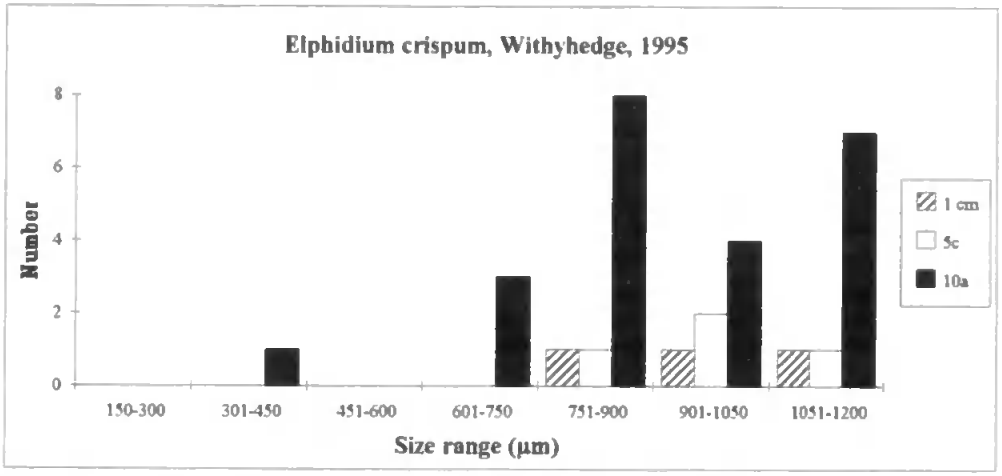


Figure 2.5: Comparison of size ranges of *Elphidium crispum* from Withyhedge core 1995 living at different depths.

From Figure 2.4 it can be seen that the large number of *Elphidium crispum* at these depths produces normally distributed abundances of the groups of live adult specimens in 1994. At 1 cm depth, *Elphidium crispum* is of all size ranges and peaks in the size range of 601 μm to 750 μm, as do the *Elphidium crispum* at 28 cm depth (10a), whilst the *Elphidium crispum* at 18 cm (5c) peak in the size range of 751 μm to 900 μm.

From Figure 2.5 it can be seen that the *Elphidium crispum* collected in 1995 are fewer in number and do not form normally distributed patterns of abundance of adult specimens. The numbers of specimens at 1 cm are very few in this core, numbering only 1 specimen in each of the size ranges of 751-900 μm, 901-1050 μm and 1051-1200 μm. Few specimens were found at 18 cm depth (5c); 1 in the size range 751-900 μm, 2 in the size range 901-1050 μm and 1 in the size range 1051-1200 μm. More specimens were found at depth of 28 cm (10a); 1 in the size range of 301-450 μm, whilst most were mature and peak in the size ranges above 601 μm.

2.2.4. Discussion.

Foraminiferal contamination from surface layers (surface sediment being trapped on the inside of the core tube particularly near the aluminium collar at the base of the core tubes) is believed to have occurred because of the presence of small amounts of oxidised surface sediment close to the base of the core tubes, but this is not thought to have significantly affected the results.

Although the cores were retrieved from the relatively small area of Plymouth Sound, all the cores contained different foraminiferal assemblages. The live assemblage was generally dominated by hyaline taxa. The distribution patterns of live Foraminiferida within the cores are correlated to sedimentary

facies. Particle size and sorting of the sediment probably alters the depth of oxygenation of the sediment and the chemical parameters of sediments. The lower energy facies (those dominated by silt and clay) undoubtedly have different chemical characteristics from sandy facies. It seems reasonable that the amount of oxygen and available food should strongly affect species distribution throughout the sediment (Jorissen, *et al.*, 1992). Muddy sediments exhibited very high numbers of live Foraminiferida within the uppermost centimetre which declined sharply with depth, and this is in agreement with numerous other studies (see Gooday, 1986; Jorissen *et al.*, 1992; Castignetti, 1996). The gradual decline of living Foraminiferida down the cores of sandy sediments may be associated with the greater availability of food and oxygen throughout this type of sediment (due to increased permeabilities). Sandy sediments also represent more dynamic environments and Foraminiferida may be prone to burial in such sediments.

Cores from Withyhedge Beacon showed an unusual vertical distribution of live Foraminiferida, mainly due to *Elphidium crispum* occurring in large numbers at depth. Both cores (taken at an interval of nearly one year) showed 57% and 7% of living Foraminiferida within the uppermost centimetre respectively, and 33% and 73% of living Foraminiferida at 13 cm to 28 cm depth, whereas other sections of the cores contained very few live specimens. Most species were more abundant within this lower section of sediment than they were at the surface irrespective of their morphology. *Elphidium crispum* has a typical epifaunal morphology (Severin, 1983; Corliss & Chen, 1988; Corliss & Fois, 1991) and its well-documented harbouring of algal chloroplasts (Leutenegger, 1984; Lee *et al.*, 1988; Lee & Lee, 1989; Lee & Anderson, 1991) also suggests an epifaunal mode of life. Both cores were dominated by three species between 13 cm to 28 cm: the normally epifaunal *Elphidium crispum*; the infaunal *Nonion depressulus* (Murray, 1991) and the infaunal *Ammonia batavus* (Murray, 1991). Other live species within this

zone were *Brizalina spathulata* (Williamson), *Bulimina gibba* (Fornasini), *Buliminella elegantissima* (d'Orbigny) and *Fissurina lucida* (Williamson). Rathburn & Corliss (1994) identify an organic oxygen-rich zone at 15 cm depth which supports a live assemblage of Foraminiferida. This zone was associated with turbidite activity. Radio isotope data (Castignetti, unpublished data) suggest that sediment mixing through storms, bioturbation and other disturbance only extends down to a possible maximum of 17 cm in this area. Contamination through the coring process could not account for such large numbers of these live species and others present at depth. Subsurface reproduction of Foraminiferida has been documented to occur at 3 mm depth (Frankel, 1972) and although specimens of the most abundant taxa were composed almost entirely of adults, it seems unlikely that the deep occurrence of live Foraminiferida within the sediment was due to reproductive activities. Subsurface *Elphidium crispum* from both Withyhedge cores show less size range variation than surface specimens. Deep sections of core contained mainly adults with few juveniles in the 1994 core and only adults in the 1995 core (Figures 2.4 and 2.5) which excludes the possibility that this is a reproductive strategy. Analysis of meteorological data has revealed that there were no exceptional wind or rain conditions prior to the sampling date, so potential burial by storm activity has been discounted. The observation by Palmer & Molloy (1986) that storm activity and increased flow rates caused Foraminiferida to vertically migrate is not appropriate as these phenomena were not present. These deep sub-surface occurrences of Foraminiferida were observed at the same depth and locality on subsequent years; it is speculated that these species perhaps colonised this portion of the sediment to access food, or that this section of sediment may be less heavily predated than the surface sediment and the Foraminiferida subject to less intraspecific competition. Foraminiferal life positions probably vary with environmental conditions and time (Jorissen, *et al.*, 1992; Buzas *et al.*, 1993; Alve & Bernard, 1995) and further research is required to establish if this

assemblage in deep sediments persists at the depth found throughout an annual cycle. Foraminiferida living deep within the sediment have been documented by numerous workers (Corliss, 1985; Moodley & Hess, 1992; Corliss & van Weering, 1993; Murray, 1992), although the dominant species within the 13 cm to 28 cm zone (*Elphidium crispum*) has not previously been recorded as having a deeply infaunal habit.

Localities for which two cores were retrieved in different years revealed that foraminiferal distribution within the sediment exhibits moderate inter-annual variation but are reasonably consistent. The efficiency of the Murray Grab to retrieve a significant and representative part of the living foraminiferal assemblage by sampling the top 1 cm of the sediment is evaluated. Samples collected by this method are representative of the total live assemblage within muddy sediments, but less representative of the live assemblage within sandy sediments: a deeper section of 3 cm depth would be advantageous in sandy sediments, as porcellaneous forms may be under-represented (these forms exhibited their highest abundance within the 2 cm and 3 cm zones). Numerical abundance and biomass may be significantly under-estimated in areas of sandy and gravelly sediments by sampling the uppermost 1 cm. Although deep infaunal species may be under-represented as a result of sampling the top 1 cm, live species which commonly occurred in the subsurface sections were also present in the top 1 cm: hence a proportion of species assumed to be deeply infaunal were represented at the surface. Foraminiferal species sampled by the Murray Grab and the cores were generally found to be comparable; and almost all species collected from the cores are represented in the Murray Grab samples.

2.3. COLLECTION OF FORAMINIFERIDA.

The substrata of the sites of this study were all composed of soft sediments and were subtidal. Monthly sediment samples were taken from each site (August, 1993 to July, 1994) and investigated for their foraminiferal content. The assemblage from each site each month was recorded to form the basis of this investigation. Because the physico-chemical environments around the sediment-water interface vary, micro-habitats are created (Kitazato, 1994), and it is important to accurately pin-point stations for analysis of temporal variation in species composition. A clumped pattern of distribution is typical of most micro-environments (Boltovskoy, 1964) and may affect temporal abundance in collections from a site. Sextant readings were attempted but were dismissed as being inaccurate and time-consuming. Global Positioning System (GPS) was not available on board the Research Vessel *Sepia* (which would allow accuracy of the station position within 1-2 m) and the positions of the sampling stations were determined by a combination of DECCA readings and the positions of land-based features assessed by Mike Williams (*Sepia* Captain), which it is believed, was fairly accurate.

Table 2.1: DECCA values for each site position.

Site	Green	Purple
Cawsand Bay	C 36.6	B 61.7
Drake's Island	C 31.8	B 65.0
White Patch	B 47.1	B 61.3

The Murray Grab was deployed from the Marine Biological Association Research Vessel *Sepia* by Pete Rendle (*Sepia* crew) every month at each site; usually at high tide. Upon collection, the sediment was placed into plastic containers in the ratio of approximately 20% sediment, 60% sea water and 20% air (Lee, 1974; Anderson *et al.*, 1991) and placed into a cool box. The site locations are given in Figure 2.6.

2.4. PROCESSING OF SAMPLES.

Staining of the protoplasm

Upon return to the laboratory, the recovered sediment was placed into a 63 μm Endacott sieve and the proportion of the sediment smaller than 63 μm was rinsed from the sample with tap water. The use of a protoplasmic stain allows differentiation between specimens which were living at the time of collection and empty tests. Removal of the fine portion of the sediment is necessary to allow free movement of the protoplasmic stain through the sediment. The sample was placed into a glass finger bowl and flooded with Rose Bengal solution of a concentration of 1 g per litre of distilled water (Walton, 1952) and stirred with a glass rod so that the protoplasmic stain would access all living organisms within the sediment. The sample was saturated with the Rose Bengal solution for twenty minutes to be certain that foraminiferal protoplasm was adequately stained. The sediment was returned to the 63 μm Endacott sieve and excess Rose Bengal solution was rinsed from the sediment with tap water until the water ran clear. The sample was placed into a dry-tared glass finger bowl and placed into a 60°C oven until thoroughly dry.

Sample splitting

The dry sample was weighed upon a Mettler (P.C. 4400) pan balance. The sediment was poured on to a sheet of clean paper so that it formed a cone of sediment (Ingram, 1971). This method is a simple way to prevent particle separation on the basis of size. The cone of sediment was split into quarter samples with a palette knife and one quarter was removed and weighed. This quarter sample was analysed for Foraminiferida and the remaining three quarters of the sediment retained. If the quarter sample yielded too few specimens, then a second sample was analysed similarly.

Table 2.2: Weights of sediment and fraction of the grab sample analysed for foraminiferal content.

Month	Cawsand Bay: (g)	fraction	Drake's Island: (g)	fraction	White Patch: (g)	fraction
August, 1993	28.6	¼	72.9	½	39.7	¼
September, 1993	69.9	¼	77.0	½	52.8	¼
October, 1993	36.7	¼	171.0	all	45.0	¼
November, 1993	83.8	½	74.1	½	37.6	¼
December, 1993	83.3	all	65.6	all	43.0	½
January, 1994	50.7	½	126.5	all	42.7	¼
February, 1994	70.7	½	48.2	all	41.6	¼
March, 1994	53.8	¼	97.6	all	47.5	½
April, 1994	56.6	½	70.5	all	127.0	all
May, 1994	126.2	¾	91.5	all	202.6	½
June, 1994	146.3	all	59.2	all	48.8	½
July, 1994	138.3	all	111.4	all	41.3	¼

Flotation of Foraminiferida

The quarter-grab sample of dry sediment was placed into a glass beaker in a fume cupboard. Carbon tetrachloride was added to the sample and stirred with a glass rod so that this "heavy liquid" (specific gravity 1.56) could access all parts of the sediment. The use of carbon tetrachloride (and other heavy liquids) facilitates the examination and removal of organisms from the sediment. Heavy liquids cause organisms with air-filled spaces (*i.e.* chambers) or organisms with a high surface area to volume ratio (most meiofauna) to float upon the surface of the liquid. The resultant "float" is decanted off on to a piece of Whatman No. 1 filter paper held inside a funnel. The process is repeated until no objects are observed floating on the surface of the carbon tetrachloride. The resultant Foraminiferida-rich "float" and the residue are left in the fume cupboard until the carbon tetrachloride has fully evaporated from the samples.

Residues of "float"

Residues were examined to see if some species were selectively not floated by this method. Residues from the August samples (when foraminiferal abundance was generally high and floating technique unfamiliar) were examined.

Table 2.3: Specimens of stained Foraminiferida not separated from the sediment by floatation from the quarter grab sample of August, 1993 from Cawsand Bay.

Species	> 63 µm	> 125 µm	> 250 µm	> 500 µm	> 1000 µm
Hemisphaerammina bradyii Loeblich & Tappan		1			
Cornuspirella diffusa (Heron-Allen & Earland)		1			
Quinqueloculina lata Terquem		1			
Haynesina germanica (Ehrenberg)	2				
Nonion depressulus (Walker & Jacob)		1			
Elphidium crispum (Linné)			2	2	

Table 2.4: Specimens of stained Foraminiferida not separated from the sediment by floatation from the quarter grab sample of August, 1993 from White Patch.

Species	> 63 µm	> 125 µm	> 250 µm	> 500 µm	> 1000 µm
Oolina laevigata d'Orbigny	1				
Haynesina germanica (Ehrenberg)	1				

All foraminiferid specimens were separated by the floating technique at Drake's Island. Only 12 specimens of seven species were found in the residues from both Cawsand Bay and White Patch, indicating that the omission of these specimens is not species-specific. However, eight of the specimens from the residues are planispiral in form, perhaps indicating that planispiral forms are more likely to be omitted from the floats examined. The number of stained specimens not floated appears to reflect the particle size of the sediment from each of the sites; the fine sand residue of Cawsand Bay held ten of the twelve specimens not floated, the poorly-sorted residue of White Patch held the other two specimens not floated, whilst the medium sand residue of Drake's Island contained no stained Foraminiferida. Considering that the float from Cawsand Bay for August, 1993 contained 718 stained specimens and the quarter grab sample from White Patch for August, 1993 contained 989 stained specimens only 1.4% and 0.2% of the foraminiferal assemblages respectively failed to be separated from the sediments. It is also believed that the floating technique improved with usage.

"Picking" of specimens

The "float" was sieved over Endacott sieves of apertures 63 μm, 125 μm, 250 μm, 500 μm and 1000 μm. The total number of stained/living Foraminiferida from each sieve fraction were removed from the rest of the material with a fine sable brush (0000) and mounted on to micropalaeontology slides with a solution of Gloy glue. A collection of 301 Foraminiferida from a sample is believed to provide sufficient accuracy for most quantitative examinations and is widely used by foraminiferologists both in academia and industry. Counts of more than 300 individuals have not normally been used in studies as the accuracy of percentage determination becomes asymptotic (Martin & Liddell, 1989). If the quarter-grab sample yielded less than 301 specimens a further fraction of the grab sample was floated and picked. This system of combining a fraction of the grab sample (*i.e.* a known area) and the 301-count is preferable to the 301-count alone as rare species are more likely to be encountered due to a higher number of specimens picked and also by relating back to the original area of sea bed examined. This allows the standing crop or absolute abundance of Foraminiferida per grab sample to be calculated.

2.5. SAMPLING SITE DESCRIPTIONS.

2.5.1. PLYMOUTH SOUND.

Plymouth Sound is a bay which has been used as an important naval and fishing port for many centuries. To protect shipping at anchor from storms, a breakwater was built by French prisoners of war in the early 1880s. The Breakwater serves to protect shipping in the way intended and also serves to isolate the body of water enclosed by it until this is flushed from the area by tidal activity. Plymouth Sound is a *ria* which has been substantially sedimented so that the general depth is 7-10m (Goard, 1975). The Sound is dominated by the River Tamar on the west which discharges down the Drake Channel (which is up to 38m deep, shallowing to

10.6 m at the end of Smeaton Pass and is kept clear by strong tidal scour). From Figure 2.6 it can be seen that tidal water enters Plymouth Sound through the western channel and exits through the eastern channel. Most of the fluvial waters are lost through the eastern channel. The Sound is a catchment area for fresh water input from two rivers: the River Tamar (which separates Devon from Cornwall) and the River Plym. The Plym, from the east, is relatively small and contributes little by way of volume but can be quite rich in clays, notably kaolinite (Goard, 1975). The Tamar has much more effect, being a substantial river flowing from west Dartmoor; it is tidal for 31 km. The total catchment area of the Tamar and its two tributaries of Lynher and Tavy is 1.5×10^9 m^2: the three rivers flow over Devonian and Carboniferous rocks, with the Tavy rising among the peat bogs overlying the Dartmoor granite (Butler & Tibbitts, 1972). There is little exchange of water between the Atlantic Ocean and the shelf, except as a result of southerly gales or as compensation currents replacing losses (Murray, 1973). The fauna and flora of the Sound, in their general nature, are marine rather than estuarine and although the quantity of fresh water absorbed by the Sound from the two estuaries and the city sewers is significant and may produce visible effects, the influence on the fauna is evidently not great (Marine Biological Association, 1957).

2.5.2. CAWSAND BAY.

Cawsand Bay is a well-sheltered inshore shallow bay lying off the village of Cawsand in Cornwall which has rocks bordering the northern and southern margins of the bay. The sediment at this site consists of fine sand, indicating the degree of disturbance of the sediment by currents and/or storms. Before the construction of the Breakwater to protect shipping lying within Plymouth Sound Cawsand Bay was used as a natural haven for large ships. Being sheltered from the south-west, it is protected from the most violent and frequent gales, and is only visited by heavy seas during gales from the east (Marine Biological Association, 1957). This site lies outside of the Breakwater and has less fresh water input than

Plymouth Sound. This site is consequently more marine than the other two sites sampled within the Sound.

2.5.3. DRAKE'S ISLAND.

Drake's Island is a small island at the mouth of the Hamoaze Estuary of the River Tamar. This area is affected by strong tidal currents, whilst being sheltered from the south-west, and hence not exposed to the most violent wave action (Marine Biological Association, 1957). The Tamar exerts great influence upon this site carrying fresh water and nutrients to it. Raw sewage is discharged from more than forty outlets on Plymouth Hoe, providing a high organic input. A *Zostera* (sea grass) bed occurs on the north side of the Island on the west side of the pier (Marine Biological Association, 1957), and although the sample site lies on the eastern side of the pier some *Zostera* was recovered.

2.5.4. WHITE PATCH.

White Patch is an area lying off Jennycliff Bay close under Staddon Heights off Rams Cliff Point. This site faces north-north-west and is therefore protected from the prevailing southwesterly winds; this protection is greatly enhanced by the Breakwater (Thomson, 1979). Tidal streams flood from the southwesterly end of the site to the north, and ebb in the opposite direction and this site is generally an area of deposition of sediment; the major sources being the rivers Plym and Tamar (Thomson, 1979). The change of pH as fresh water becomes mixed with more alkaline sea water will precipitate nutrients into particulate forms at this site. White Patch is so called because the Plym carries clay into the area making the sediment visibly paler than at other sites. A narrow (approximately 50 cm) reef lies off this area, separating the eastern shipping channel from White Patch. The Navy regularly dredges the eastern channel of the Sound from Smeaton's Pass to the

eastern passage of the Breakwater, although dredging does not occur between the reef and the sampling site.

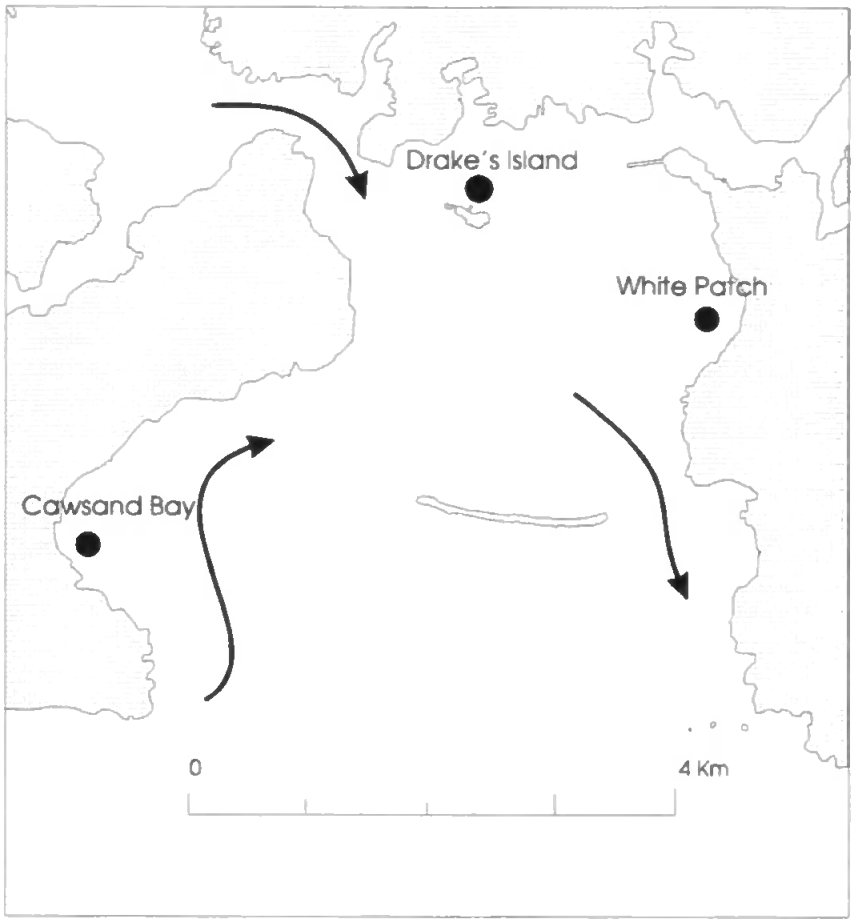


Figure 2.6: Sample site locality map showing major currents.

2.6. TAXONOMY OF FORAMINIFERIDA.

The suprageneric taxonomy for this section is based upon Loeblich and Tappan (1987). Identification of species was carried out with reference to Murray (1971{a}; 1979 {a}), Haynes (1973) and with direct reference to the Heron-Allen and Earland Collection (British Museum of Natural History: London). These publications have been used as the recommended sources for illustrations of the species; in cases where the publications do not contain illustrations of species found in the course of this study, Plate 1 is provided at the end of this Chapter. Reference lists and synonymies from these publications have been reproduced here, together with a diagnosis of each species. Reference to Murray (1991) allows discrimination between Foraminiferida of different life positions and feeding strategies.

The uptake of the protoplasmic stain Rose Bengal was used to differentiate between live and dead specimens at the time of collection. The use of any stain can be problematic, due to the visible stain colouring not only foraminiferid protoplasm, but also that of bacteria and of the organic linings of the test. Different species accept staining differently (Douglas, 1979) and the staining characteristics for each species have been detailed below and used to discriminate between live and recently dead, or contaminated, tests. The data for live species collected each month for a period of a year are contained in Appendix II.

Phylum PROTOZOA
Class RHIZOPODEA
Subclass GRANULORETICULOSIA
Order FORAMINIFERIDA Eichwald, 1930

Suborder TEXTULARIINA Delage & Hérouard, 1896

Superfamily ASTRORHIZACEA Brady, 1881
Family PSAMMOSPHAERIDAE Haeckel, 1894
Subfamily PSAMMOSPHAERINAE Haeckel, 1894
Genus PSAMMOSPHAERA Schultze, 1875
***Psammosphaera bowmani* Heron-Allen and Earland**
Plate I, Figure 1.

1912 *Psammosphaera bowmani* Heron-Allen & Earland, pl. 5, figs 5-6.

Diagnosis
A *Psammosphaera* with a unilocular test which is irregularly spherical and coarsely agglutinated. The aperture is simple, rounded and terminal.

Remarks
All specimens collected had some translucent mica in the composition of the wall; often a relatively large micaceous plate was present. The red stain of Rose Bengal could be seen through the micaceous plates, possibly indicating that this species harbours chloroplasts beneath the micaceous "windows", or has a symbiotic relationship with contained unicellular algae.

Family SACCAMMINIDAE Brady, 1884
Subfamily SACCAMMININAE Brady, 1884
Genus LAGENAMMINA Rhumbler, 1911
***Lagenammina arenulata* (Skinner)**
Recommended source for illustration: Haynes, 1973, pl. 2, fig. 17.

1884 *Reophax difflugiformis* Brady, p. 289, pl. 30, fig. 5.
1918 *Proteonina difflugiformis* (Brady): Cushman, p. 47, pl. 21, figs 1, 2.
1952 *Proteonina atlantica* Parker, p. 393, pl. 1, fig. 2.
1961 *Reophax difflugiformis* Brady subspec *arenulata* Skinner, p. 1239.
1973 *Lagenammina arenulata* (Skinner): Haynes, p. 19, pl. 2, fig. 17; pl. 8, fig. 12; text-fig. 3, nos 1-3.

Diagnosis
An irregularly flask-shaped species of *Lagenammina* with a simple, rounded terminal aperture borne on a short neck.

Remarks
A very rare species from the sites sampled in this study. Staining occurs within the aperture. It is believed that this species is an infaunal detritivore.

Family SACCAMMINIDAE Brady, 1884
Subfamily SACCAMMININAE Brady, 1884
Genus TECHNITELLA Norman, 1878
***Technitella teivyense* Haynes**
Recommended source for illustration: Haynes, 1973, pl. 1, figs 1-2, 4.

1973 *Technitella teivyense* Haynes, p. 17, pl. 1, figs 1-4.

Diagnosis
This species of *Technitella* has a unilocular test rising from an encrusting base which is roughly cylindrical. The test is composed of free monaxon sponge spicules arranged at approximately 45° to the axis of growth. The aperture is relatively large, rounded and simple.

Remarks
The test has a bushy appearance and staining occurs throughout the structure.

Family HEMISPHAERAMMINIDAE Loeblich & Tappan, 1961
Subfamily HEMISPHAERAMMININAE Loeblich & Tappan, 1961
Genus HEMISPHAERAMMINA Loeblich & Tappan, 1957
***Hemisphaerammina bradyi* Loeblich & Tappan**
Recommended source for illustration: Haynes, 1973, pl. 6, figs 1, 2.

1884 *Webbina hemisperica* Brady, p. 350, pl. 41, fig. 11.
1957 *Hemisphaerammina bradyi* Loeblich & Tappan, p. 224, pl. 72, fig. 2a, b.

Diagnosis
A smooth species of *Hemisphaerammina* which is hemispherical and always occurs attached to a piece of quartz.

Remarks
This species stains throughout the test. Sometimes when dried the test becomes compressed and buckled. There is some confusion as to whether this species is a foraminiferid; some similar organisms have been identified as gastropod egg cases. No aperture is visible although it may occur as fine pores. This species is believed to be an epifaunal herbivore.

Superfamily HORMOSINACEA Haeckel, 1894
Family HORMOSINIDAE Haeckel, 1894
Subfamily REOPHACINAE Cushman, 1910.
Genus REOPHAX de Montfort, 1808
***Reophax scottii* Chaster**
Recommended source for illustration: Murray, 1971 {a}, pl. 1, figs 6-9.

1892 *Reophax scottii* Chaster, Appendix 57, pl. 1, fig. 1.

Diagnosis
A delicate and fragile species of *Reophax*. Up to twelve cow-bell-shaped chambers composed of overlapping mica flakes. The aperture is simple, rounded and terminal.

Remarks
This species is flexible at the deeply-incised sutures and easily broken. The chambers are often iridescent. Staining typically occurs in all chambers in approximately three-quarters of the volume of each chamber. Generally whole specimens are rare and only fragments remain. Representatives of this species in sieve-fractions are therefore often not truly of the size analysed and may over-represent the true numbers present within the sample. Living members of this species are believed to be infaunal detritivores.

Superfamily LITUOLACEA de Blainville, 1827
Family HAPLOPHRAGMOIDIDAE Maync, 1952
Genus CRIBROSTOMOIDES Cushman, 1910
***Cribrostomoides jeffreysii* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 4, figs 1-5.

1858 *Nonionina jeffreysii* Williamson, p. 34, pl. 3, figs 72-3.
1878 *Haplophragmium jeffreysii* (Williamson): Berthelin, p. 24, no. 20.
1884 *Haplophragmium canariense* Brady, p. 310, pl. 35, figs 1-3, 5.
1920 *Haplophragmoides canariense* Cushman, p. 38, pl. 8, fig. 1.
1944 *Haplophragmoides columbiensis* Cushman, p. 12, pl. 2, fig. 1.
1947 *Labrospira jeffreysi* (Williamson): Höglund, p. 146, pl. 11, fig. 3.
1953 *Alveophragmium jeffreysi* (Williamson): Loeblich and Tappan, p. 31, pl. 3, figs 4-7.
1973 *Cribrostomoides jeffreysii* (Williamson): Haynes, p. 29, pl. 2, figs 5, 6; pl. 8, fig. 9; pl. 29, fig. 10; text-fig. 5, nos 8-10.

Diagnosis
A laterally compressed species of *Cribrostomoides*, having six to seven chambers in the final whorl. Test composed of fine silt grains. The sutures are depressed and radial. The aperture is a protruding lipped arch.

Remarks
This epifaunal detritivore has a golden-brown un-stained test and staining typically occurs within the aperture and the terminal chamber.

Family DISCAMMINIDAE Mikhalevich, 1980
Genus AMMOSCALARIA Höglund, 1947
***Ammoscalaria pseudospiralis* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}; pl. 7, figs 1-5

1858 *Proteonina pseudospiralis* Williamson, p. 2, pl. 1, figs 2-3.
1971 *Ammoscalaria pseudospiralis* (Williamson) Murray, {a}, p. 29, pl. 7, figs 1-5.

Diagnosis
This species of *Ammoscalaria* forms a planispiral test in juvenile stages and is dorso-ventrally compressed. The test is composed of variably-sized adventitious material. The sutures between the chambers are not externally visible. The aperture is a simple, terminal slit.

Remarks
This infaunal detritivore stains within the slitted aperture and also within the rectilinear part of the test.

Superfamily SPIROPLECTAMMINACEA Cushman, 1927
Family SPIROPLECTAMMINIDAE Cushman, 1927
Subfamily SPIROPLECTAMMININAE Cushman, 1927
Genus SPIROPLECTAMMINA Cushman, 1927
***Spiroplectammina wrightii* (Silvestri)**
Recommended source for illustration: Haynes, 1973, pl. 3, figs 1, 2.

1858 *Textularia cuneiformis* Williamson, p. 75, pl. 6, figs 158-159.
1884 *Textularia sagittula* Brady, p. 361, pl. 42, figs 17, 18.
1891 *Spiroplecta sagittula* Wright, p. 471.
1894 *Textularia sagittula* Defrance var. *cuneiformis* Goës, p. 36, pl. 7, figs 288-290.
1903 *Spiroplecta wrightii* Silvestri, p. 59, text figs 1-6.
1949 *Spiroplectammina wrightii* (Silvestri): Cushman, p. 6, pl. 1, figs 2-4.

Description
A *Spiroplectammina* with a compressed test and a carinate, lobate periphery. The sides of the test tend to become parallel in adults. The sutures are horizontal and depressed. The aperture is an interiomarginal arch.

Remarks
This species is often confused with *Textularia sagittula* which lacks the rounded planispiral early stage and is more inflated. Staining occurs within the interiomarginal arch, which may sometimes also extrude stained protoplasm.

Superfamily TROCHAMMINACEA Schwager, 1877
Family TROCHAMMINIDAE Schwager, 1877
Subfamily POLYSTOMAMMININAE Brönnimann & Beurlen, 1977
Genus DEUTERAMMINA Brönnimann, 1976
***Deuterammina (Lepidodeuterammina) ochracea* (Williamson) *sinuosa* (Brönnimann)**
Recommended source for illustration: Brönnimann & Whittaker, 1990, p. 129, pl. 2, (not pl. 1 as stated), figs 9-12.

1930 *Trochammina ochracea* (Williamson): Heron-Allen & Earland, p. 71.
1978 *Asterotrochammina sinuosa* Brönnimann, pp. 6-7, pl. 2, figs 1, 2, pp. 6-8.
1984 *Deuterammina (Lepidodeuterammina) ochracea sinuosa* (Brönnimann): Brönnimann & Zaninetti, pp. 87-90, figs AD1, AE1-3, AF1-3.

Diagnosis
A species of *Deuterammina* with a very compressed concavo-convex test. This species has ten to eleven chambers in the final whorl separated by sinuous sutures on the dorsal side. The sutures on the umbilical side are depressed and arcuate. The umbilicus is shallow and stellate and the inflated umbilical portions of the chambers terminate in a secondary umbilical aperture. The primary aperture is a peripheral interiomarginal arch.

Remarks
This species stains red throughout the test. The tests of unstained specimens are golden-brown.

***Deuterammina (Deuterammina) rotaliformis* (Heron-Allen & Earland)**
Recommended source for illustration: Brönnimann & Whittaker, 1990, p. 129, pl. 2 (not pl. 1 as stated), figs 13-16.

1885 *Trochammina inflata* (Montagu) var. Balkwill & Wright, p. 331, pl. 13, figs 11a, 12b.
1911 *Trochammina rotaliformis* Wright MS (sic): Heron-Allen & Earland, p. 309.
1930 *Trochammina rotaliformis* Wright (sic): Heron-Allen & Earland, p. 71.
1983 *Deuterammina (Deuterammina) rotaliformis* (Heron-Allen & Earland): Brönnimann & Whittaker, pp. 349-352, figs 1-12, 25.

Diagnosis
A species of *Deuterammina* with four to five chambers in the final whorl. The sutures are depressed and curved on the convex dorsal side, but radial and straight on the concave ventral side. The umbilicus is stellate and each chamber on the umbilical side possesses an arched primary aperture and single secondary opening.

Remarks
This species stains red throughout the test.

Superfamily TEXTULARIACEA Ehrenberg, 1838
Family EGGERELLIDAE Cushman, 1937
Subfamily EGGERELLINAE Cushman, 1937
Genus EGGERELLOIDES Haynes, 1973
***Eggerelloides scabrum* (Williamson)**
Recommended source for illustration: Haynes, 1973, pl. 2, figs 7-8.

1858 *Bulimina scabra* Williamson, p. 65, pl. 5, figs 136-137.
1870 *Textularia scabra* (Williamson): Fischer, p. 393.
1884 *Verneuilina polystropha* Brady, p. 386, pl. 47, figs 15-17.
1922 *Verneuilina scabra* (Williamson): Cushman {a}, p. 55, pl. 10, figs 5-6.
1937 *Eggerella scabra* (Williamson): Cushman, p. 50, pl. 5, figs 10-11.
1973 *Eggerelloides scabrum* (Williamson): Haynes, p. 44-46, pl. 2, figs 7,8; pl.19, figs 10, 11; text-fig. 8, nos 1-4.
1988 *Eggerelloides scabrus* (Williamson): Loeblich & Tappan, pl. 189, figs 5-7.

Diagnosis
A species of *Eggerelloides* with a test composed of adventitious material of variable size. Chambers increase rapidly in size, often becoming globose. The aperture is a terminal interiomarginal arch.

Remarks
Attachment of flat-worm egg cases to this species can cause the area of attachment to stain red, but this is easily distinguished from the true staining of foraminiferid protoplasm which occurs throughout the arched aperture and often in the terminal chamber. This species is infaunal and detritivorous.

Family TEXTULARIIDAE Ehrenberg, 1838
Subfamily TEXTULARIINAE Ehrenberg, 1838
Genus TEXTULARIA Defrance, 1824
***Textularia earlandi* Parker**
Recommended source for illustration: Murray, 1971 {a}, pl. 9, figs 1-5.

1931 *Textularia elegans* Lacroix, p. 14, fig. 11.
1933 *Textularia tenuissima* Earland, p. 95, pl. 3, figs 21-40.
1952 *Textularia earlandi* Parker, p. 458.
1966 *Spiroplectammina elegans* (Lacroix): Norvang, p. 14, pl. 1, fig. 24.

Diagnosis
A species of *Textularia* which has inflated chambers which increase slowly in size. The sutures are depressed and horizontal. The aperture is a small, terminal interiomarginal arch.

Remarks
This epifaunal detritivore stains in the terminal aperture and the final chamber.

***Textularia sagittula* Defrance group**
Recommended source for illustration: Murray, 1971 {a}, pl. 8, figs 1-9.

1824 *Textularia sagittula* Defrance, p. 177, pl. 13, fig. 5-5a.

Diagnosis
A species of *Textularia* which has a laterally compressed test with a sub-angular periphery. The sutures are slightly depressed. The aperture is a relatively short, terminal, simple interiomarginal arch.

Remarks
This epifaunal detritivore stains within the interiomarginal aperture.

Family VALVULINIDAE Berthelin, 1880
Subfamily VALVULININAE Berthelin, 1880
Genus CLAVULINA d'Orbigny, 1826
***Clavulina obscura* Chaster**
Recommended source for illustration: Murray, 1971 {a}, pl. 17, figs 1-3.

1892 *Clavulina obscura* Chaster, p. 58, pl. 1, fig. 4.

Diagnosis
A species of *Clavulina* which has inflated chambers separated by deeply depressed sutures. The terminal chamber is characteristically pyriform. The terminal aperture is irregular in shape and bordered by a rim of cement.

Remarks
This species stains throughout the final chamber.

Suborder SPIRILLININA Hohenegger & Piller, 1975

Family SPIRILLINIDAE Reuss & Fritsch, 1861

Genus SPIRILLINA Ehrenberg, 1843

***Spirillina vivipara* Ehrenberg**

Recommended source for illustration: Murray, 1971 {a}, pl. 60, figs 1-2.

1843 *Spirillina vivipara* Ehrenberg, pp. 323, 422, pl. 3, fig. 41.

Diagnosis

This species of *Spirillina* has a planispiral and compressed test consisting of the proloculus and a long tubular chamber. The aperture is terminal, rounded and simple.

Remarks

Spirillina vivipara is epifaunal and staining is visible throughout the test.

***Spirillina vivipara* Ehrenberg var. *runiana* Heron-Allen & Earland**

Recommended source for illustration: Murray, 1971 {a}, pl. 60, figs 3-4.

1930 *Spirillina vivipara* Ehrenberg var. *runiana* Heron-Allen & Earland, p. 179, pl. 4, figs 51-53.

Diagnosis

A variant of *Spirillina vivipara* which is ornamented by radial ribs of material extending from the antecedent whorl to the next whorl. It has a flat ventral side, forming an angular lower periphery. The aperture is terminal, simple and arch-shaped.

Remarks

Spirillina vivipara var. *runiana* is epifaunal and staining occurs throughout the test.

Subfamily PATELLININAE Rhumbler, 1906

Genus PATELLINA Williamson, 1858

***Patellina corrugata* Williamson**

Recommended source for illustration: Murray, 1971 {a}, pl. 61, figs 2-5.

1858 *Patellina corrugata* Williamson, p. 46, pl. 3, figs 86-89.

1913 *Arpatellum dunst-corrugatum* (Williamson): Rhumbler, p. 437, figs 134a-c, 136, pl. 5, figs 5-7, pl. 7, figs 11-15.

1951 *Discobolivina corrugata* (Williamson): Hofker, {b}, p. 358.

Diagnosis

A species of *Patellina* which has coarse perforations on the dorsal side. The chambers are separated by imperforate, raised sutures. Each chamber is a narrow crescent, except for the oval proloculus. The aperture is arched, situated on the ventral side and opens beneath a large, hammer-shaped flap.

Remarks

This epifaunal herbivore stains in the final chamber only.

Suborder MILIOLINA Delage & Hérouard, 1896

Superfamily CORNUSPIRACEA Schultze, 1854
Family CORNUSPIRIDAE Schultze, 1854
Subfamily CORNUSPIRINAE Schultze, 1854
Genus CYCLOGYRA Wood, 1842

***Cyclogyra involvens* (Reuss)**

Recommended source for illustration: Murray, 1971 {a}, pl. 18, figs 1-3.

1850 *Operculina involvens* Reuss, p. 370, pl. 46, fig. 20a, b.
1971 *Cyclogyra involvens* (Reuss): Murray, p. 53, pl. 18, figs 1-3.

Diagnosis
This species of *Cyclogyra* may carry growth incremental marks in the undivided second chamber. The test is circular in plan-view. The aperture is a simple, terminal high arch.

Remarks
The proloculus of this species is dark and glassy in appearance. Staining occurs in the outer whorl. Loeblich & Tappan (1988) have suppressed the genus of *Cyclogyra* in favour of the genus *Cornuspira* for complex reasons. It is preferred to retain this species under the genus of *Cyclogyra*.

Subfamily CORNUSPIROIDINAE Saidova, 1981
Genus CORNUSPIRELLA Cushman, 1928

***Cornuspirella diffusa* (Heron-Allen and Earland)**

Recommended source for illustration: Murray, 1971 {a}, pl. 18, figs 4-8.

1913 *Cornuspira diffusa* Heron-Allen and Earland {b}, pp. 272-276, pl. 12.
1971 *Cornuspirella difffusa* (Heron-Allen & Earland): Murray, {a}, p. 53, pl. 18, figs 4-8.

Diagnosis
This species of *Cornuspirella* has a laterally flattened test which is very irregular in shape. It has a flattened tubular structure, branching asymmetrically into several flattened smaller tubes; each terminating in simple, relatively large irregular apertures. Often growth increments are present as transverse thickenings.

Remarks
The fragile tests are often broken and staining is clearly visible within the whole test.

Superfamily MILIOLACEA Ehrenberg, 1839
Family SPIROLOCULINIDAE Wiesner, 1920
Genus ADELOSINA d'Orbigny, 1826

***Adelosina* sp. 1**

Plate I, Figure 2.

Diagnosis
The test is calcitic, porcellaneous and white or cream in colour. The test is coiled on a quinqueloculine plan in later stages of development with three to four chambers visible on the exterior of the adult test. The aperture is terminal, rounded and produced on a neck with a bifid tooth. This species has a smooth test which is comma-shaped in outline.

Remarks
Staining is visible throughout the test when wet and in the central area when the test is dry.

***Adelosina* sp. 2**

Plate I, Figure 3.

Diagnosis
The test is calcitic, porcellaneous and white or cream in colour. The test is coiled on a quinqueloculine plan in later stages of development with three to four chambers visible on

the exterior of the adult test. The aperture is terminal, rounded and produced on a neck with a bifid tooth. This species has a costate test having coarse, flaring costae ranging from the anterior edge of the chamber up the apertural neck.

Remarks
Staining is visible throughout the test when wet and in the central area when the test is dry.

Genus SPIROLOCULINA d'Orbigny, 1826
Spiroloculina excavata **d'Orbigny**
Recommended source for illustration: Murray, 1971 {a}, pl. 19, figs 1-3.

1846 *Spiroloculina excavata* d'Orbigny, p. 271, pl. 16, figs 19-21.

Diagnosis
This species of *Spiroloculina* is eye-shaped in outline, laterally compressed, with a rectangular periphery. The test is biumbilicate and the aperture is arch-shaped and bears a simple, terminal, rod-like tooth.

Remarks
Staining occurs just inside the aperture only.

Family HAUERINIDAE Schwager, 1876
Subfamily HAUERININAE Schwager, 1876
Genus MASSILINA Schlumberger, 1893
Massilina secans (d'Orbigny)
Recommended source for illustration: Murray, 1971 {a}, pl. 25, figs 1-6.

1826 *Quinqueloculina secans* d'Orbigny, p. 303.
1884 *Miliolina secans* Brady, p. 167, pl. 6, figs 1, 2.
1887 *Sigmoilina secans* (d'Orbigny): Schlumberger, p. 118.
1893 *Massilina secans* (d'Orbigny): Schlumberger, p. 218, pl. 4, figs 82, 83.
1900 *Miliolina secans* (d'Orbigny): Mills, p. 143, pl. 10, fig. 18.

Diagnosis
A species of *Massilina* with a test which is laterally compressed and oval in outline. The wall may be finely striated and/or carry transverse thickenings indicative of incremental growth. The periphery is sub-angular. The aperture is terminal, lipped, rounded and carries a long, thin bifid tooth.

Remarks
Staining occurs within the terminal aperture and stained extruded protoplasm may also be visible from the aperture. This species is epifaunal and herbivorous.

Genus QUINQUELOCULINA d'Orbigny, 1826
Quinqueloculina aspera **d'Orbigny**
Recommended source for illustration: Haynes, 1973, pl. 7, figs 1-3.

1826 *Quinqueloculina aspera* d'Orbigny, p. 301.
1865 *Miliola (Quinqueloculina) agglutinans* Parker & Jones, p. 410, pl. 15, fig. 37a, b.
1884 *Miliolina sclerotica* Balkwill & Millett, p. 24, pl. 1, fig. 2.
1948 *Quinqueloculina aggluitinata* Cushman, p. 33, pl. 3, fig. 13.

Diagnosis
A species of *Quinqueloculina* which incorporates silt grains into the chamber walls together with relatively large dark mineral grains; superficially resembling an arenaceous foraminiferid. The chambers are rounded and inflated. The aperture is circular and terminal borne on a prominent lip and and bears a short cupped tooth.

Remarks
Staining is visible in the aperture only and each specimen should be manipulated to view stained protoplasm. Stained protoplasm may also be extruded from the aperture. This species is epifaunal and herbivorous.

Quinqueloculina aspera **var. 1**
Plate I, Figure 4.

Diagnosis
The test is calcitic, porcellaneous and white or cream in colour. The test is coiled on a quinqueloculine plan and silt and mineral grains are incorporated into the chamber walls; superficially resembling an arenaceous foraminiferid. The chambers are subquadrate, producing a rectangular periphery. The aperture is circular, terminal, lipped and circular and bears a short cupped tooth.

Remarks
This variant differs from *Quinqueloculina aspera* by having subquadrate chambers. Staining is visible in the aperture only and each specimen should be manipulated to view stained protoplasm. Stained protoplasm may also be extruded from the aperture. This species is epifaunal and herbivorous.

Quinqueloculina bicornis
Recommended source for illustration: Murray, 1971 {a}, pl. 20, figs 1-5.

1784 *Serpula bicornis ventricosa* Walker & Boys, p. 1, pl. 1, fig. 2.
1798 *Serpula bicornis* Walker & Jacob, p. 633, pl. 14, fig. 2.
1875 *Quinqueloculina bicornis* (Walker & Jacob): Terquem, p. 443, pl. 6, fig. 6.
1884 *Miliolina bicornis* (Walker & Jacob): Brady, p. 171, pl. 6, fig. 9.

Diagnosis
A globose species of *Quinqueloculina* which has coarse costae and a high arched aperture.

Remarks
Staining occurs within the aperture only and this species is very rarely found living, although dead tests were common in samples. This species is epifaunal and herbivorous.

Quinqueloculina cliarensis **(Heron-Allen and Earland)**
Recommended source for illustration: Murray, 1971 {a}, pl. 22, figs 1-4.

1930 *Miliolina cliarensis* Heron-Allen & Earland, p. 58, pl. 3, figs 26-31.
1971 *Quinqueloculina cliarensis* (Heron-Allen & Earland): Murray, {a}, p. 61, pl. 22, figs 1-4.

Diagnosis
This species of *Quinqueloculina* has chambers that are greatly laterally compressed and curved. The periphery is acute and a neck is present which bears the terminal aperture which is round and may, or may not, carry a bifid tooth.

Remarks
Staining is visible within the aperture. This species is epifaunal and herbivorous.

Quinqueloculina **cf.** *cliarensis* **(Heron-Allen & Earland)**
Recommended source for illustration: Haynes, 1973, pl. 7, figs 8, 9.

1949 *Quinqueloculina cliarensis* (Heron-Allen & Earland): Cushman, p. 9, pl. 1, fig. 10a-c.
1973 *Quinqueloculina* cf. *cliarensis* (Heron-Allen & Earland): Haynes, pp. 68-70, pl. 7, figs 8, 9; text-fig. 17, nos 1-4.

Diagnosis
This species of *Quinqueloculina* is laterally flattened with an angular periphery, but becomes rounded towards the apex. Sutures are slightly impressed. The aperture is round at the end of the produced neck and bears a stout, simple tooth.

Remarks
Staining occurs within the terminal aperture. This species is epifaunal and herbivorous. Refer to Haynes (1973) for a full taxonomic discussion; pp. 68-70.

***Quinqueloculina dimidiata* Terquem**
Recommended source for illustration: Murray, 1971 {a}, pl. 22, figs 5-8.

1876 *Quinqueloculina dimidiata* Terquem, p. 81, pl. 40, fig. 5 a-c.

Diagnosis
This small species of *Quinqueloculina* has very oblique sutures. The outline of the test is oval and rounded in cross-section. The terminal aperture is relatively large, arch-shaped and toothless.

Remarks
Staining is visible throughout the test, especially in the central section. This species is epifaunal and herbivorous.

***Quinqueloculina lata* Terquem**
Recommended source for illustration: Haynes, 1973, pl. 7, figs 10-13.

1876 *Quinqueloculina lata* Terquem, p. 173, pl. 11, fig. 8a, b.
1930 *Miliolina oblonga* var. *lata* (Terquem): Heron-Allen & Earland, p. 55, pl. 2, figs 12-15.

Diagnosis
This species of *Quinqueloculina* is oblong in outline. In cross-section it is rounded triangular. The sutures are only slightly depressed. The aperture is terminal, arch-shaped and bears a small tooth.

Remarks
This species is very similar to *Quinqueloculina seminulum* which has a more oval, well-inflated outline, a slightly narrower aperture and a long, slender tooth. The sutures of *Quinqueloculina seminulum* are less distinct. *Quinqueloculina lata* may often be coloured green or brown along the sutures, whilst *Quinqueloculina seminulum* is almost always pure white when live. Staining of this species is visible (best if specimen is wetted) through the test. This species is epifaunal and herbivorous.

***Quinqueloculina mediterranensis* Group, Le Calvez & Le Calvez**
Recommended source for illustration: Haynes, 1973, pl. 7, figs 4, 5, pl. 8, fig. 1.

1904 *Miliolina bicornis* Sidebottom, p. 14, pl. 4, figs 13, 14.
1958 *Quinqueloculina mediterranensis* Le Calvez & Le Calvez, p. 177, pl. 4, figs 29-31.

Diagnosis
A species of *Quinqueloculina* which has quadrangular, bicarinate chambers. The chambers have regular costae parallel to the periphery. The test is compressed with an acute to carinate periphery, becoming inflated. The final chamber is often wrapped around the base of the test and at the apex it produces a gently tapering neck bearing a terminal, rounded lipped aperture and has a short tooth.

Remarks
This group is morphologically diverse and produces a series of fine, sparsely ornamented to robust bicarinate, highly costate specimens. This species is epifaunal and herbivorous. Staining occurs within the aperture.

***Quinqueloculina oblonga* (Montagu)**
Recommended source for illustration: Murray, 1971 {a}, pl. 23, figs 4-8.

1803 *Vermiculum oblongum* Montagu, p. 522, pl. 14, fig. 9.
1971 *Quinqueloculina oblonga* (Montagu): Murray, {a}, p. 63, pl. 23, figs 4-8.

Diagnosis
This species of *Quinqueloculina* has a very elongate test, which is oval in section. It bears an arch-shaped aperture which contains a small simple tooth.

Remarks
This species is epifaunal and herbivorous and has very characteristic staining of the protoplasm; wet or dry, staining is visible in an inner chamber which runs at an angle of approximately 45° to the longitudinal axis.

***Quinqueloculina seminulum* (Linné)**
Recommended source for illustration: Haynes, 1973, pl. 7, figs 14 & 19.

1767 *Serpula seminulum* Linné, p. 1264.
1884 *Miliolina seminulum* (Linné): Brady, p. 157, pl. 5, fig. 6a-c.
1929 *Quinqueloculina seminulum* (Linné): d'Orbigny, p. 24, pl. 2, fig. 2a-c.

Diagnosis
A species of *Quinqueloculina* which has wide, slightly compressed chambers. It is ovate, subtrigonal in section and the arch-shaped terminal aperture bears a simple tooth.

Remarks
The test is white and lustrous. Stained protoplasm is visible within the aperture only. This species is epifaunal and herbivorous.

Subfamily MILIOLINELLINAE Vella, 1957
Genus MILIOLINELLA Wiesner, 1931
***Miliolinella circularis* (Bornemann) var. *elongata* Kruit**
Recommended source for illustration: Murray, 1971 {a}, pl. 28, figs 1-4.

1955 *Miliolinella circularis* (Bornemann) var. *elongata* Kruit, p. 110, pl. 1, fig. 15a, b.

Diagnosis
A species of *Miliolinella* with elongate and inflated chambers. The terminal aperture is distinctive; it is arch-shaped and bears a large flap which covers approximately three-quarters of the opening.

Remarks
This species is epifaunal and herbivorous; staining is visible throughout the test.

Miliolinella subrotunda (Montagu)
Recommended source for illustration: Haynes, 1973, pl. 5, figs 5, 6, 12, 13.

1784 *Serpula subrotunda dorso elevato* Walker & Boys, p. 2, pl. 1, fig. 4.
1803 *Vermiculum subrotundum* Montagu, p. 521.
1826 *Quinqueloculina subrotunda* (Montagu): d'Orbigny, p. 302.
1858 *Miliolina seminulum* var. *disciformis* (Macgillivray): Williamson, p. 86, pl. 7, figs 188, 189.
1865 *Miliolina subrotunda* (Montagu): Parker & Jones, p. 411, pl. 15, fig. 38a, b.
1870 *Miliolina subrotunda* (Montagu): Fischer, p. 386.
1931 *Miliolinella subrotunda* (Montagu): Weisner, p. 63.
1944 *Quinqueloculina disciformis* (Macgillivray): Cushman, p. 15, pl. 2, figs 17, 18.
1954 *Triloculina subrotundum* (Montagu): Boltovskoy, p. 127, pl. 1, figs 8, 9.
1964 *Miliolinella* cf. *subrotundum* (Montagu): Feyling-Hanssen, p. 262, pl. 7, fig. 1.

Diagnosis
A species of *Miliolinella* which is ovate. The test is circular in outline and sub-circular in section. Chambers are arranged in a flattened quinqueloculine to triloculine spiral. The aperture is terminal, arch-shaped with a small (approximately covers one sixth the height of the opening) flap.

Remarks
This species is epifaunal and herbivorous and stains throughout the test, especially along the sutures.

Genus PYRGO Defrance, 1824
***Pyrgo depressa* (d'Orbigny)**
Recommended source for illustration: Murray, 1971 {a}, pl. 27, figs 1-4.

1826 *Biloculina depressa* d'Orbigny, p. 298.
1971 *Pyrgo depressa* (d'Orbigny): Murray, {a}, p. 71, pl. 27, figs 1-4.

Diagnosis
A species of *Pyrgo* in which only the last two chambers of the final whorl are visible. The test is involute and planispiral, circular in outline and appears to bear an outer carina. In cross-section the test is eye-shaped. The aperture is an elongated slit along the acute periphery.

Remarks
This species stains in the aperture and must be oriented to check if staining of the protoplasm has occurred. Loeblich & Tappan (1964) state that the genus of *Biloculina*, as described by d'Orbigny, is the same as that of *Pyrgo* Defrance.

Suborder LAGENINA Delage and Hérouard, 1896
Superfamily NODOSARIACEA Ehrenberg, 1838
Family VAGINULINIDAE Reuss, 1860
Subfamily LENTICULININAE Chapman, Parr, & Collins, 1934
Genus LENTICULINA Lamarck, 1804
***Lenticulina orbicularis* (d'Orbigny)**
Plate I, Figure 5.

1826 *Robulina orbicularis* d'Orbigny, p. 288, pl. 15, figs 8-9.
1910 *Cristellaria orbicularis* (d'Orbigny): Cushman, p. 67, pl. 36, figs 4-5.

Diagnosis
The test is calcareous, perforate radial and translucent. The test is free, smooth, lenticular and bi-umbonate. The sinuous sutures sweep back towards the angled periphery. The terminal aperture consists of radiating slits and may be slightly produced.

Remarks
This species stains at the aperture and staining is visible throughout the test. *Lenticulina orbicularis* is epifaunal and detritivorous. Loeblich & Tappan (1964, 1987) place *Cristellaria* within *Lenticulina*, and the author uses *Lenticulina* for this species.

Subfamily MARGINULININAE Wedekind, 1937
Genus AMPHICORYNA Schlumberger, 1881
***Amphicoryna* sp. cf. *A. scalaris* (Batsch)**
Recommended source for illustration: Murray, 1971 {a}, pl. 29, figs 1-4.

1791 *Nautilus (Orthoceras) scalaris* Batsch, pp. 1, 4, pl. 2, fig. 4a, b.
1971 *Amphicoryna* sp. cf. *A. scalaris* (Batsch): Murray, {a}, p. 77, pl. 29, figs 1-4.

Diagnosis
A species of *Amphicoryna* with one to five chambers. Regular costae are produced from the initial chambers and typically fade half way up the last chamber. The aperture is terminal, lipped, circular and is surrounded by several small teeth. Specimens usually have a small basal spine.

Remarks
This species stains with red patches within the neck and in the terminal chamber.

Family LAGENIDAE Reuss, 1862
Genus LAGENA Walker & Jacob, 1798
***Lagena clavata* (d'Orbigny)**
Recommended source for illustration: Haynes, 1973, pl. 12, fig. 1.

1846 *Oolina clavata* d'Orbigny, p. 24, pl. 1, figs 2-3.
1848 *Lagena laevis* (Montagu) var. *amphora* Williamson, p. 12, pl. 1, figs 3-4.
1858 *Lagena vulgaris* Williamson var. *clavata* (d'Orbigny): Williamson, p. 5, pl. 1, fig. 6.
1894 *Lagena clavata* (d'Orbigny): Goës, p. 75, pl. 13, figs 725-727.
1900 *Lagena gracillima* (Seguenza): Mills, p. 146, pl. 10, fig. 19.

Diagnosis
This species of *Lagena* has a smooth and clavate test. The base of the test has a short, rounded spine which is often broken. The aperture is terminal, round and simple at the end of a long, slender neck and has an everted lip.

Remarks
Staining in this species is visible through the test as a singular red patch within the chamber.

***Lagena gracilis* Williamson**
Recommended source for illustration: Murray, 1971 {a}, pl. 31, figs 4-6.

1848 *Lagena gracilis* Williamson, p. 13, pl. 1, fig. 5.

Diagnosis
A species of *Lagena* which bears fine widely-spaced costae, which do not quite reach the neck. The aperture is round, terminal and simple.

Remarks
Very similar in outline to *Lagena clavata*, although generally a more delicate species. Staining occurs as a singular red patch within the chamber.

***Lagena sulcata* var. *interrupta* (Williamson)**
Recommended source for illustration: Haynes, 1973, pl. 12, fig. 10

1848 *Lagena striata* (Montagu) Williamson var. α, *interrupta*, p. 14, pl. 1, fig. 7.
1973 *Lagena sulcata* var. *interrupta* (Williamson) Haynes, p. 92, pl. 12, fig. 10.

Diagnosis
A species of *Lagena* in which ribs run from the base up the chamber to the neck. The neck is ornamented with a hexagonal pattern of ribs. The aperture is terminal and round. This species is also more elongate than that of *Lagena sulcata*.

Remarks
The staining of this species occurs as a patch within the oval chamber.

***Lagena perlucida* (Montagu)**
Recommended source for illustration: Murray, 1971 {a}, pl. 33, figs 1-3.

1803 *Vermiculum perlucidum* Montagu, p. 525, pl. 14, fig. 3.
1844 *Lagena perlucida* (Montagu): Brown, p. 3, pl. 56, fig. 29.
1848 *Lagena striata* var. *perlucida* (Montagu): Williamson, p. 15, pl. 1, fig. 11.
1858 *Lagena vulgaris* Williamson var. *semistriata* Williamson, p. 6, pl. 1, fig. 9.
1923 *Lagena semistriata* (Williamson): Cushman, p. 50, pl. 9, fig. 15.

Diagnosis
A species of *Lagena* with a clavate test and a long neck which has strong spiral costae leading to the aperture. The chamber has sparse strong ribs which begin just up from the base and terminate half way up the chamber. The aperture is terminal, rounded, simple and lipped.

Remarks
Staining in this species occurs as a singular red patch within the chamber.

***Lagena substriata* Williamson**
Recommended source for illustration: Haynes, 1973, pl. 12, fig. 11.

1848 *Lagena substriata* Williamson, p. 15, pl. 2, fig. 12.
1858 *Lagena vulgaris* Williamson var. *substriata* (Williamson), p. 7, pl. 1, fig. 14.
1962 *Lagena sulcata* Haake, p. 32, pl. 1, figs 18-19.
1964 *Lagena striata* (d'Orbigny) forma *substriata* (Williamson):Feyling-Hanssen, p. 294, pl. 12, fig. 6.

Diagnosis
This species of *Lagena* has an elongate oval test and is covered in many longitudinal striae (more than thirty). The neck is relatively short and some striae are continued from the chamber up the neck, which is slightly twisted. The aperture is terminal, circular and simple.

Remarks
Staining in this species occurs as a singular red patch within the chamber.

***Lagena sulcata* (Walker & Jacob)**
Recommended source for illustration: Murray, 1971 {a}, pl. 34, figs 5-8.

1784 *Serpula* (*Lagena*) *striata sulcata rotunda* Walker & Boys, p. 2, pl. 1, fig. 6.
1798 *Serpula Lagena Sulcata* Walker & Jacob, p. 634, pl. 14, fig. 5.
1803 *Vermiculum striatum* Montagu, p. 523.
1844 *Lagena striata* (Montagu): Brown, p. 3, pl. 56, fig 36.
1865 *Lagena sulcata* (Walker & Jacob): Parker & Jones, p. 351, pl. 13, figs 24, 28-32, pl. 16.

Diagnosis
A species of *Lagena* with a sub-spherical, globular test with a short neck. The test has a rough surface and is covered with approximately twenty blade-like costae, half a dozen of which run up the neck to the aperture. The terminal aperture is lipped, circular and simple.

Remarks
Some specimens of this *Lagena* have slightly spiralled necks; they do not show the same degree of spiralling as the specimen figured by Haynes (1973, pl. 12, fig. 14.), and because of this these specimens are included in *Lagena sulcata*.

Family POLYMORPHINIDAE d'Orbigny, 1839
Subfamily POLYMORPHININAE d'Orbigny, 1839
Genus GLOBULINA d'Orbigny, 1839
***Globulina gibba* (d'Orbigny)**
Recommended source for illustration: Murray, 1971 {a}, pl. 36, figs 1-3.

1826 *Polymorphina (Globuline) gibba* d'Orbigny, p. 266.
1971 *Globulina gibba* (d'Orbigny): Murray, {a}, p. 91, pl. 36, figs 1-3.
1987 *Globulina gibba* (d'Orbigny): Loeblich & Tappan, pl. 457, figs 6,7.

Diagnosis
A species of *Globulina* which has a globular test. The chambers overlap and the sutures are flush. The aperture is terminal and consists of radiate slits.

Remarks
Some tests show two or three protruding chambers. Staining of the protoplasm is visible in the inner chambers.

***Globulina gibba* d'Orbigny var. *myristiformis* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 36, figs 4-8.

1858 *Polymorphina myristiformis* Williamson, pp. 73-74, pl. 6, figs 156, 157.
1971 *Globulina gibba* d'Orbigny var. *myristiformis* (Williamson): Murray, {a}, p. 91, pl. 36, figs 4-8.

Diagnosis
A species of *Globulina* which has a globular test which is oval in outline with longitudinal ribs. The aperture is terminal and is composed of a ring of small circular pores within an imperforate area.

Remarks
This variant differs from *Globulina gibba* by being more coarsely perforate and having differences in the aperture as above.

Family ELLIPSOLAGENIDAE A. Silvestri, 1923
Subfamily OOLININAE Loeblich & Tappan, 1961
Genus OOLINA d'Orbigny, 1839
***Oolina laevigata* d'Orbigny**
Recommended source for illustration: Haynes, 1973, pl. 14, fig. 11

1839 *Oolina laevigata* d'Orbigny, {b},p. 19, pl. 5, fig. 3.

Diagnosis
A smooth tear-drop-shaped *Oolina* which has an aperture of radiating slits.

Remarks
Staining occurs as a singular red patch within the chamber.

***Oolina melo* d'Orbigny**
Recommended source for illustration: Murray, 1971 {a}, pl. 37, figs 4-6.

1839 *Oolina melo* d'Orbigny, {a}, p. 20, pl. 5, fig. 9.

Diagnosis
A species of *Oolina* that is characterised by having longitudinal ribs and arching interconnections. There is a small boss on the base. The simple, circular aperture is borne on a short collar.

Remarks
Staining occurs as a singular red patch within the chamber.

***Oolina squamosa* (Montagu)**
Recommended source for illustration: Murray, 1971 {a}, pl. 38, figs 1-3.

1803 *Vermiculum squamosum* Montagu, p. 526, pl. 14, fig. 2.
1839 *Oolina melo* d'Orbigny, {b}, p. 20, pl. 5, fig. 9.
1844 *Lagena squamosa* (Montagu): Brown, p. 3, pl. 56, fig. 32.
1848 *Entosolenia squamosa* var. *catenulata* Williamson, p. 19, pl. 2, fig. 20.
1857 *Entosolenia globosa* (Montagu) var. *catenulata* (Williamson): Parker & Jones, p. 278, pl. 11, fig. 26.
1858 *Entosolenia squamosa* (Montagu): Williamson, p. 12, pl. 1, fig. 29.
1923 *Lagena catenulata* (Williamson): Cushman, p. 9, pl. 1, fig. 11.
1949 *Lagena melo* (d'Orbigny): Cushman, p. 21, pl. 4, fig. 6.
1948 *Entosolenia hexagona* Williamson var. *scalariformis* (Williamson): Cushman, p. 64, pl. 7, fig. 6.
1951 *Oolina squamosa* (Montagu): Van Voorthuysen, p. 24, pl. 1, fig. 12.

Diagnosis
A species of *Oolina* which bears a basal boss seated in a hollow. The simple, circular aperture is borne on a short collar and is terminal.

Remarks
This species is distinguished from *Oolina melo* by the ornamentation, which while being of a similar shape, is finer. Staining occurs as a singular red patch within the chamber.

Subfamily ELLIPSOLAGENINAEA Silvestri, 1923
Genus FISSURINA Reuss, 1850
***Fissurina lucida* (Williamson)**
Recommended source for illustration: Haynes, 1973, pl. 14, figs 1-2.

1848 *Entosolenia marginata* (Montagu) var. *lucida* Williamson, p. 17, pl. 2, fig. 17.
1862 *Lagena lucida* (Williamson): Reuss, p. 324, pl. 2, figs 25, 26.
1930 *Entosolenia lucida* (Williamson): Cushman & Cole, p. 98, pl. 13, figs 11, 12.
1950 *Fissurina lucida* (Williamson): Bandy, p. 274, pl. 41, fig. 12a, b.

Diagnosis
A pyriform compressed species of *Fissurina*. The flattened sides are ornamented with an opaque horse-shoe shaped band of coarse perforations. The aperture is a terminal long slit and passes into an entosolenian tube.

Remarks
This species stains with irregular patches within the test and near to the aperture, sometimes becoming completely stained throughout the test.

***Fissurina marginata* (Walker & Boys)**
Recommended source for illustration: Murray, 1973, pl. 39, figs 4-6.

1748 *Serpula (Lagena) marginata* Walker & Boys, p. 3, tab. 1, fig. 7.
1803 *Vermiculum marginatum* Montagu, p. 524.
1844 *Lagena marginata* Walker: Brown, p. 3, pl. 56, figs 30, 31.
1858 *Entosolenia marginata* (Walker): Williamson, p. 9, pl. 1, fig. 21.
1865 *Lagena sulcata* Walker & Jacob var. (*Entosolenia*) *marginata* (Montagu): Parker & Jones, p. 355, pl. 13, figs 42, 43.
1953 *Fissurina marginata* (Montagu): Loeblich & Tappan, p. 77, pl. 14, figs 6-9.

Diagnosis
A species of *Fissurina* which has a compressed test which is round in outline. This species has a thick peripheral keel which bifurcates to encircle a compressed, lenticular aperture.

Remarks
The entosolenian tube typically stains in this species together with other patches of stain within the test.

Fissurina orbignyana **Seguenza**
Recommended source for illustration: Murray, 1971 {a}, pl. 40, figs 1-5.

1862 *Fissurina orbignyana* Seguenza, p. 66, pl. 2, figs 19-20.

Diagnosis
A species of *Fissurina* with a compressed, pyriform test. The periphery is tri-carinate and the central carina bifurcates around the slightly everted lenticular aperture.

Remarks
Staining in this species occurs as patches of staining within the chamber.

Fissurina **sp. 1.**
Plate I, Figure 6.

Diagnosis
Wall calcitic, of radially arranged crystallites, with very fine pores, often transparent. Test is monothallamous and compressed. The aperture is a lenticular slit in the periphery, with an entosolenian tube extending into the chamber.

Description
This species of *Fissurina* has an elongate to almost rectangular outline, is very compressed and is tricarinate. The central keel extends forwards at the anterior to produce a short almost square neck on shoulders bearing a narrow slitted aperture with slightly everted lip.

Remarks
Staining in this species occurs as patches of stain in the chamber.

Fissurina **sp. 2.**
Plate I, Figure 7.

Diagnosis
Wall calcitic, of radially arranged crystallites, with very fine pores, often transparent. Test is monothallamous and compressed. The aperture is a lenticular slit in the periphery, with an entosolenian tube extending into the chamber.

Description
This species of *Fissurina* is globular and has opaque coarsely perforated areas of the test. When viewed from above this species is globular trihedral. The two edges of each face bear translucent bands from the aperture to the base. The three faces are opaque except for a translucent band running down from the aperture to half way down the chamber. The aperture is a narrow slit.

Remarks
Staining in this species occurs as patches of stain in the chamber.

Suborder ROTALIINA Delage & Hérouard, 1896

Superfamily BOLIVINACEA Glaessner, 1937

Family BOLIVINIDAE Glaessner, 1937

Genus BOLIVINA d'Orbigny, 1839

***Bolivina pseudoplicata* Heron-Allen & Earland**

Recommended source for illustration: Murray, 1971 {a}, pl. 43, figs 1-7.

1870 *Bolivina plicata* Brady, p. 302, pl. 12, fig. 7a, b.
1930 *Bolivina pseudoplicata* Heron-Allen & Earland, p. 81, pl. 3, figs 36-40.

Diagnosis
A species of *Bolivina* with a compressed test and depressed, oblique sutures. The surface is covered in folds or ridges which rise to form irregular processes and form a recticulate surface. The coarse perforations are set in depressions in the test. The aperture is terminal, arch-shaped and bears a tooth-plate.

Remarks
This species stains in the terminal chamber and within the aperture. *Bolivina pseudoplicata* is infaunal and detritivorous.

***Bolivina striatula* Cushman**

Recommended source for illustration: Haynes, 1973, pl. 10, figs 1: 1 (stereopair).

1922 *Bolivina striatula* Cushman {a}, p. 27, pl. 3, fig. 10.

Diagnosis
A species of *Bolivina* with an elongate, compressed test whose sides become parallel. The periphery is initially rounded, becoming acute in the later part of the test. Wall pores are very fine and evenly distributed, except in the terminal few chambers, when they become restricted to the lower half of each chamber. The lower half of the test is highly ornamented with parallel costae. The aperture is arch-shaped with a tooth plate.

Remarks
Staining is visible in the final chamber of this infaunal detritivore.

***Bolivina pseudopunctata* Höglund**

Recommended source for illustration: Murray, 1971 {a}, pl. 44, figs 3-6.

1894 *Bolivina punctata* Goës, p. 49, pl. 9, figs 478, 480.
1947 *Bolivina pseudopunctata* Höglund, pp. 273-4, pl. 24, fig. 5a, b, pl. 32, figs 23, 24.

Diagnosis
A slightly compressed species of *Bolivina*, with ribs present on the initial chambers. Wall pores are present only upon the distal half of each chamber. The terminal aperture is a high arch, which bears a tooth plate.

Remarks
This species stains in the final chamber and is an infaunal detritivore.

***Bolivina variabilis* (Williamson)**

Recommended source for illustration: Haynes, 1973, pl. 10, fig. 8.

1858 *Textularia variabilis* Williamson, p. 76, pl. 6, figs 162-163.
1892 *Bolivina variabilis* (Williamson): Chaster, p. 59.

Diagnosis
A species of *Bolivina* which has a compressed test, with deeply depressed straight and oblique sutures. The wall is coarsely perforate with each pore set into a depression. The arch-shaped aperture bears a tooth plate.

Remarks
Staining typically occurs in the final two chambers of this infaunal detritivore.

Genus BRIZALINA O. G. Costa, 1856
***Brizalina spathulata* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 45, figs 1-4.

1858 *Textularia variabilis* Williamson, var. *spathulata* Williamson, p. 76, pl. 6, figs 164-165.
1884 *Bolivina dilatata* Brady, p. 418, pl. 52, figs 20, 21.
1930 *Bolivina spathulata* (Williamson): Macfadyen, p. 57, pl. 4, fig. 20a, b.
1965 *Brizalina spathulata* (Williamson): Hedley, Hurdle & Burdett, p. 21, pl. 6, fig. 23.

Diagnosis
A species of *Brizalina* which has a compressed test with an acute periphery. The sutures are slightly depressed and curve towards the initial part of the test. This species has an arrow-head-shaped periphery and often has a serrated appearance, due to the formation of elongate points developed at the end of most chambers. The aperture is high, arch-shaped and bears a tooth plate.

Remarks
This species is an infaunal detritivore and typically stains in the chambers proximal to the aperture.

Superfamily TURRILINACEA Cushman, 1927
Family STAINFORTHIIDAE Reiss, 1963
Genus STAINFORTHIA Hofker, 1956
***Stainforthia concava* (Hoglund) var. *loeblichi* (Feyling-Hanssen)**
Recommended source for illustration: Haynes, 1973, pl. 5, fig. 10.

1954 *Virgulina loeblichi* Feyling-Hanssen, p. 191, pl. 1, figs 14-18.
1973 *Stainforthia concava* (Hoglund) var. *loeblichi* (Feyling-Hanssen): Haynes, pp. 123-124, pl. 5, fig. 10.

Diagnosis
This variety of *Stainforthia concava* is round in section. The aperture is a broad interiomarginal arch with a rounded lip

Remarks
This variety of *Stainforthia concava* lacks an initial spine. Staining occurs throughout the entire test of this infaunal detritivore.

Superfamily BULIMINACEA Jones, 1875
Family BULIMINIDAE Jones, 1975
Genus BULIMINA d'Orbigny, 1826
***Bulimina elongata* d'Orbigny**
Recommended source for illustration: Haynes, 1973, pl. 10, figs 9, 11.

1846 *Bulimina elongata* d'Orbigny, p. 187, pl. 11, figs 19, 20.
1884 *Bulimina elegans* Brady, p. 398, pl. 50, figs 3, 4.
1952 *Bulimina* aff. *aculeata* Parker, p. 445, pl. 4, figs 7, 13.

Diagnosis
This species of *Bulimina* has slightly depressed sutures. The chambers are well-inflated. Some chambers develop small tubercles on their lower edges. The terminal aperture is oval and partially surrounded by a lip.

Remarks
This species stains in the final chamber and is an infaunal detritivore.

Bulimina marginata d'Orbigny
Recommended source for illustration: Murray, 1971 {a}, pl. 49, figs 1-7.

1826 *Bulimina marginata* d'Orbigny, p. 269, pl. 12, figs 10-12.
1858 *Bulimina pupoides* var. *marginata* Williamson, p. 62, pl. 5, figs 126, 127.
1865 *Bulimina Presli*, Reuss, var. *marginata* d'Orbigny: Parker & Jones, p. 372, pl. 15, fig. 10, pl. 17, fig. 70.

Diagnosis
A species of *Bulimina* which has depressed sutures and has very inflated chambers with angular lower edges which bear small spines. The aperture is rounded.

Remarks
Bulimina marginata is an infaunal detritivore which stains in the final chamber.

Family BULIMINELLIDAE Hofker, 1951
Genus BULIMINELLA Cushman, 1911
Buliminella elegantissima (d'Orbigny)
Recommended source for illustration: Murray, 1971 {a}, pl. 42, figs 1-4.

1839 *Bulimina elegantissima* d'Orbigny {b}, p. 51, pl. 7, figs 13, 14.
1911 *Buliminella elegantissima* Cushman, p. 88.

Diagnosis
A species of *Buliminella* which has a sub-ovoid test. The chambers are coiled in a high trochospiral, and elongated. The sutures are depressed and the terminal aperture is comma-shaped and bordered by part of the terminal chamber.

Remarks
This species is an infaunal detritivore which stains throughout the test.

Subfamily UVIGERININAE Haeckel, 1894
Genus UVIGERINA d'Orbigny, 1826
***Uvigerina* sp. 1.**
Plate I, Figure 8.

Diagnosis
The test is calcareous, perforate and the surface is covered in platy longitudinal costae. The elongated test is triserial in initial chambers becoming more biserial in later chambers. The sutures are distinct and depressed and oblique. The aperture is terminal produced on a neck with a phialine lip.

Description
This species of *Uvigerina* is elongated in outline with a round cross-section and the chambers are rounded and inflated. This diminutive species has a granular, frosted appearance.

Remarks
Staining of this species is visible throughout the test. Representatives of this genus are infaunal detritivores.

Subfamily ANGULOGERININAE Galloway, 1933
Genus TRIFARINA Cushman, 1923
***Trifarina angulosa* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 51, figs 1-6.

1858 *Uvigerina angulosa* Williamson, p. 67, pl. 5, fig. 140.
1865 *Uvigerina pygmaea* d'Orbigny, var. *angulosa* (Williamson): Parker & Jones, p. 364, pl. 13, fig. 58; pl. 17, fig. 66a, b.
1927 *Angulogerina angulosa* (Williamson): Cushman, p. 69.
1964 *Trifarina angulosa* (Williamson): Loeblich & Tappan, C571, fig. 450, 1-3.

Diagnosis
A species of *Trifarina* in which the test is trigonal in cross-section. Longitudinal imperforate ribs run over the lower chambers and three carina continue to the terminal, collared, oval, lipped aperture which bears a tooth plate.

Remarks
This infaunal detritivore stains throughout the test.

Superfamily FURSENKOINACEA Loeblich & Tappan, 1961
Family FURSENKOINIDAE Loeblich & Tappan, 1961
Genus FURSENKOINA Loeblich & Tappan, 1961
***Fursenkoina fusiformis* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 77, figs 1-5.

1858 *Bulimina pupoides* d'Orbigny var. *fusiformis* Williamson, p. 63, pl. 5, figs 129, 130.
1887 *Bulimina fusiformis* (Williamson): Brady, p. 897.
1947 *'Bulimina' fusiformis'* (Williamson): Hoglund, p. 232, pl. 20, fig. 3, text-figs 219-233.
1960 *Virgulina fusiformis* (Williamson): Van Voorthuysen, p. 250, pl. 11, fig. 13.
1965 *Fursenkoina fusiformis* (Williamson): Murray, {a}, p. 503, pl. 1.

Diagnosis
A species of *Fursenkoina* with an elongate, fusiform test. The chambers are inflated and initially are twisted and biserial. The aperture is terminal, round and bears a tooth plate.

Remarks
The staining in this infaunal detritivore is visible through the test in all chambers.

Superfamily DISCORBACEA Ehrenberg, 1838
Family ROSALINIDAE Reiss, 1963
Genus GAVELINOPSIS Hofker, 1951
***Gavelinopsis praegeri* (Heron-Allen & Earland)**
Recommended source for illustration: Murray, 1971 {a}, pl. 55, figs 1-5.

1913 *Discorbina praegeri* Heron-Allen & Earland {a}, p. 122, pl. 10, figs 8-10.
1971 *Gavelinopsis praegeri* (Heron-Allen & Earland): Murray, {a}, p. 133, pl. 55, figs 1-5.
1988 *Gavelinopsis praegeri* (Heron-Allen & Earland): Loeblich & Tappan, pl. 608, figs 6-12.

Diagnosis
A species of *Gavelinopsis* which has a flat ventral side and convex dorsal side. The test is low trochospiral and planoconvex, with five to six chambers in the final whorl. The sutures are flush on the dorsal side, whilst strongly curving backwards. The sutures on the ventral side are depressed and radial. The aperture is ventral and consists of an interiomarginal slit.

Remarks
This epifaunal suspension-feeder stains in the final chamber. Loeblich & Tappan (1964, 1988) have replaced the genus of *Discorbina* with *Gavelinopsis* for this species.

Genus ROSALINA d'Orbigny, 1826

Rosalina anomala **Terquem**

Recommended source for illustration: Haynes, 1973, pl. 17, figs 1-3.

1951 *Discopulvinulina globularis* Hofker, {a}, p. 457, text-fig. 311.
1858 *Rotalina concamerata* Williamson, p. 52, pl. 4, figs 104, 105.
1865 *Discorbina globularis* var. *vesicularis* sub. var. *globularis* Parker & Jones, p. 386, pl. 14, figs 20-23.
1875 *Rosalina anomala* Terquem, p. 438, pl. 5, fig. 1.
1894 *Discorbina globularis* Goës, p. 94, pl. 15, fig. 793a, b.
1931 *Discorbis globularis* Cushman, p. 22, pl. 4, fig. 9a-c.
1962 *Rosalina globularis* Haake, p. 43, pl. 3, figs 10-11.
1967 *Rosalina globularis* d'Orbigny var. *anglica* Heron-Allen & Earland: Le Calvez & Boillot, p. 397, pl. 1, figs 7, 8.

Diagnosis

A species of *Rosalina* in which the test is coarsely perforate on the dorsal side and imperforate on the ventral side. The test is a low trochospiral. The chambers develop beak-like lobes in the ventral umbilicus. The aperture is a low interiomarginal arch near the periphery on the umbilical side separated by an umbilical folium from a small secondary opening at the preceding suture on the opposite margin. Other secondary openings of the final whorl remain open.

Remarks

Rosalina anomala is an epifaunal herbivore which stains in the final chamber.

***Rosalina globularis* d'Orbigny**

Recommended source for illustration: Murray, 1971 {a}, pl. 56, figs 1-6.

1826 *Rosalina globularis* d'Orbigny, p. 271, pl. 13, figs 1, 2.

Diagnosis

A species of *Rosalina* which is trochospirally coiled and convex. The chambers number five to six on the spiral side and are lobate. Sutures are slightly depressed and curve backwards. The ventral side is concave, with an open umbilicus which has slightly depressed radial sutures. The aperture is a low interiomarginal arch near the periphery on the umbilical side separated by an umbilical folium from a small secondary opening at the preceding suture on the opposite margin. Other secondary openings of the final whorl remain open.

Remarks

The walls of this species are coarsely perforate, although not as coarsely perforated as *Rosalina anomala*. *Rosalina globularis* is an epifaunal herbivore which stains in the final chamber.

***Rosalina williamsoni* (Chapman & Parr)**

Recommended source for illustration: Haynes, 1973, pl. 17, figs 13-15.

1858 *Rotalina nitida* Williamson, p. 54, pl. 4, figs 106-108.
1864 *Rotalia nitida* (Williamson): Brady, p. 474.
1889 *Discorbina nitida* (Williamson): Wright, p. 449.
1931 *Discorbis nitida* (Williamson): Cushman, p. 26, pl. 6, fig. 1a-c.
1932 *Discorbis williamsoni* Chapman & Parr, p. 226, pl. 21, fig. 25.
1962 *Rosalina williamsoni* (Chapman & Parr): Haake, p. 43, pl. 4, figs 1, 2.

Diagnosis

A species of *Rosalina* which is trochospirally coiled and plano-convex. The sutures curve strongly backwards. Five or six chambers are visible on the ventral side. The umbilical lobes are small and irregular and small umbilical bosses may be present. The aperture is a low interiomarginal arch near the periphery on the umbilical side separated by an

umbilical folium from a small secondary opening at the preceding suture on the opposite margin. Other secondary openings of the final whorl remain open.

Remarks
This species differs from *R. williamsoni* and *R. globularis* by being very finely perforate and keeled; having a slightly lobate outline. This species is an epifaunal herbivore which stains in all chambers.

Superfamily PLANORBULINACEA Schwager, 1877
Family CIBICIDIDAE Cushman, 1927
Subfamily CIBICIDINAE Cushman, 1927
Genus CIBICIDES de Montfort, 1808.
***Cibicides lobatulus* (Walker & Jacob)**
Recommended source for illustration: Murray, 1971 {a}, pl. 73, figs 1-7.

1798 *Nautilus lobatulus* Walker & Jacob, p. 642, pl. 14, fig. 36.
1826 *Truncatulina tuberculata* = *Truncatulina lobatula* (Walker & Jacob): d'Orbigny, p. 279, no. 1, mod. 37.
1828 *Lobatula vulgaris* Fleming, p. 232.
1839 *Truncatulina lobatula* (Walker & Jacob): d'Orbigny {a}, , p. 134, pl. 2, figs 22-24.
1865 *Planorbulina farcta* Fichtel & Moll sp. var. (*Truncatulina*) *lobatula* (Walker & Jacob): Parker & Jones, p. 381, pl. 14, figs 3-6; pl. 16, figs 18-20.
1894 *Planorbulina lobatula* (Walker & Jacob): Goës, p. 88, pl. 15, fig. 774.
1927 *Cibicides lobatulus* (Walker & Jacob): Cushman, p. 93, pl. 20, fig. 4.
1969 *Heterolepa lobatula* (Walker & Jacob): Gonzalez-Donoso, p. 6, pl. 2, fig. 1.

Diagnosis
A species of *Cibicides* which is attached and plano-convex. It is dorsally a low trochospiral and ventrally convex. The periphery is angular with imperforate thickening of the keel. The chambers are coarsely perforate. Initially compact and regular but may become twisted, uncoiled, sprawling and lobate. The aperture is an arch.

Remarks
Staining occurs in the final chamber only and should not be confused with tests which stain throughout all chambers, as these individuals are considered to be not living at the time of collection. This attached species is an epifaunal suspension-feeder.

***Cibicides pseudoungerianus* (Cushman)**
Recommended source for illustration: Murray, 1971, pl. 74, figs 1-6.

1922 *Truncatulina pseudoungeriana* Cushman {b}, p. 97, pl. 20, fig. 9.
1971 *Cibicides pseudoungerianus* (Cushman): Murray, {a}, p. 177, pl. 74, figs 1-6.

Diagnosis
A compact and regular species of *Cibicides*. An imperforate boss is visible on the dorsal side. The aperture is an arch.

Remarks
This species is distinguished from *C. lobatulus* by its more regular pattern of growth, coarser umbilical perforations and by the production of an imperforate boss on the dorsal surface. This attached species is epifaunal and a suspension-feeder which stains in the terminal chamber.

Family PLANORBULINIDAE Schwager, 1877
Subfamily PLANORBULININAE Schwager, 1877
Genus PLANORBULINA d'Orbigny, 1826
***Planorbulina mediterranensis* d'Orbigny**
Recommended source for illustration: Murray, 1971 {a}, pl. 75, figs 1-6.

1826 *Planorbulina mediterranensis* d'Orbigny, p. 280, pl. 14, figs 4-6.

Diagnosis
A species of *Planorbulina* in which the early part of the test is trochospiral, but later chambers are added in a cyclical pattern, producing a quadrate outline. The test is coarsely perforate. The spiral side is flat, whilst the umbilical side is convex. Each external chamber has two lipped, arched apertures.

Remarks
This attached species stains within the apertures at the corners of the test and is epifaunal and a suspension-feeder.

Superfamily ASTERIGERINACEA d'Orbigny, 1839
Family ASTERIGERINATIDAE Reiss, 1963
Genus ASTERIGERINATA Bermúdez, 1949
***Asterigerinata mamilla* (Williamson)**
Recommended source for illustration: Murray, 1971 {a}, pl. 59, figs 1-6.

1858 *Rotalina mamilla* Williamson, p. 54, pl. 4, figs 109-111.
1864 *Discorbina rosacea* H. B. Brady, p. 194.
1913 *Discorbis planorbis* Heron-Allen & Earland {a}, p. 124, pl. 11, figs 10-12.
1931 *Discorbis mamilla* (Williamson): Cushman, p. 23, pl. 5, fig. 1a-c.
1949 *Discorbis? rosacea* Cushman, p. 44, pl. 8, fig. 6a-c.
1951 *Asterigerinata mamilla* (Williamson): Hofker, {a}, p. 472, text-figs 322-326.
1954 *Heminwayina mamilla* (Williamson): Troelsen, p. 466.
1960 *Rosalina mamilla* (Williamson): Voorthuysen, p. 251, pl. 11, fig. 17a-c.
1967 *Gavelinopsis mamilla* (Williamson): Le Calvez & Boillot, p. 394.

Diagnosis
A species of *Asterigerinata* in which the test is trochospirally coiled, having a convex dorsal side and a planar ventral side. The walls are finely perforate except close to the sutures on the dorsal side, where the pores are coarse. The sutures on the dorsal side are curved backwards, whilst on the ventral side are only slightly depressed. The umbilicus is closed. The aperture is an arch at the base of the last chamber.

Remarks
This epifaunal herbivore stains within the final aperture.

Superfamily NONIONACEA Schultze, 1854
Family NONIONIDAE Schultze, 1854
Subfamily NONIONINAE Schultze, 1854
Genus HAYNESINA Banner & Culver, 1978
***Haynesina germanica* (Ehrenberg)**
Plate I, Figure 9.

1840 *Nonion germanica* Ehrenberg, p. 23.
1858 *Nonionina crassula* Williamson, p. 33, pl.3, figs 70-71.
1867 *Nonionina depressula* Brady, p. 106.
1930 *Nonion depressulus* Cushman, p. 3, pl. 1, figs 3-6.
1965 *Protelphidium depressulum* Adams & Haynes, p. 36.
1965 *Protelphidium anglicum* Murray {b}, p. 149, pl. 25, figs 1-5, pl. 26, figs 1-6.
1971 *Nonion germanicum* (Ehrenberg); Hofker, p. 63, pl. 95, figs 14-15.
1978 *Haynesina germanica* (Ehrenberg); Banner & Culver, p. 177-207.

Diagnosis
A species of *Haynesina* in which the test is planispiral and involute. There are five to eleven chambers in the final whorl. The sutures are slightly depressed at the periphery, becoming very depressed towards the umbilicus. Tubercular ornament extends from the umbilicus to the inner sutures. The aperture is a row of pores at the base of the last chamber, with tubercles above them.

Remarks
This species stains in the final chamber. The test of stained specimens may be cream/green in the initial chambers. *Haynesina germanica* is an infaunal herbivore.

Genus NONION de Montfort, 1808
***Nonion depressulus* (Walker & Jacob)**
Recommended source for illustration: Murray, 1971 {a}, pl. 82, figs 1-8.

1784 *"Nautilus spiralis utrinque subumbilicatus"* Walker & Boys, p. 19, pl. 3, fig. 68.
1798 *Nautilus depressulus* Walker & Jacob, p. 641, pl. 14, fig. 33.
1913 *Nonion asterizans* Heron-Allen & Earland {a}, p. 143, pl. 13, figs 12, 13.
1930 *Nonion depressulum* (Walker & Jacob): Cushman, p. 3, pl. 1, fig. 3.
1971 *Nonion depressulus* (Walker & Jacob): Murray, {a}, p. 195, pl. 82, figs 1-8.

Diagnosis
A species of *Nonion* having a planispiral test with seven to eleven chambers in the final whorl. The sutures are slightly depressed in the early portion, later becoming strongly depressed. Tubercular ornament fills the umbilici and inner parts of the sutures. The aperture is a series of interiomarginal openings obscured by tubercles.

Remarks
This species can be distinguished from *Haynesina germanica* by being more compressed and the test being more translucent under a light microscope.
Staining occurs in the final chamber of this infaunal herbivore.

Genus NONIONELLA Cushman, 1926
***Nonionella turgida* (Williamson)**
Recommended source for illustration: Haynes, 1973, pl. 22, fig. 12.

1858 *Rotalina turgida* Williamson, p. 50, pl. 4, figs 95-97.
1862 *Nonionina asterizans* var. *turgida* (Williamson): Carpenter, Parker & Jones, p. 311.
1865 *Polystomella crispa* sp., var. (*Nonionina*) *turgida* (Williamson): Parker & Jones, p. 405, pl. 17, fig. 57a-c.
1884 *Nonionina turgida* (Williamson): Brady, p. 731, pl. 109, figs 17-19.
1930 *Nonionella turgida* (Williamson): Cushman, p. 15, pl. 6, figs 1-4.

Diagnosis
A compressed species of *Nonionella* with chambers increasing very rapidly in height and the final one extending in a broad lobe across the ventral umbilicus. The aperture is a small arch.

Remarks
Staining occurs in the final chamber only in this infaunal herbivore.

***Nonionella* (? *Nonionellina*) sp. A Haynes**
Recommended source for illustration: Haynes, 1973, pl. 22, figs 17, 18.

1973 *Nonionella* (? *Nonionellina*) sp. A. Haynes, p. 215, pl. 22, figs 17, 18, pl. 23, fig. 3, text-fig. 46, nos 1-4.

Diagnosis
A species of *Nonionella* in which the test is compressed and chambers becoming more than three times as high as wide. The test tends to become planispiral and aequilateral in later chambers, with a slightly lobate, subround periphery. The ventral umbilicus is tuberculate. The aperture is a small, almost equatorial arch which extends slightly to the ventral side and is surrounded by tubercles.

Remarks
This species is infaunal and detritivorous. Staining occurs in the final chamber.

Superfamily CHILOSTOMELLACEA Brady, 1881
Family TRICHOHYALIDAE Saidova, 1981
Genus BUCCELLA Andersen, 1952
***Buccella frigida* (Cushman)**
Recommended source for illustration: Murray, 1971 {a}, pl. 53, figs 1-5.

1922 *Pulvinulina frigida* Cushman {a}, p. 12.
1930 *Buccella frigida* (Cushman) var. *calida* Cushman & Cole, p. 98, pl. 13, fig. 13a-c.
1931 *Eponides frigida* Cushman, p. 45.
1952 *Buccella frigida* (Cushman): Anderson, p. 144, figs 4a-c, 5, 6a-c.

Diagnosis
A species of *Buccella* in which the test is biconvex and trochospirally coiled. Two whorls are visible on the dorsal side, the chambers having flush sutures. The ventral side is ornamented with tubercles, which extend from the umbilicus along the radial depressed sutures. The aperture is an interiomarginal slit which is almost obscured by tubercles and located midway between the umbilicus and the periphery.

Remarks
Buccella frigida is infaunal and detritivorous and stains through all chambers of the test.

Superfamily ROTALIACEA Ehrenberg, 1839
Family ROTALIIDAE Ehrenberg, 1839
Subfamily AMMONIINAE Saidova, 1981
Genus AMMONIA Brünnich, 1772
***Ammonia batavus* (Hofker)**
Recommended source for illustration: Murray, 1971 {a}, pl. 62, fig. 4, (as *Ammonia beccarii*); Haynes, 1973, pl. 18, figs 5, 6, 14, 16.

1858 *Rotalina beccarii* Williamson, p. 48, pl. 14, figs 90-92.
1951 *Streblus batavus* Hofker, {a}, pp. 498, 340, 341.
1952 *Rotalia beccarii* Parker, p. 457, pl. 5, fig. 5a, b.
1964 *Ammonia batavus* (Hofker): Feyling-Hanssen, p. 349, pl. 21, figs 4-13.
1965 *Ammonia beccarii* (Linné) var. *batavus* (Hofker): Murray {a}, p. 502 (list), pl. 1, figs 1, 1; 2, 2 (stereopairs).

Diagnosis
A biconvex *Ammonia* with a sub-round periphery. It produces an umbilical calcite boss which seems to increase in size as the individual grows. The aperture is an interiomarginal slit which is ventral.

Remarks
This species is distinguished from others in having an umbilical calcite boss and should be mounted with the ventral side uppermost, to allow identification. The final chamber stains when live. The characteristic umbilical boss of this species is only present once the first whorl of chambers is formed. With small, juvenile specimens the umbilical calcite boss is not visible and it is assumed that these are juvenile *Ammonia batavus*, as no other such species appeared live in the samples studied. This species is believed to be infaunal and herbivorous.

Family ELPHIDIIDAE Galloway, 1933
Subfamily ELPHIDIINAE Galloway, 1933
Genus ELPHIDIUM de Montfort, 1808
***Elphidium crispum* (Linné)**
Recommended source for illustration: Murray, 1971 {a}, pl. 64, figs 1-6.

1758 *Nautilus crispus* Linné, p. 709.
1882 *Polystomella crispa* (Linné); Lamark, p. 625, pl. 1, fig. 2d-f.
1927 *Elphidium crispum* (Linné); Cushman & Grant, p. 73, pl. 7, fig. 3a-b.

Diagnosis
A biconvex, planispiral and involute species of *Elphidium*. This species has many narrow chambers which have long retral processes extending from the sutures. The periphery is carinate and it has a large calcite boss in the umbilici. The aperture is a series of interiomarginal pores.

Remarks
This species is characterised by having a keel, an acute periphery and a calcite boss. Staining is visible by the aperture and also through the sutures of the last few chambers of this epifaunal herbivore.

***Elphidium gerthi* Van Voorthuysen**
Recommended source for illustration: Murray, 1971 {a}, pl. 67, figs 1-7.

1957 *Elphidium gerthi* Van Voorthuysen, p. 32, pl. 23, fig. 12a, b.

Diagnosis
This species of *Elphidium* is characterised by having smooth umbilici and a subrounded periphery. The test is planispiral, slightly evolute and compressed. The periphery is sub-round and the sutures are depressed and curve backwards towards the periphery. There are nine to eleven chambers in the outer whorl, crossed by short retral processes. The aperture is a series of interiomarginal arches.

Remarks
This species stains in the final chamber and is epifaunal and herbivorous.

***Elphidium macellum* (Fichtel & Moll)**
Recommended source for illustration: Haynes, 1973, pl. 24, figs 1-3.

1798 *Nautilus macellus* Fichtel & Moll, p. 66, var. β, pl. 10, figs h-k.
1808 *Elphidium macellum* (Fichtel & Moll): Montfort, p. 15.
1901 *Polystomella macella* (Fichtel & Moll) var. *aculeata* Silvestri, p. 45.
1949 *Elphidium macellum* (Fichtel & Moll) var. *aculeatum* (Silvestri): Cushman, p. 27, pl. 5, fig. 10.
1969 *Elphidium crispum* (Linné) subsp. *spinosum* Atkinson, p. 537, fig. 6, fig. 4a, b.

Diagnosis
A species of *Elphidium* which has an acute periphery with a keel. The aperture is a series of pores.

Remarks
This species greatly resembles *Elphidium crispum*, but as a juvenile carries spines arising from the keel of the test and lacks the umbilical bosses. There is some discussion of whether this species matures into *Elphidium crispum* but specimens of *Elphidium crispum* which reproduced in experiments produced offspring lacking in spinose keels and so for this work it is assumed that they are a separate species. This species is epifaunal and herbivorous.

***Elphidium magellanicum* Heron-Allen & Earland**
Recommended source for illustration: Murray, 1971 {a}, pl. 68, figs 1-7.

1932 *Elphidium magellanicum* Heron-Allen & Earland, p. 440, pl. 16, figs 26-28.

Diagnosis
A species of *Elphidium* with a planispiral, compressed test, with six to seven chambers in the final whorl. The sutures are curved backwards and depressed. Small, undeveloped retral processes are present. Tubercular ornament extends from the umbilici along the sutural areas. The aperture is a series of interiomarginal pores.

Remarks
This species is distinguished from other species of the genus because it has a subrounded periphery and its umbilici are covered in tubercles. The sutures also have an area covered in tubercles. Staining is visible throughout the test of this epifaunal herbivore.

***Elphidium margaritaceum* (Cushman)**
Recommended source for illustration: Haynes, 1973, pl. 24, figs 12, 13.

1909 *Polystomella macella* Heron-Allen & Earland, p. 696, pl. 21, fig. 3a, b.
1930 *Elphidium advenum* (Cushman) var. *margaritaceum* Cushman, p. 25, pl. 10, fig. 3.
1961 *Elphidium margaritaceum* (Cushman): Todd & Low, p. 19, pl. 2, fig. 3.

Diagnosis
A species of *Elphidium* which has a compressed test and sometimes becomes lobate in outline. This species lacks a keel and has an acute periphery. Specimens have eight to twelve chambers, with depressed backwards-curving sutures, which are crossed by several short retral processes. The surface is densely covered with tubercles.

Remarks
The tubercles which cover the entire test give the test a frosted appearance.
This species is infaunal and herbivorous and stains throughout the test.

2.7. SUMMARY.

The Murray Grab collects the most numerous specimens of live Foraminiferida by sampling the upper 1 cm of sediment. This sampling device cuts deeper into the sediment in sandy facies such as Drake's Island, where Foraminiferida would have a more diffuse vertical distribution.

The sampled live fauna is typical of a nearshore marine environment with no planktonic species identified. The live fauna from the three sites consisted of five sub-orders, 47 genera and eighty five species of benthonic Foraminiferida.

PLATE I.

Figures of species not illustrated elsewhere.

Figure 1: *Psammosphaera bowmani* Heron-Allen & Earland

Figure 2: *Adelosina* sp. 1

Figure 3: *Adelosina* sp. 2

Figure 4: *Quinqueloculina aspera* var. 1

Figure 5: *Lenticulina orbiculatis* (d'Orbigny)

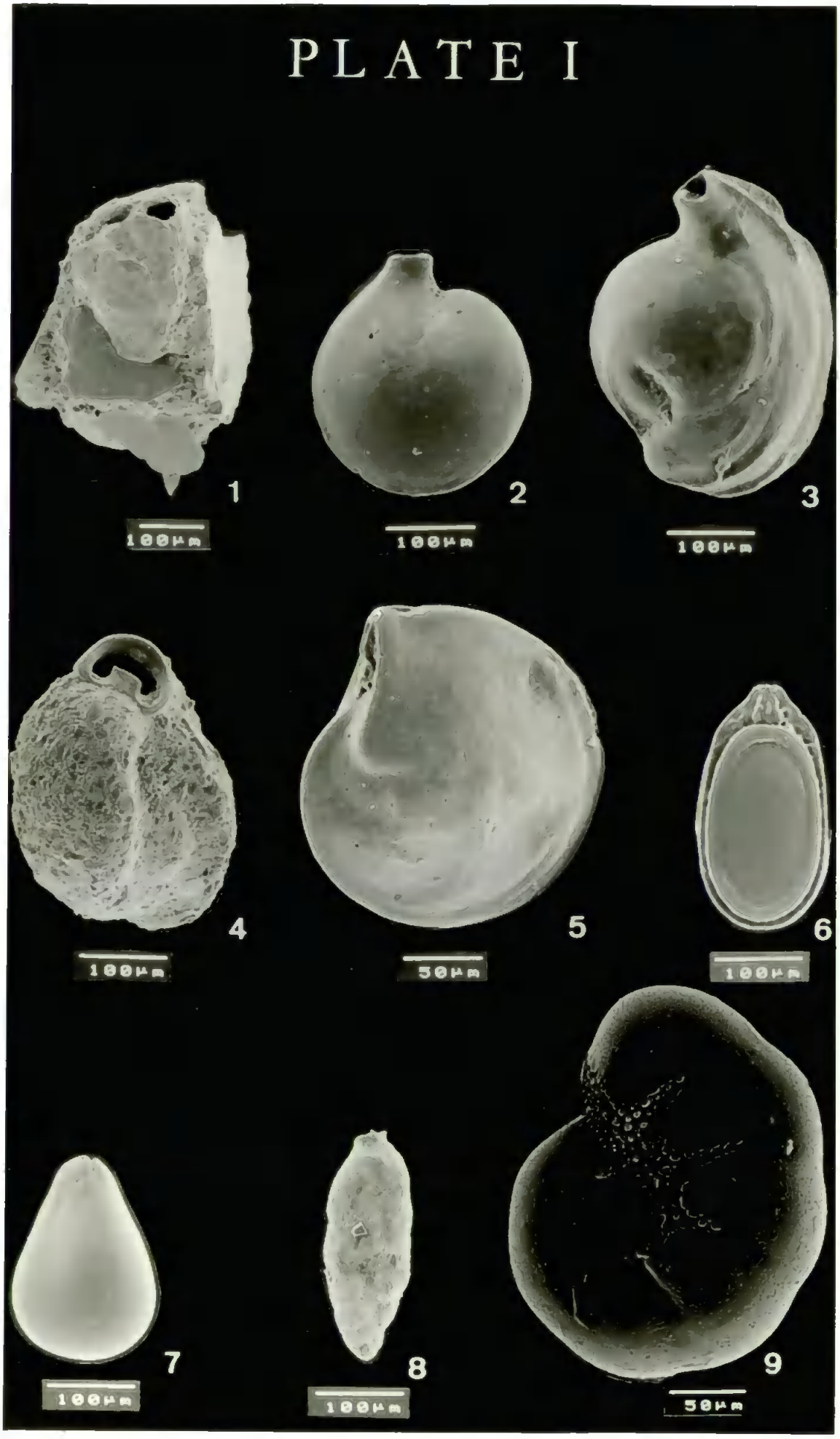
Figure 6: *Fissurina* sp. 1

Figure 7: *Fissurina* sp. 2

Figure 8: *Uvigerina* sp.

Figure 9: *Haynesina germanica* (Ehrenberg)

PLATE I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CHAPTER 3.

SAMPLED FORAMINIFERIDA.

3.1. INTRODUCTION.

A community is a collection of species living together and is usually linked to a particular habitat (Round, 1981). Amongst benthonic meiofauna there appears to be a primary interaction between the environment (particularly depth and type of substratum) and the individual, with a secondary interaction occurring between species living within the habitat. Each benthonic species living within an area will have different requirements for food and space (niche) which, in theory, would lead to competition, but in practice there are no data to suggest that competition occurs. The community is dynamic as individual species have different requirements and the components of communities often have cyclical patterns of abundance of less than one year. This means that the community structure is variable and should be studied for at least one year. Variability over a short time span can occur to communities and this in turn may be part of long term cycling. Buchanan & Moore (1986) found in a community of 140 species that the dominant 20 species set the pattern of community structure and that there was density-dependent recruitment in the benthos off Northumberland with high mortality during winter and high recruitment in September. If the stability of a community is governed by a few dominant species, an environmental factor which affects them would result in the collapse of the community. In the marine environment, the time of disruption is vital, as this governs the opportunistic species which will be recruited into the area. The time span of oscillations in the marine system is shorter than that of terrestrial systems due to the flux in food supply, turbidity and currents. Perturbation of an area may be caused by storms, pollution, predators, competition, temperature *etc.* and a large perturbation to the community may result

in a high risk of local extinction and a large chance of immigrating species being very different to the original community.

Foraminiferida are represented by numerous species in all nearshore environments. The empty tests remain in the sediment and can be collected in large quantities (Alve, 1991). Although some Foraminiferida live on hard substrata such as shells or rocks, or attached to plants, most live on or in soft sedimentary substrata (Lee, 1974; Murray, 1991). Species of benthonic Foraminiferida will respond to the natural changes of environmental factors in different ways and respond by reproducing at different times of the year. Because species of Foraminiferida are so diverse in feeding strategies, timing of reproduction and requirements for abiotic factors, the foraminiferid community will change temporally. Theoretically, asexual reproduction should dominate in stable environments, whereas sexual reproduction leads to genetic variability and is advantageous in variable conditions (Murray, 1991).

The aim of this part of the study is to discover the changes in community structure at each of three sampling sites throughout a year-long sampling programme. Ideally, in a study of this nature, numerous samples of the sites should be taken before the main sampling, and replicate samples taken at the time of sampling, to understand the variability of the assemblages. This was not carried out due to the extra volume of work this would create.

3.2. ANALYSIS OF THE DATA.

Only Foraminiferida living/stained at the time of collection form the basis of this study; data are provided in Appendix III. Abundance of Foraminiferida is both calculated to provide number of Foraminiferida per 100 cm^3 (grab sample) of sediment and also the abundance of Foraminiferida per 100 g dry sediment for comparison. Shannon-Weiner diversity indices are calculated, together with indices for species richness (Margalef) and evenness (Pielou). The species are separated into the three major test types to provide the numbers of individuals which are agglutinated, porcellaneous or hyaline. Representatives of five suborders of Foraminiferida are encountered in this study and the number of individuals within

each suborder at each site is calculated. The fauna has been further analysed to provide data on test and aperture shape. Also, the number of individuals with suggested feeding strategies and life position (with reference to Murray, 1991) are calculated. Micropalaeontologists working with Foraminiferida will often only pick 301 specimens from a sample and often have no data on absolute abundance. The use of relative abundances of subdivisions of the fauna (*i.e.* percentages) aids the understanding of the distribution of fossilised Foraminiferida when absolute abundance cannot be calculated. In this study both the absolute abundances and relative abundances of the assemblage groups are compared. Alve & Nagy (1990) state that no Recent foraminiferid species occur pre-Eocene and so it is important to attempt to correlate not species with the environment, but faunal features. Because species of Foraminiferida will be components of many of the groups under investigation (*e.g. Quinqueloculina lata* is a member of the Miliolina, has an arch-shaped aperture and is an epifaunal herbivore common in the size range of 125 μm to 250 μm) the dominant members of the assemblage will greatly influence all the groups under investigation.

3.3. ABUNDANCE.

Absolute abundance is "the precise number of individuals of a taxon in a given area, volume, population or community" (Lincoln *et al.*, 1982). It is an important measurement in studies of live Foraminiferida as it provides information upon the productivity of an area for the taxon under investigation. The abundance of live Foraminiferida from the three sites is standardised to a number of live specimens per unit area and weight. This allows temporal abundance throughout the year to be compared both within and between sites. An increase in abundance generally reflects reproduction by the taxa, whereas a decrease in abundance represents the death or removal from the area of the taxa. Reproduction occurs when the adults of a species reach maturity and the timing of reproduction varies between species. Death of Foraminiferida can be caused by predation, lack of nutrition, disease,

changes in abiotic and biotic factors, or burial. The juveniles of any organism are more affected by environmental factors than adults of the species and, given the relatively large amount of offspring produced by Foraminiferida, many will die before reaching maturity.

Abundance per unit area

The Murray Grab was used to collect sediment samples for the extraction of Foraminiferida and provides an excellent grab for sampling subtidal sites for sediment without loss of the fine portion of the sediment as it passes up through the water column. This grab collects sediment from a set area of sea bed (100 cm^2) and is designed to collect a volume of 100 cm^3 by cutting 1 cm into the surface of the sediment. The volume of sediment collected was not consistent, however, and varied mainly between site locations but also slightly within sites. The grab appeared to retrieve more sediment from a muddy substratum than from a sandy substratum due to it cutting deeper into the sediment. The abundance of Foraminiferida varies vertically within the sediment, but the majority of live benthonic Foraminiferida are found living on, or within, the upper 1 cm of sediment (see Chapter 2). Many authors express the abundance of Foraminiferida as number per unit area or volume (see Boltovskoy & Lena, 1969; Murray, 1983) and therefore give standing crop data. The standing crop size is thought to be related to the fertility of the water (Murray, 1967; Murray, 1979 {b}). Phleger (1964) states that the large standing crop of Foraminiferida off rivers may be due to the input of trace minerals which may encourage the growth of Foraminiferida directly or encourage the growth of their food supply. Lankford (1959) states that the standing crop size is small when the sedimentation rate is low and in areas of large standing crops the specimen size of Foraminiferida is relatively small. The standing crop is thought to be a function of predation, mortality and species productivity (Loubere, 1989).

Samples were visually assessed for size at the time of collection and if they seemed too small or too large the sample was repeated. The fraction of the grab sample floated and picked for Foraminiferida was recorded, and so by simple division of the number of live Foraminiferida by the numerator and multiplication by the denominator the number of live Foraminiferida within the whole grab sample could be calculated.

Abundance per unit weight

Abundance of Foraminiferida has been calculated by some authors for the weight of sediment analysed (*e.g.* Yanko *et al.*, 1994). The dry sediment of the grab sample >63 μm was weighed and also the fraction of the sample floated for foraminiferal content. Duplicate samples were taken for particle size analysis and the proportion of the sediment less than 63 μm was calculated. By multiplying the weight of sediment examined by the percentage of less than 63 μm sediment, the total weight of sediment analysed could be calculated; from this numbers of Foraminiferida found can be standardised to number of live Foraminiferida per 100 g. This method of calculating abundance is also subject to the volume (*i.e.* the depth) of sediment retrieved by the grab.

From Table 3.1 and Figure 3.1 it can be seen that both methods for calculation of abundance generally produce similar patterns in temporal abundance. The abundance per grab at all sites is usually higher than the abundance per 100 g of sediment: this may be due to larger than normal grab samples being taken, therefore elevating numbers in the fraction/s examined.

Absolute abundance (both for Foraminiferida and meiofauna) rather than abundance per unit weight is used in this study because it is the standard way to calculate abundance. Calculation of abundance per unit weight is abandoned because the determination of the less than 63 μm fraction of the sediment for

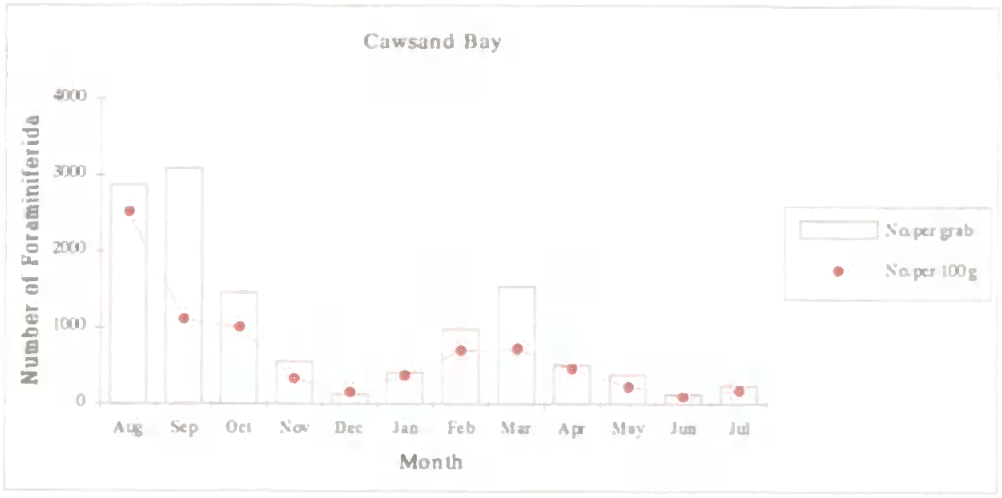
particle size analysis involved treating the duplicate sample differently to that for Foraminiferida content.

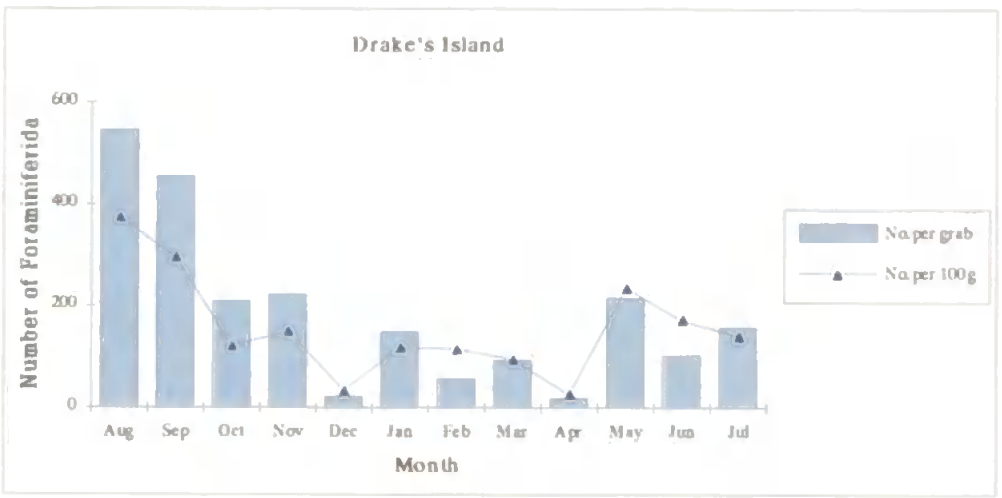
Table 3.1: Comparison of abundance of live Foraminiferida calculated by unit volume and unit weight for the three sampling sites 1993/1994.

Month	Cawsand Bay		Drake's Island		White Patch	
	No. per grab	No. per 100 g	No. per grab	No. per 100 g	No. per grab	No. per 100 g
Aug.	2872	2513	546	374	3924	2473
Sep.	3092	1106	454	295	4580	2169
Oct.	1460	995	208	122	1012	562
Nov.	558	333	222	150	1644	1093
Dec.	132	158	22	34	602	700
Jan.	418	379	149	118	1836	1074
Feb.	984	696	56	116	2600	1561
Mar.	1540	716	93	95	870	916
Apr.	514	454	18	26	101	80
May.	392	233	216	236	988	244
Jun.	136	93	102	172	710	727
Jul.	252	182	157	141	3184	1926

Comparison of Productivity

From Table 3.1 and Figure 3.2 it can be seen that White Patch was the most productive of the three sites for live benthonic Foraminiferida. Cawsand Bay was slightly less productive; but Drake's Island samples produced very few live Foraminiferida compared to the other two sites. After an increase in foraminiferal abundance at each of the sites there is a period of decrease of abundance probably reflecting the vulnerability of juveniles to death. All sites decrease in abundance in December, 1993, indicating that foraminiferal reproduction in any great numbers does not occur during this month at the locations sampled.





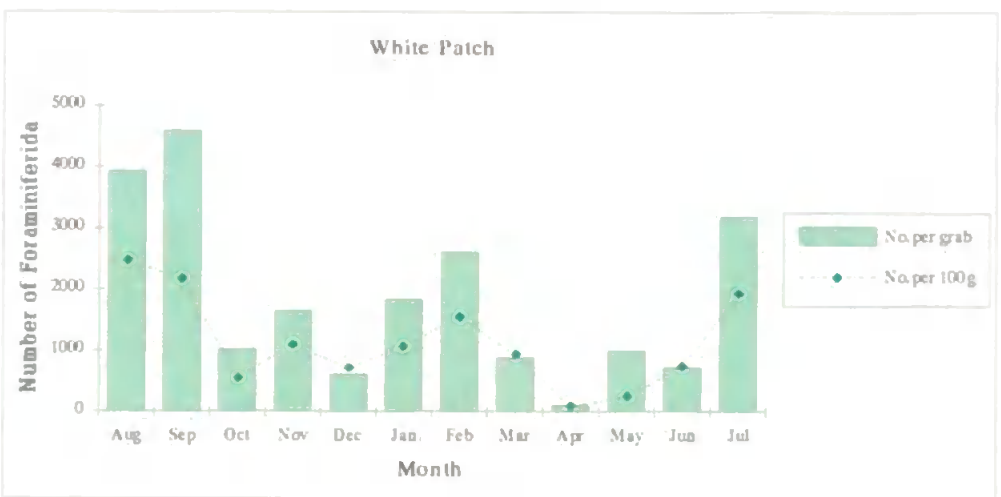
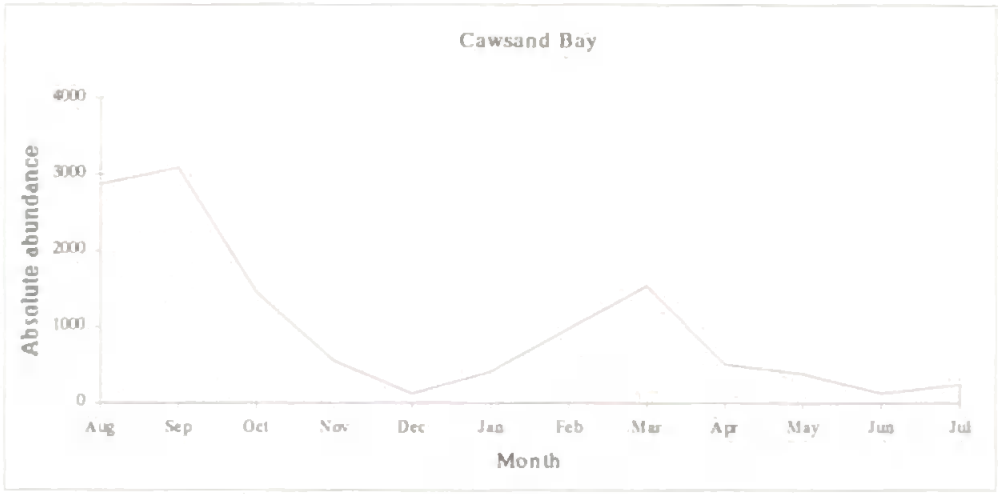
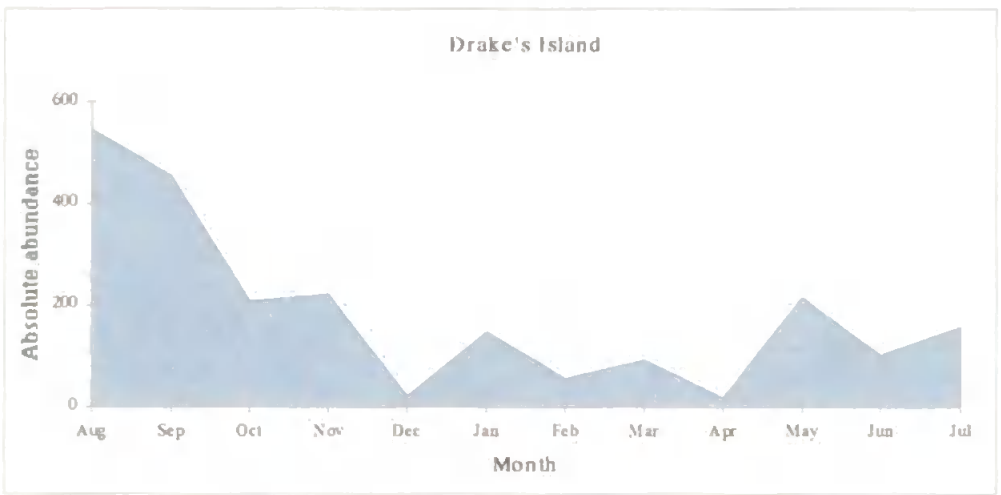


Figure 3.1: Comparison of foraminiferal abundance calculated per unit area and unit weight of sediment for the three sites, 1993 to 1994.





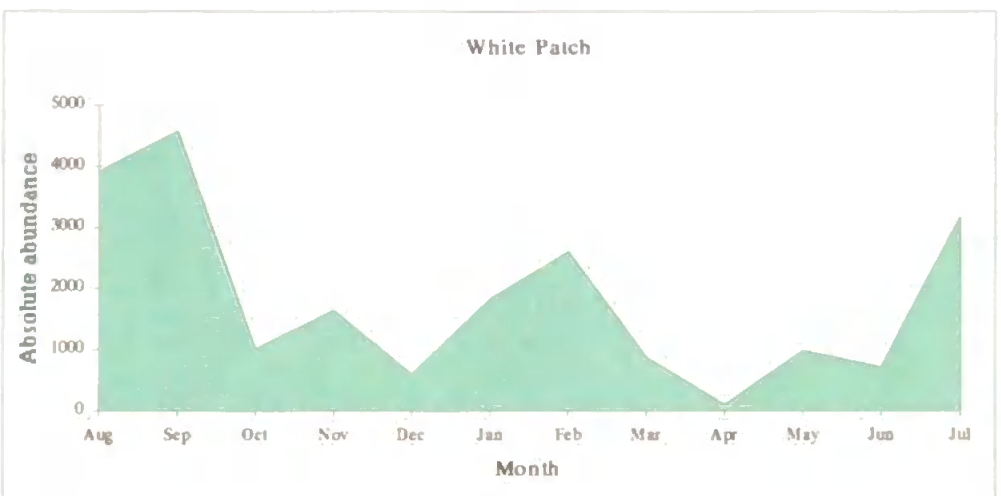


Figure 3.2: Absolute abundance of live benthonic Foraminiferida (number per grab) from the three sampling sites, 1993/1994.

Cawsand Bay

Phytoplankton (followed by zooplankton) is known to bloom in temperate seas in spring and autumn (Tait, 1981), and it seems that at Cawsand Bay maximum occurrences of live Foraminiferida coincide with these blooms of planktonic organisms. This site is the most marine of the three sites with little input of nutrients by fresh water run-off or detrital algae. The Foraminiferida at this site seem, therefore, to depend upon the plankton blooms for nutrition to allow reproduction and an increase in abundance. This clear pattern of two peaks in abundance probably reflects a very stable system, with the major species of the assemblage reproducing at two different times of the year.

Drake's Island

The pattern of abundance at Drake's Island is less stable than that of Cawsand Bay with a cyclical pattern of increase and decrease in foraminiferal abundance. This may reflect a more disturbed environment or that a different species composition exists at this site and these species reproduce throughout the annual cycle and therefore have different reproductive needs.

White Patch

The pattern of abundance of White Patch Foraminiferida in 1993/1994 has three major peaks in the annual cycle; September, 1993; February, 1994 and July, 1994 and smaller peaks in foraminiferal abundance occurred in November, 1993 and May, 1994. It appears that different groups of species at this site reproduce at different times throughout the year and probably each group has different requirements before the commencement of reproduction.

Comparison of sites

From Figure 3.1 it can be seen that live Foraminiferida from Drake's Island and White Patch showed the same pattern of abundance, although the numbers of live Foraminiferida from Drake's Island were far fewer than those from White Patch.

The live Foraminiferida from these two sites peaked in August, 1993 at Drake's Island and September, 1993 at White Patch and numbers at both sites declined until October and produced a slight peak in abundance in November. Live Foraminiferida decreased at both sites in December and produced a peak for the months of January, February and March, before again declining in April. Numbers of Foraminiferida increased sharply at Drake's Island for the month of May and declined slightly in June and July. White Patch Foraminiferida also sharply increased during May and June to peak again in July, 1994. The Foraminiferida from Cawsand Bay gradually decreased from maximum abundance in September, 1993 to December. Numbers then increased throughout January, February and March before steadily declining through April, May and June. Numbers at Cawsand Bay slightly increased in July from the June abundance.

From Table 3.1 and Figure 3.1 it can be seen that Cawsand Bay and White Patch had maximum abundance of live Foraminiferida in the month of September, whereas maximum abundance of Foraminiferida at Drake's Island occurred in August. From Figure 3.1 it can be seen that Drake's Island sediment contained fewer live species than sediments from either Cawsand Bay or White Patch. The maximum number of live specimens from the Drake's Island site was 546 in August compared to September numbers of 3092 and 4580 from Cawsand Bay and White Patch respectively.

3.4. DIVERSITY, RICHNESS & EVENNESS.

3.4.1. DIVERSITY.

The use of diversity measures is widespread in biology and micropalaeontology and provides information of the number of different species in samples. Diversity is a measure of both the variety and the relative abundance of species in samples (Magurran, 1988). The index produced represents the diversity of the community

with a single number. In this study two methods of measuring the diversity of the samples have been used because they differ in the information they yield: for both measures, the higher the index number the greater the diversity. Both indices have been calculated on the number of Foraminiferida per grab.

Fisher α index

The α index of diversity described by Fisher *et al.* (1943) is commonly used in the study of Foraminiferida and assumes that the number of each species follows a logarithmic series. The number of individuals and the number of species in a sample are read off a graph to provide an α index of diversity (Appendix III). This method therefore takes account of rarer species, but Murray (1968 {b}) found that this index tends to increase with sample size.

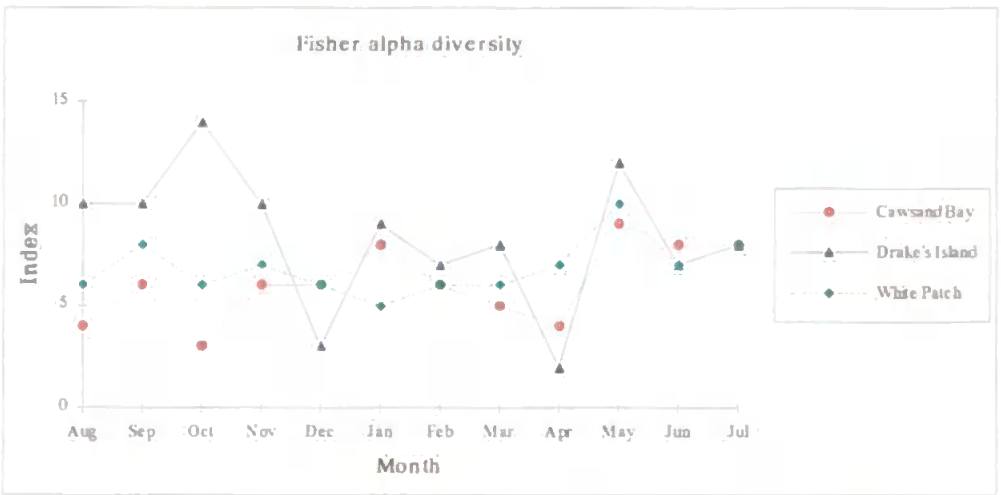


Figure 3.3: Comparison of Fisher α diversities for the three sampling sites, 1993/1994.

From Figure 3.3 it can be seen that the Fisher index for diversity varies at all sites, but fluctuates greatly at Drake's Island and less so at Cawsand Bay and White Patch respectively. Foraminiferida at Cawsand Bay peak in this diversity measure in the months of January and May and trough with respect to this diversity in the months of October and April: indices range at this site between 3 and 9. Foraminiferida at Drake's Island peak in this diversity measure in the months of October and May and trough with respect to this index in the months of December

and April: indices range at this site between 3 and 14. Foraminiferida at White Patch peak in the α coefficient in May and trough with respect to this index in January: indices range at this site between 5 and 10.

Shannon-Weiner index

The Shannon-Weiner diversity index:

$H' = -\sum_i p_i (\log p_i)$ where p_i is the proportion of the total count (or biomass etc.) arising from the ith species.

This index is commonly called the Shannon index of diversity, and is sometimes wrongly referred to as the Shannon-Weaver diversity index. This index is commonly used by biologists, although it is becoming more frequently used by foraminiferologists. The Shannon-Weiner index of diversity has been calculated by use of the PRIMER software package produced by PML and natural logarithms were used to transform the information (Appendix III). This index takes into account both the number of species in a sample and also the number of specimens within each species. The value of the Shannon diversity index is usually found to fall between 1.5 and 3.5 and only rarely surpasses 4.5 (Margalef, 1972).

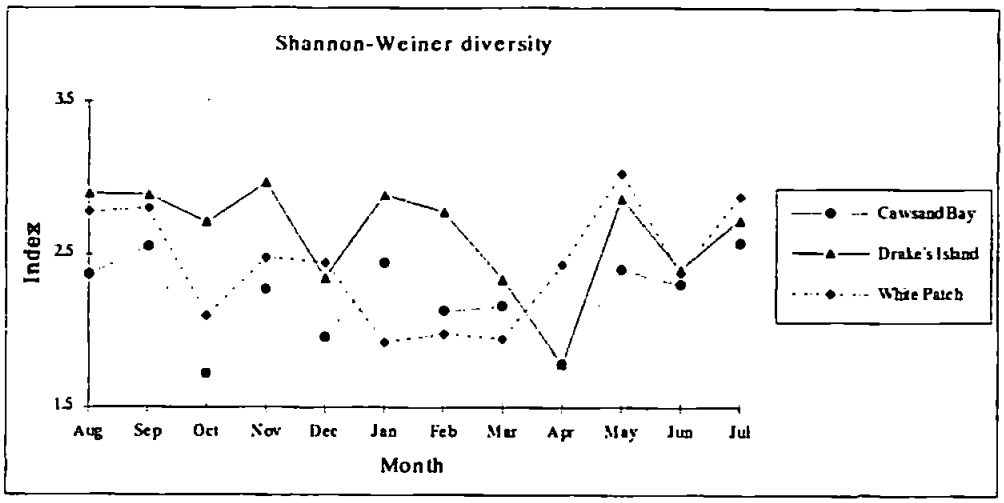


Figure 3.4: Comparison of Shannon diversities for the three sampling sites, 1993/1994.

Cawsand Bay

From Figure 3.4 it can be seen that the Shannon index for diversity fluctuates at all sites. Foraminiferida at Cawsand Bay peak in this diversity measure in the months of September and July and trough with respect to this diversity in the months of October and April: indices range at this site between 1.72 and 2.57. The Shannon diversity for Cawsand Bay rose and fell in a cyclical pattern on alternate months.

Drake's Island

Foraminiferida at Drake's Island peak in this diversity measure in the month of November and trough with respect to this index in the months of December and April: indices range at this site between 1.78 and 2.97.

White Patch

Foraminiferida at White Patch peak in this diversity measure in May and trough with respect to this index in the months of January, February and March: indices range at this site between 1.93 and 2.80.

Comparison of sites

The diversity indices for Cawsand Bay were generally lower than the other two sites except for the months of January, February and March when they surpass

those of White Patch. The diversity indices produced for White Patch were lower than those of Drake's Island from August to November, slightly higher in December and lower than those for January, February and March than either Cawsand Bay or Drake's Island. In April, May and July White Patch diversity is greater than Cawsand Bay and Drake's Island and almost equal to their indices in June.

3.4.2. RICHNESS.

Margalef's Richness index:

$d = (S-1)/ \log N$ which incorporates the total number of individuals (N) and is a measure of the number of species present for a given number of individuals.

The Margalef measure of richness is a measure of the number of species in a sample. Species richness increases with sample size as more rare species are collated and identified. Diversity measures are commonly used to gauge the adverse effects of pollution and environmental disturbance. Stressed environments experience an increase in dominance and decrease in species richness.

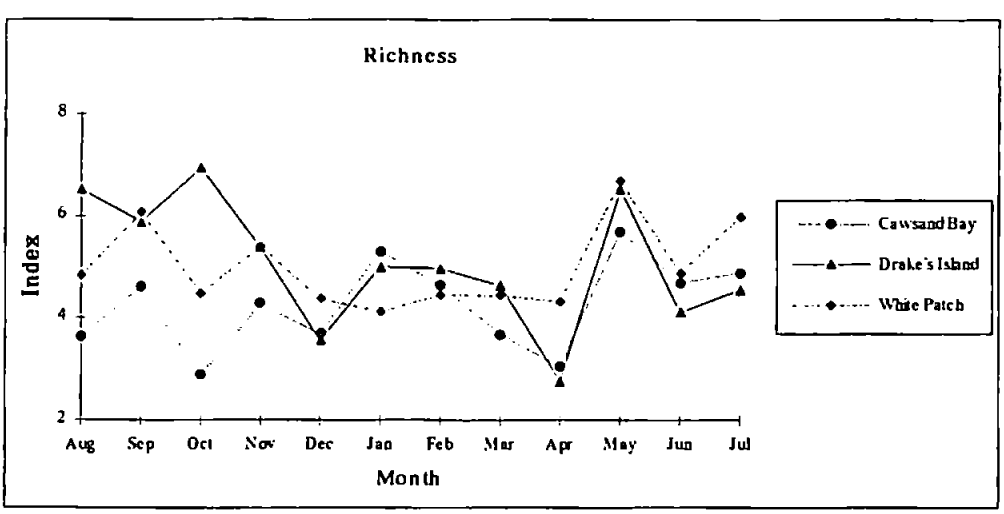


Figure 3.5: Comparison of richness of species of Foraminiferida for the three sites sampled, 1993/1994.

From Figure 3.5 all the patterns for species richness for the three sites follow no common trends, although the pattern of species richness of Foraminiferida from

Cawsand Bay is similar to that of Foraminiferida from White Patch. The richness of Foraminiferida from Drake's Island appears to be the most variable of the three sites. All sites increase in species richness in May, 1994, possibly indicating the immigration of species into the sites at this time.

3.4.3. EVENNESS.

Pielou's Evenness index:

$J' = H'$ (observed)/ H'_{max} where H'_{max} is the maximum possible diversity which would be achieved if all species were equally abundant (= log S).

Evenness of species indicates whether the foraminiferid assemblage is dominated by a few species or whether all species within the assemblage have the same abundance as each other. Pielou's measure of evenness numbers lie between 0 and 1.0, with 1.0 representing a situation in which all species are equally abundant. From Figure 3.6 it can be seen that evenness of the sampled assemblages fluctuate throughout the annual cycle. From Figure 3.6 monthly evenness indices show that Drake's Island was consistently higher than those of White Patch and Cawsand Bay. The levels for Cawsand Bay and White Patch alternated for evenness throughout the year.

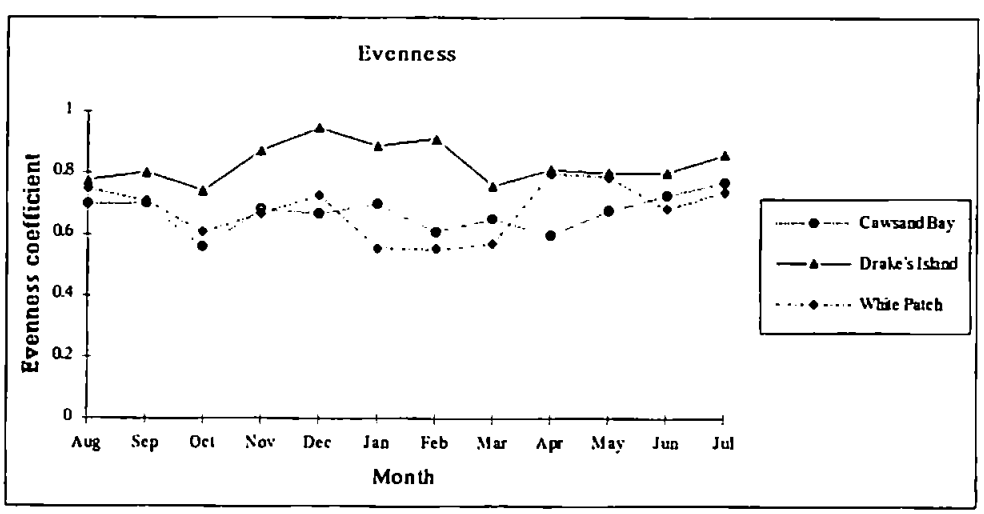


Figure 3.6: Comparison of evenness of species of Foraminiferida for the three sites sampled 1993 to 1994.

3.5. TEST TYPE.

The test of Foraminiferida is constructed in different ways. D'Orbigny was the first person to separate Foraminiferida having a calcareous test from those having an agglutinated test (Vinogradov, 1953) and the calcareous tests of Foraminiferida can be further subdivided into those tests which are hyaline (glassy and perforate) and those which are porcellaneous (imperforate). The test types are distinguished further to form the sub-orders, five of which are present in this study. The tests which are agglutinated compose the sub-order Textulariina; porcellaneous tests compose the sub-order Miliolina and the hyaline species are sub-divided into three sub-orders in this study: the Spirillinina, the Lagenina and the Rotaliina. The abundances of these sub-orders and the three major sub-divisions of test type are given below.

3.5.1. THE THREE MAJOR TEST TYPES.

Cawsand Bay

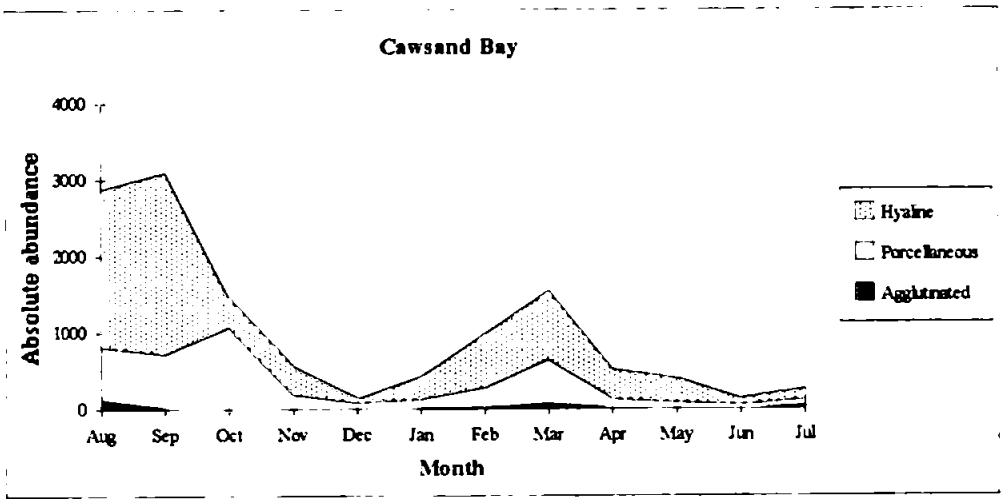


Figure 3.7: Temporal variation in absolute abundance of the three major test types of Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.7 it can be seen that the hyaline Foraminiferida constitute the majority of specimens during the main peak in abundance in August and September at this site. Hyaline Foraminiferida also form approximately half of all foraminiferal

abundance in March. The porcellaneous forms increase in abundance later than the hyaline forms in the autumn, the increase in the month of October preventing a sharp decrease in total abundance if the porcellaneous forms did not reproduce during this month. Porcellaneous forms appear to reproduce during the month of March, coinciding with hyaline reproduction at this site. Agglutinated individuals are relatively rare at this site and form a minor component of the assemblage at Cawsand Bay: these Foraminiferida appear to reproduce in August and March.

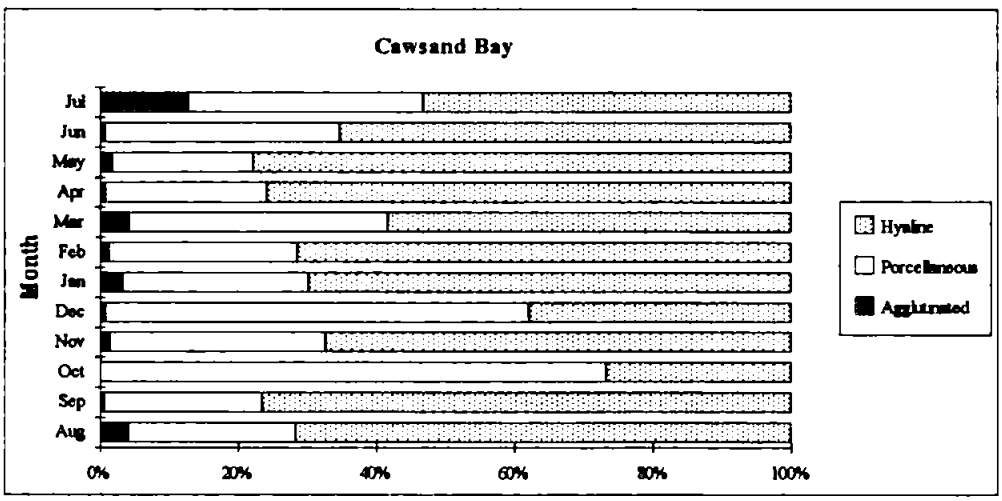


Figure 3.8: Temporal variation in relative abundance of three major test types at Cawsand Bay, 1993/1994.

From Figure 3.8 it can be seen that hyaline individuals dominate the assemblage at Cawsand Bay except during the months of October and December, when the porcellaneous forms constitute a greater percentage of the assemblage. Agglutinated individuals form 4.0%, 4.2% and 12.7% of the assemblage in the months of August, March and July respectively.

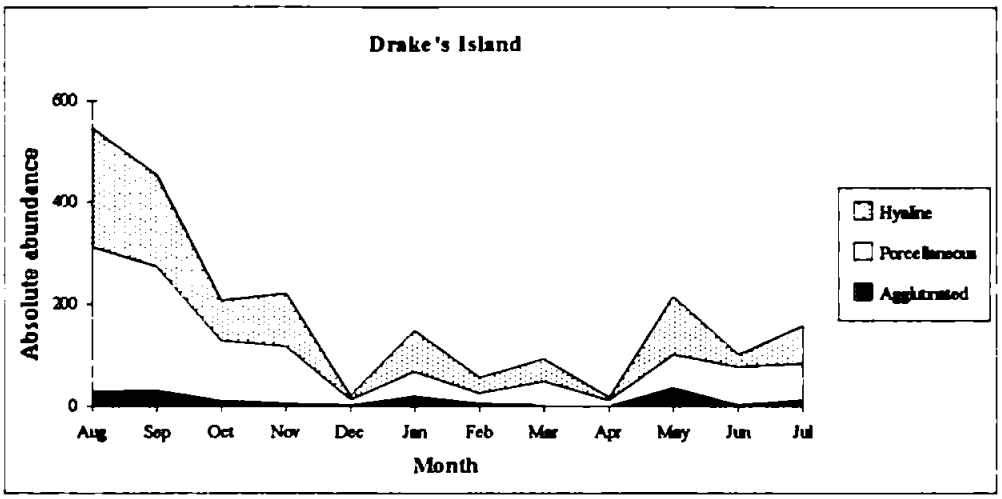


Figure 3.9: Temporal variation in absolute abundance of the three major test types from Drake's Island, 1993/1994.

From Figure 3.9 it can be seen that the assemblage from Drake's Island is quite different to that of Cawsand Bay; at this site porcellaneous and agglutinated individuals form larger proportions of the assemblage. Although the number of hyaline foraminiferids exceeds that of porcellaneous and agglutinated specimens in the months of January, February, May and July; the porcellaneous foraminiferids exceed the number of hyaline specimens in the major abundance peaks of August, September and November (and also in the months of October, December, March, April and June). The agglutinated Foraminiferida at this site appear to reproduce mainly during the months of September, January and May.

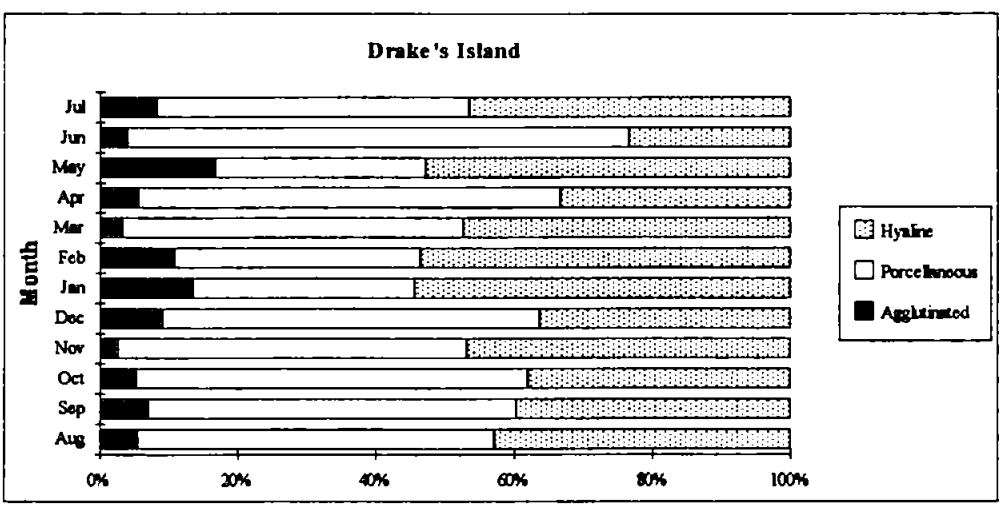


Figure 3.10: Temporal variation in relative abundance of three major test types at Drake's Island, 1993/1994.

From Figure 3.10 it can be seen that the proportions of porcellaneous and hyaline Foraminiferida are fairly even throughout the annual sampling period, although the percentage of porcellaneous forms generally exceeds that of hyaline forms. The agglutinated fauna is always present at this site and ranges between 2% and 16.7% of the assemblage. There appears to be an inverse relationship between the agglutinated and porcellaneous suborders at this site: the agglutinated fauna appears to increase as a percentage of the assemblage when the percentage of porcellaneous forms decreases.

White Patch

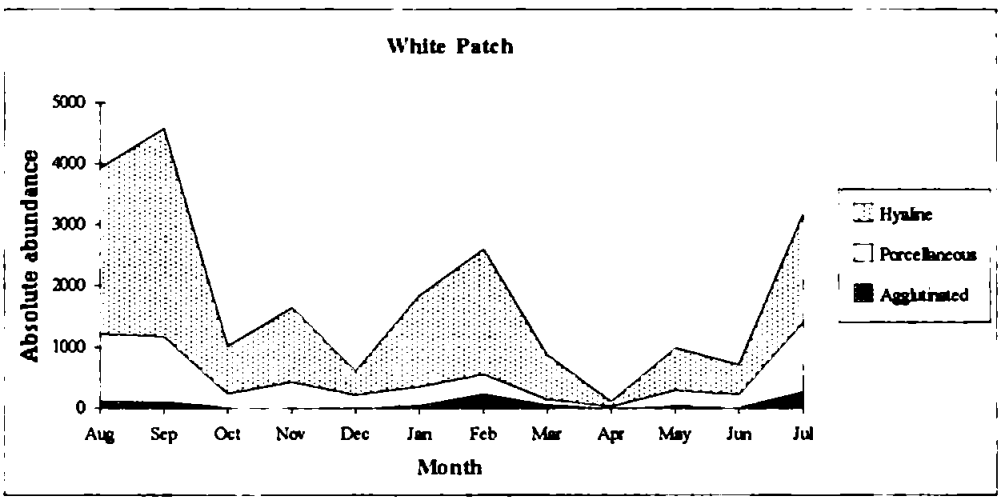


Figure 3.11: Temporal variation in absolute abundance of the three major test types from White Patch, 1993/1994.

From Figure 3.11 it can be seen that the assemblage at this site is dominated by hyaline Foraminiferida which mostly determine the peaks in abundance throughout the year. The peaks in abundance of Foraminiferida in the months of September, November, February, May and July are mainly due to the reproduction of hyaline specimens. Porcellaneous forms appear to peak in abundance at this site in the months of August, September and July, whereas the agglutinated Foraminiferida appear to reproduce in the months of August, September, February and July.

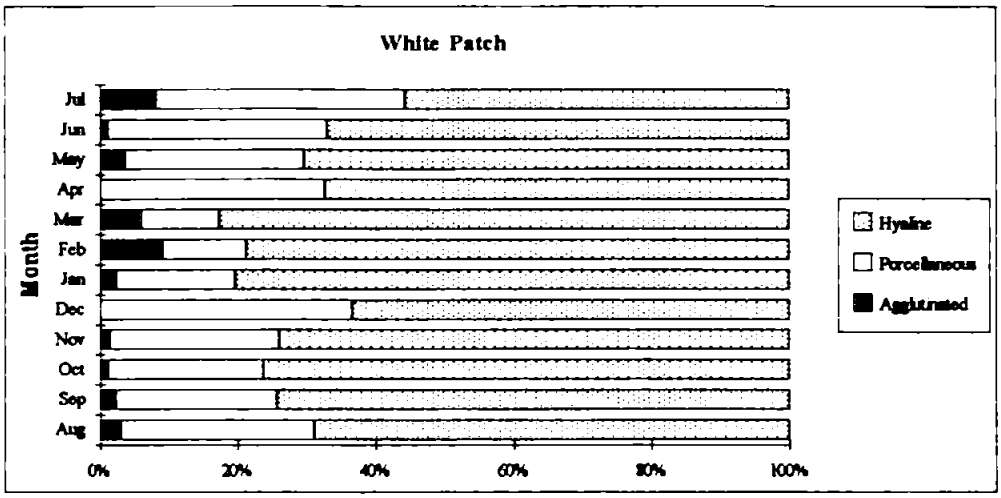


Figure 3.12: Temporal variation in relative abundance of three major test types at White Patch, 1993/1994.

From Figure 3.12 it can be seen that hyaline individuals dominate the assemblage at White Patch throughout the annual sampling period. The percentage of porcellaneous individuals at this site range between 11.5% and 36.5% and agglutinated specimens form a small proportion of the assemblage at this site.

Comparison of sites

From the above graphs it appears that the three sites differ for component test types within the assemblages. Cawsand Bay and White Patch are similar in that the assemblages are dominated by hyaline Foraminiferida (although they reproduce at different times) and the number of agglutinated taxa is relatively low. Drake's Island assemblages are dominated by porcellaneous forms and the number of agglutinated Foraminiferida is higher at this site than at Cawsand Bay or White Patch. Hyaline Foraminiferida reproduce at Cawsand Bay in the months of August, September and March; at Drake's Island in January, February, May and July; at White Patch in the months of September, November, February, May and July. Porcellaneous Foraminiferida reproduce at Cawsand Bay in the months of October and March; at Drake's Island in August, September, and November; at White Patch in the months of August, September and July. Agglutinated Foraminiferida reproduce at Cawsand Bay in the months of August and March; at Drake's Island in September, January and May; at White Patch in the months of August,

September, February and July. These differences in timing of reproduction may be because each site has different species present or because the environmental factors differ at each site.

3.5.2. THE FIVE SUB-ORDERS.

The distribution of Textulariina and Miliolina are as above, but the category of hyaline Foraminiferida is divided into the sub-orders of Spirillinina, Lagenina and Rotaliina.

Cawsand Bay

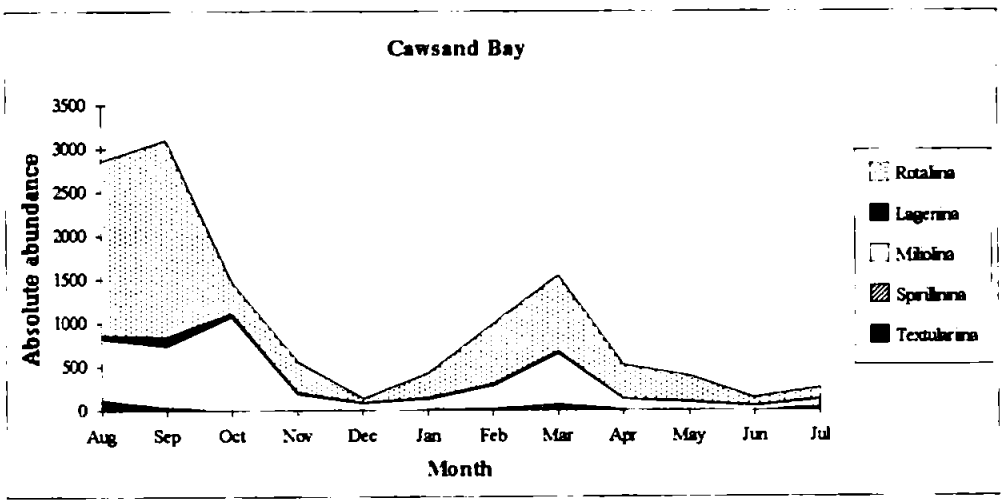


Figure 3.13: Temporal variation in absolute abundance of the five sub-orders of Foraminiferida present at Cawsand Bay, 1993/1994.

From Figure 3.13 it can be seen that Rotaliina dominate the hyaline Foraminiferida present at this site throughout the annual sampling period. Lagenina form a small proportion of the assemblage but appear to peak in abundance in September. The Spirillinina at this site appear in few numbers on alternate months from September until March, and form a very small component of the assemblage.

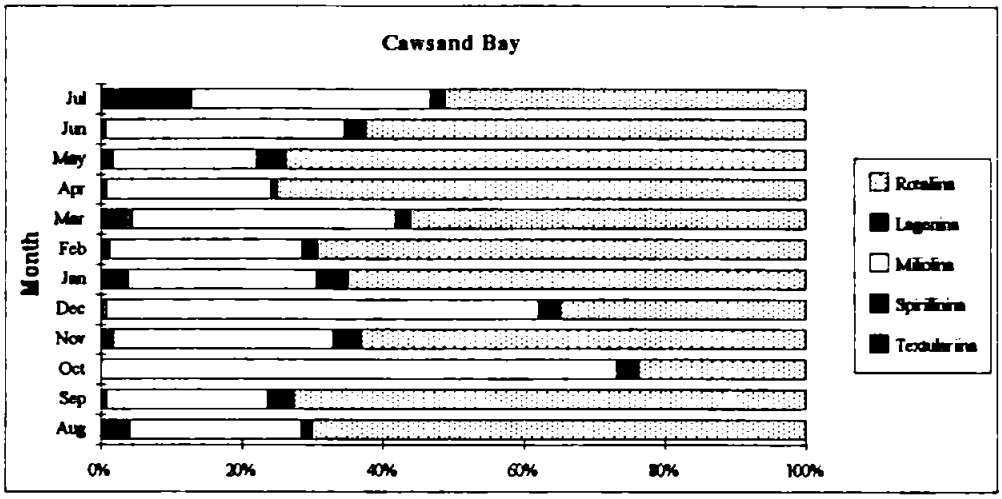


Figure 3.14: Temporal variation in relative abundance of the five sub-orders of Foraminiferida present at Cawsand Bay, 1993/1994.

From Figure 3.14 it can be seen that the Spirillinina and Lagenina form very small components of the assemblage, although the Lagenina sometimes form a greater proportion of the assemblage than the Textulariina. Rotaliina dominate the hyaline specimens at this site, and dominate all other sub-orders.

Drake's Island

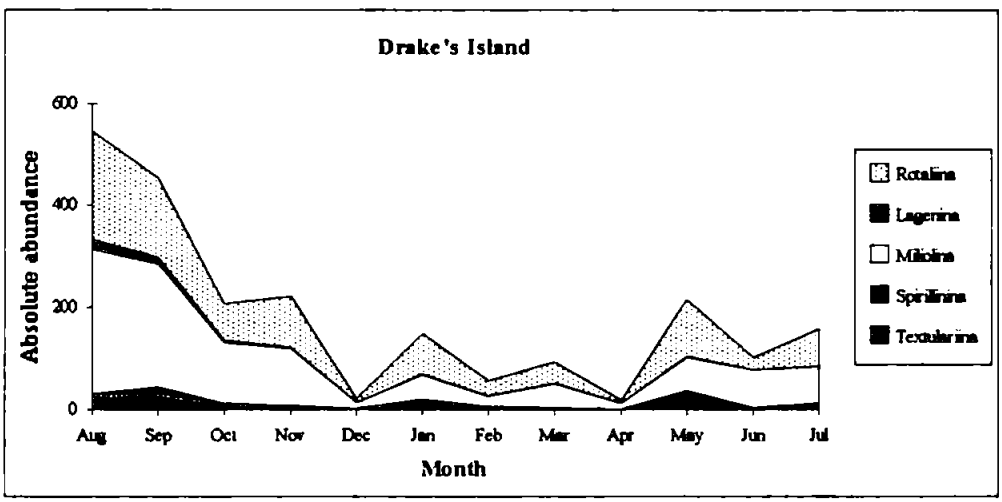


Figure 3.15: Temporal variation in absolute abundance of the five sub-orders of Foraminiferida present at Drake's Island, 1993/1994.

From Figure 3.15 it can be seen that the hyaline Foraminiferida at this site are mainly composed of Rotaliina. Both the Spirillina and the Lagenina are represented by relatively few specimens, although both groups appear to increase in abundance in August and September.

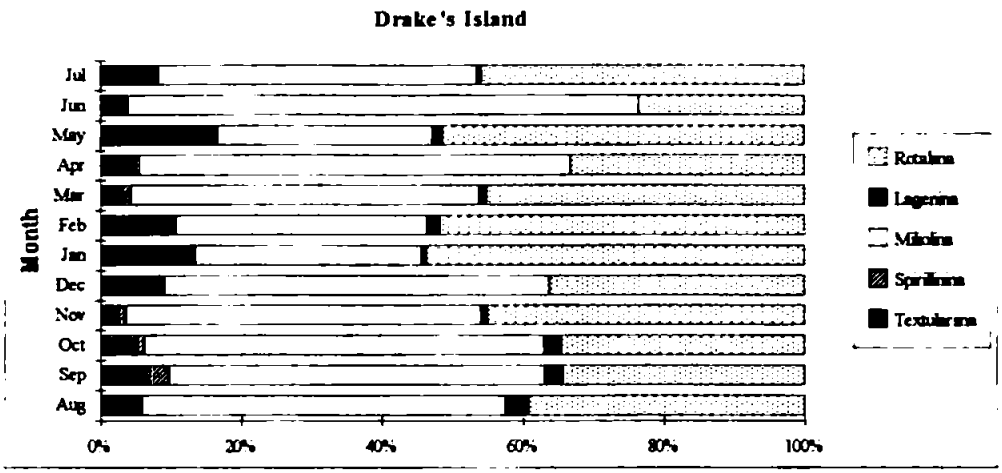


Figure 3.16: Temporal variation in relative abundance of the five sub-orders of Foraminiferida present at Drake's Island, 1993/1994.

From Figure 3.16 it can be seen that the Spirillina and Lagenina form small proportions of the assemblage at Drake's Island with the Spirillinina increasing in proportion in September, October, November and March and the Lagenina increasing as a proportion of the assemblage in August, September and October. Neither sub-order is ever greater than the percentage of Textulariina at this site and form small components of the hyaline fauna.

White Patch

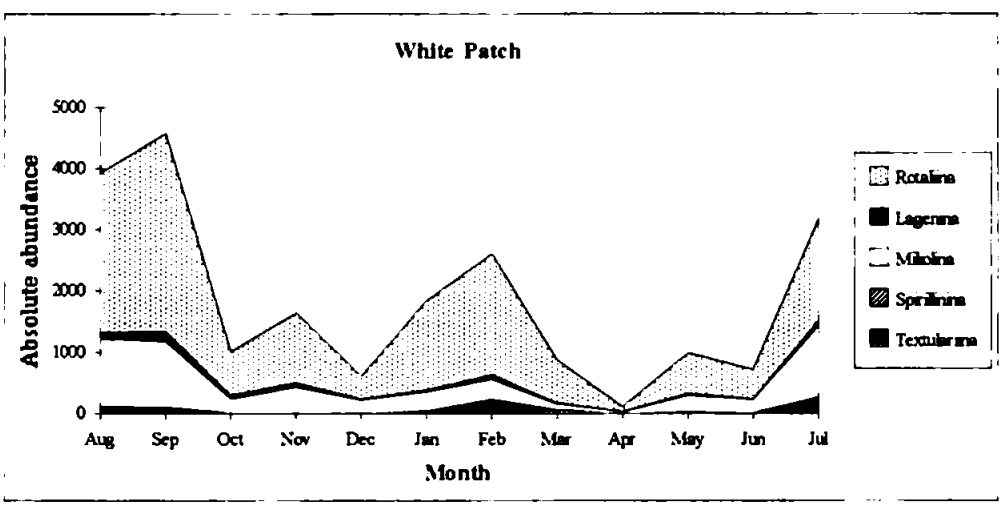


Figure 3.17: Temporal variation in absolute abundance of the five sub-orders of Foraminiferida present at White Patch, 1993/1994.

From Figure 3.17 it can be seen that the hyaline Foraminiferida at this site are largely composed of Rotaliina. Spirillina are extremely rare at this site, although the

Lagenina occur in relatively large numbers, exceeding in abundance the Textulariina at this site in September, October, November, December and April.

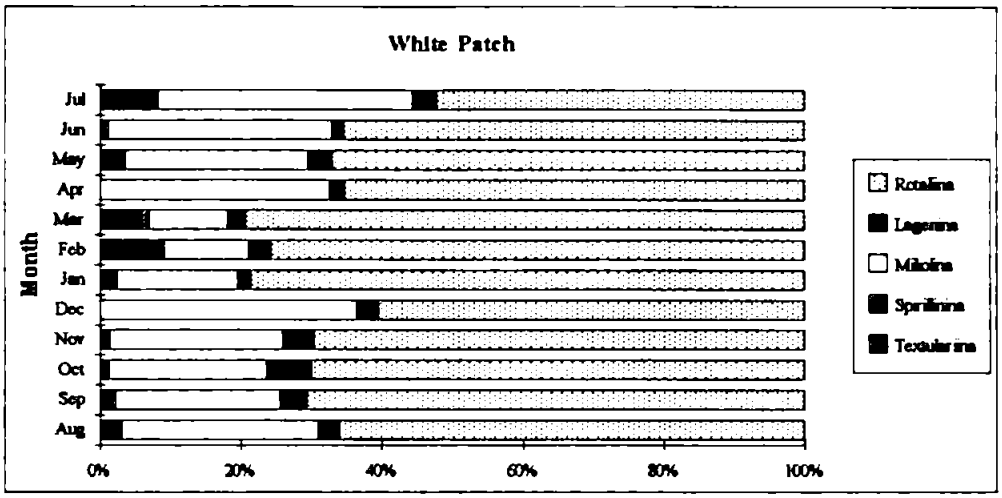


Figure 3.18: Temporal variation in relative abundance of the five sub-orders of Foraminiferida present at White Patch, 1993/1994.

From Figure 3.18 the Spirillina form a rare component of the assemblage, whilst the Lagenina form a significant proportion of the hyaline specimens throughout the annual cycle at this site, often exceeding the percentage of Textulariina.

Comparison of sites

The hyaline Foraminiferida at all three sites are dominated by Rotaliina with comparatively small proportions of Spirillinina and Lagenina. The Lagenina peak at all sites in September and, at both Cawsand Bay and White Patch, at times exceed the number of Textulariina.

3.6. TEST SHAPE.

Many organisms show a good correlation between their form and the environment in which they live, although shape is often a compromise of many requirements (Murray, 1991). Convergent evolution of test shapes is correlated with environment (see Brasier, 1975; Kitazato, 1984; Haynes, 1990; Corliss,1991), species symbiotic with algae (Röttger *et al.*, 1984) feeding strategy (Jones &

Charnock, 1985). "Morphogroup" analyses of Foraminiferida have linked the shape of foraminiferid tests to feeding habits and also to life position (see Jones & Charnock, 1985). In addition Bernhard (1986) associates test morphology with oxygen availability. The number of different test shapes of Foraminiferida has been collated from the data to show how the sites differ in terms of foraminiferid test morphologies and how those morphologies might change throughout the annual sampling period.

Cawsand Bay

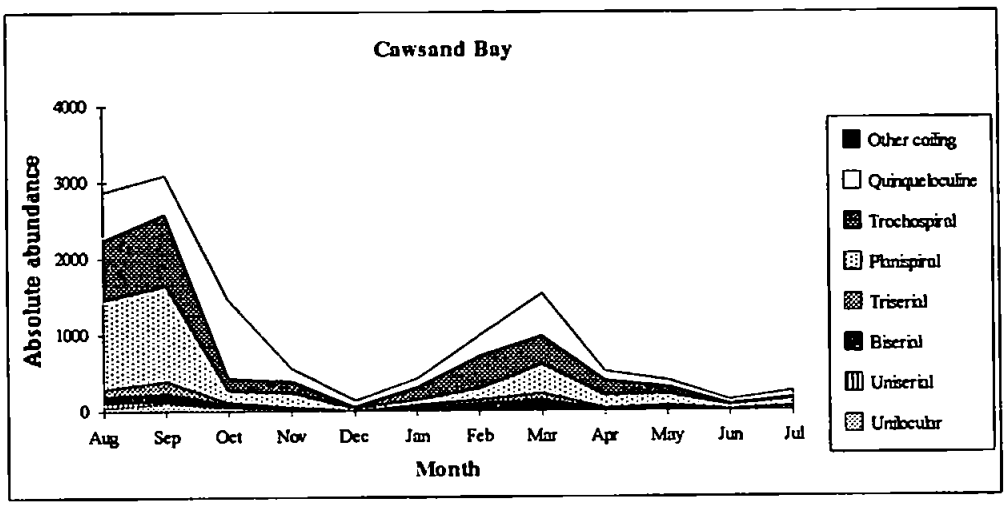


Figure 3.19: Temporal variation in absolute abundance of test shapes of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.19 it can be seen that the major peaks in abundance at this site are mainly comprised of quinqueloculine, trochospiral and planispiral Foraminiferida. At Cawsand Bay it appears that these three shapes of live Foraminiferida have two major reproductive phases which correspond with the phytoplankton blooms. Whereas the peak in abundance in March is comprised of equitable numbers of quinqueloculine, trochospiral and planispiral forms, the peak in abundance in September is comprised of more planispiral than trochospiral and quinqueloculine forms respectively. This indicates that at this site the autumn period is more important for planispiral forms to reproduce than other periods of the year.

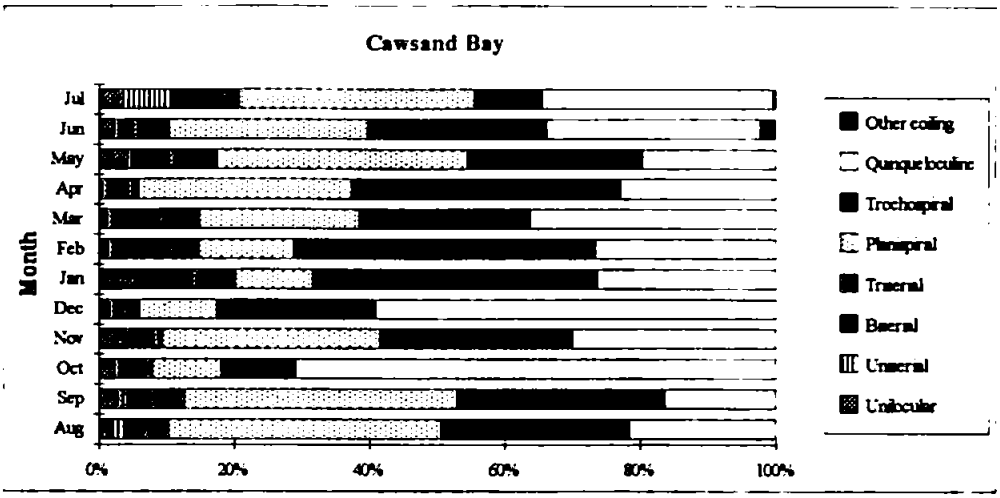


Figure 3.20: Temporal variation in relative abundance of test shapes of live Foraminiferida from Cawsand Bay, 1993/1994.

Figure 3.20 shows that the Foraminiferida at Cawsand Bay is mainly comprised of quinqueloculine, trochospiral and planispiral Foraminiferida. Quinqueloculine coiling Foraminiferida form increased proportions of the assemblage in October and December, with corresponding decreases in the proportions of trochospiral and planispiral Foraminiferida at this site. The other shapes of Foraminiferida are fairly stable throughout the annual cycle, although uniserial forms increase in July; biserial forms increase in the spring months; and Foraminiferida of other coiling increase as a proportion of the assemblage in June and July.

Drake's Island

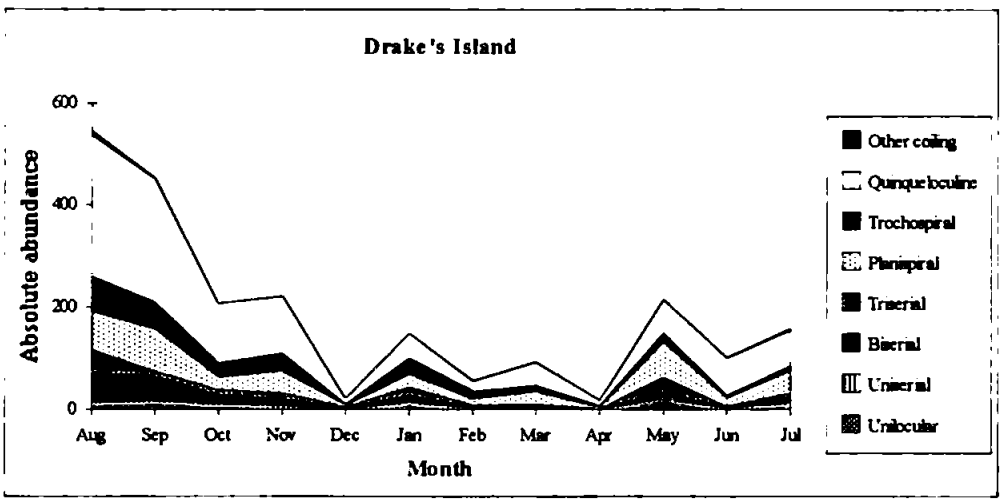


Figure 3.21: Temporal variation in absolute abundance of test shapes of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.21 it can be seen that the Drake's Island assemblage is dominated throughout the annual cycle by quinqueloculine coiling Foraminiferida. Unlike Cawsand Bay, this site has fewer numbers of trochospiral and planispiral Foraminiferida than quinqueloculine forms. Uniserial forms are almost absent from Drake's Island, possibly because the environment is too dynamic at this site to allow fragile uniserial forms such as *Reophax scottii* to proliferate.

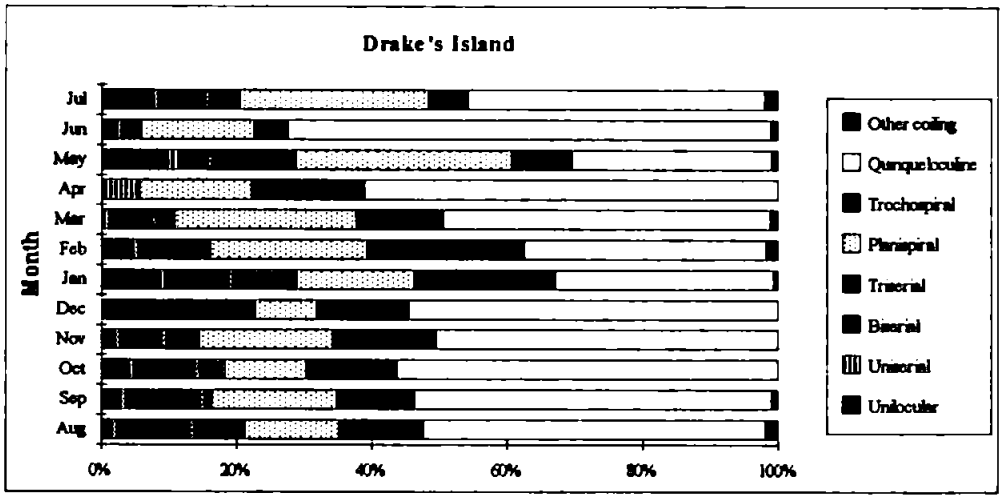


Figure 3.22: Temporal variation in relative abundance of test shapes of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.22 it can be seen that although quinqueloculine Foraminiferida dominate the live assemblage at Drake's Island throughout the annual cycle, most of the other test shapes of Foraminiferida are fairly stable components of the assemblage. The quinqueloculine Foraminiferida form a larger part of the assemblage at this site in October, April and July. Unilocular forms increase as a proportion of the assemblage in January and May; biserial forms in December; triserial in May and January; planispiral in May; trochospiral in January and February; other types of coiling in December and June.

White Patch

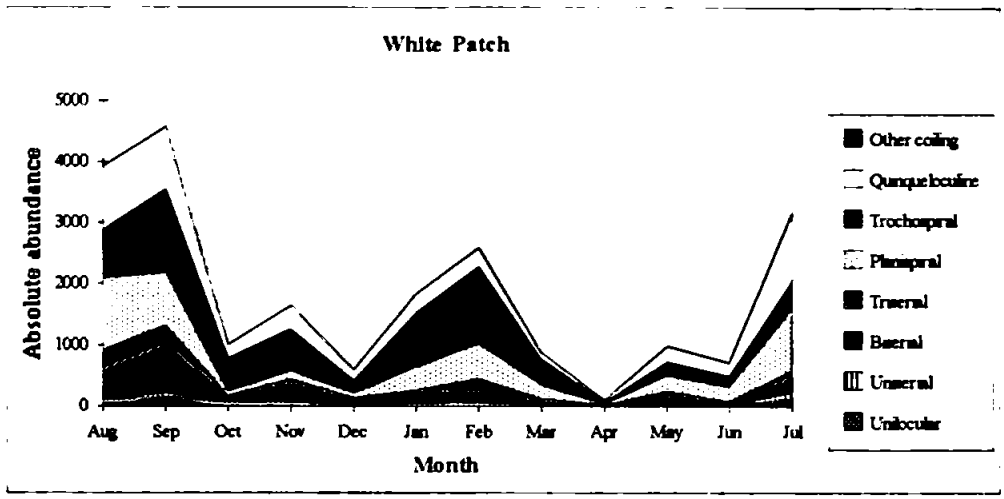


Figure 3.23: Temporal variation in absolute abundance of test shapes of live Foraminiferida from White Patch, 1993/1994.

From Figure 3.23 it can be seen that the peaks in abundance of live Foraminiferida at White Patch during September, November and February are dominated by trochospiral and planispiral forms, whereas the peak in abundance in July is formed mainly by planispiral Foraminiferida. Biserial Foraminiferida peak in abundance in September.

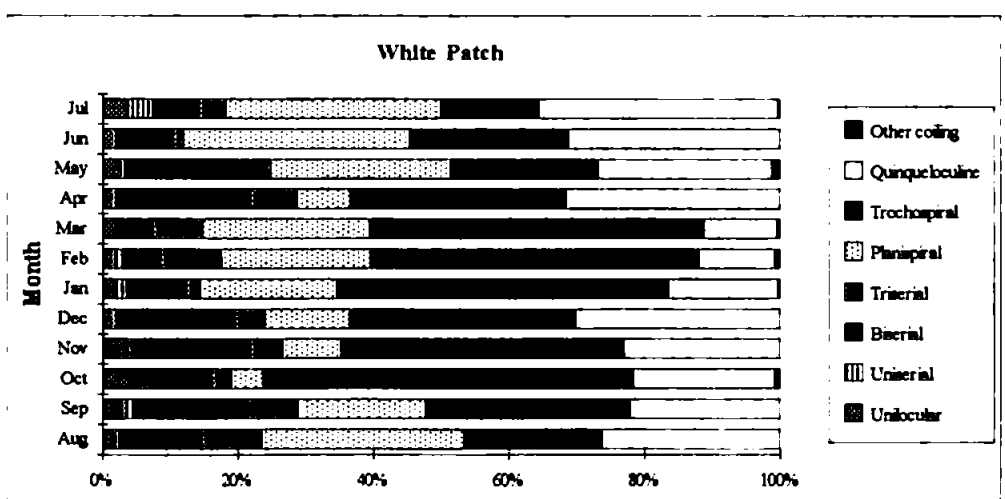


Figure 3.24: Temporal variation in relative abundance of test shapes of live Foraminiferida from White Patch, 1993/1994.

All shapes of Foraminiferida at this site have a fairly stable proportional distribution. Trochospiral forms dominate the assemblage in October and the spring months, and planispiral Foraminiferida increase as a proportion of the

assemblage in August, June and July. Quinqueloculine forms are fairly stable and increase in December and April, whereas the biserial Foraminiferida increase as a proportion of the assemblage in September.

Comparison of sites.

The sampled sites differ for the abundance of coiling forms of Foraminiferida throughout the annual sampling period. The foraminiferal fauna at Cawsand Bay has a fairly even distribution of quinqueloculine, trochospiral and planispiral forms; at Drake's Island the fauna is dominated throughout the year by quinqueloculine forms, whereas at White Patch the assemblage mainly consists of trochospiral and planispiral Foraminiferida.

3.7. APERTURE SHAPE.

The apertural shape of Foraminiferida is important in the taxonomy of these organisms but has not been investigated with reference to temporal fluctuations of assemblages. Little is known of the importance of the apertural shape diversity displayed by Foraminiferida and this characteristic may reflect the feeding strategy of Foraminiferida or perhaps indicate the shape of diatoms preferred as prey by herbivorous taxa.

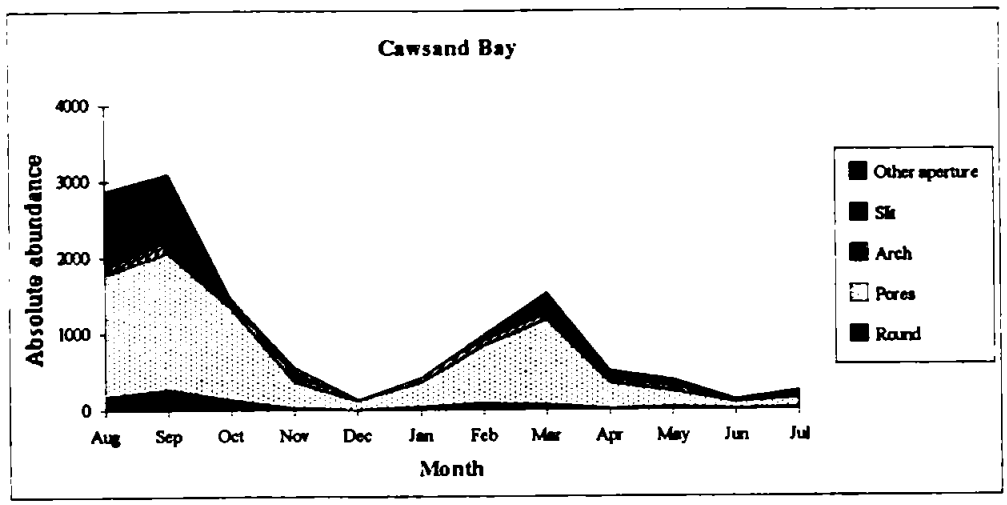


Figure 3.25: Temporal variation in absolute abundance of apertural shapes of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.25 it can be seen that peaks in foraminiferal abundance at Cawsand Bay are determined by increases in pore, arch and slit-apertured Foraminiferida with an increase in round-apertured Foraminiferida in September. The assemblage in October is dominated by Foraminiferida with arch-shaped apertures.

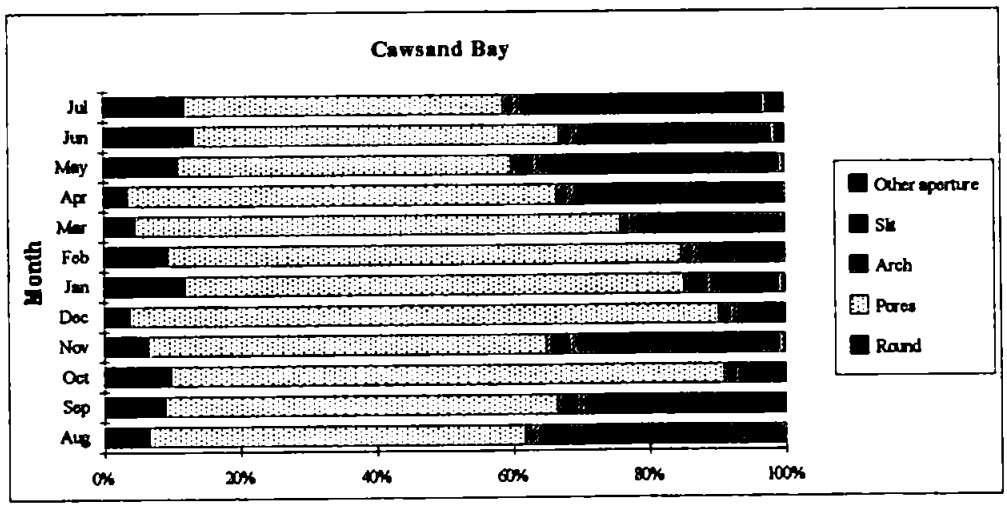


Figure 3.26: Temporal variation in relative abundance of apertural shapes of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.26 it can be seen that the distribution of Foraminiferida with pore, arch and slit apertures have a fairly even temporal distribution, whereas there is an increase in slit-apertured Foraminiferida in January and February, and arch-shaped apertured Foraminiferida in March.

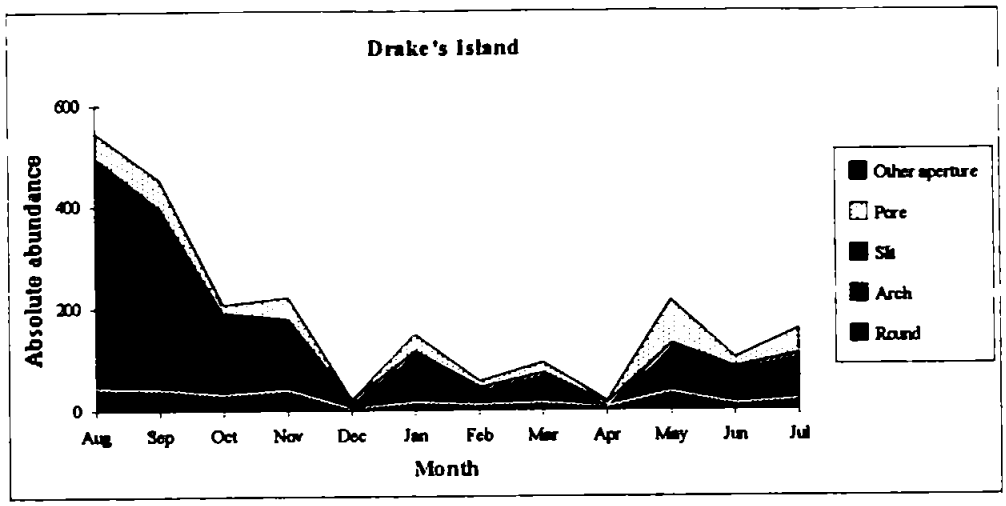


Figure 3.27: Temporal variation in absolute abundance of apertural shapes of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.27 it can be seen that the assemblage at Drake's Island is dominated by arch-shaped-apertured Foraminiferida and is the same pattern of distribution as displayed by the Miliolina and quinqueloculine-coiled Foraminiferida. Foraminiferida with round-shaped and pore apertures have a minor contribution to peaks in abundance at this site.

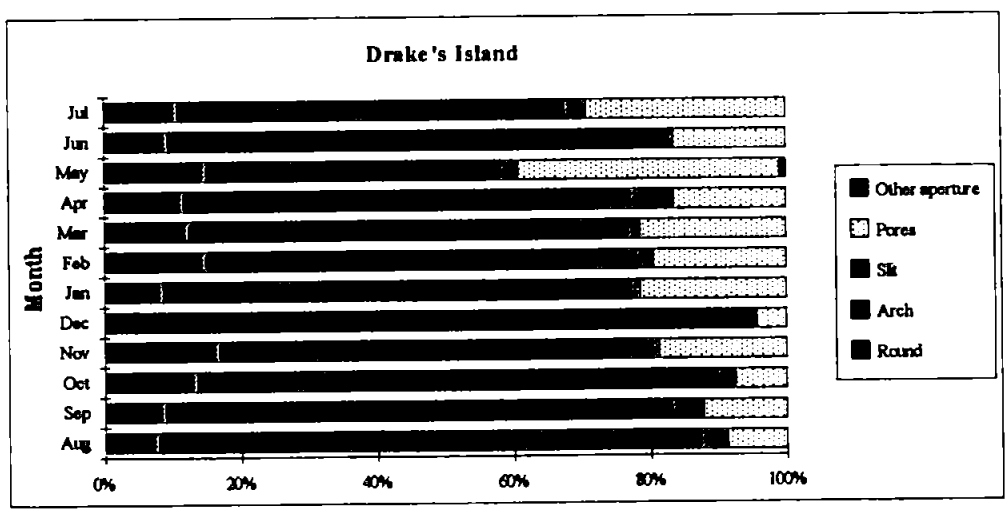


Figure 3.28: Temporal variation in relative abundance of apertural shapes of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.28 it can be seen that the assemblage is dominated throughout the year at Drake's Island by arch-shaped-apertured Foraminiferida, especially in December when live numbers of Foraminiferida sharply decrease at this site.

Foraminiferida with pore apertures form a fairly even proportion of the assemblage throughout the year, but increase in proportion of the assemblage in May.

White Patch

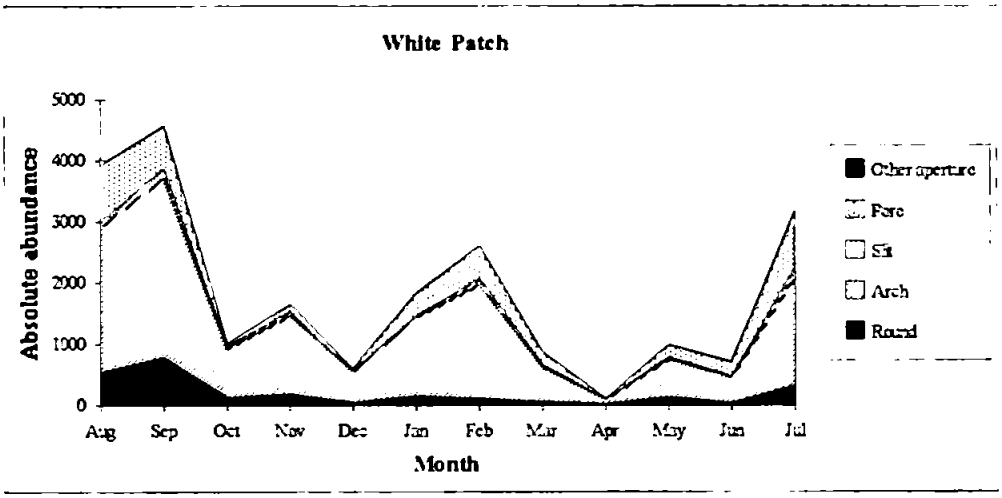


Figure 3.29 Temporal variation in absolute abundance of apertural shapes of live Foraminiferida from White Patch, 1993/1994.

The major peaks in abundance at White Patch, except in July, have a fairly even distribution of arch, slit and pore-apertured Foraminiferida. In the month of September there is a peak in round-apertured Foraminiferida at this site. The peak in abundance in July is determined mainly by pore and arch-shaped-apertured forms, with minor contributions by those with slit and round apertures.

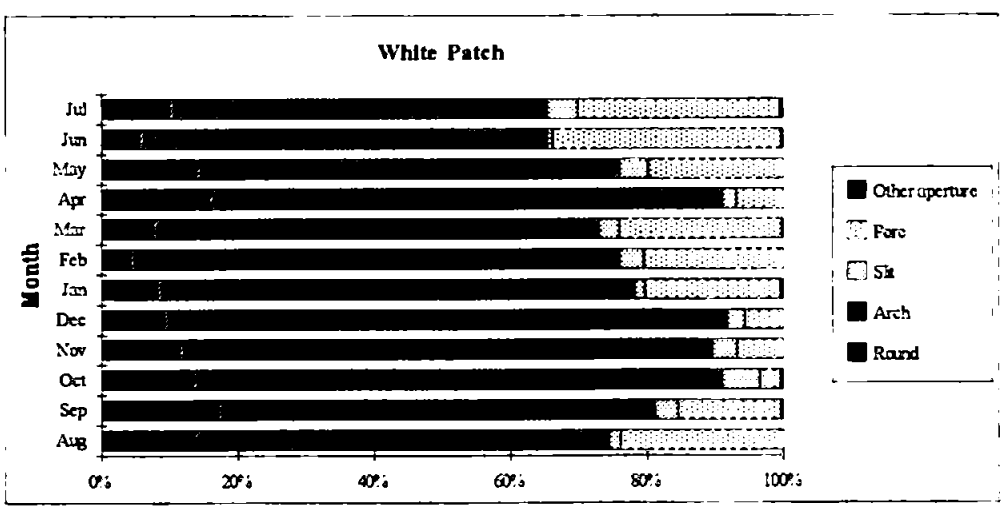


Figure 3.30 Temporal variation in relative abundance of apertural shapes of live Foraminiferida from White Patch, 1993/1994.

Foraminiferida with round apertures form a fairly stable proportion of the foraminiferid assemblage throughout the year at this site, although they form a slightly greater proportion of the assemblage in the spring months and in September. Foraminiferida with pore apertures fluctuate as a proportion of the assemblage, with relatively few present in the winter months and before the phytoplankton bloom in April. Foraminiferida with arch-shaped apertures also form a fairly stable proportion of the assemblage at this site but diminish in proportion in the months of January, February and March, when there is a corresponding increase in those with slit apertures.

Comparison of sites.

The temporal distribution of Foraminiferida of different apertural shapes is remarkably similar for the assemblages at Cawsand Bay and White Patch, with both assemblages having fairly even patterns of distributions of Foraminiferida with pore, arch and slit apertures. The assemblage at Drake's Island is markedly different from the other assemblages in that it is dominated by Foraminiferida with arch-shaped apertures.

3.8. LIFE POSITION.

A synopsis of inferred life position of most genera of Foraminiferida encountered in this study is given by Murray (1991) and used here to illustrate the temporal variation in abundance of foraminiferal life positions. As the life position of all genera encountered in this study is not known, the relative abundance of life position of the Foraminiferida will not total 100%.

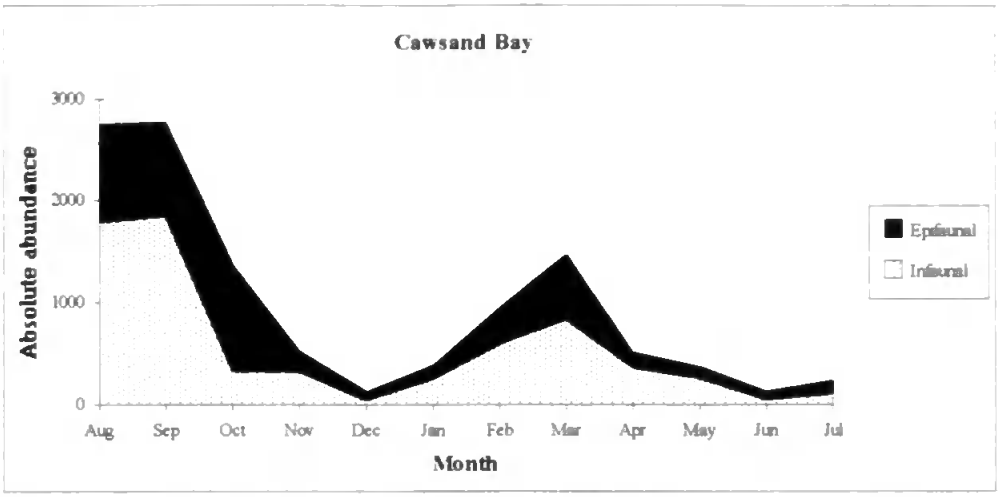


Figure 3.31: Temporal variation in absolute abundance of life position of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.31 it can be seen that the foraminiferid assemblage at Cawsand Bay is dominated by infaunal Foraminiferida except in October and July.

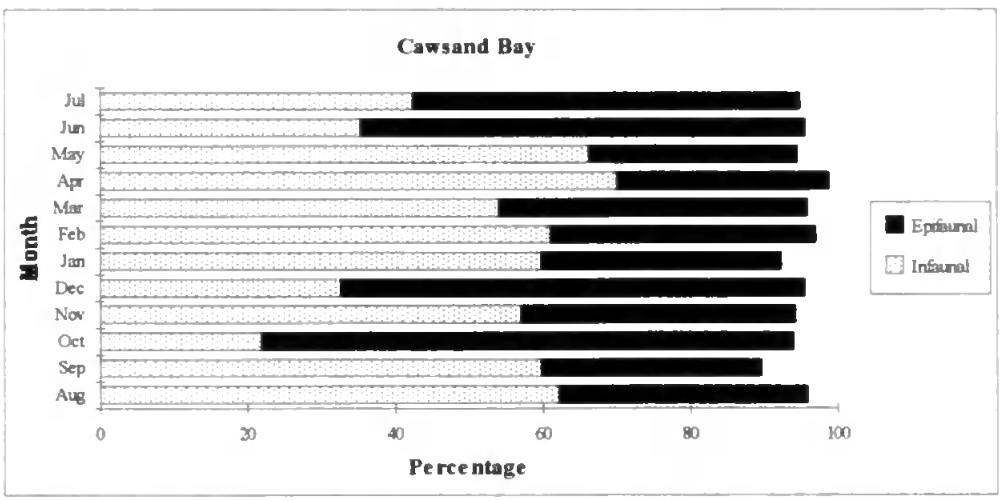


Figure 3.32 Temporal variation in percentage abundance of life position of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.32 it can be seen that the relative abundances of epifaunal and infaunal forms fluctuate throughout the annual sampling period. Infaunal Foraminiferida form a larger proportion of the assemblage in August and September and in April and May and epifaunal forms form a larger proportion of the assemblage in October, December and June.

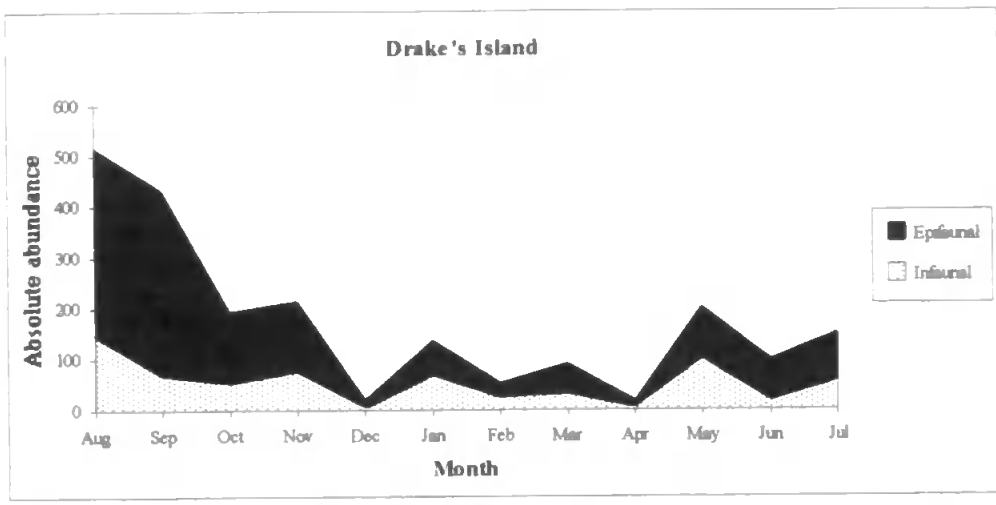


Figure 3.33: Temporal variation in absolute abundance of life position of live Foraminiferida from Drake's Island, 1993/1994.

The foraminiferal assemblage at this site, unlike that of Cawsand Bay, is dominated by epifaunal forms which determine the major peaks in foraminiferid abundance at this site, especially in September. The infaunal Foraminiferida do form minor peaks in abundance, but not to the same extent as that of the epifaunal forms.

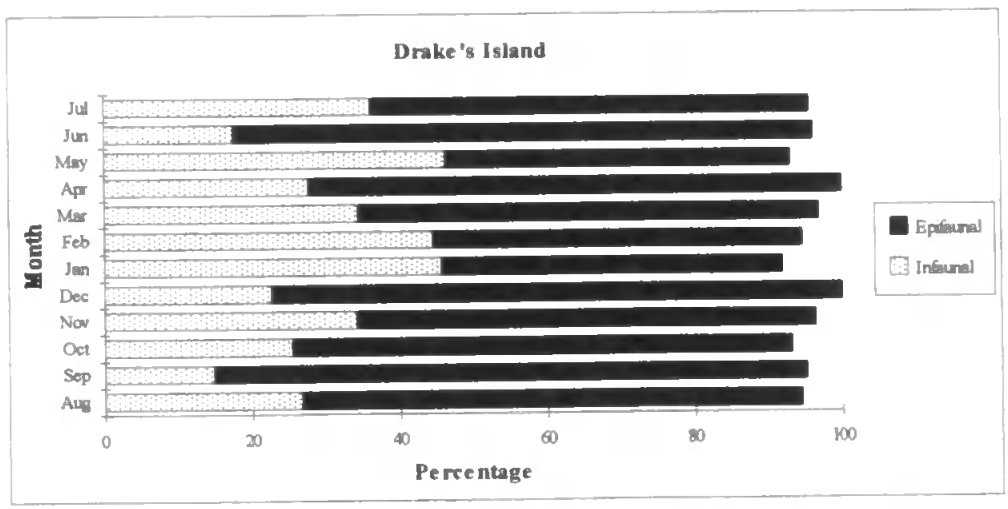


Figure 3.34: Temporal variation in percentage abundance of life position of live Foraminiferida from Drake's Island, 1993/1994.

It can be seen from Figure 3.34 that epifaunal Foraminiferida dominate the Drake's Island assemblage in all months sampled except January and February, when there is a fairly even distribution of Foraminiferida of both life positions.

White Patch

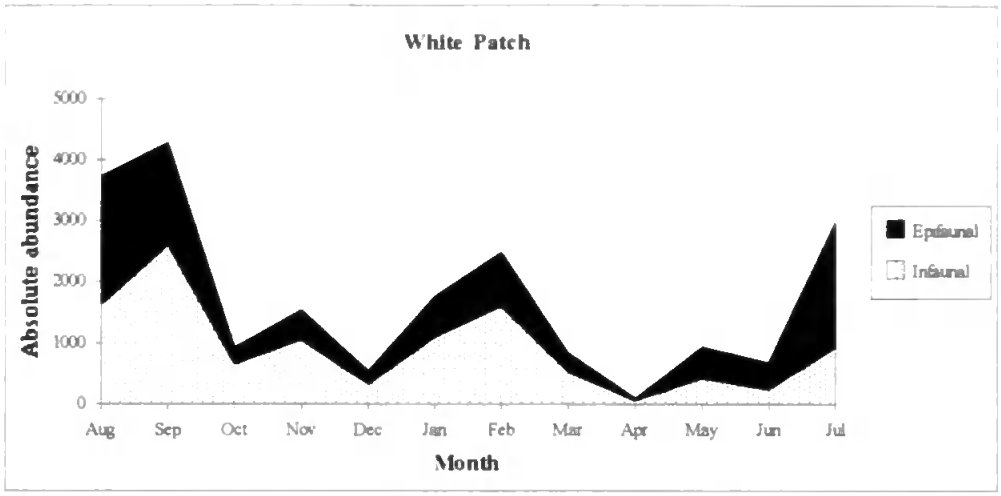


Figure 3.35: Temporal variation in absolute abundance of life position of live Foraminiferida from White Patch, 1993/1994.

The temporal distribution of epifaunal and infaunal Foraminiferida from White Patch bears a close resemblance to that of Foraminiferida from Cawsand Bay in that the infaunal taxa dominate most months. In August and July, however, epifaunal taxa exceed the number of infaunal taxa at this site, and in May and June the numbers of infaunal and epifaunal specimens is fairly equal.

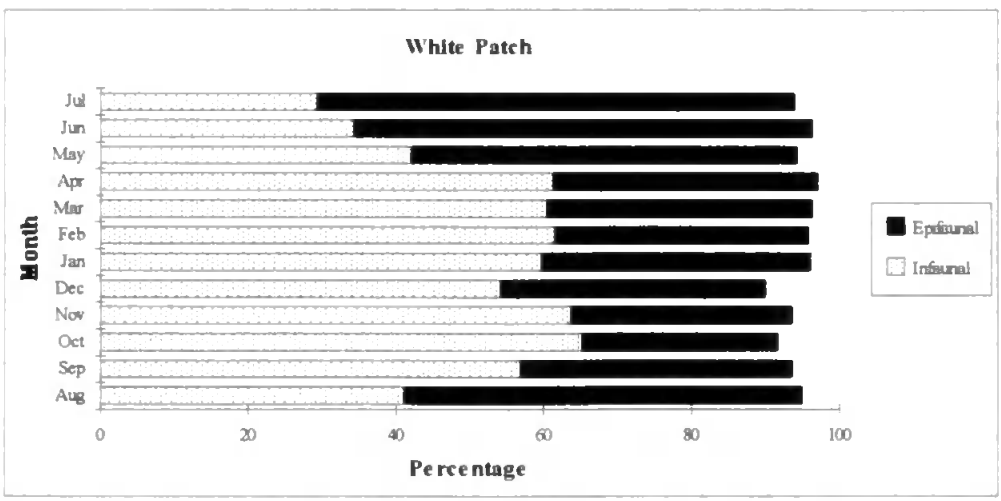


Figure 3.36: Temporal variation in percentage abundance of life position of live Foraminiferida from White Patch, 1993/1994.

The graph of relative abundances of infaunal and epifaunal specimens at White Patch shows that in August, May, June and July epifaunal specimens out-number

the infaunal specimens, whilst the infaunal specimens dominate the assemblage from September through to April.

Comparison of sites.

The abundance of infaunal and epifaunal Foraminiferida appears to fluctuate with seasonal change and appears to be related to the nature of the substrata. The relatively more stable substrata of Cawsand Bay and White Patch support more infaunal specimens in the winter months, whilst in summer the epifaunal specimens proliferate. In the relatively unstable substratum of Drake's Island epifaunal specimens dominate the assemblage. Infaunal Foraminiferida form a larger proportion of the assemblage at Cawsand Bay in August and September and in April and May possibly due to the damaging effect of autumn and spring gales upon the substratum and therefore, upon the epifaunal Foraminiferida. The relative lack of infaunal forms at Drake's Island may be because these Foraminiferida are not as motile as epifaunal Foraminiferida, and in this dynamic environment are not as well-adapted to movement of the substratum. It may be that the poorly-sorted substratum at White Patch protects infaunal forms from the disturbance of autumnal and spring gales which may allow infaunal specimens to proliferate at the expense of epifaunal specimens which would be disturbed/buried at this time of year. In the summer months at White Patch the epifaunal Foraminiferida have a more stable substratum to colonise which would be rich in unicellular algae.

3.9. FEEDING STRATEGY.

The feeding strategy of many of the genera within this study have been observed/inferred and reference to Murray's (1991) list of the ecology of genera has been used to divide the data set into those Foraminiferida which are

herbivorous, detritivorous and suspension-feeders. Suspension-feeders require a stable hard substratum on to which they can attach themselves and extend the pseudopodial network. The number of this group of Foraminiferida may well be underestimated in this study, which has sampled the soft substrata of the sites, and not the subtidal rocks or macro-flora. It would be expected that herbivorous individuals would reproduce to take advantage of the spring (and perhaps autumn) bloom of diatoms, whilst detritivores may be expected to reproduce after the autumn gales have loosened decaying macro-algae to produce detritus. It is also to be expected that herbivorous Foraminiferida will exceed detritivorous Foraminiferida in these nearshore sites, which all lie in the photic zone.

Cawsand Bay

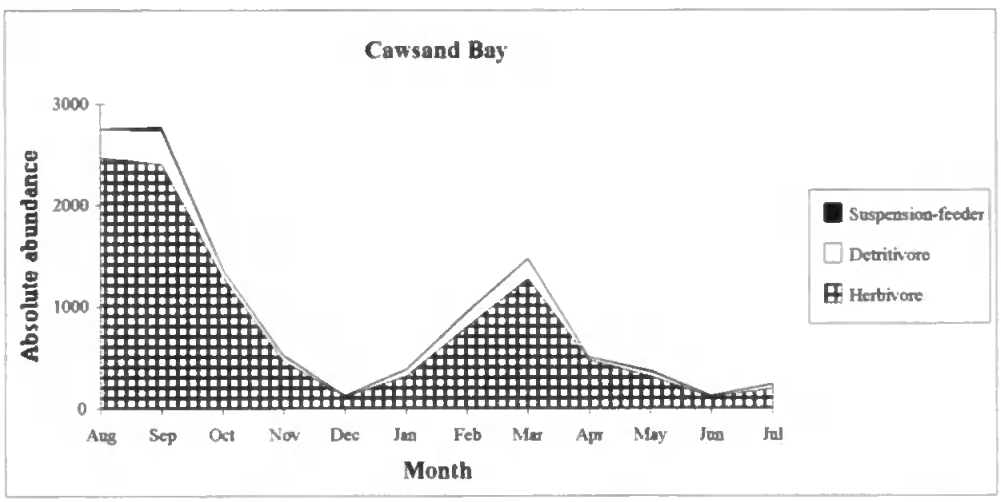


Figure 3.37: Temporal variation in absolute abundance of feeding strategies of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.37 it can be seen that the foraminiferid assemblage at Cawsand Bay is strongly dominated by herbivorous specimens throughout the annual cycle, although detritivorous Foraminiferida are present throughout the sampling year also. Detrivorous Foraminiferida are present at this site in greater numbers in August and September possibly in response to the presence of detrital macro-algae and its break-down products. There are very few suspension feeders at this site, but they increase slightly in numbers in September, perhaps to take advantage of

the seston produced by the autumnal bloom of phytoplankton and decomposing material placed into suspension by gales. Suspension-feeders are rare at this site.

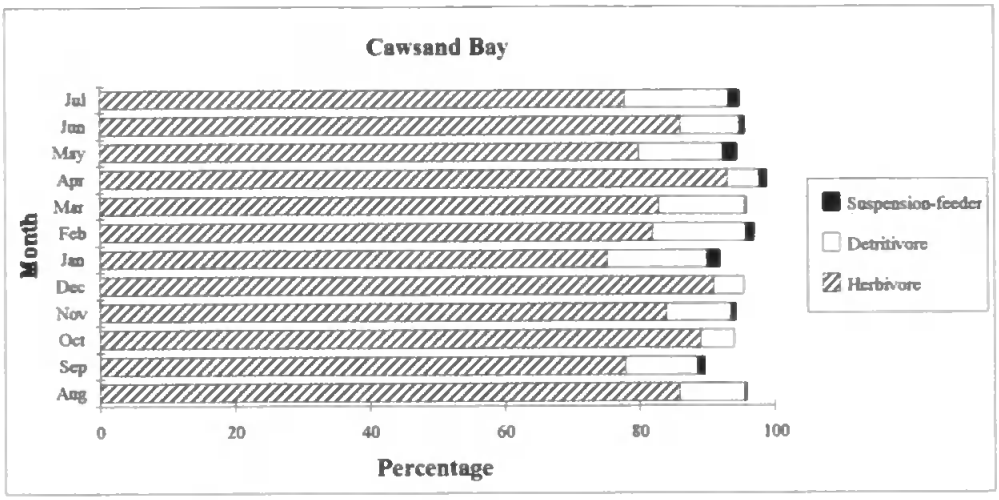


Figure 3.38: Temporal variation in percentage abundance of feeding strategies of live Foraminiferida from Cawsand Bay, 1993/1994.

From Figure 3.38 it can be seen that the ratio between herbivorous and detrivorous specimens at this site is relatively constant, although the detritivores increase as a proportion of the assemblage in the months of January and February; perhaps reproducing in response to detrital algae at this site at this time.

Drake's Island

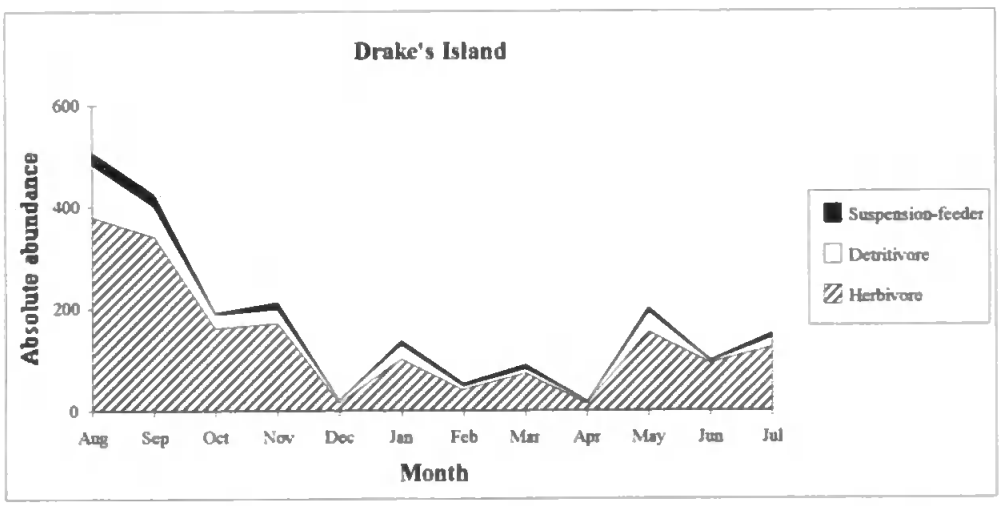


Figure 3.39: Temporal variation of absolute abundance of feeding strategies of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.39 it can be seen that the ratio between herbivores and detritivores at this site is very similar to that of the Cawsand Bay, although the number of suspension feeders at this site is comparatively high. Detritivores increase in numbers in August and September, as do suspension feeders. The number of suspension feeders is also comparatively high in November.

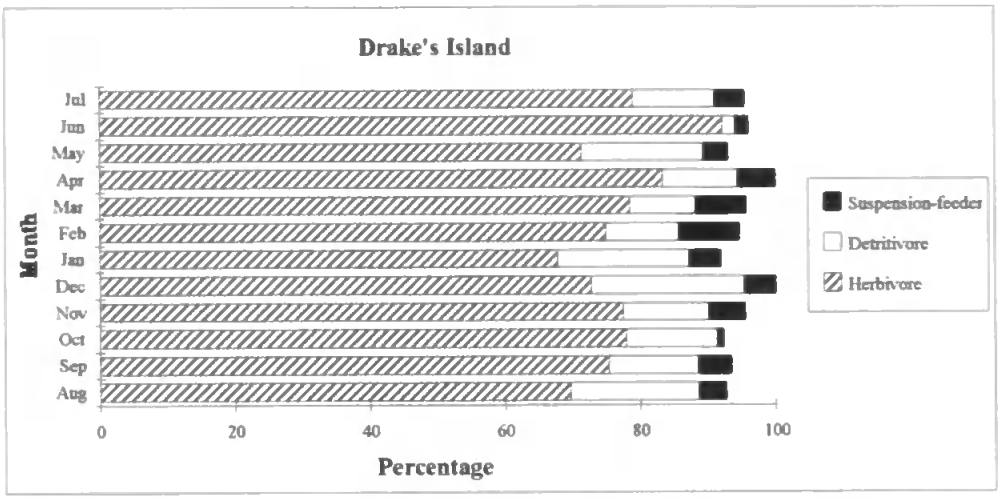


Figure 3.40: Temporal variation in percentage abundance of feeding strategies of live Foraminiferida from Drake's Island, 1993/1994.

From Figure 3.40 it can be seen that the proportions of herbivores and detritivores remain fairly constant throughout the annual sampling period, except in June, when the number of detritivores sharply declines. The proportion of suspension feeders at this site fluctuates, but is highest in the spring months; perhaps in response to increased seston in the water column.

White Patch

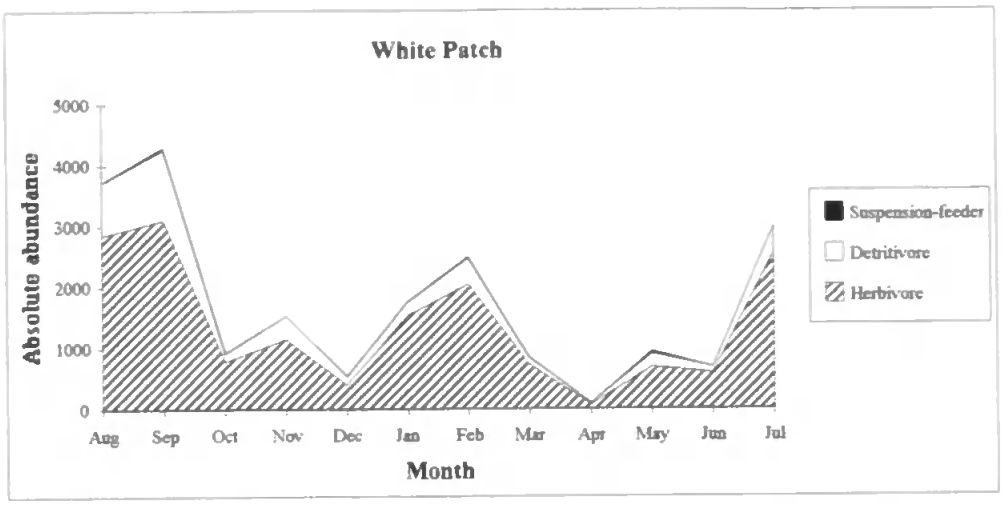


Figure 3.41: Temporal variation in absolute abundance of feeding strategies of live Foraminiferida from White Patch, 1993/1994.

The peaks in abundance of Foraminiferida at this site are also mainly comprised of herbivorous individuals. Detritivores are present throughout the annual sampling period and are most numerous in the month of September. Suspension feeders are fairly infrequent members of the assemblage at this site.

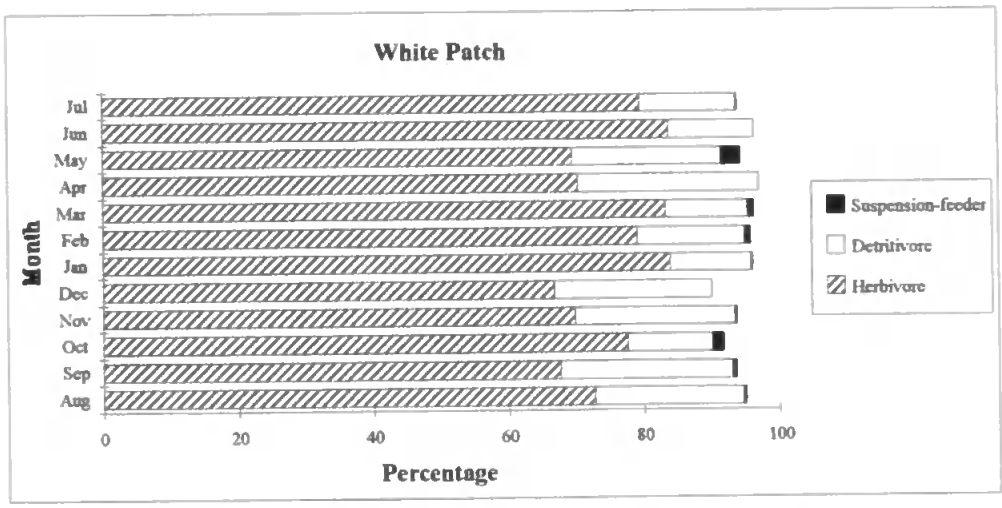


Figure 3.42: Temporal variation in percentage abundance of feeding strategies of live Foraminiferida from White Patch, 1993/1994.

From Figure 3.42 it can be seen that detritivores make a higher proportion of the assemblage at this site during the months of September, November, December, April and May. Herbivorous Foraminiferida form over 60% of the assemblage at all times, however.

Comparison of sites

All sampled assemblages were dominated by herbivorous Foraminiferida, probably because all sites lie within the photic zone and water depth above the sampled substrata does not exceed 11 m. The influence of the rivers Tamar and Plym bringing nutrients necessary for the reproduction and proliferation of diatoms also perhaps aids the growth and reproduction of herbivorous species in the area. All sites are bordered by hard substrata and attached macro-algae, which accommodate unicellular algae. Detritivorous Foraminiferida are present at all sites, although less numerous, and obviously occupy an important niche within the habitat. Suspension feeders at Drake's Island form a greater part of the assemblage than at Cawsand Bay or White Patch, and may be partially due to the close vicinity of sewage outlets (Devil's Point) providing an almost constant rain of seston. The mean values of herbivores are highest at Cawsand Bay followed by Drake's Island and White Patch, possibly reflecting the differences in water depth at the sites and therefore light quality within the photic zones of these sites for proliferation of algae. Detritivore mean values are highest at White Patch followed by Drake's Island and Cawsand Bay, possibly reflecting the sorting of the substrata at the sites with White Patch sediment being poorly-sorted and therefore able to hold detrital material; Drake's Island sediments whilst being fairly well-sorted has input of detrital material from river run-off and input of sewage and the well-sorted sediment of Cawsand Bay having comparatively little detrital input except from detrital macroalgae. Suspension feeders mean values are highest at Drake's Island followed by Cawsand Bay and White Patch, possibly reflecting differences in current strengths between the three sites.

3.10. ABUNDANCE OF FORAMINIFERID TEST SIZE.

The abundance of foraminiferid test size is standardised to number per grab each month. From sieving the Foraminiferida-rich "float" with sieves of apertures 63 μm, 125 μm, 250 μm, 500 μm and 1000 μm the number of Foraminiferida of

specific size ranges was recorded. The sediment in the pan beneath the 63 µm sieve was periodically examined for Foraminiferida, but as the sediment less than this size was mostly removed by the processing technique, Foraminiferida less than 63 µm were extremely rare. The size range of Foraminiferida from the three sites investigated usually ranged from between 63 µm to greater than 1000 µm, yet Foraminiferida above 1000 µm (1 mm) were not frequent and rarely much greater than this size. The sieving of sediment into size ranges allows easier recognition of specimens and greatly facilitates the picking of individuals from the sediment. Picking Foraminiferida from un-sieved sediment would doubtless be subject to bias from picking the more obvious larger specimens and a tendency to not recognise small individuals which may lie on, or under, larger specimens. The 63 µm to 125 µm fraction of sediment in Recent nearshore sediments yields a fauna which differs from that of the larger sieve sizes in that although juveniles of some species appear in this size fraction, there are a number of species which do not grow greater than this size. The information provided by abundance of the size ranges may help to infer the periods of reproduction of relatively larger Foraminiferida at the sites under investigation.

Cawsand Bay

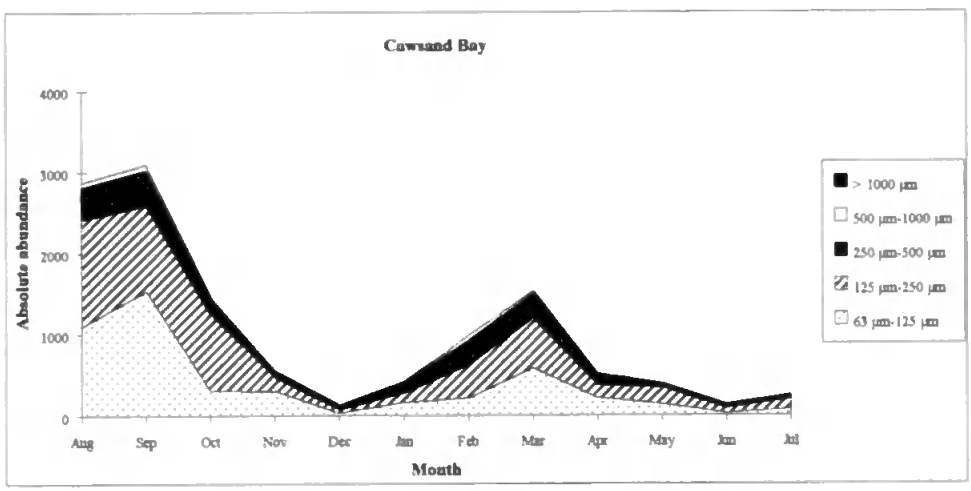


Figure 3.43: Temporal variation in absolute abundance of live Foraminiferida of different size ranges per grab from Cawsand Bay, 1993/1994.

From Figure 3.43 it can be seen that Cawsand Bay Foraminiferida do not exceed 500 µm in size. The peaks in foraminiferid abundance at this site occurring in September, 1993 and March, 1994 are composed of comparable numbers of Foraminiferida with test sizes of >63 µm and >125 µm, with a smaller number of test size >250 µm. Specimens of >500 µm occur in relatively low numbers throughout the annual cycle, but have the highest numbers in September, and probably represent the maximum size for some species to attain before reproducing.

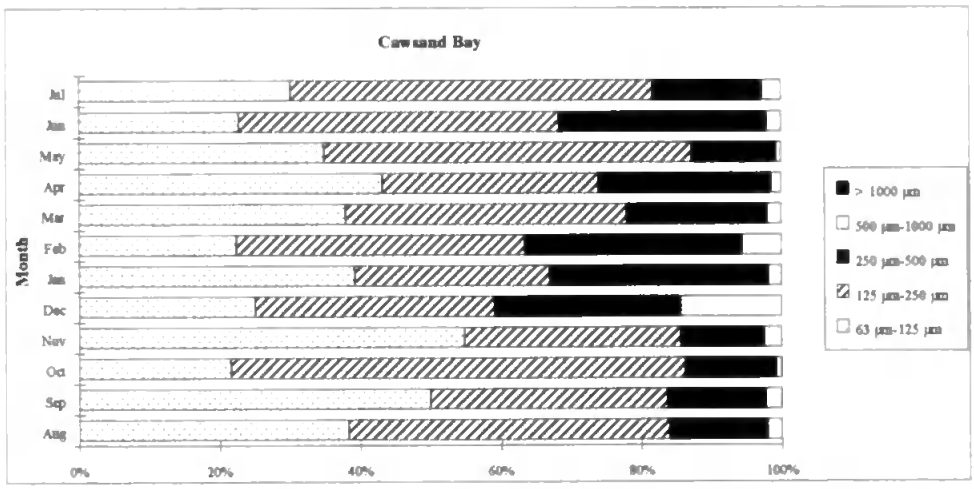


Figure 3.44: Temporal variation in relative abundance of Foraminiferida of different size ranges per grab from Cawsand Bay, 1993/1994.

Figure 3.44 shows that Foraminiferida of >63 µm form a significant proportion of the foraminiferal assemblage at Cawsand Bay throughout the annual sampling period. This group of Foraminiferida account for more than 20% of the assemblage throughout the year, with peaks in the proportion of this test size in September, November and April. These peaks probably represent the juveniles of larger species which reproduced at these times, whereas the base-line of approximately 20% probably represents the proportion of the foraminiferid assemblage which are of diminutive species which never grow greater than 125 µm. The Foraminiferida of 125 µm to 250 µm are represented at this site at greater than 25% of the assemblage and peak in August, October, May and July. As with the >63 µm fraction there are some Foraminiferida which never grow greater than this size, but

many at this size are juveniles of relatively large Foraminiferida, and therefore these peaks in abundance may represent the offspring of these larger Foraminiferida. The Foraminiferida in the 250 µm to 500 µm size fraction peak in January, February and June, whereas the 500 µm to 1000 µm Foraminiferida peak in December with a minor peak in February. There are comparatively few Foraminiferida alive in December and the presence of these large specimens probably reflects the relative invulnerability of these larger specimens to disease, starvation and death.

Drake's Island

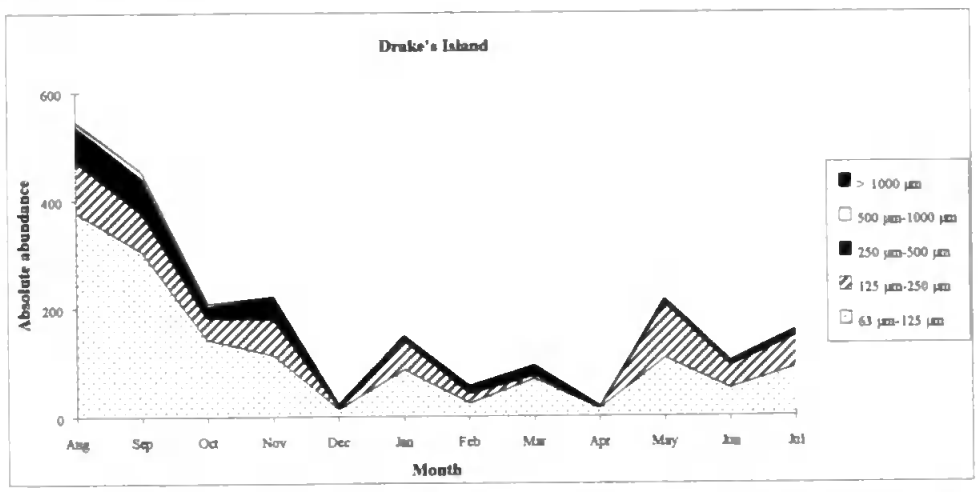


Figure 3.45: Temporal variation in absolute abundance of Foraminiferida of different size ranges per grab from Drake's Island, 1993/1994.

From Figure 3.45 it can be seen that the Drake's Island assemblage is dominated by specimens in the 63 µm to 125 µm size range, and that this group of Foraminiferida is responsible for the peaks in abundance at this site in the months of August, January and May. It may be that the peaks in >63 µm foraminiferid abundance observed are caused by the reproduction of Foraminiferida; however it also appears that there is a strong contingent of >63 µm specimens at this site throughout the year, probably due to the presence of diminutive species such as *Quinqueloculina dimidiata*. The presence of other sizes of Foraminiferida at this site is variable, although sizes of >500 µm peak in September, perhaps indicating the reproductive potential of these specimens, although the expected peak in >63 µm Foraminiferida in the following month of October does not occur.

Abundance of Foraminiferida at this site is relatively low and therefore assumptions of the reproductive strategy of Foraminiferida at this site must be tenuous.

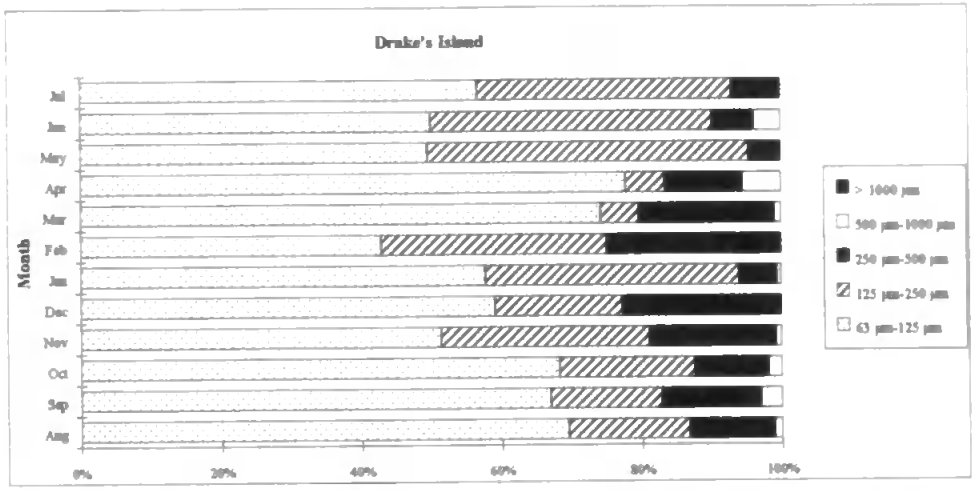


Figure 3.46: Temporal variation in relative abundance of Foraminiferida of different size ranges per grab from Drake's Island, 1993/1994.

Figure 3.46 shows that the proportion of the assemblage peaks in size >63 µm in March and April, but also in August, September and October, perhaps indicating the major reproductive periods of species at this site. Individuals of >125 µm peak in May, June and July indicating the growth of some species to this size from >63 µm in March and April.

White Patch

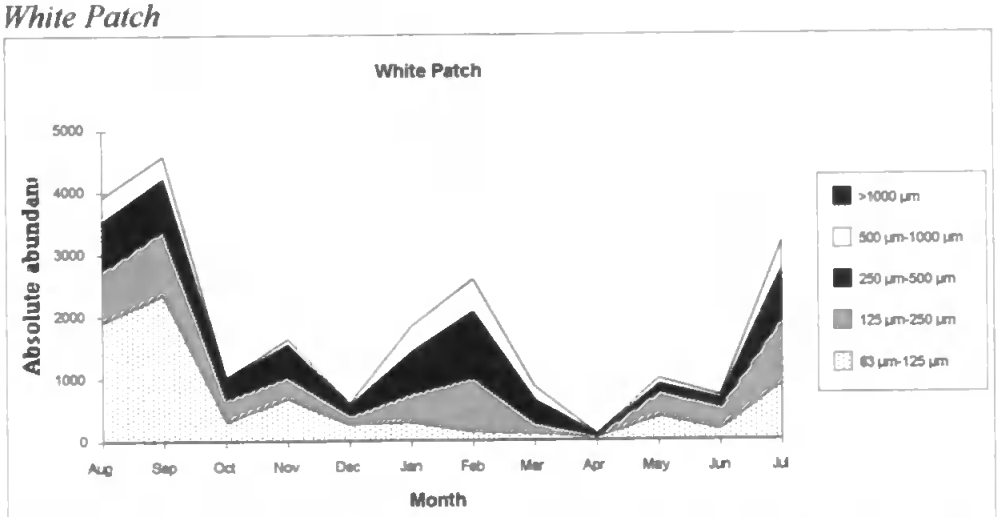


Figure 3.47: Temporal variation in absolute abundance of Foraminiferida of different size ranges per grab from White Patch, 1993/1994.

From Figure 3.47 it can be seen that the abundance of Foraminiferida at this site is a function of all test sizes. Individuals of >63 µm peak in the months of September and July, with minor peaks in November and May, perhaps indicating the different reproductive periods of species at this site. Individuals of >125 µm peak in September, February and July; >250 µm Foraminiferida peak in August, September and February; whilst individuals of >500 µm peak in abundance in August, September and February. Abundance of individuals greater than 1000 µm is represented by few specimens in February, March and July, possibly indicating the reproductive potential of larger species such as *Elphidium crispum*.

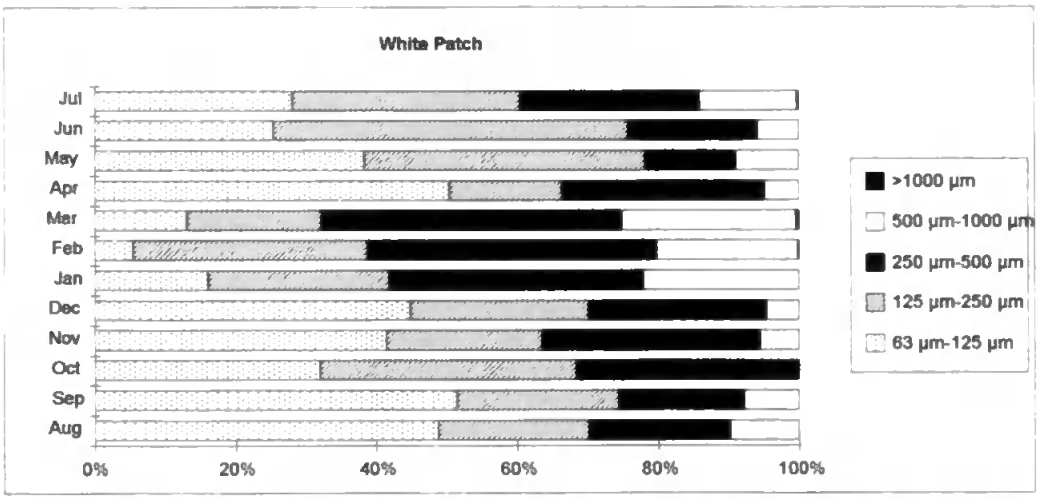


Figure 3.48: Temporal variation in relative abundance of Foraminiferida of different size ranges per grab from White Patch, 1993/1994.

From Figure 3.48 it can be seen that the percentages of most size ranges of Foraminiferida at this site are relatively comparable, although fewer large specimens form a major proportion of the assemblage. >63 µm specimens form a large proportion of the assemblage at this site in September and April, whereas >125 µm specimens form a large proportion of the assemblage in June. Tests of >250 µm peak in February and March and those of >500 µm peak in January, February and March.

Comparison of sites

It can be seen from the above graphs for foraminiferid test sizes that the sites each have a different distribution for abundance (and percentage abundance) of test

sizes throughout the sampling period. The peaks in abundance of Foraminiferida at the sites show that Drake's Island has more small Foraminiferida (>63 μm), Cawsand Bay having more tests of >125 μm and White Patch having more of the larger tests (>250 μm and >500 μm) than the other two sites. These differences may rely upon nutritional input and stability of the sediment at the sites to allow growth and reproduction.

3.11. MULTI-VARIATE ANALYSIS OF THE DATA.

Multi-variate analysis of the foraminiferid data was carried out using the PRIMER software package produced by PML. This package compares the abundance of each species each month between sites. The data were transformed by natural logarithms. Using this system both a dendrogram and a Multidimensional Scaling Plot are produced which allows easy visual comparisons of similarities of the assemblages through time at the sampling sites. Professor R. Warwick (PML) supplied invaluable help in the input of the data.

Dendrogram

A dendrogram is a graphical presentation of the relationship between factors. In this case, the dendrogram shows the relationship between foraminiferid assemblages. Similar assemblages will be grouped together to form a cluster based upon the Bray-Curtis similarity index. Similarity of not only the species present but of the abundance of each species are used to determine the similarity of assemblages. The produced dendrogram should be visualised as a mobile in which the clusters of assemblages can be rotated upon the horizontal bars so that the positions of the two end members of each cluster can be switched. The dendrogram produced from the foraminiferid data consists of twelve months' data from each of the three sites. It can be seen from Figure 3.49 that the sampled assemblages are roughly similar within sites.

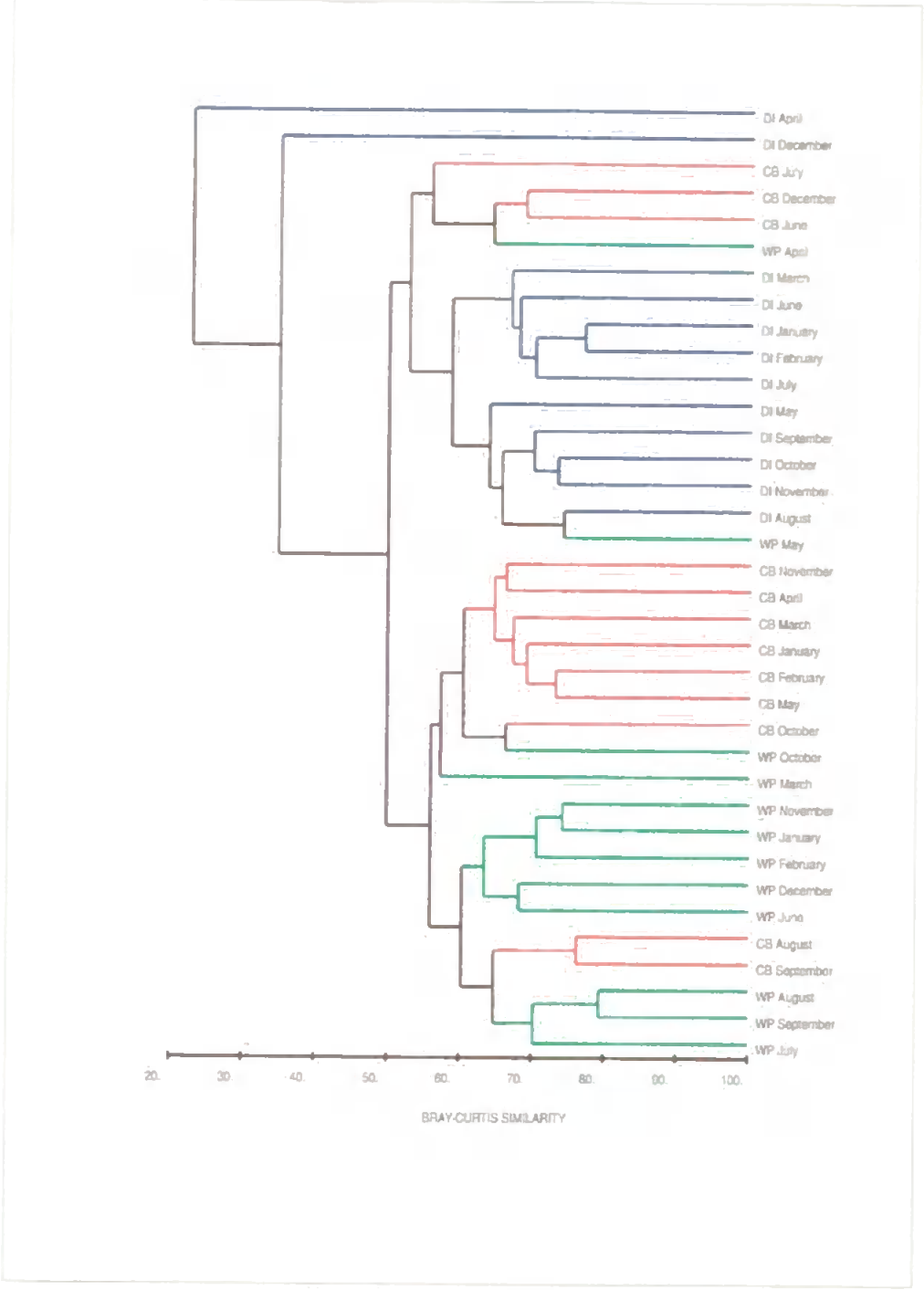


Figure 3.49: Dendrogram of similarity between sampled foraminiferid assemblages, 1993/1994.

Cawsand Bay

Cawsand Bay assemblages are the least delineated in terms of site. One cluster of Cawsand Bay assemblages is formed encompassing the months of November, January, February, March, April and May; however the months of February, May, April and November show more similarity in composition to each other than to antecedent and precedent months. The assemblage composition of Cawsand Bay

Foraminiferida of August and September is more similar to the August and September assemblages at White Patch than to assemblages from the same site. Cawsand Bay assemblages of December, June and July form a cluster with that of April at White Patch surrounded by assemblages from Drake's Island.

Drake's Island

Drake's Island assemblages form two main clusters of similarity of January, February, March, June and July; August, September, October, November, and May respectively. The August Drake's Island assemblage bears some similarity to the May assemblage of White Patch. The Drake's Island assemblages of April and December are totally different to the Foraminiferida of other months and sites.

White Patch

The assemblages from White Patch form two main clusters of similarity; the assemblages in the months of November, December, January, February and June; August, September and July. This latter cluster is more similar to the assemblages from Cawsand Bay in the months of August and September than to the other assemblages from White Patch. The assemblages in May and April are more similar to assemblages from Drake's Island and Cawsand Bay respectively and those of October and March to Cawsand Bay fauna.

Multi-dimensional Scaling (MDS)

Multi-dimensional scaling of the data produces a plot of the assemblages where the distance between the assemblages is an indication of their similarity to each other. The further the distance two assemblages are apart on the plot, the more dissimilar the assemblages are. This method is more accurate for the graphical presentation of biological data. The inclusion of colour-coded lines outlining the samples within the plot is to highlight the geographical areas and not to influence the interpretation of the plot.

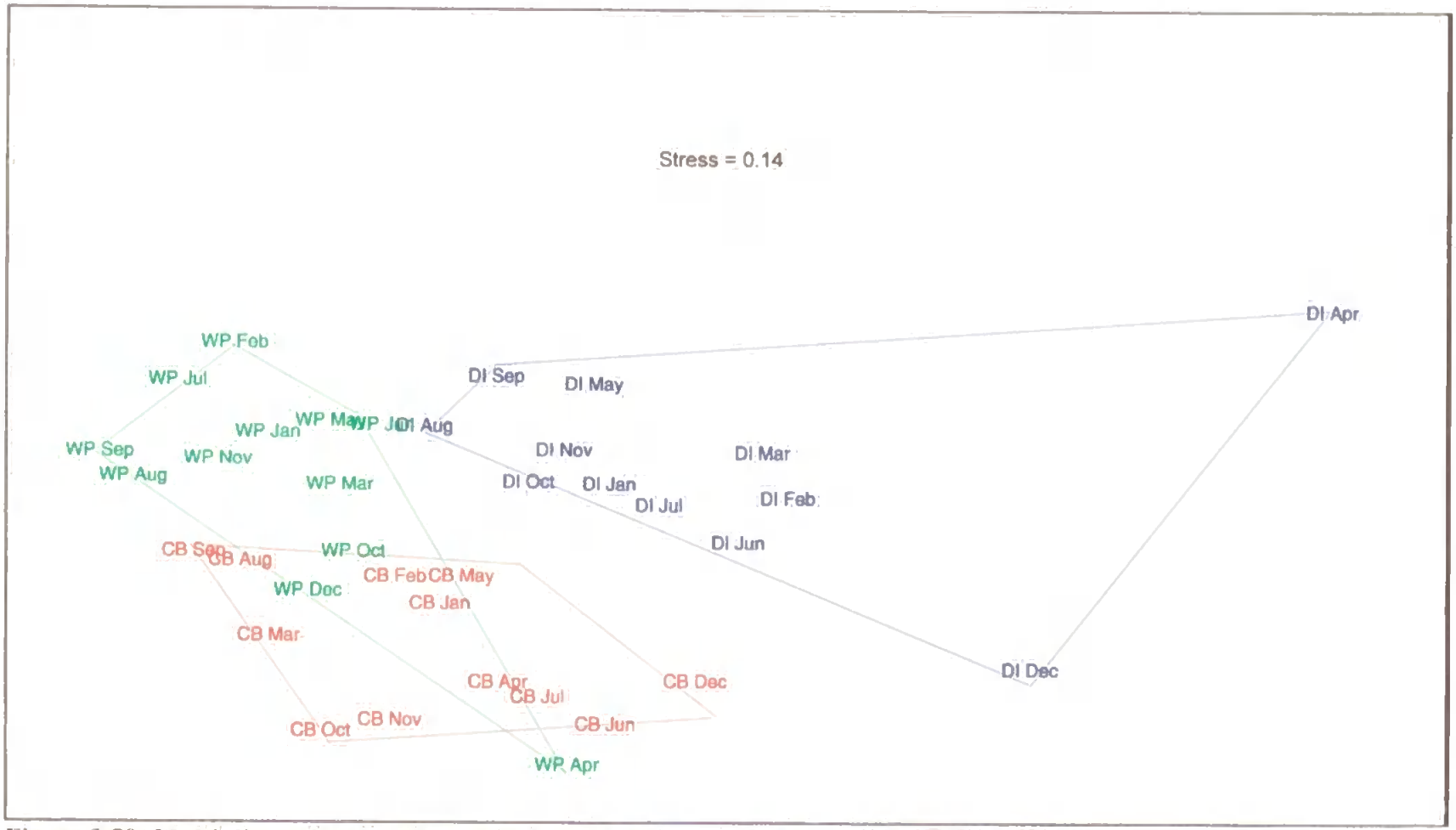


Figure 3.50: Multi-dimensional scaling plot of sampled foraminiferid assemblages, 1993/1994.

From Figure 3.50 it can be seen that the foraminiferid assemblages from each of the three sampling sites form distinct groups. Drake's Island assemblages form a discrete group of assemblages indicating that this site contains Foraminiferida particular to that habitat. Cawsand Bay and White Patch Foraminiferida are also fairly distinct, although assemblages from White Patch in December are more similar to Cawsand Bay assemblages, and that from White Patch in April is distinct from all other groups, whilst being more similar to those from Cawsand Bay.

3.12. SUMMARY.

The abundance of Foraminiferida was quite high at the three sites sampled and the number of Foraminiferida found at White Patch exceeded those found at Cawsand Bay and Drake's Island respectively. The input of nutrients to these nearshore environments probably increases reproduction and supports the growth of offspring. Drake's Island and White Patch benefit from the input of nutrients from land run-off and, with the exception of Cawsand Bay, from the nutrient input from the River Tamar. White Patch probably also benefits from the additional input of nutrients from the River Plym. Sedimentation is probably highest at White Patch, supporting the premise of Lankford (1959) that high sedimentation rates increase productivity. The stability of the substratum appears to be important to productivity and survivorship of foraminiferid offspring, with the poorly-sorted sediment of White Patch providing a better environment than the fine sand of Cawsand Bay and the medium sand of Drake's Island respectively. Reproduction of Foraminiferida at Cawsand Bay appears to coincide with phytoplankton blooms, whilst the abundances of Foraminiferida at Drake's Island and White Patch are more complex, apparently with different species reproducing at different times of the year.

The Fisher diversity measure was not very different between sites, indicating that the number of species per number of individuals was similar at all three sites. The Shannon-Weiner diversity measures were generally highest at Drake's Island,

followed by White Patch and Cawsand Bay respectively indicating that the number of species and the number of specimens within each species differed. Although richness of species was not very different, evenness of species appeared to differ, with Drake's Island having generally higher values than White Patch and Cawsand Bay Foraminiferida respectively. The relatively higher Shannon diversity and evenness measures for Drake's Island probably mean that this site supports a more varied assemblage than the other sites. This may be due to this dynamic environment preventing domination of the assemblage by a few species.

Size analysis of foraminiferid tests reveal that Drake's Island has more small specimens, Cawsand Bay has more specimens of >125 μm and White Patch has more Foraminiferida of >250 μm and >500 μm. The peaks in abundance of Foraminiferida at Cawsand Bay and Drake's Island are formed of individuals of >63 μm and >125 μm, whereas the abundance peaks at White Patch are formed of a more even distribution of sizes. This suggests that Cawsand Bay and Drake's Island contain more diminutive species than White Patch, and also rely more upon foraminiferid reproduction for peaks in abundance than White Patch assemblages do.

Cawsand Bay and White Patch assemblages have similar distributions of test types with hyaline taxa exceeding all others and very limited numbers of agglutinated forms, whereas the Drake's Island assemblages are dominated by porcellaneous forms. The hyaline fauna at all sites is dominated by Rotaliina with comparatively small numbers of Spirillinina and Lagenina. The similarity of the assemblages at Cawsand Bay and White Patch may depend upon the substrata at the two sites and the more marine nature of these two sampling stations. Drake's Island assemblages are dominated by porcellaneous taxa, possibly due to the higher energy environment that this site provides. The inferred life positions of Foraminiferida, like the abundance of test types, appear to be related to the nature of the substrata with infaunal Foraminiferida at both Cawsand Bay and White Patch benefiting from

the more stable substrata at these sites during the winter months and epifaunal forms reproducing in summer months. At Drake's Island the relatively more unstable substratum supports more epifaunal forms than infaunal.

The three sampling sites differed in coiling forms of specimens present. The Drake's Island assemblages were dominated by quinqueloculine-coiling forms because this site was dominated by porcellaneous taxa, most of which were quinqueloculine in coiling. Assemblages at Cawsand Bay had a fairly even distribution of quinqueloculine, trochospiral and planispiral forms, whilst the White Patch fauna was dominated by trochospiral and planispiral forms. These differences may be due to the differences in substratum and/or strength of currents which determine which species are capable of growing and reproducing in the area. The main types of aperture shapes displayed by the fauna at each of the sampling sites reflects the coiling types with Cawsand Bay fauna having mostly pore, arch and slit apertured forms: Drake's Island fauna is dominated by arch-shaped specimens reflecting dominance by quinqueloculine-coiled forms; and the White Patch fauna mainly consists of pore and arch-shaped apertured taxa reflecting the dominance of planispiral and trochospiral forms.

Feeding strategies of Foraminiferida at all sites are dominated by herbivorous taxa, reflecting the fact that all lie within the photic zone; and detritivores at all sites are less numerous than the herbivorous taxa. Suspension-feeders are more numerous at Drake's Island than at the other two sites and, although all sites are surrounded by hard substrata capable of supporting suspension-feeders, this site has more suspension-feeding Foraminiferida. This may be due to the greater quantity of seston at this site to feed these Foraminiferida from sewage and re-suspension of the sediment.

The multi-variate analysis of the data revealed that although not separated by great distances geographically, the assemblages from the sites investigated were fairly

distinct. Assemblages from Cawsand Bay were not as well separated as assemblages from White Patch and Drake's Island respectively. The distinct grouping of the Drake's Island assemblages indicate further the importance of porcellaneous taxa to this site to make it distinct from the other two sites. Cawsand Bay and White Patch share hyaline taxa in similar abundances; especially so in the months of December and April.

CHAPTER 4.

ABIOTIC VARIABLES.

4.1. INTRODUCTION.

It is generally assumed that the abiotic factors present within an area act as the primary control over biotic factors. Early studies of live Foraminiferida recorded only abiotic variables and often water depth was the only environmental variable recorded (Douglas, 1979). Kinne (1963) states that temperature and salinity serve to characterise the physico-chemical properties of a body of water, and are two of the most potent factors in the life of marine and brackish water organisms. With advancement of measuring devices temperature, salinity and soft-sediment characteristics were also recorded and related to the foraminiferal fauna. Because of this, faunal-environmental correlations between live populations and measured physical properties of the environment are the principal source of information on what limits and controls faunal distributions (Douglas, 1979); and, in variable environments such as marginal marine settings, the abiotic rather than biotic variables are probably more important in shaping communities (Pringsheim, 1949; Douglas, 1979; Murray, 1991). Temperature, salinity and depth are usually considered to be the most important abiotic factors (*e.g.* Boltovskoy *et al.*, 1980). The character of the substratum has also been shown to be important (Lee & Muller, 1973; Lee, 1974; Walton & Sloan, 1990), but is less studied and, therefore, less understood.

The chemical composition of the waters and sediments in marginal marine environments is very changeable (Walton & Sloan, 1990), with parameters such as oxygen content, pH, chlorinity and magnesium concentrations and calcium levels being the most variable (Howarth & Murray, 1969). Rivers draining into the sampling sites can alter temperature, salinity and organic content of the area and may also be important to marginal marine benthonic Foraminiferida (Uchio, 1962).

Despite attempts to correlate foraminiferid occurrence and distribution with abiotic variables it is often not possible to distinguish the effects of any one factor (Douglas, 1979; Boltovskoy *et al.*, 1980); and Hart & Thompson (1974) suggest that the most important parameter is the physiography of the bay. In addition, Ellison (1984) states that it is difficult and perhaps fallacious to relate the distribution of microfauna to specific physico-chemical factors of the environment; and Douglas (1979) states that storms and sediment-transport may move live species into less favourable environments, making it difficult to discriminate indigenous from displaced populations. Foraminiferida may also be affected by disturbance of the sediment by fish, especially rays, which would not be realised at the time of sample collection.

The aim of this study is to determine the importance of temperature, salinity or sediment characteristics upon the occurrence and distribution of Foraminiferida at the three sites sampled.

4.2. TEMPERATURE.

4.2.1. INTRODUCTION.

Temperature is of great importance to all marine organisms (Boltovskoy & Wright, 1976) and in most environments the temperature fluctuates. Temperature is a variable which affects all living organisms; it affects metabolic rate, growth, reproduction and survival. Species which can only withstand a very small variation of temperature are described as stenothermal, whilst those which can withstand a wide variation in temperatures are termed eurythermal (Tait, 1981).

Foraminiferida are poikilothermic (organisms whose body temperature fluctuates with that of the immediate environment) and, although it is assumed that most poikilotherms operate at lower rates in colder habitats and seasons, it may be that poikilotherms are relatively independent of temperature, within limits, in nature (Bullock, 1955). Benthonic

Foraminiferida are known to exhibit periods of reduced activity (termed dormancy) which, however, do not appear to be connected to temperature: Myers (1943) found that British foraminiferid dormancy was well advanced by October 15th, when mean temperature was 14°C. This temperature was 6°C greater than that in March when growth and reproduction were at a maximum.

Laboratory experiments have been carried out upon Foraminiferida to determine the optimal temperature ranges for species. It has been found that reproduction of benthonic Foraminiferida occurs only in a narrow temperature range, whilst growth occurs in a broader temperature range but stops close to the limits which cause death (Murray, 1973). The temperature limits of reproduction may not be fixed for a species, but may vary as a result of local thermal conditions (Schnitker, 1974). Experiments have been carried out to attempt to acclimatise species to higher temperatures. Although Schnitker (1974) found that individuals of *Ammonia beccarii* may become acclimated to temperature during the early stages of growth, ciliated Protozoa appear to be more adaptable to increased heat; *Paramecium caudatum* acclimatised to increased heat in three hours (Bullock, 1955). Acclimation is characterised by a major restructuring of the organism (Schnitker, 1974) and as acclimation of Foraminiferida to various temperatures did not cause significant changes in lethal temperatures, this indicates that the ability to tolerate high temperatures may be an inherent genetic trait (Bradshaw, 1961).

Temperature tolerances differ widely between species, but each is restricted in distribution within its own particular temperature range (Tait, 1981). Temperature is, therefore, important physiologically and may limit a species geographically (by killing, or preventing vital processes like reproduction), or the effect of temperature on growth and reproduction may selectively favour one species more than another (Bradshaw, 1961). Off Plymouth, some indigenous foraminiferid species are at their northern limit of distribution and may reproduce at different times of the year to compensate for low temperatures thus, perhaps, affecting diversity and abundance. These effects of temperature, combined with other variables, should result in a different distribution pattern for each species of Foraminiferida.

Protoplasm can only exist within physico-chemical limits which are quite narrow for each species and temperature is a variable which must be appropriate for enzyme-catalysed processes to function properly within cells (Davenport, 1985). Temperature appears to be the primary factor which controls the geographic distribution of species and is, therefore, an important factor affecting vertical distribution (Boltovskoy & Wright, 1976). The temperature factor cannot be solely responsible for the distribution of genera, however, since many genera live in waters of greatly differing temperature but always at the same depth; *e.g. Elphidium* lives in shallow water at all latitudes (Boltovskoy & Wright, 1976). Studies which have correlated temperature with distribution include that of Murray (1965{a}), who finds that the variable temperature of the River Tamar is probably the primary factor in governing foraminiferal populations on the Tamar-to-Eddystone transect. Ellison (1984) has also correlated *Haynesina germanica* in mudflats at the mouth of the River Tamar with sea water temperature. Hart & Thompson (1974) find that temperature is important in the distribution of Foraminiferida around the British Isles, but not important within local regions. Murray (1979 {a}) also observes the same effect, although Bradshaw (1961) states that he could find little direct evidence for a causal relationship between temperature and the distribution of Foraminiferida.

Whilst many authors have correlated the distribution of Foraminiferida with temperature, few have discussed how temperature has affected abundance and diversity. Bates & Spencer (1979) state that particle size and temperature are the most important influences on living foraminiferal densities, whilst Walton (1955) suggests that in California the maximum abundance of benthonic Foraminiferida may be associated with spring and summer blooms of phytoplankton and the maximum temperature of the sea during August. Wang and Zhao (1985) state that the temperatures in the East China Sea and the Huanghai Sea influence species diversity.

It appears from the literature that temperature of the water on the sea floor has little influence upon foraminiferid species distribution within local areas, but is an important

factor on a global scale. Temperature does, however, appear to be a factor which may affect abundance and diversity within localised habitats.

4.2.2. MATERIALS & METHODS.

Temperature at depth was recorded monthly from R. V. *Sepia*; sampling of Foraminiferida and measurement of environmental variables was carried out simultaneously.

The temperature for each site was recorded from a Temperature/ Salinity Bridge, type M.C.5 (manufactured by Electronic Switchgear {London} Ltd). The probe was weighted and lowered until the bottom was reached, so that the temperature on the sea bed could be measured.

4.2.3. RESULTS.

Table 4.1: Annual variation in temperature (degrees Celsius) at depth 1993/1994.

Month	Cawsand Bay	Drake's Island	White Patch
August	14.8	15.4	15.6
September	16.4	16.6	16.6
October	15.8	15.4	15.6
November	12.7	12.6	12.6
December	10.2	9.15	9.68
January	9.7	9.3	9.5
February	8.9	8.7	8.8
March	8.9	9.3	8.8
April	9.4	9.3	9.4
May	10.5*	11.05*	10.6*
June	11.6	12.8	11.8
July	14.1*	14.75*	14.2*

(* average temperature of preceding and following months {instrument malfunction}).

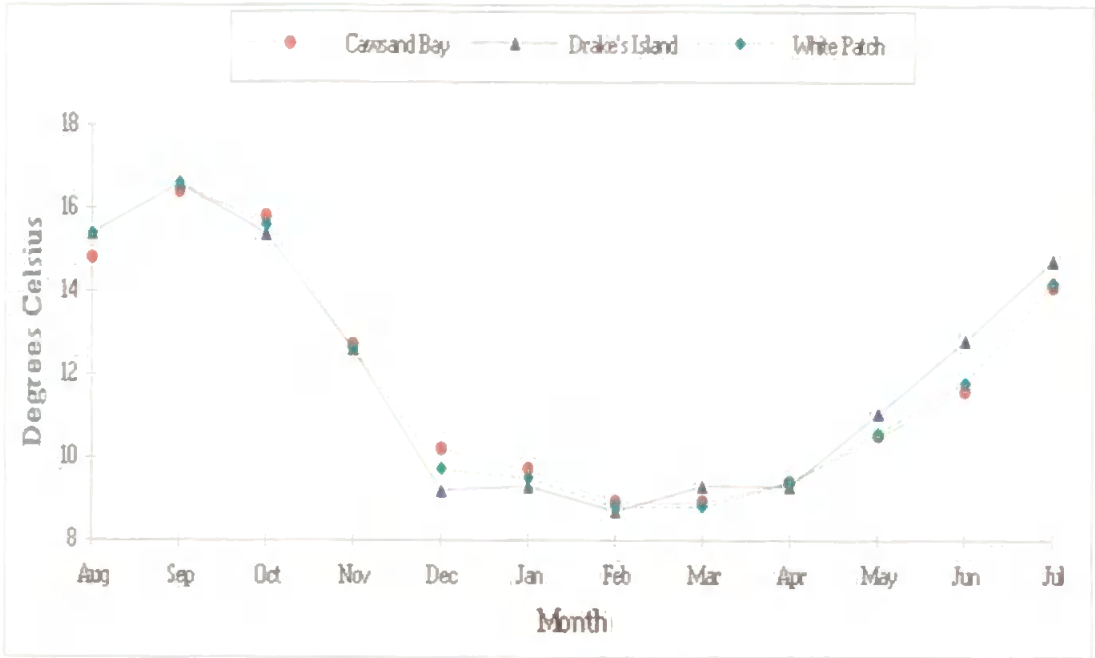


Figure 4.1: Monthly variation in temperature 1993/1994 at depth at each locality.

From Figure 4.1 it can be seen that all sites show very similar patterns of temperature fluctuation throughout the year; all sites peak in September and trough in February. The maximum temperatures recorded for each site were all in the month of September: Cawsand Bay 16.4°; Drake's Island 16.6°; White Patch 16.6°. The minimum temperatures recorded for each site were: Cawsand Bay 8.9° (February and March); Drake's Island 8.7° (February); White Patch 8.8° (February and March).

4.2.4. DISCUSSION.

Off the south-west coast of the British Isles the temperature usually varies between about 7° C in winter and 16° C in summer (Tait, 1981) and the temperatures measured in the Plymouth area correlate well with this. The temperatures between the sites were not significantly different from each other, probably because the sampling stations are geographically close and affected by the same water mass.

The three sites varied little in mean temperature throughout the annual cycle, although the temperature at depth for Cawsand Bay appears to be governed by its being more marine in

nature compared to the other two sites, as it was cooler in summer and warmer in winter than the others. Drake's Island has the largest fluctuations of temperature at depth of the three sites, possibly due to the influence of the River Tamar bringing cold river water past this site as it enters Plymouth Sound in winter. In the summer, the incoming sea water from Plymouth Sound passes over the shallows of Queen's Ground, warming the water mass before it forms vortices at Drake's Island and mixes with the water of the River Tamar. White Patch has the same water mass passing over it as Drake's Island, but the water is subject to less mixing. White Patch has lower temperatures in summer than Drake's Island, possibly due to the greater depth of water at this site.

4.3. SALINITY.

4.3.1. INTRODUCTION.

Salinity is a measure of the total concentration of dissolved salts in sea water (Lincoln *et al.*, 1982). The amount of inorganic material dissolved in sea water expressed as weight in grams per kilogram of sea water usually amounts to thirty-five grams per kilogram, *i.e.* thirty-five parts per thousand (Tait, 1981). Salinity is a much more potent factor in altering density of water than temperature (Barnes & Hughes, 1988). The salinity of neritic water is subject to fluctuations due to dilution by fresh water from the land (Tait, 1981) and land drainage is responsible for the slightly-lower-than-normal salinities found along all (except arid) coasts (Bradshaw, 1961). The salinity of water is termed brackish or hyposaline if it ranges between 0.5 parts per thousand (‰) to 30‰, normal sea water if it ranges between 30‰ to 40‰ and hypersaline ranging between 40‰ and 80‰ (Raup and Stanley, 1971).

The majority of open-sea organisms have a very limited tolerance of salinity change, *i.e.* they are stenohaline. Euryhaline forms can withstand wider fluctuations of salinity and are typical of the less stable conditions of coastal water (Tait, 1981). Estuarine species are typically extremely euryhaline (Tait, 1981).

Except for teleosts and higher vertebrates, the majority of marine creatures are in osmotic equilibrium with the surrounding water. The ionic composition of their internal fluids has, in most cases, a close similarity to that of sea water (Tait, 1981). It is generally assumed that microscopic marine animals are isotonic with sea water and therefore poikilosmotic. Salinity changes are certainly known to affect the osmosis of Foraminiferida (Murray, 1968{b}; 1973). Reduced salinity is usually correlated with reduced pH and the ability of sub-orders of Foraminiferida to precipitate calcareous tests in such waters is also affected.

Salinity appears to be critical to Foraminiferida; few species are found in brackish and hypersaline waters, compared to normal marine conditions (Bradshaw, 1961) and Alve & Nagy (1986) find that estuarine fauna can be mainly composed of agglutinated species. Hyposaline marshes have high numbers of Textulariina, some Rotaliina and generally an absence of Miliolina (Murray, 1971 {b}). As water becomes more marine in nature, the marine calcareous forms become more competitive (Alve & Nagy, 1990) and, before the Carbonate Compensation Depth is reached, the calcareous Foraminiferida dominate the benthonic fauna. Below the Carbonate Compensation Depth the agglutinated Textulariina dominate, due to the inability of the calcareous forms to precipitate carbonate tests. Murray (in 1968 {b}) carried out experiments to study the effects of salinity upon *Quinqueloculina seminulum* (Linné). He showed that in salinities of 30‰ this species withdrew its pseudopodial reticulum and, after a few seconds, the protoplasm streamed out of the test in rounded masses. When placed into sea water of normal salinity, the protoplasmic masses were withdrawn and a pseudopodial net was re-established. This experiment showed an osmotic effect and demonstrated that this species is not physiologically adapted to withstand hyposaline conditions. This may be true of most, if not all, miliolids (Murray, 1968 {b}).

In experimental work, many species have such wide salinity tolerances that this factor has little importance in cultures (Arnold, 1954 {b}). Boltovskoy & Wright (1976) state that salinities within the normal range (30‰-40‰) seem to have little effect on the survival of benthonic species. In studies of natural populations, however, Hart & Thompson (1974)

discovered that reduced salinity can be tolerated by a few species (which compete with each other) and salinity was the most important parameter on a local scale. Wang and Zhao (1985) found that water salinity in the East China Sea and the Huanghai Sea was the main factor controlling species distribution. Murray (1965{a}) suggests that the salinities of the River Tamar are secondary to temperature for seasonal changes in populations on the Eddystone-to-Tamar profile.

From the literature it appears that, unlike temperature, salinity affects the distribution of the three major sub-orders of Foraminiferida due to their ability to precipitate calcareous tests. Textulariina dominate in hyposaline conditions and below the Carbonate Compensation Depth. Rotaliina can be present in regions/areas of fluctuating salinities and more stable marine environments. Miliolina are characteristic of stable marine conditions.

4.3.2. MATERIALS & METHODS.

Salinity at depth was recorded monthly for the three sites under investigation from R. V. *Sepia*. Sampling of Foraminiferida and environmental variables was carried out simultaneously. Salinity for each site was recorded from a Temperature/ Salinity Bridge, type M.C.5 (manufactured by Electronic Switchgear {London} Ltd). The probe was weighted, lowered until the sea bed was reached, and the salinity measured.

Table 4.2: Annual variation of salinity (parts per thousand) at depth 1993/1994.

Month	Cawsand Bay	Drake's Island	White Patch
August	35.0	34.4	34.5
September	35.2	34.8	35.0
October	34.9	34.3	34.6
November	35.0	34.8	35.0
December	33.8	32.0	32.5
January	35.1	32.7	34.7
February	34.8	33.7	34.8
March	31.9	34.1	34.7
April	35.0	34.1	34.7
May	-	-	-
June	35.1	33.5	35.1
July	35.2	35.1	35.3

(May salinity not recorded due to instrument malfunction)

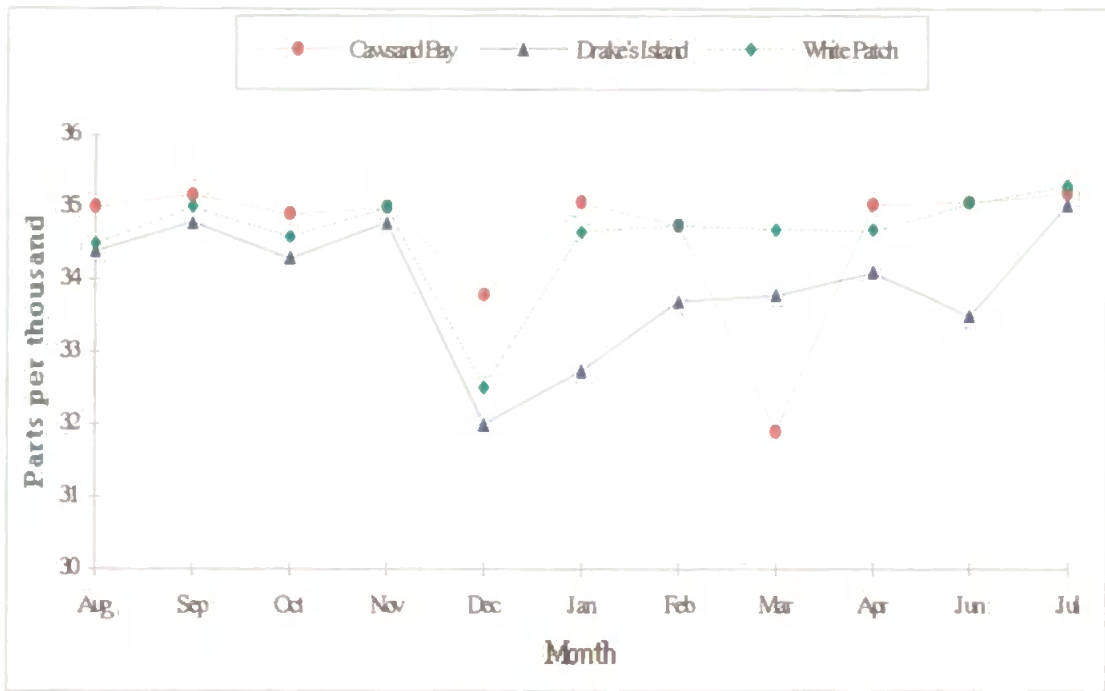


Figure 4.2: Monthly variation in salinity (parts per thousand) 1993/1994 at depth at each site.

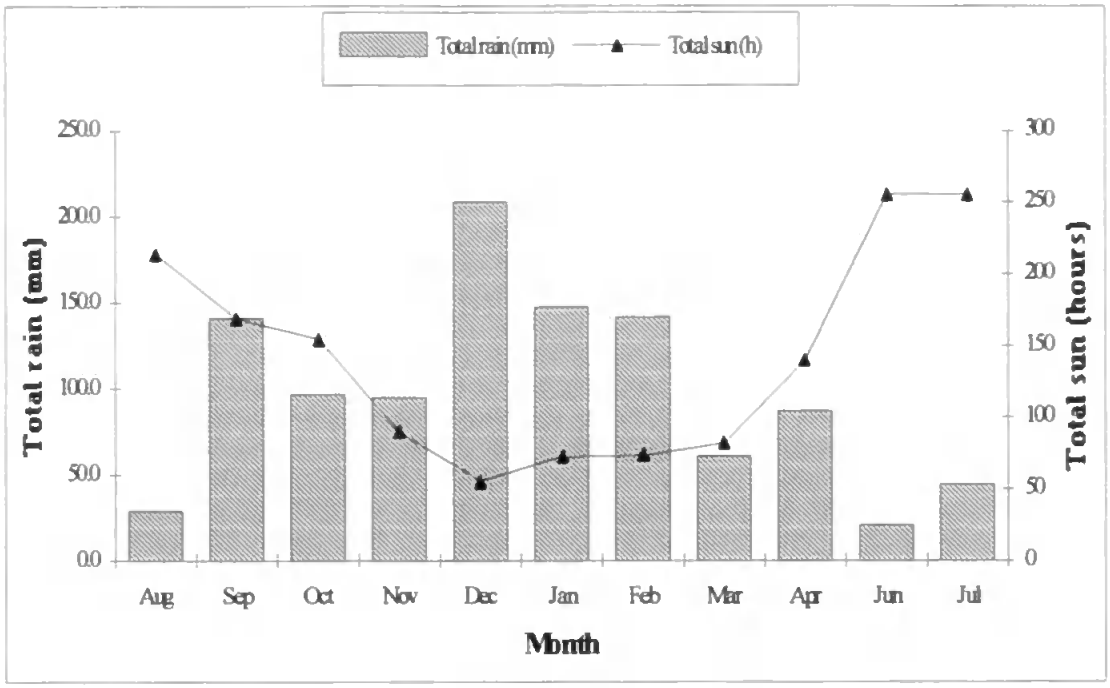


Figure 4.3: Meteorological data for Plymouth 1993/1994 collated by Helen Nance (Institute Marine Sciences: University of Plymouth).

The salinity of the sea water at all three sites was normal marine, although it was comparatively low in December. From Fig. 4.3 the highest rainfall of the year occurred in December and sampling was carried out when the tide had been falling for one and a half hours. These two factors probably account for the low salinity recorded for December (Table 4.2).

4.3.4. DISCUSSION.

From Figure 4.2 it can be seen that the salinity at Cawsand Bay was usually higher than at the other two sites because it lies seaward of the Breakwater. It was consistently more marine in nature than the other two sites and apart from an anomalous low reading for March it recorded a good, marine, salinity throughout the year. Drake's Island had consistently lower salinity readings throughout the year, except for Cawsand Bay in March. This site is subject to fresh water dilution from the River Tamar and the low salinities recorded at this site throughout the year are probably due to this factor. The salinity of White Patch was generally intermediate between the other two sites. The water mass is

subject to less mixing than Drake's Island and, as such, demonstrated a higher salinity than that of Drake's Island.

The patterns of salinity at the three sampling sites were similar to those observed of temperature, probably for the same reasons. It would be expected that, because Drake's Island is subject to freshwater input from the River Tamar (and, to a lesser extent, White Patch to the River Plym), salinities might be different between the sites; however this was not the case, suggesting that the main water mass controls the gross salinity at each site, and sampling at depth is below the halocline.

4.4. PARTICLE SIZE.

4.4.1. INTRODUCTION.

The sea bed in subtidal sites may be composed of either a hard substratum or unconsolidated sediment. Hard and soft substrata have characteristic assemblages (Newell, 1979), with each adapted to the problems created by each substratum type. The fauna living on hard substrata differs from that living on, or in, particulate sediment in that it is usually attached directly to the rock surface or to macro-algae attached to the rock. Fauna (and flora) attached to hard substrata will be primarily adapted to minimise hydrodynamic forces, usually by having a morphology which minimises the force of currents. Fauna living in an area of unconsolidated sediment are subject to the hydrodynamics of the area as the sediment will be affected by currents and, unless in a calm depositional area, will be in a medium which is in a constant state of movement. Macro-algae are sparse in an area of particulate substratum as attachment is not possible, except in relatively calm areas. The fauna of particulate substrata have two types of distribution; either living at the surface/water interface (epifaunal) or burrowing into the sediment (infaunal) where currents are less likely to affect them. The composition of the particulate substratum is, therefore, of vital importance to the fauna of the area: it may affect the ability of organisms to burrow (Tait, 1981), the oxygenation of interstitial pore water, and the stability of the sediment.

The study areas all have unconsolidated particulate sediments. Sediment consists of three major components: detrital material derived from the erosion of the land, biogenic material formed from biological productivity, and authigenic material formed *in situ* by the precipitation of mineral phases (Malcolm & Stanley, 1982).The geology of the area therefore affects the detrital component of the sediment and most of South West England is formed of Upper Palaeozoic rocks, comprising a section through the Variscan fold belt (Hobson, 1978). Jennycliff Bay is composed of Lower and Middle Devonian rocks and adjacent to the area sampled in this study these comprise dark grey slates with brown siliceous layers. Cawsand Bay cliffs are composed of the Dartmouth Beds and the Meadfoot Group (Hobson, 1978) of the Lower Devonian, together with a small outcrop of Permian rhyolite (volcanic rock) and Permian breccia, and a few rotted basic dykes. Sediments carried by the River Tamar are accompanied by solution products from the granites of Dartmoor; the River Plym carries china clays and silt in suspension as well as solutions from the granite of Dartmoor; and influx from the marine environment carries sands and silt into the sampling area. The former loading of coal in the Cattedown area has also led to coal fragments occurring in sediments.

The hydrodynamics of an area determine the sediment particle size. The velocity of currents and particle size of the sediment are correlated by the relationship between the velocity of water and the size of particle which the water is capable of moving. This means that particle size is a positive exponential function of relative wave energy (Newell, 1979). Grain size, therefore, commonly reflects the degree of wave or current agitation in the depositional environment. Fine-grained sediments are normally deposited in areas of quiet water (Arnold, 1974), whereas coarse-grained sediments typify areas of strong wave and current activity (Raup & Stanley, 1971). The velocity of the water just above the sea-bed also affects the nutritional quality and oxygenation of the sediment, as slow-moving water allows organic matter to settle, and poor or absent oxygenation leads to anoxic waters. In areas of faster bottom-water movement oxygenation is better, but sediments are not as organically rich (Tait, 1981).

Small irregularly-shaped grains of sediment become compressed together, and clays (composed of thin flakes) compact and allow laminar flow: the pore space is reduced and it is more difficult for the water to re-suspend these particles. The surface of the sediment alters the flow of water over it. A smooth interface results in a more laminar flow whereas a rough interface causes turbulence and particles may be re-suspended from the bottom of the sediment due to the high water-velocity associated with turbulent flow. The proportion of clay in the sediment has important implications for not only laminar flow, but also because clay minerals have very large surface areas and play a role in controlling the distribution of major cations (sodium, potassium, calcium, magnesium and ammonium), whilst also providing adsorption sites for bacteria (Malcolm & Stanley, 1982).

Analysis of particle size distribution within sediments can take into consideration many aspects of the quality of the sediment and each property may affect the ability of meiofauna to colonise it. The most common parameters of sediments are particle size, mean grain size, sorting, skewness and kurtosis.

Particle size distribution of the sediment is the first parameter to be determined. Some authors differ slightly in the definition of some particle sizes. For example Raup & Stanley (1971) define clay as <0.004 mm, silt ranging between 0.004 mm to 0.0625 mm and sand ranging from 0.0625 mm to 2 mm. The Udden-Wentworth grain-size scale is commonly used and correlates well with Krumbein's Phi (ϕ) scale. This system describes ten classes of particle based on size (see Lindholm, 1987). The mean grain size is commonly calculated and provides a more useful variable than either the median or mode. The mode is the phi (or mm) value of the mid-point of the most abundant class interval (Tucker, 1981); the median is the grain size at 50% on the frequency curve; and the mean grain size is an average value, taking account of grain sizes at the 16th, 50th and 84th percentiles (Tucker, 1981). A high mean phi size corresponds to a low mean mm size of the sediment as the phi scale is an inverse of the actual diameter-size of the particles of the sediment.

Sorting is a measure of the standard deviation, *i.e.* spread of the grain-size distribution. It gives an indication of the effectiveness of the depositional medium in separating grains of different classes. The value calculated for the sorting of the sediment fits into one of seven classes ranging from very well-sorted to extremely poorly-sorted sediment (see Briggs, 1977). The grain-size frequency curve may form a peak in one size-class of particle (unimodal), peak in two size-classes (bimodal), or peak in more than two size-classes (polymodal). The shape of the curve, and the number of peaks within it, illustrates the degree of sorting of the sediment. Sorting is determined by several factors. Sedimentary source-rock type, grain size itself (as coarse sediments and fine sediments are generally more poorly-sorted than easily transported sand-sized sediments) and also the depositional mechanism (shallow shelf seas have much better sorted sediments {Tucker, 1981}) can affect the sorting of the sediment. In areas affected by fast currents the sediment will be well-sorted, with the coarser portion of the sediment dropping out of suspension in one area and the finer fractions dropping out of suspension a little further on. This leads to a sediment that is predominantly of one particle size, or well-sorted. A well-sorted sediment of particles greater than 0.0625 mm results in a loosely-compacted sediment, which will have interstitial spaces for oxygenated water to pass. Movement of water reduces stagnation, toxins are easily flushed from the system and the depth at which aerobic organisms can live is increased. In a poorly-sorted sediment, there is a mixture of particle sizes. This leads to compaction of the sediment and there are less interstitial spaces for water to pass through. The pore spaces are smaller and not interconnected. As a result, the oxygenated sedimentary layer is much reduced. Sorting, will therefore, affect the depth at which aerobic endofauna can survive and affects tube-forming organisms which might serve to aerate these sediments at depth (bioturbators). Bioturbators rely on the thixotropic nature of sediment (sediment which becomes liquid as a result of agitation or pressure {Lincoln *et al.*, 1982}) and only when the water content of the sediment is greater than twenty five per cent does the sediment become thixotropic (Newell, 1979). Poorly-sorted sediment has interstitial pore volume reduced to only 20% of the total volume, whereas well-sorted sediments contain up to forty five per cent of pore volume (Giere, 1993).

Skewness describes the grain size frequency curve in terms of symmetry. If the sediment is predominantly of large particles (coarse) then the sediment is described as negatively skewed; if fine material predominates the skew is positive (Tucker, 1981). The value calculated for the skewness of the sediment fits into one of five classes (see Briggs, 1977) ranging from very negatively skewed (coarse tail) to very positively skewed (fine tail). Beach sands are usually of negative skew as the fines are removed, whereas river sands are positively skewed as silt and clay persist (Tucker, 1981).

Kurtosis is related to both the sorting of the sediment and to the non-normality of the distribution of the sediment. Kurtosis measures the ratio between the sorting in the "tail" of the distribution and the sorting in the central portion of the distribution (Lindholm, 1987). If the central portion is better sorted than the tail, the frequency curve is said to be excessively peaked or leptokurtic. If the tail is better sorted than the central portion the curve is flat-peaked or platykurtic (Lindholm, 1987). A normal distribution is mesokurtic (Briggs, 1977). The value calculated for the kurtosis of the sediment fits into one of six classes (Briggs, 1977) ranging from very platykurtic to extremely leptokurtic.

The distribution of infauna and epifauna may show a clear correlation with sedimentary type. Two sediments with disparate grain size characteristics will, in most cases, show demonstrable and related differences in many other physical and biological properties *i.e.* bulk density, porosity, capillarity, thixotropy, permeability, oxygenation, content and nature of organic matter, and bacterial count (Buchanan, 1984). It is generally accepted that particle size and the characteristics of the sediment greatly influence the fauna living both in and on the sediment. Buchanan (1984), Bellan (1985) and Lankford (1959) found it was possible to correlate the sediment type with the distribution of an organism, and that communities on soft substrata depend primarily on the nature of the substrata and the processes of sedimentation. Grain-size is, therefore, a key factor for meiofaunal habitats (Giere, 1993). Perkins (1971) is quoted by Ellison (1984) that fine sediments generally support larger meiobenthonic populations than coarse sediments. Muddy sediments are often characterised by rich populations of a limited number of species restricted to the

surface layer. Raup & Stanley (1971) found that muddy bottoms in quiet areas tend to have no epifauna and the infauna consists of small animals with thin shells.

The association of Protozoa with sediment-type has been investigated and Fenchel (1987) found that the mechanical properties of sediments are an important factor for the qualitative and quantitative distribution of ciliated Protozoa. In well-sorted sands with small amounts of silt and clay, the interstitial spaces harbour Protozoa and other organisms and, as grain size decreases, these are confined to the surface layer except for some Foraminiferida.

Particle size is an important variable for benthonic Foraminiferida and has been described by many authors. British marine Foraminiferida range in size from approximately 60 microns to 1000 microns and, as such, are subject to the forces which determine the characteristics of the sediment. Foraminiferida can be epifaunal or infaunal and the relationship between Foraminiferida and substratum-type vary generically. Whereas most benthonic Foraminiferida are free in the inter-grain spaces, some are attached to the grain surfaces (Frankel, 1972). Although some authors have discounted the importance of particle size upon foraminiferal abundance (*e.g.* Lankford, 1959; Akpati, 1975; Buzas *et al.*, 1989) many studies of Foraminiferal distribution have accepted the importance of particle size. Wang & Zhao (1985) state that sediment type and hydrodynamic conditions govern foraminiferal abundance, and Murray (1979 {b}) notes that the substratum causes local differences in species distribution. Uchio (1962) states that the total benthonic population in Japan was clearly influenced by median phi distribution, and generally the coarser the sediment the smaller the foraminiferid population. Bates & Spencer (1979) found that particle size and temperature were the most important influences on living foraminiferid densities, and Hansen (1965) found that foraminiferid densities were probably related to sediment size and to the degree of sorting, as this would govern the amount of available food. Although Said (1950/51) states that the concentration of Foraminiferida increases with grain size many authors have stated that fine sands support a rich foraminiferid fauna (Arnold, 1974; Ansari *et al.*, 1980; Cheng, 1987). Murray (1979 {a}) and Hart & Thompson (1974) found that, in general, muddy substrata are more productive for living Foraminiferida than clean sands.

The diversity of organisms is also affected by the characteristics of the sediment. Substrata composed of mud-sand mixtures usually differ from shifting sand and quiet mud bottoms in being both stable and firm. Commonly such substrata are inhabited by a wide variety of species. Animals that form permanent dwelling burrows are largely restricted to muddy sand because of its cohesiveness (Raup & Stanley, 1971). The diversity of organisms increases as the sediment particle size decreases. Moderately-well-sorted medium-sand harbours the most diverse meiofauna (Giere, 1993) and in coarser sand the species number remains relatively high although population density may decrease.

The properties of the sediment can affect the distribution of meiofauna, but can also be affected by meiofaunal aggregates that help to improve the cohesiveness of the sediment. This may alter the porosity, density, permeability and water content of the sediment. In some sediments faecal pellets form more than fifty percent of the surface sediment. The foraminiferid *Ammonia beccarii* is a fervent microflora predator which often forms dense colonies in the field. The surrounding sediment becomes extensively pelleted, mucus-bound and depleted in microfloral food, which probably inhibits re-colonisation by copepodite and naupilar stages of *Amphascoides limicola* (Chandler, 1989).

The properties of the sediment may change temporally and the temperature of the water determines inversely the viscosity and the ability of the water to hold sediments in suspension and therefore the composition of the sediment may vary season to season.

4.4.2. MATERIALS & METHODS.

Separate sediment samples for particle size analysis were collected monthly from the three sites at the same time as samples for Foraminiferida and other variables from August, 1993, until July, 1994, by the Murray Grab deployed from R.V. *Sepia*.

More than 30g of wet sediment from each site was placed into a one-litre conical glass flask. 100 ml of 6% hydrogen peroxide was added to it and agitated to access all portions of the sediment to remove the organic matter (Buchanan, 1984). As well as this, the hydrogen peroxide generates oxygen in the pore spaces of the sediment, which in effect pushes individual particles away from each other (Galehouse, 1971). The sediment was left for more than two days and heated, to complete the reaction. 10 ml of 0.17M sodium hexametaphosphate solution was then added to each flask to separate flocculated clay particles and this was then left overnight.

The sediments were added to tared metal trays and placed into an oven at 110°C for at least two days to thoroughly dry the particles. The dry weight of the total sediment was noted, and distilled water was added to the sediment to re-constitute it and to disaggregate the dried particles. The sediment was then wet-sieved on a 63 μm Endacott sieve to remove the silt-clay fraction and the >63 μm portion of the sediment was then re-dried and weighed. From this procedure the proportion of sediment <63 μm could be assessed by weight.

The >63 μm portion of the sediment was dry-sieved on Endacott sieves of 63 μm, 90 μm, 125 μm, 180 μm, 250 μm, 355 μm, 500 μm, 710 μm, 1000 μm and 2000 μm. Settling velocity of a particle is a function of its volume, density, roundness and sphericity: sieving merely separates grains according to their least cross-sectional area (Galehouse, 1971). Each fraction of the sediment was weighed on a Mettler (P.C. 4400) pan balance and the data entered into a computer package designed by R. Hartley (University of Plymouth), to provide Folk and Ward values for mean particle size, sorting, skewness and kurtosis.

Samples were collected on the 6th June, 1995, to assess the composition of the <63 μm fraction for each site. The sediments were wet-sieved over an Endacott 63 μm sieve and 100 ml hydrogen peroxide was added to the resultant sediment. Calgon fluid (sodium hexametaphosphate and sodium carbonate) was added to the sediments which were then dispersed in an ultra-sonic bath. The <63 μm fraction was then placed into a Malvern Instruments Mastersizer to assess the proportion of silts and clays from each site. All particle size characteristics are recorded in Appendix IV.

4.4.3. RESULTS.

Table 4.3: Particle size statistics of Cawsand Bay sediments 1993/1994.

Month	Mean ϕ	Sorting value	Sorting description	Skewness value	Skewness description	Kurtosis value	Kurtosis description
August	3.17	0.51	moderately well-sorted	-0.15	negatively skewed	1.17	leptokurtic
September	3.22	0.45	well-sorted	-0.07	symmetrical	1.08	mesokurtic
October	3.11	0.53	moderately well-sorted	-0.01	symmetrical	0.92	mesokurtic
November	2.84	0.44	well-sorted	0.11	positively skewed	1.11	mesokurtic
December	2.94	0.46	well-sorted	0.20	positively skewed	1.07	mesokurtic
January	2.85	0.43	well-sorted	0.24	positively skewed	1.56	very leptokurtic
February	3.00	0.49	well-sorted	0.02	symmetrical	1.04	mesokurtic
March	3.16	0.47	well-sorted	0.02	symmetrical	0.83	platykurtic
April	2.88	0.46	well-sorted	0.14	positively skewed	1.09	mesokurtic
May	2.92	0.50	well-sorted	0.15	positively skewed	1.04	mesokurtic
June	2.72	0.49	well-sorted	0.10	symmetrical	1.17	leptokurtic
July	2.78	0.51	moderately well-sorted	0.13	positively skewed	1.19	leptokurtic

Table 4.4: Particle size statistics of Drake's Island sediments 1993/1994.

Month	Mean ϕ	Sorting value	Sorting description	Skewness value	Skewness description	Kurtosis value	Kurtosis description
August	2.25	0.69	moderately well-sorted	-0.14	negatively skewed	0.95	mesokurtic
September	1.64	1.13	poorly-sorted	-0.27	negatively skewed	1.26	leptokurtic
October	1.31	0.76	moderately-sorted	-0.06	symmetrical	0.83	platykurtic
November	1.87	0.72	moderately-sorted	-0.17	negatively skewed	1.04	mesokurtic
December	1.72	0.69	moderately well-sorted	-0.06	symmetrical	1.08	mesokurtic
January	1.54	0.80	moderately-sorted	-0.11	negatively skewed	0.94	mesokurtic
February	1.51	0.78	moderately-sorted	-0.09	symmetrical	0.90	mesokurtic
March	1.47	0.76	moderately-sorted	-0.04	symmetrical	0.95	mesokurtic
April	1.33	0.87	moderately-sorted	-0.05	symmetrical	0.80	platykurtic
May	2.11	0.63	moderately-well-sorted	0.01	symmetrical	1.10	mesokurtic
June	1.99	0.67	moderately-well-sorted	-0.02	symmetrical	1.15	leptokurtic
July	1.79	0.71	moderately-sorted	-0.06	symmetrical	1.13	leptokurtic

Table 4.5: Particle size statistics of White Patch sediments 1993/1994.

Month	Mean	Sorting	Sorting description	Skewness	Skewness description	Kurtosis	Kurtosis description
August	1.07	1.80	poorly-sorted	-0.26	negatively skewed	0.92	mesokurtic
September	2.09	1.35	poorly-sorted	-0.24	negatively skewed	1.36	leptokurtic
October	1.91	1.38	poorly-sorted	-0.41	v. negatively skewed	1.47	leptokurtic
November	1.99	1.13	poorly-sorted	-0.28	negatively skewed	1.48	leptokurtic
December	0.99	1.83	poorly-sorted	-0.37	v. negatively skewed	0.58	very platykurtic
January	0.60	1.80	poorly-sorted	0.07	symmetrical	0.69	platykurtic
February	1.91	1.21	poorly-sorted	-0.18	negatively skewed	1.21	leptokurtic
March	1.41	1.39	poorly-sorted	-0.23	negatively skewed	1.26	leptokurtic
April	1.41	1.41	poorly sorted	-0.13	negatively skewed	1.14	leptokurtic
May	0.99	1.80	poorly-sorted	-0.24	negatively skewed	0.93	mesokurtic
June	1.52	1.33	poorly-sorted	-0.20	negatively skewed	1.20	leptokurtic
July	1.20	1.61	poorly-sorted	-0.33	v. negatively skewed	1.21	leptokurtic

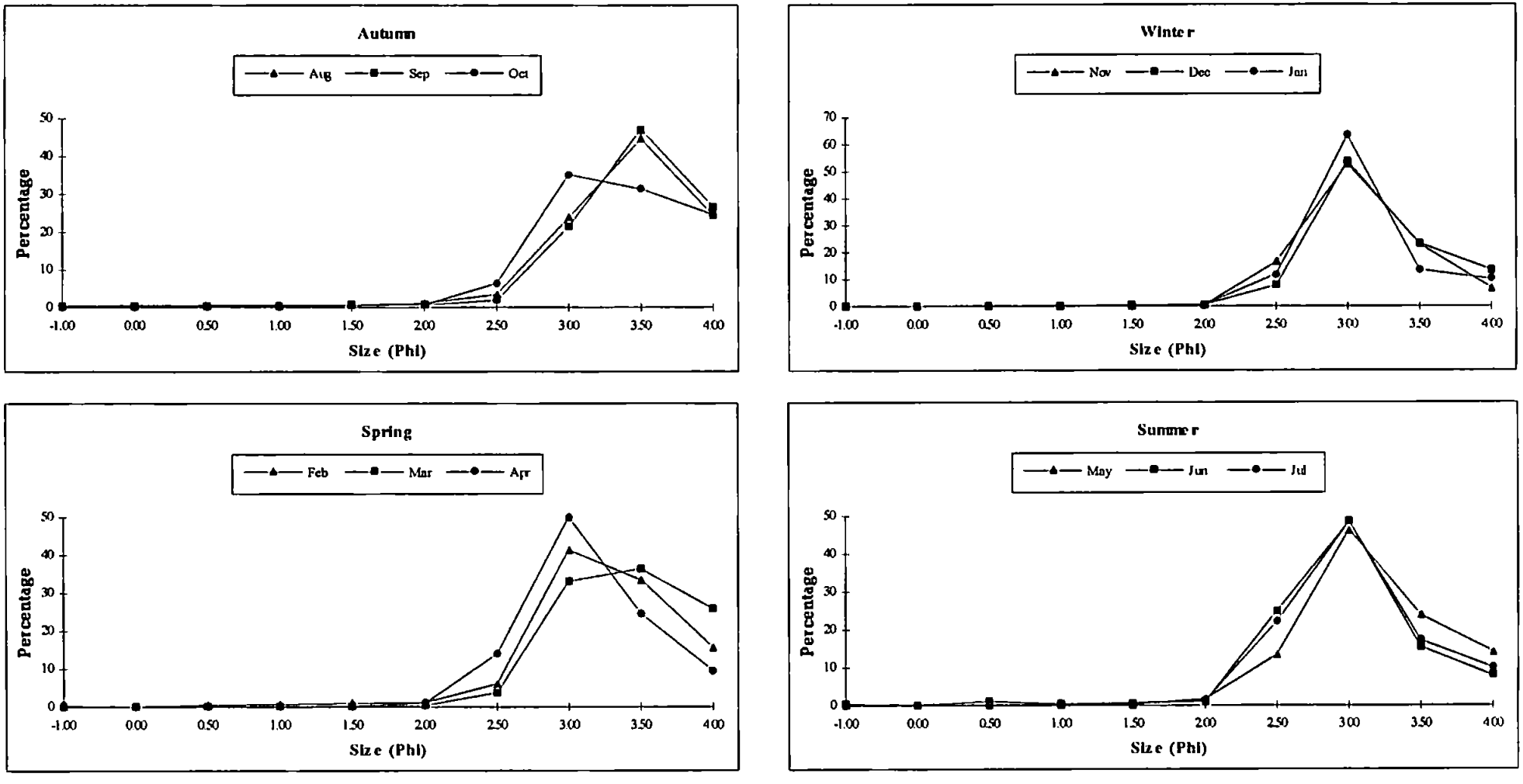


Figure 4.4: Seasonal variation in particle size distribution in sediments from Cawsand Bay 1993/1994.

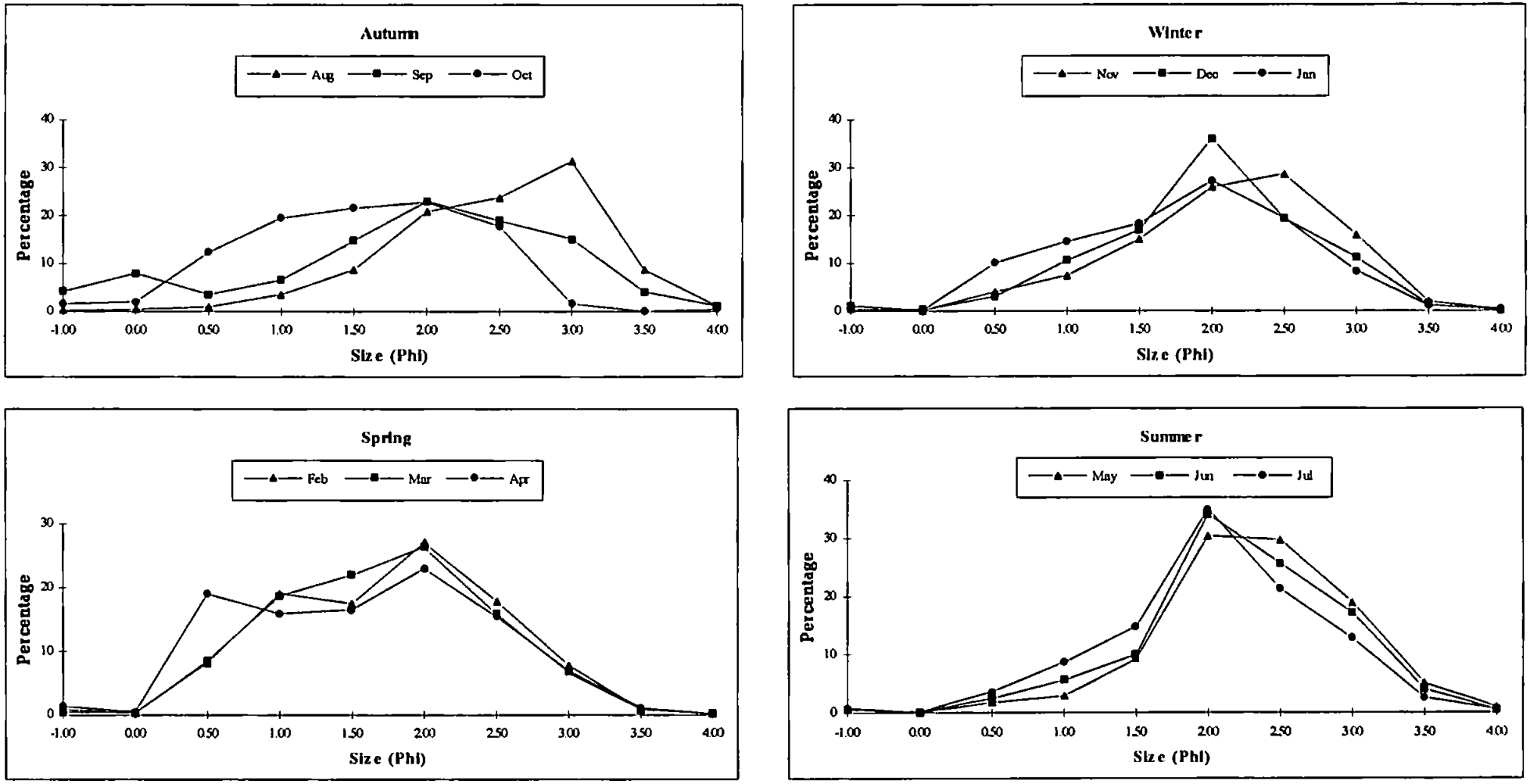


Figure 4.5: Seasonal variation in particle size distribution in sediments from Drake's Island 1993/1994.

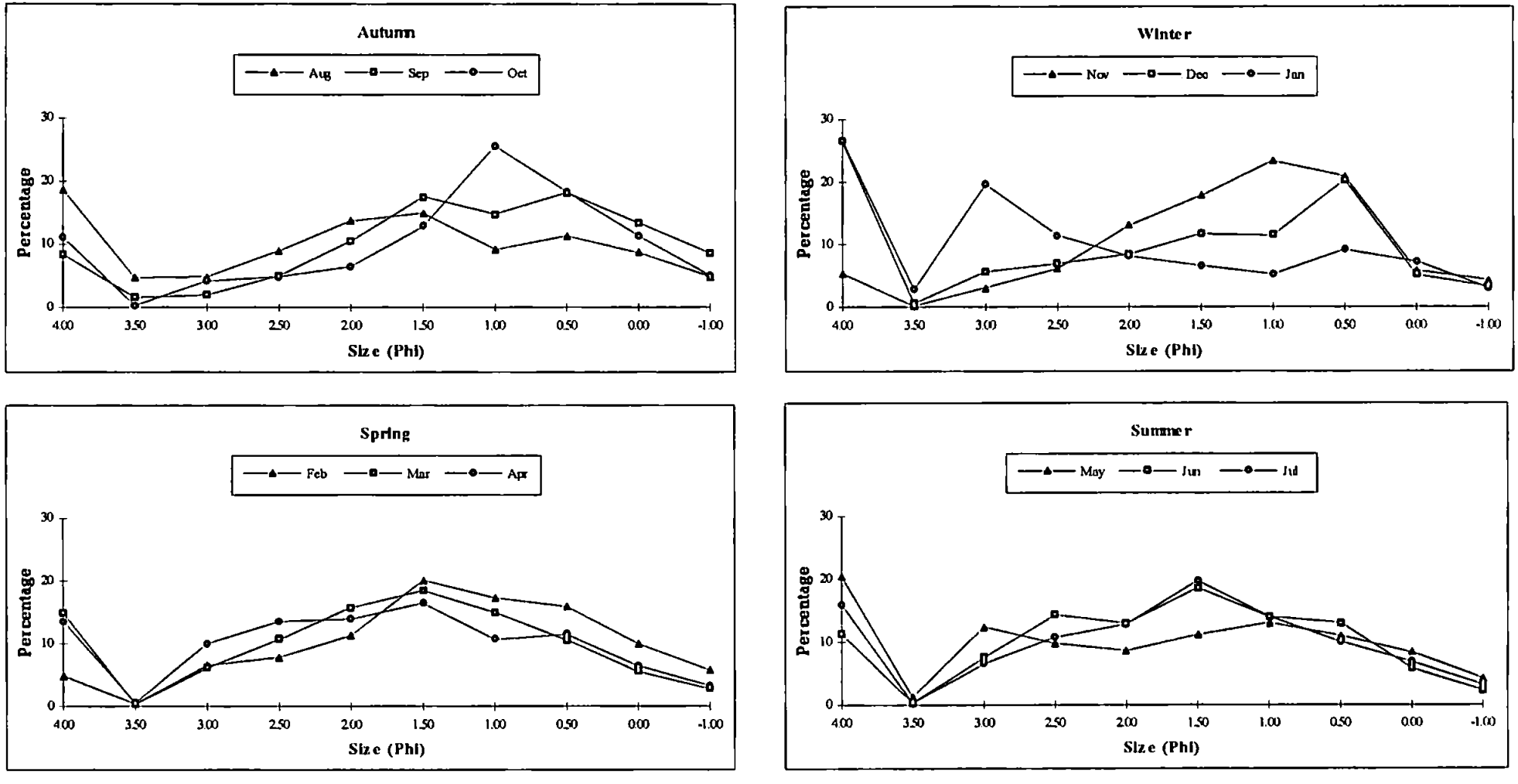
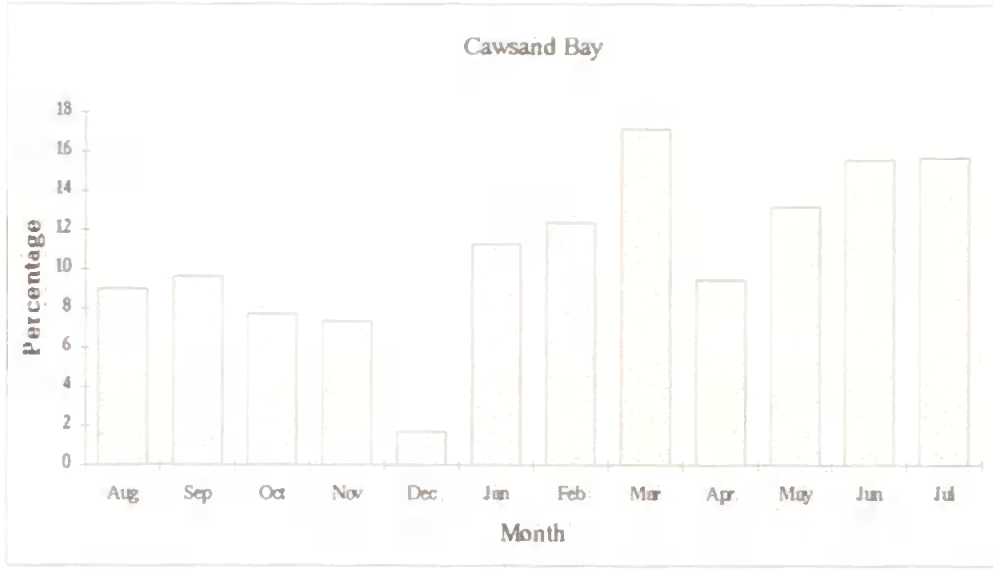
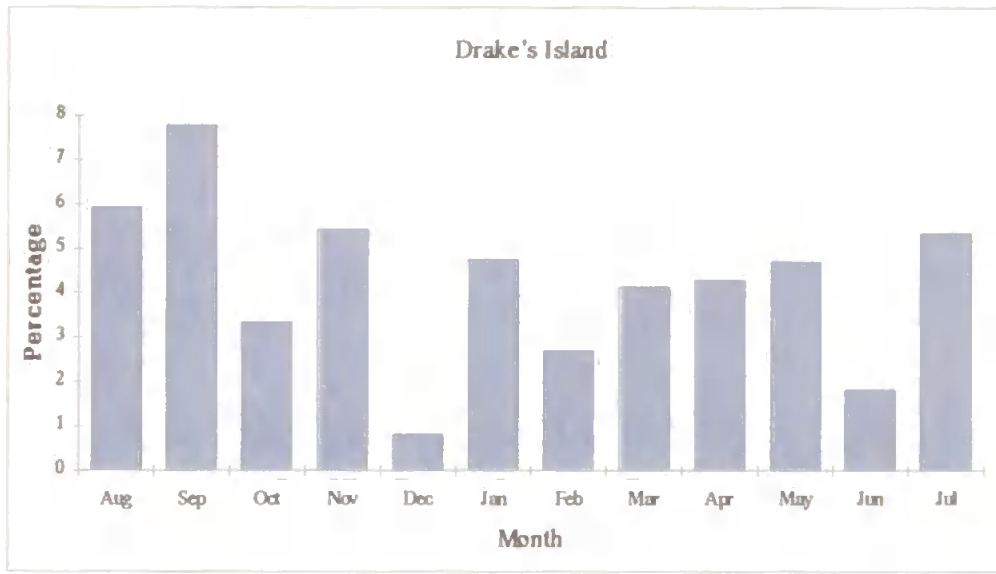


Figure 4.6: Seasonal variation in particle size distribution in sediments from White Patch 1993/1994.





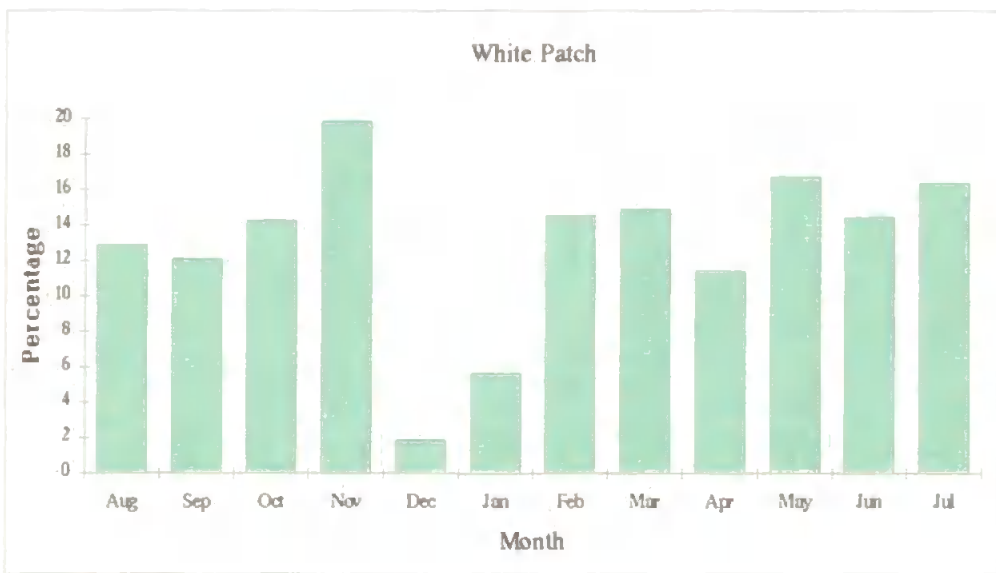


Figure 4.7: Monthly variation in the percentage of the sediment less than 63 µm 1993/1994.

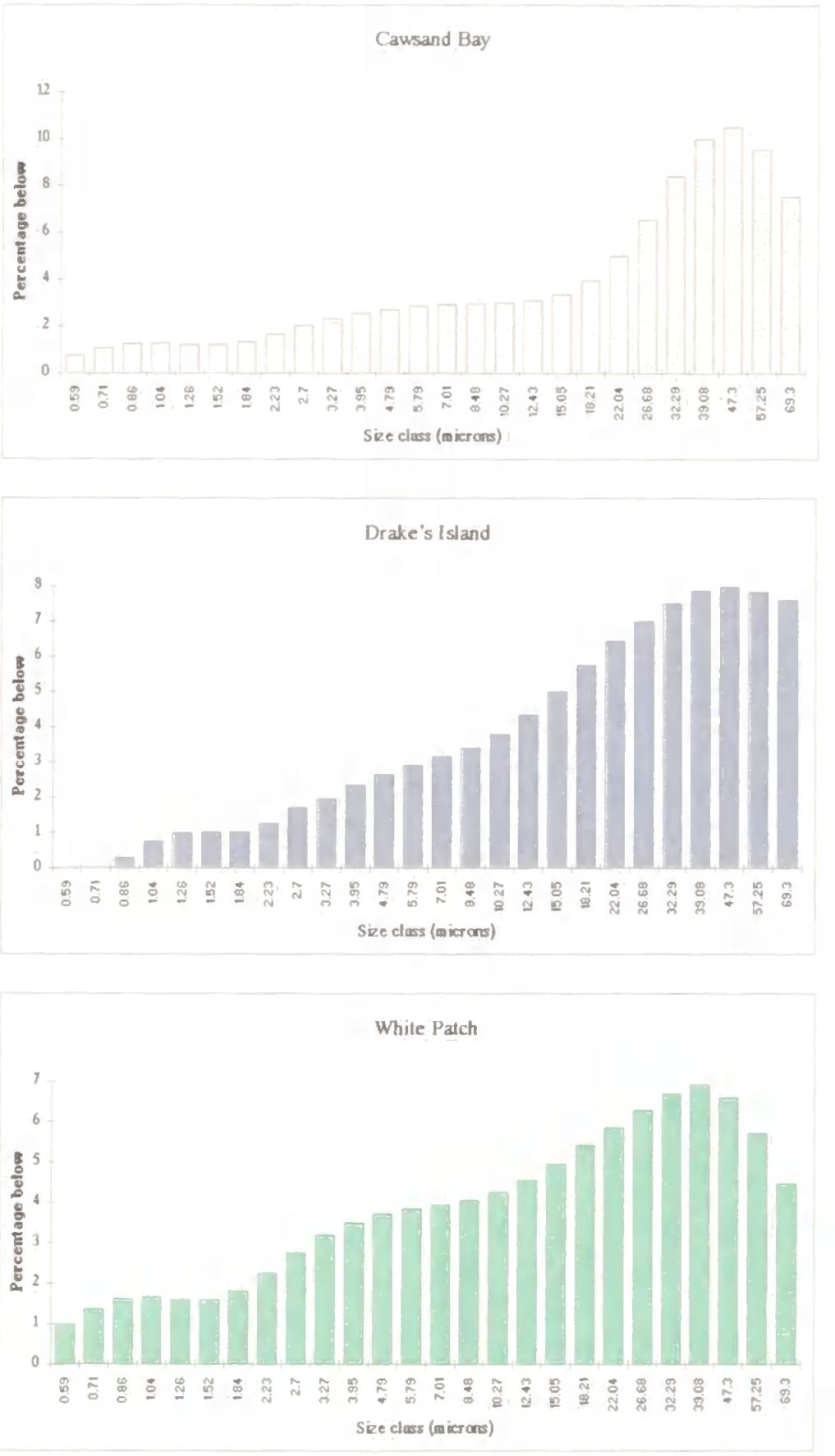


Figure 4.8: Grain-size distribution below 70 μm for all three sites, based upon one sample (6th June, 1995) for each site.

Mean phi differed between sites, with Cawsand Bay sediment generally having higher mean phi particle size than Drake's Island, which was in turn generally higher than sediment from White Patch. Sorting of the sediment also appeared to differ, with generally White Patch having higher values than Drake's Island, which was also higher in sorting coefficients than Cawsand Bay. Cawsand Bay seemed to have higher skewness values than Drake's Island, which had higher values than White Patch. Although kurtosis of the sediments was similar at the sites, they appeared to differ in the percentage of the sediment less than 63 μm, with White Patch having a higher proportion of fines in the sediment than Cawsand Bay, which also had a higher proportion of fine sediment than that from Drake's Island.

Cawsand Bay

From Figure 4.4 it can be seen that all the frequency distributions were unimodal. From Table 4.3 the mean particle size for each month for Cawsand Bay ranges from a phi size of 2.72-3.22, corresponding to metric sizes of approximately 180 μm to less than 125 μm particles of fine sand. Mean particle size shows little variability, indicating that sediment composition at this site varied little throughout the annual cycle. The sediments were all moderately-well to well-sorted, supported by the majority of the sediments being mesokurtic (equally well-sorted in the central portions as in the tail portions) or leptokurtic (tails of the distribution being more poorly-sorted than the central portion). Skewness at this site was mainly symmetrical or positively skewed, dominated by relatively fine particles.

Drake's Island

From Figure 4.5 it can be seen that the particle size distributions for this site are mainly unimodal, becoming bi-modal in September, February and April. From Table 4.4 the mean particle size ranged from a phi size of 1.31 to 2.25, corresponding to metric sizes of less than 500 μm to greater than 180 μm particles of medium sand. Mean particle size shows greater variability than Cawsand Bay sediments, indicating that sediment composition at this site varied more than in the

Cawsand Bay sediments. The sediments were moderately to moderately-well sorted, only becoming poorly-sorted once in September, perhaps due to storm activity. The majority of the sediments were mesokurtic or leptokurtic, supporting the sorting values. Skewness at this site was mainly symmetrical, with the remaining sediments being negatively skewed, or dominated by coarse particles.

White Patch

From Figure 4.6 the distributions are all bi- or polymodal in distribution. From Table 4.5 the mean particle size ranged from a phi size of 0.6 to 3.09, corresponding to metric sizes of less than 710 μm to 250 μm particles of medium sand. The variation in mean particle size was relatively large compared to the other two sites, indicating that sediment composition at this site varied greatly throughout the annual cycle. The sediments were consistently poorly-sorted at this site and mainly leptokurtic (indicating that the tails of the distribution were also poorly-sorted). Skewness was mainly negatively to very negatively-skewed, demonstrating a high proportion of coarse particles to be present.

Comparison of sites

The three sampled sites differed greatly sedimentologically. Cawsand Bay consists of well-sorted, mainly symmetrical mesokurtic sediment which is unimodally distributed and becomes slightly finer in particle size in the autumn. Drake's Island consists of moderately sorted, slightly platykurtic sediment which is usually unimodal but becomes more bimodal in the Spring months. White Patch consists of poorly sorted, negatively skewed mainly leptokutic sediment which is generally polymodal in distribution. The mean phi of the sediments was greatest at Cawsand Bay, Drake's Island and White Patch reflecting that the mean particle size in mm diameter was greatest in White Patch, Drake's Island and Cawsand Bay respectively. Sorting of the sediment was poorest at White Patch, Drake's Island and Cawsand Bay respectively. The skewness coefficients reflect that Cawsand Bay sediments are fine, with Drake's Island and White Patch sediments becoming

more coarse in distribution. White Patch sediments have a higher proportion of sediment less than 63 μm than Cawsand Bay and Drake's Island respectively and all sites have a lower proportion of this fine sediment in the month of December. The distribution of the sediment less than 70 μm reveals that Cawsand Bay sediments are mainly close to the 70 μm with little clay or silt present; Drake's Island sediments have a more even distribution of fine sediment decreasing gradually from 70 μm to 1 μm; White Patch sediments have three peaks in distribtuion especially in the silt and clay sections of the sediment.

4.5. DISCUSSION.

The mean phi size and skewness of the sediments reflects the degree of wave and current energy with the more marine habour of Cawsand Bay producing fine sediments and the dynamic environment of Drake's Island producing well-sorted medium-sized sediments; the poorly-sorted sediment of White Patch reflects little current activity in the area and the sediment contains both fine and coarse material. Sorting of the sediment was poorest at White Patch, Drake's Island and Cawsand Bay respectively reflecting that the relatively shallow Cawsand Bay is subject to greater wave energy than Drake's Island, and the greater depth of water above White Patch probably serves to protect the sediment at this site from waves. This effect is mirrored in the proportion of the sediment which is less than 63 μm and the input of clay from the River Plym to the White Patch site is shown in the proportion of this sediment less than 2 μm. The reduction in the proportion of the sediment less than 63 μm in the month of December may show that gales and/or extra freshwater flow at this time of year flushed all sediments of the fine material.

4.6. SUMMARY.

The monthly measurement of temperature, salinity and particle size characteristics has revealed that the sites investigated are remarkably similar for temperature and salinity, whilst the characteristics of the substrata differ greatly. The temperature of Cawsand Bay was higher in winter and colder in summer than the other two sites and the salinity was higher. Drake's Island temperature was coldest in winter and warmest in summer and salinity the lowest of the three sites. White Patch temperatures and salinity were generally intermediate between the other two.

Cawsand Bay sediments consist of fine, well-sorted sand with a generally symmetrically skewed distribution. The substratum of Drake's Island was well-sorted medium sand which was generally symmetrical or negatively skewed in distribution. White Patch sediments were polymodal in distribution and consisted of poorly-sorted medium sand. Skewness of White Patch substrata was mainly negatively to very negatively-skewed, demonstrating a high proportion of coarse particles to be present.

The substrata of the sites varied throughout the annual sampling period with White Patch sediments being more variable than Drake's Island sediments and Cawsand Bay sediments respectively. It appears to be important to measure this variable every time the sediment is examined for Foraminiferida.

CHAPTER 5.

BIOTIC VARIABLES.

5.1. INTRODUCTION.

Whilst studies of abiotic factors dominated in the 1960s and early 1970s, meiobenthonic studies concentrating on biotic factors have increased since about 1975 (Giere, 1993). Ecology is the study of the interrelationship between organisms and the environment, and within any ecosystem chemical, physical and biological processes interact with the organisms present (Raup & Stanley, 1971). It is realised that biotic factors are most relevant for the understanding not only of meiobenthonic assemblages, but also for the benthonic habitat in general (Giere, 1993). Whilst abiotic factors are relatively easy to measure, biotic factors are problematical to quantify, and hence difficult to measure and interpret (Giere, 1993).

Due to the importance of Foraminiferida to the oil industry and because they are not medically important (unlike ciliated Protozoa) most work to identify environmental factors affecting the distribution and occurrence of Foraminiferida has been carried out by geologists. This has led to abiotic factors rather than biotic factors being used to correlate species distribution to the environment. This is still true today, with foraminiferologists with biological backgrounds largely concentrating upon culturing techniques and laboratory-based experiments. The tendency of geologists to consider only the physical characteristics of sediments and sedimentary rocks is noted by Uchio (1962), who claims that this appears to be an erroneous and short-sighted view.

The necessity of studying the possible effects of biotic factors upon living Foraminiferida has been recognised and Mageau & Walker (1976) state that workers attempting to study the ecology or paleoecology of Foraminiferida should be concerned with the total biotic system, as the fluctuations of other flora and fauna populations may well influence those of

Foraminiferida. Bacteria and unicellular algae are the most important prey of Foraminiferida (Murray, 1979 {a}; Lee, 1980) and, as such, must be of vital importance to their distribution. Lee (1974) found in experiments with radio-labelled substrata that changes in the population structure of Foraminiferida reflected changes in the available nutrition due to different growth patterns of bacteria and diatoms on different media. Mageau & Walker (1976) also state that information on algal/bacterial complexes is indispensable in the interpretation of foraminiferal distribution patterns. Wefer (1976) finds that although variables such as substratum type, salinity and temperature are recorded with the distribution of benthonic Foraminiferida, factors such as oxygen and food availability are rarely considered. Bradshaw (1961) states that he knows of no field study comparing the natural distribution of a species of Foraminiferida with a known food source, and it is probable that this would be an important consideration in the distribution of Foraminiferida.

The possible interaction between Foraminiferida and other organisms has been little investigated. The taxa encompasses members which obtain food by dissolved organic matter uptake, herbivory, carnivory, omnivory, suspension-feeding, detritivory and bacterial ingestion, parasitism, cannibalism and symbiosis (Lipps, 1983). Several properties of the marine environment usually vary together; the effects of variation in single factors are seldom evident in natural conditions (see Buzas, 1969; Tait, 1981). The distribution of a species is consequently associated with a complex of variables and it is not easy to assess the role of each parameter independently (Tait, 1981). Apart from the effects of the inorganic environment, there are also many ways in which organisms influence each other: even where physical and chemical conditions seem suitable, a species may not flourish if the presence or absence of other species has an unfavourable effect (Tait, 1981). Murray (1991) states that in theory competition between species for space and food may be ecological controls, but that there are no data to suggest that either takes place among small benthonic sediment habitats. The complex interactions between an assemblage and the environment is unclear, but a start can be made by first studying the individual parameters of the environment, noting the extent to which each can be correlated with the distribution of different species (Tait, 1981). The aim of this part of the study is to measure and record the

levels and variability of organic, bacterial, diatom and other meiofaunal content of the sediment at the three sampling sites.

5.2. TOTAL ORGANIC CONTENT.

5.2.1. INTRODUCTION.

Organic matter is derived from living organisms and may be either particulate or soluble in form. Heterotrophic organisms require organic matter for growth and the measurement of organic matter in an ecosystem provides an estimate of the organic nutrients available for growth (Atlas & Bartha, 1981). In the photic zone the major proportion of suspended organic matter is composed of phytoplankton and particulate aggregates, which are metabolised and transferred through different food chains (Iturriaga, 1979). Most of the photosynthetically-produced organic material reaching the ocean floor is transported as settling particles, among which larger particles such as faecal pellets and macroaggregates are particularly important and are rapidly colonised by bacteria and Protozoa (flagellates and Foraminiferida) (Gooday & Turley, 1990). Whilst most organic matter arriving at the sediment-water interface settles from suspension, it is suggested that the transport of organic matter by bioturbators is a dominant additional input at shallower depths (Hinga *et al.*, 1979). The total organic content of sediment gives only a rough guide to the nutrient input in a sampling area as material such as coal and wood, although not available to organisms as a nutrient source, are included in this measurement.

The amount of organic material in a system may limit the ability of benthonic organisms to grow and develop, and govern the timing of benthonic reproduction. Whilst too little organic matter in the system may be detrimental to the benthos by not providing enough nutrients, too much organic material may prove to be toxic (see Atlas & Bartha, 1981; Fabrikant, 1984).The amount of organic matter has also been shown to affect the community structure of Copepoda (Gee *et al.*, 1985) and may well, therefore, affect foraminiferid community structure.

From 1960, some studies of Recent benthonic Foraminiferida have recorded the organic content of sediments (Boltovskoy & Wright, 1976), but its value as a potentially important variable to the abundance of living Foraminiferida has only been studied by other authors within the last decade.

A relationship between increasing organic matter in sediments and an increase in benthonic Foraminiferida has been identified by authors such as Said (1950/51), Sieglie (1968), Hart & Thompson (1974), Phleger (1976), Ansari *et al.* (1980), Lukashina (1987), Moodley (1990 {a}) and Jorrisen *et al.* (1992).

Decomposing organic matter lowers the pH (Myers, 1943), produces ammonia, decreases nitrogen, depletes oxygen (Seiglie, 1968) and sulphate becomes the major oxidant after the consumption of oxygen (Malcolm & Stanley, 1982). Sea water is usually supersaturated with oxygen at the surface due to the atmospheric content and production by plant photosynthesis (Myers, 1943), however, an excess of organic matter depletes oxygen in the surrounding area. The combination of an excess of organic content and depleted oxygenation appears to affect foraminiferid behaviour (Alve & Bernhard, 1995), physiology (Corlis, 1985) and the distribution of benthonic Foraminiferida (Miao & Thunell, 1993) probably because some genera appear to have a very high requirement for oxygen (Hannah *et al.*, 1994). It is also believed that some species may be facultative anaerobes (Moodley & Hess, 1992; Sen-Gupta & Machain-Castillo, 1993) and both arenaceous and calcareous species have been found in anoxic layers (Bernhard, 1989). Alve & Bernhard (1995) find that in response to increased organic content of the sediment benthonic Foraminiferida vertically migrated upwards in response to depleted oxygen levels.

An influx of total organic matter may, therefore, affect different species of Foraminiferida in different ways. Anantha *et al.* (1986) found that sub-recent Nonionidae and Miliolidae in hyposaline water were negatively affected by organic carbon content in the sediment and Bao (1987) found that a negative correlation existed between organic content and abundance of Foraminiferida in deep-sea sediments. Sieglie (1968) states that species living

in areas of high organic carbon include the genera *Buliminella*, *Bulimina*, *Fursenkoina*, *Florilus*, *Nonionella* and probably *Uvigerina*, whilst Alve (1990) finds a correlation between dissolved organic content and *Stainforthia fusiformis*. Where there has been an anthropogenic input of organic matter to the marine system (usually in the form of sewage), it appears that this increased level of nutrients is correlated with an increase in foraminiferid populations (Watkins, 1961; Bandy *et al.*, 1964; Bandy *et al.*, 1965; Nagy & Alve, 1987; Yanko *et al.*, 1994). If Foraminiferida are situated too close to an excess of organic matter, however, abundance (Bandy *et al.*, 1964; Schafer & Cole, 1974; Setty, 1976, 1982; Varshney, 1985) and diversity (Schafer, 1973; Schafer & Cole, 1974) may decrease. The proportion of hyaline Foraminiferida also rises close to such a source, with hyaline Foraminiferida being eight times more abundant than arenaceous species (Bandy *et al.*, 1964; Bandy *et al.*, 1965). Industrial and urban waste often generate a benthonic environment gradient from abiotic to hypertrophic with radial distance from the outfall (Schafer & Cole, 1976).

Organic content of sediments is related to other environmental variables and a relationship exists between the grain size of the sediment and the organic content (Trask, 1939). Slow-moving water allows organic matter to settle (Tait, 1981) and sorting and skewness of the sediment bear relationships with the organic content (Goard, 1975). In silty muds the dry weight of the organic particles can account for up to 10% of a sample while on sandy shores this value is often <1% (Giere, 1993). Hart & Thompson (1974) state that a high organic content of sediments results in high concentrations of bacteria which form an essential part of the diet of Foraminiferida.

The purpose of this investigation is to determine the total organic content of sediments at three sampling sites within the same geographical area so that possible effects upon living foraminiferal abundance or diversity could be assessed.

5.2.2. MATERIALS & METHODS.

The sediment at each site was assessed monthly for total organic content. Approximately 1g of wet sediment from each was placed into a tared crucible of high silica content and weighed on a Sartorius (2001 MP2) balance. All crucibles were then placed into an oven at 110°C for at least two days to dry the samples thoroughly. After being placed into a desiccator for exactly one hour the weights of the dry sediments were obtained, after which the crucibles were placed into a pre-heated Gallenkamp Muffle Furnace at 400°C for a period of six hours. The crucibles were removed from the furnace and placed into a desiccator for exactly one hour before the ashed weight was recorded. Care must be taken that the combustion temperature does not exceed 580°C or volatization of sedimentary carbonates occurs and gives incorrect data (Giere, 1993).

The total organic content was calculated from the wet, dry and ashed weights of the sediments after a correction for salt content. This procedure was provided by G. Burt (PML) and is given in Appendix V. together with the wet, dry and ashed weights obtained.

5.2.3. RESULTS.

Table 5.1: Monthly percentage total organic content of the sediment, 1993/1994.

Month	Cawsand Bay	Drake's Island	White Patch
August	2.08	8.10	5.62
September	3.08	2.70	5.15
October	3.49	5.70	5.57
November	2.10	9.88	5.71
December	2.24	20.06	5.19
January	2.96	6.73	4.84
February	3.17	8.14	4.58
March	2.28	5.03	4.86
April	2.09	6.93	2.83
May	2.20	2.51	5.85
June	2.53	2.32	4.15
July	2.10	5.02	3.60

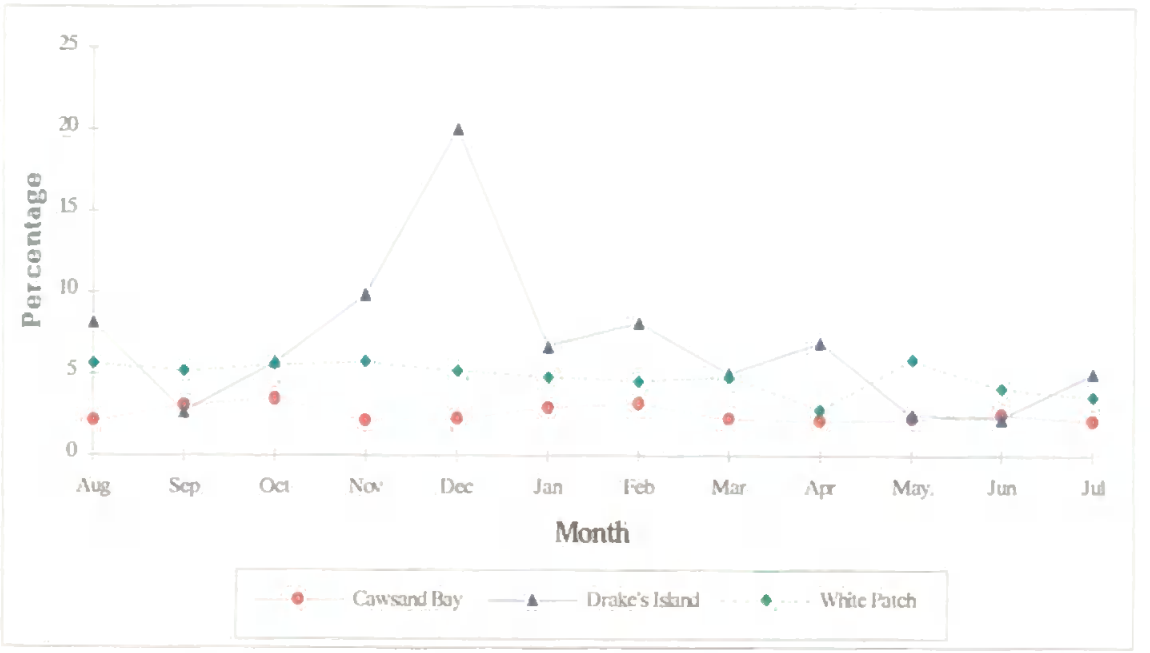


Figure 5.1: Monthly variation in percentage total organic content of the sediment 1993/1994.

It can be seen from Table 5.1 and Figure 5.1 that the sediments from three sampling sites have very different contents of organic matter. Sediments from Cawsand Bay have generally the lowest amount of organic content of the sampling sites throughout the year with a cyclical rise and fall in organic content. Drake's Island sediments generally contained the highest amount of organic matter of the sites, but this fluctuated greatly. Organic content of White Patch sediments was generally intermediate of the other two sites and remained relatively stable.

5.2.4. DISCUSSION.

Cawsand Bay

Cawsand Bay has a fairly stable temporal total organic content, probably because this sheltered bay has little hydrodynamic influence upon it and flushing of particulate organic matter from the sediments is limited. These sediments are also subject to comparatively low levels of sewage discharge. The highest levels of total organic content at Cawsand Bay occur in October, perhaps due to the degradation of detrital algae or autumn phytoplankton.

The cyclical pattern of increase in total organic content in sediments from Cawsand Bay every four months may be indicative of bacterial blooms.

Drake's Island

In winter at Drake's Island there is a peak in the percentage of total organic matter held in the sediment. This may be due to re-suspension of organic matter by gales or may be due to the decomposition of detrital macro-algae. The total organic content at this site was generally the highest of the sites and was also highly variable; this may be due to the variable discharge of organics from the River Tamar and the relatively high ability of water to flush organics from this well-sorted substratum. Peaks in organic content occur at this site in the months of December, February and April and the first two months are probably due to the decomposition of detrital algae and the autumn phytoplankton bloom, whereas the peak in April is probably in response to the spring bloom of phytoplankton settling at this site. The River Tamar will also bring both particulate and suspended organic matter past this site, and is probably a very important source of nutrients for organisms in the Sound. Extensive mud flats border the River Tamar and freshwater discharge from the River Tamar will probably be rich in humic acid from its tributary of the River Tavy. The anomalously high content of 20.06% organic matter in the month of December is unlikely to be the result of experimental error, as all sediments were treated in the same way and the organic matter from Cawsand Bay and White Patch from this month do not appear to be excessively high.

White Patch

The sediments from White Patch were generally intermediate between Cawsand Bay and Drake's Island for total organic content. The organic content varied very little throughout the annual cycle (Fig. 5.1), although it troughs slightly in April and increases slightly from

this in May, to give a slight peak, perhaps in response to the spring phytoplankton bloom settling on the sediment, or to unicellular algae proliferating in the River Plym and becoming deposited at White Patch.

Comparison of sites

Sediments from Cawsand Bay generally had the lowest total organic content of the three sites sampled, and from Fig. 5.1 it can be seen that it varied very little throughout the course of the annual sampling programme. The fluctuation of organic content appears, however, to have a cyclical pattern, with slight increases approximately every four months. These slight increases in organic content occur in the months of October, February and June at Cawsand Bay. From Figure 5.1 the sediments from Drake's Island showed the greatest fluctuations of total organic content for the three sites and generally the highest levels. The organic content troughs in the months of September, March, May and June, whilst it peaks (20.06%) in December at this site. The sediments from White Patch were generally intermediate between Cawsand Bay and Drake's Island for organic content, which varied very little throughout the year of sampling (Fig. 5.1), although it troughed slightly in April and increased slightly in May.

5.3. BACTERIA.

5.3.1. INTRODUCTION.

Bacteria have survived longer than any other organisms and still constitute the most abundant type of cell on Earth (Alberts *et al.*, 1983). They are prokaryotic organisms which lack a perforated nuclear membrane and organelles and have a well-defined nucleus

(Berkeley, 1979). There is a great variation in size of bacterial cells, although most range from 0.2 μm to 1.5 μm (Berkeley, 1979).

Morphologically bacteria are either spherical or cylindrical cells (Alberts *et al.*, 1983). The spherical-shaped bacteria are termed cocci, whilst the straight or very slightly curved cylinders are termed rods (Berkeley, 1979). Bacterial cells may also be pigmented. The highest numbers of bacteria and fungi are almost always found in the top few centimetres of sediment (Rheinheimer, 1992) and therefore, the use of the Murray Grab to sample for sublittoral benthonic bacteria is very important for this investigation.

Two types of bacteria have evolved, and can be differentiated by a staining technique. These bacterial types have different proportions of cell wall constituents and the Gram stain was devised in 1884 by the Danish physician H. C. Gram (Rheinheimer, 1992) to distinguish the two. Gram negative bacteria have complex walls, with a lipopolysaccharide membrane outside the cytoplasmic membrane and peptidoglycan is present in this envelope in varying amounts (Costerton *et al.*, 1974). In a large proportion of marine organisms the Gram negative cell surface is covered in a paracrystalline arrangement of spheres which form multiple layers in some species and which are believed to be proteinaceous (Costerton *et al.*, 1974). Gram positive bacteria may have a thick wall, either amorphous or with some layers, or in some cases only a thin amorphous wall (Moriarty & Hayward, 1982). These differences between the two types of bacteria may well result in different nutritional properties.

Phytoplankton supplies organic matter for bacteria to use by both exudation and lysis: the exudates present depend upon the phytoplankton which produce them. Wolter (1982) states that bacteria assimilate up to 90% of all available exudates produced when dinoflagellates and nanoflagellates predominate, but only 10% when diatoms dominate the phytoplankton. Billen (1982) states that most of the microbiological activity in the sediments occurs in the top 5-10 cm layer, and although Iturriaga (1979) relates bacterial activity to seasons, Wolter (1982) finds that bacterial activity begins to increase shortly after the first phytoplankton

bloom even if the water temperature is low, whereas in autumn bacterial activity decreases with a decrease in algal activity whilst the water temperature remains relatively high. Phytoplankton seem to play a major role in nutrient supply for bacteria (Wolter, 1982), and release glycolic acid which is a potentially important bacterial substrate (Fenchel & Jørgensen, 1977).

Organic compounds are known to stimulate the growth of saprophytic bacteria (Rheinheimer, 1992) and in aerobic environments most bacteria are highly versatile and can use a large variety of organic compounds as a carbon energy source (Veldkamp *et al.*, 1984). It is not the concentration of organics that is important, however, but the fraction of organic compounds which are easily assimilated, like proteins and their constituents, sugars, starch, organic acids, fats *etc.* (Rheinheimer, 1992). Sewage-rich waters are high in protein content and cellulose leading to proteolytic and cellulose-decomposing bacteria and fungi (Rheinheimer, 1992). The importance of bacteria is not only in their remineralisation of organic substances, but also in their transportation of dissolved organic material to a particulate form which is then available for bacterial feeders (Wolter, 1982). Secondary production of heterotrophic bacteria and fungi in waters can be very considerable, since about 20-60% of the organic matter consumed as food is used for their own body organic material and 40-80% is used for energy (Rheinheimer, 1992). Invertebrates release a range of dissolved organic matter both by secretion and excretion (much will be low-molecular-weight material), and bacteria remove this very rapidly from aquatic habitats (Fry, 1982).

Bacteria are essential to the energy-flow in the marine environment. Autotrophic and heterotrophic micro-organisms play a decisive role in the cycling of matter in waters: they produce, transform and remineralise organic material and also convert inorganic compounds (Rheinheimer, 1992). The importance of heterotrophic micro-organisms for the remineralisation of organic matter is very great, for bacteria and fungi are able to break down virtually all naturally-occurring compounds and, given favourable conditions, degrade them into the compounds from which they originated *i.e.* carbon dioxide, water and some inorganic salts (Rheinheimer, 1992). Organic materials of producers, herbivores and

carnivores not assimilated by species higher in the food chain are broken down by decomposers which are chiefly bacteria (Raup & Stanley, 1971). Finally, other transforming organisms (also mostly bacteria) chemically alter certain decomposition compounds to render them utilisable once again by producers (Raup & Stanley, 1971). Bacteria are thus extremely important in effecting completion of cycles: without them, ecosystems as we know them could not exist (Raup & Stanley, 1971). Newell (1979) states that predation of bacteria serves to keep the population in check and claims that some 90% of energy flow does not derive from living photosynthetic organisms, but passes along the detrital food chain.

Bacteria are essential to the nutrient cycling in the marine environment. These organisms perform a series of steps to cycle nitrogenous and phosphorous compounds which are essential for primary production and, therefore, the whole marine ecosystem. In the coastal sea, a significant portion of the detritus decomposition takes place in the sediment. This is mediated through a series of fermentative and respiratory processes in which bacteria have a dominating role (Sørensen, 1984). Nitrogen is a vital element, utilised by green plants mainly in the form of ammonia or nitrate and converted into plant protein. When the plants are consumed by animals the protein becomes animal protein, which, when the animal dies, is converted back into ammonia and nitrate by bacteria (Rheinheimer, 1992). A lack of phosphoric compounds may limit plant growth and plants convert pyrophosphate compounds into phosphorous derivatives: detrital macro-algae are degraded to release phosphates by micro-organisms (Rheinheimer, 1992). Therefore, after any decline of algal populations a new burst of bacterial growth will replenish the euphotic zone with the necessary metabolites for new algal populations (Provasoli, 1960).

In all waters, bacteria and fungi have important functions in the food web (Rheinheimer, 1992) with bacteria forming essential links between the primary producers and animals (Moriarty & Hayward, 1982). Bacteria are trophically important to deposit-feeding animals and although bacterial biomass may be a small percentage of the organic matter in many sediments, their biosynthetic products may represent a much larger proportion (Moriarty &

Hayward, 1982). Many animals lack the enzymes necessary to digest some, or all, of the food resources available to them and require the assistance of microbial populations for this task (Atlas & Bartha, 1981). Organic matter is primarily supplied to the sediments in a particulate form. It is essentially composed of macromolecules, such as proteins, carbohydrates, fats and nucleic acids (Billen, 1982). Such compounds cannot be directly taken up by micro-organisms and have first to be hydrolysed into smaller units such as amino-acids, sugars, fatty acids, purine and pyrimidine bases, probably mainly through the action of exoenzymes (Billen, 1982). Bacteria take up dissolved organic substances released into the water by primary producers and substances derived from animals and from the land (Rheinheimer, 1992). They are rapidly converted into particulate material and then a substantial part is consumed by other organisms (Rheinheimer, 1992). Micro-organisms also absorb inorganic nitrogenous ions converting them to protein: the initially low nitrogen-to-carbon ratio of the plant residues is thus increased and the nutritional value of the detritus is upgraded (Newell, 1979; Atlas & Bartha, 1981). Some animals live almost exclusively on bacteria or fungi, because these are very high value in protein nutrient (Rheinheimer, 1992). In addition, most bacterial cells are enveloped in extracellular slime layers or envelopes (Moriarty & Hayward, 1982) which may be nutritionally important.

Some microbial populations also produce vitamins (Atlas & Bartha, 1981) and the bacterial flora of the sea can be presumed to be the main source of vitamin B_{12} (Provasoli, 1960). In culture experiments Lee (1980) finds that biotin and thiamine stimulate growth of all isolated Foraminiferida and they probably represent absolute requirements for some, whilst some species had an absolute requirement for B_{12}. The addition of 1µM glutamic acid, histidine, thiamine and methionine doubled the growth of some species (Lee *et al.*, 1962) and Lee (1980) states that trace amounts of phosphate and vitamin B_{12} are very active in stimulating reproduction in axenic cultures of *Allogromina* sp. Bacterial biomass can adapt itself very rapidly to the flux of direct substrates produced, maintaining them at low constant concentrations (Billen, 1982) and, because they divide by binary fission, can replicate rapidly in response to changes in their environment (Alberts *et al.*, 1983).

Bacteria are the main food of deposit-feeding macrofauna, meiofauna and microfauna (Gerlach, 1978) and as such produce an enormous contribution to food chains; both directly in their role as prey to many marine predators and also indirectly by being prey for Protozoa (Belser, 1960; Clarholm, 1984). The individual populations of the microbial community associated with detrital particles interact as a predator-prey system: the bacteria are the prey and Protozoa are the primary predators (Atlas & Bartha, 1981). Plant detritus can become covered in bacteria and when Protozoa graze over the detritus they engulf large numbers of bacteria with no additional effort: this fortuitous energy-rich food source is of more value than the plant detritus alone (Nisbet, 1984). It has also been discovered that many, or perhaps most, Protozoa carry endo- and/or ecto-symbiotic bacterial cells (Fenchel, 1987). Estimates of *in situ* bacteriophagy by protozoan assemblages range from 20-100% of daily bacterial production (Capriulo *et al.*, 1991).

Foraminiferida are holozoic and depend on particulate food (Mageau & Walker, 1976). Bacteria and unicellular algae constitute the major food source and as such play a vital role in the development and growth of the foraminiferal community (Mageau & Walker, 1976). In those Foraminiferid species which carry endosymbiotic algal chloroplasts, bacteria may be important providers of thiamine, biotin and vitamin B_{12} for photosynthesis (Lee, 1992). Muller & Lee (1969) also discovered that bacteria were indispensable in a foraminiferid culture and hypothesised that they provide some nutritional factor which was either unavailable or in insufficient quantities in a purely algal diet. The use of antibiotics in axenic foraminiferal cultures also greatly inhibited their fecundity (Muller & Lee, 1969; Lee, 1980) and so the presence of bacteria appears to be essential for foraminiferid well-being. Lee (1974) finds that whilst selected species of bacteria were eaten by Foraminiferida in large numbers, most species of bacteria were not consumed, indicating selective predation.

Some invertebrates are thought specifically to encourage the growth of bacteria within sediments so that they are secured a supply of bacterial food (Fry, 1982). Some Foraminiferida are also thought to utilise this strategy. A farming-feeding strategy is

suggested for two species of Foraminiferida which leave organic traces on seagrass as they graze, and return to harvest the densely colonised traces (Langer & Gehring, 1993).

Bacterial populations are mainly controlled by protozoan grazing (Clarholm, 1984; Fenchel, 1987) and Protozoa are believed to facilitate the turnover of inorganic nutrients *via* their grazing on bacteria and phytoplankton (Sherr & Sherr, 1984). Protozoa liberate dissolved organic matter into the water, which promotes the growth of bacteria; and phytoplankton and organic decomposition is enhanced by their activities (Sherr & Sherr, 1984). Meiofauna, by their activities and by excreting metabolic end products, induce a bacterial productivity which would not be there without them, and feed on it (Gerlach, 1978). The grazing of benthonic invertebrates is believed to increase the growth rate and activity of sedimentary bacteria (Fry, 1982) and Protozoa appear to maintain the bacteria in a state of physiological youth by their grazing activities (Caron, 1991). It has been hypothesised by Meyer-Reil & Koester (1991) that in the deep-sea sediments of the Norwegian-Greenland Sea agglutinated epibenthonic Foraminiferida were main contributors to the pool of hydrolytic enzymes which break down organic material, and suggest that in this specific environment the bacteria benefit from the metabolism of Foraminiferida rather than being the main decomposers. Thomsen & Altenbach (1993) find that Foraminiferida are up to three times more abundant in *Echiurus echiurus* tubes where bacterial abundance is twice as high as in the surrounding sediment.

From the literature it is evident that the presence of bacteria is necessary for the presence of Foraminiferida. Bacteria are essential prey of Foraminiferida and may produce essential compounds in a form not available in the environment. In turn, foraminiferid grazing upon bacteria helps to release nutrients and sustain the marine ecosystem, whilst maintaining the bacterial population in a young and active state.

Because so little is known of the importance of bacteria to Foraminiferida, it is necessary to evaluate the basic characteristics of the bacteria together with the distribution and abundance of Foraminiferida. Bacterial abundance, shape and Gram-stain characteristics

were investigated in an attempt to discover if any of these factors was important to foraminiferid abundance or diversity and to the pigmentation noted.

5.3.2. MATERIALS & METHODS.

Bacteria at each site were counted and their Gram-staining characteristics assessed monthly, and sampled simultaneously with Foraminiferida samples and other environmental variables. Approximately 1g of wet sediment from each site was placed into sterile Universal Bottles at the time of sampling and placed into a cool box until return to the laboratory. As it was necessary to process the samples rapidly to accurately reflect the numbers of micro-organisms present (Atlas & Bartha, 1981), the samples were processed within six hours of collection.

For each site, four sterile Universal Bottles containing 9 ml of a diluent of sterile Peptone Buffered Saline solution were prepared and labelled 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4}. The 10^{-1} bottles were tared and each had 1g of wet sediment added to them. Bacteria are microfauna, and as such live on the surface of the grain or hold on to the grain (Newell, 1979; Rheinheimer, 1992), so the sediment was inverted manually five times to ensure equal dispersal of bacteria from the sediment for each site. From the 10^{-1} bottle serial dilutions were prepared until a dilution of 10^{-4} was obtained. 0.1 ml of each dilution was spread onto two duplicate nutrient plates. As most marine bacteria are halophilic (*i.e.* they need salt for optimal development), Tryptone Soy Agar plates plus additional salt were utilised. The nutrient plates were incubated at 20°C (Rheinheimer, 1992) for 24 hours and then placed into a cold room (4°C), so that the colonies could develop pigmentation and become morphologically differentiated.

Because marine bacteria grow relatively slowly (marine sediment inoculates need 14-18 days before being colony counted {Rheinheimer, 1992}), after a period of two weeks the plates were removed from the cold room and the bacterial colonies counted by choosing a dilution which yielded between 20 and 200 colonies. An average of the number of colonies produced on the duplicate plates was recorded and each colony was assumed to originate

from a single bacterium termed a colony forming unit (cfu). The number of morphologically differentiated colonies was recorded for each site and each different colony subjected to a Gram-stain. The Gram-staining characteristic and the shape of the bacteria from each colony were recorded.

The method of growing bacteria upon nutrient agar plates is a compromise. Tryptone Soy Agar is a general purpose agar medium, containing two peptones, which will support the growth of a wide variety of organisms (Bridson, 1990) and should provide the nutrients for the growth of most types of bacteria, although bacteria with other nutritional needs will perish. The addition of 10 g of salt to the agar may provide stenohaline bacteria with an unfavourable environment for growth. Likewise, the incubation temperature of 20°C will exclude the growth of bacteria with particular needs for temperature. It is felt, however, that the growth of all types of marine bacteria is a very complex task and the conditions supplied for the growth of sampled bacteria provide a favourable environment for most types of bacteria likely to be present in the sediment samples. Mrs J. Carter (Biological Sciences, University of Plymouth) provided invaluable advice and assistance for this part of the study.

5.3.3. RESULTS.

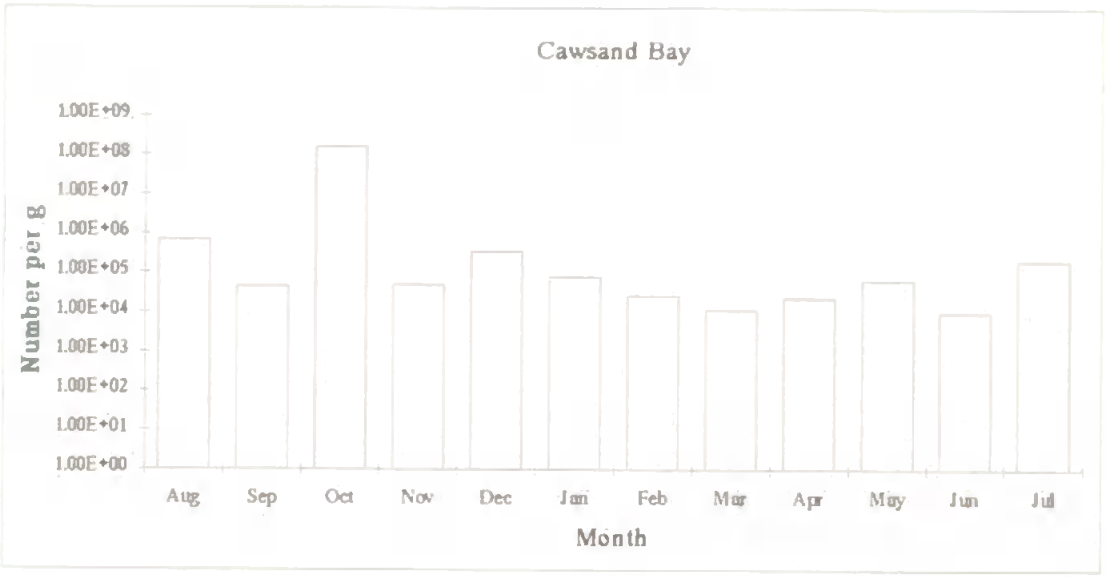
Table 5.2: Annual variation in number of bacteria per gram of wet sediment from each of the three sites 1993/1994.

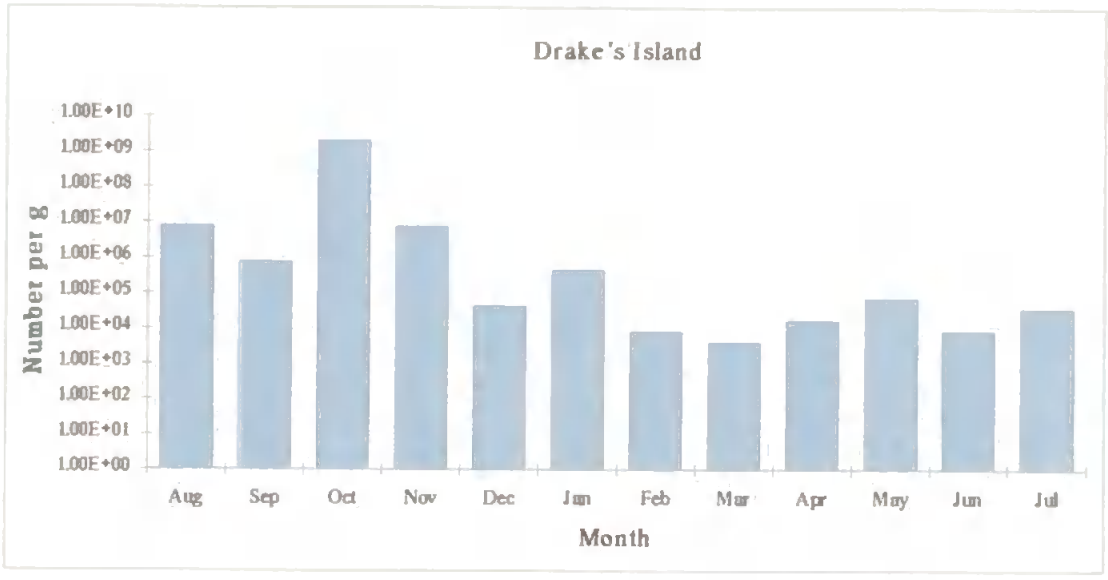
Month	Cawsand Bay	Drake's Island	White Patch
August	700000	7750000	74000
September	44000	765000	28500
October	160000000	2000000000	160000000
November	50000	7650000	25000
December	350000	42500	85000
January	82000	450000	2000000
February	26600	8000	105000
March	11500	4000	348000
April	23000	17000	113000
May	65200	72600	364000
June	10000	8600	19000
July	200000	36000	180000

Abundance of bacteria.

From Table 5.2 and Figure 5.2 it can be seen that monthly bacterial abundance of bacteria at all sites fluctuates greatly. There appears to be no common pattern to the increases and

decreases in abundance at the sites, except that all sites peak in bacterial abundance in the month of October. At Cawsand Bay bacterial abundance ranges from 1.0×10^4 to 1.6×10^8; Drake's Island 4.0×10^3 to 2.0×10^9; White Patch 1.9×10^4 to 1.6×10^8. At Cawsand Bay, except for the peak in abundance in October, there is a cyclical pattern of abundance with a gradual increase in abundance in the winter and spring months. At Drake's Island there is also a cyclical pattern of abundance, with increases in bacteria at this site in the winter and spring months. At White Patch, except for the peak in October, the abundance of bacteria appears to be relatively constant but is slightly higher from January to May. The method of extracting the bacteria from the wet sediments does not take into account the different composition of the sediments from the sites. A wet gram of a poorly-sorted sediment will hold more water than a wet gram of a well-sorted sediment, and because more bacteria will be attached to sedimentary grains than in the interstitial water, will have less bacteria extracted from it. It would be expected therefore, that White Patch sediments will have less bacteria extracted by this method than Cawsand Bay and Drake's Island sediments respectively, and may be artificially lowered.





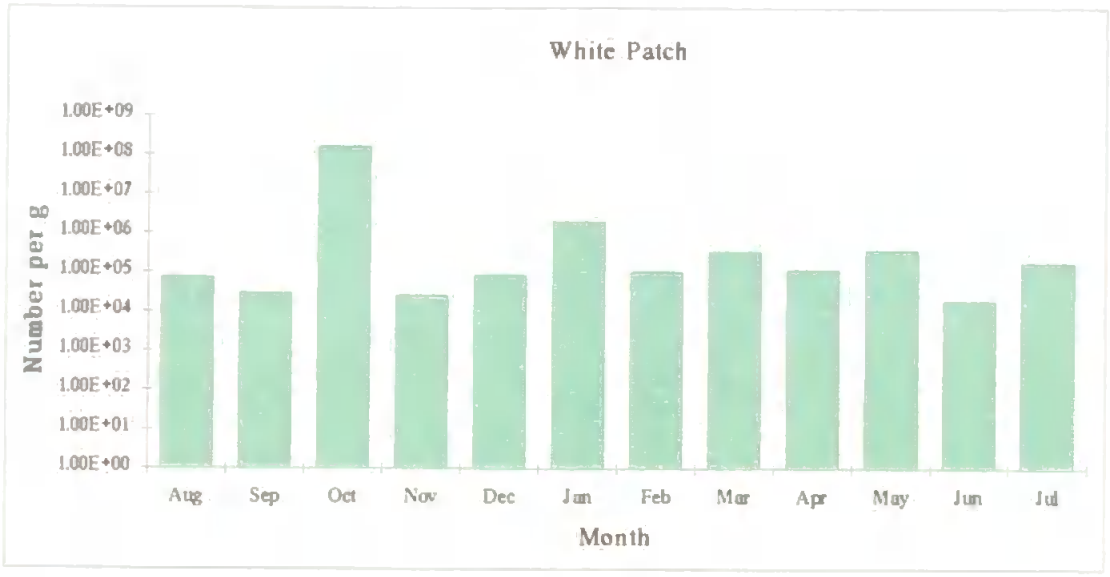


Figure 5.2: Annual variation in number of bacteria per gram of wet sediment from each of the three sites 1993/1994.

Abundance of cfu.

The number of bacterial morphologically differentiated colony forming units provides some idea of the diversity of bacteria in the sediments at the time of sampling. The number of cfu ranges from 3 to 11 at Cawsand Bay and Drake's Island and from 4 to 11 at White Patch. There is no common pattern of abundance of cfu at the sites and the sediments from each site appear to fluctuate for cfu content. From Table 5.3 and Figure 5.3 it can be seen that the number of cfu at Cawsand Bay form two peaks in October and February, whereas the number of cfu peak at Drake's Island in September and February and at White Patch in December and April.

Table 5.3: Annual variation in number of morphologically differentiated colony forming units (cfu) 1993/1994.

Month	Cawsand Bay	Drake's Island	White Patch
August	3	3	4
September	6	8	9
October	10	6	7
November	4	5	6
December	8	7	11
January	9	5	8
February	11	11	8
March	7	4	6
April	8	7	10
May	5	4	4
June	5	7	6
July	6	3	8

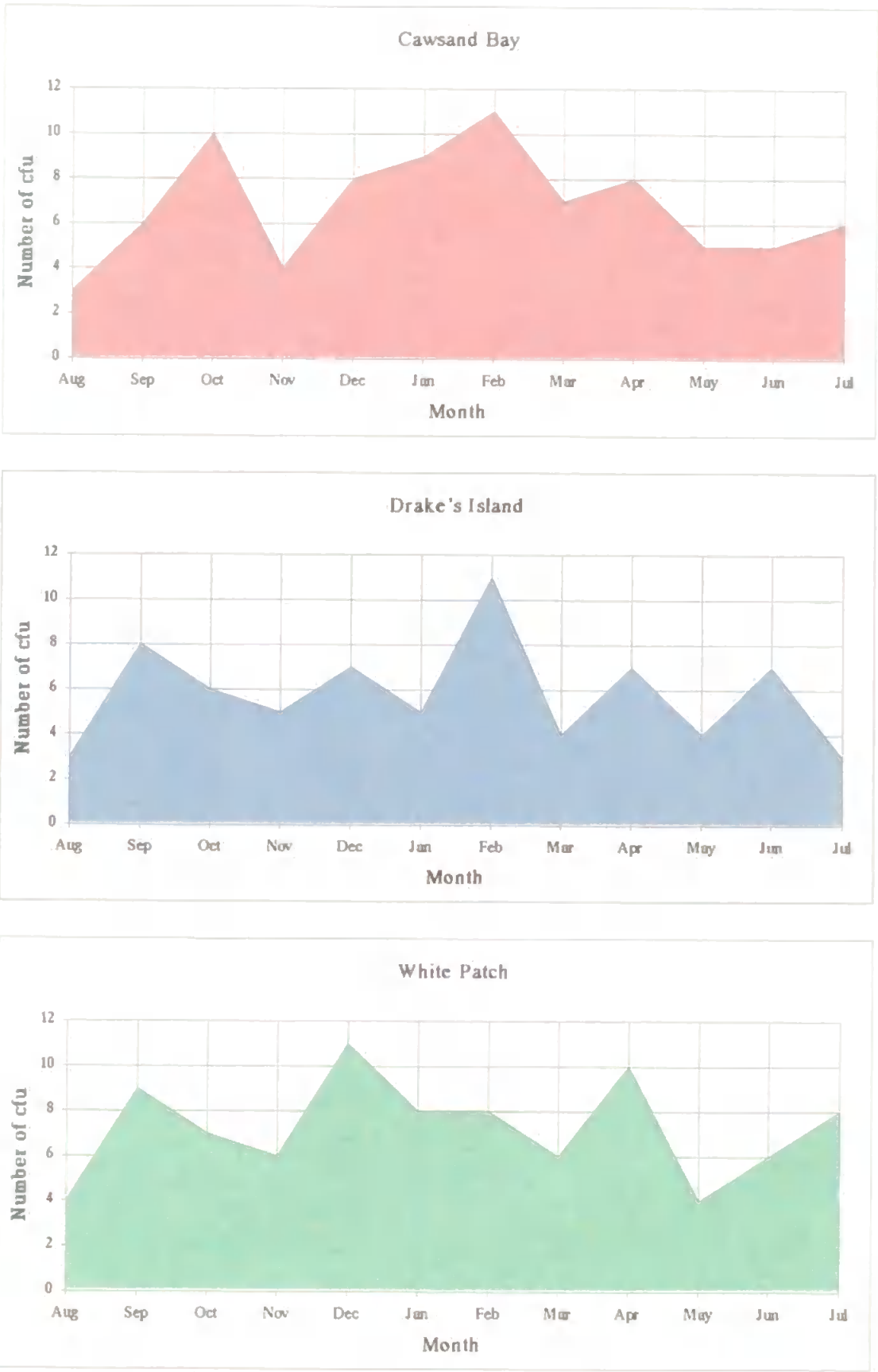


Figure 5.3: Annual variation in number of morphologically differentiated colony forming units (cfu) 1993/1994.

Table 5.4: Annual variation in stain and shape characteristics of bacteria from Cawsand Bay sediments 1993/1994.

Month	% Gram positive rods	% Gram positive cocci	% Gram negative rods	% Gram negative cocci	% Gram positive bacteria	% cocci
August	33	67	0	0	100	67
September	33	0	67	0	33	0
October	30	40	30	0	70	40
November	50	0	25	25	50	25
December	12.5	50	12.5	25	62.5	75
January	22	33	33	12	55	45
February	27	18	37	18	45	36
March	0	14	57	29	14	43
April	12.5	12.5	62.5	12.5	25	25
May	20	0	40	40	20	40
June	60	20	20	0	80	33
July	33	0	67	0	33	0

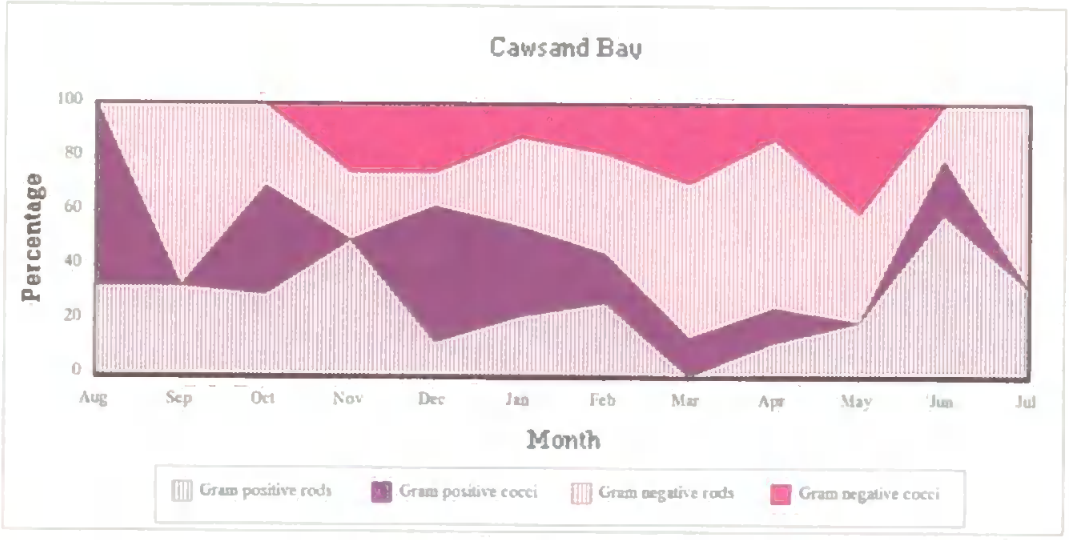


Figure 5.4: Temporal variation in percentage of stain and shape characteristics of bacteria from sediments from Cawsand Bay, 1993/1994.

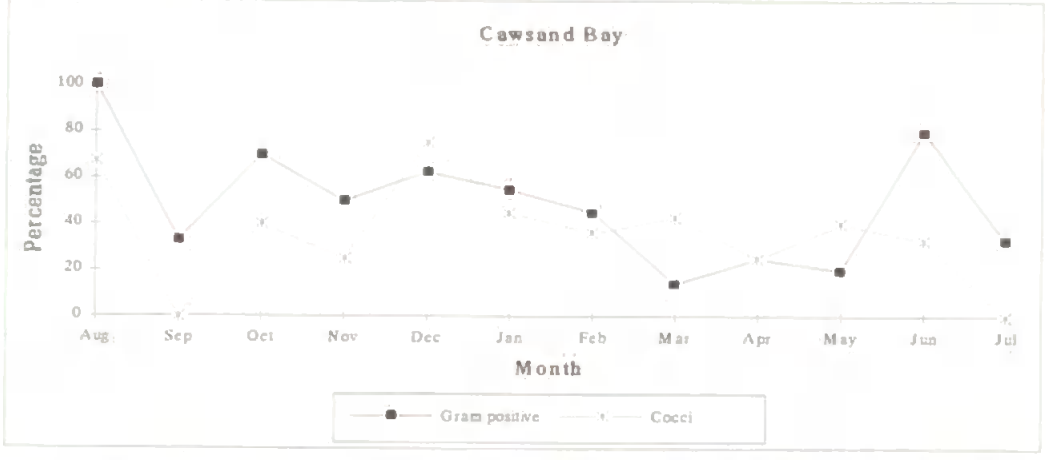


Figure 5.5: Temporal variation in percentage of total stain and shape characteristics of bacteria from sediments from Cawsand Bay, 1993/1994.

From Table 5.4 and Figure 5.4 it can be seen that the sediments at Cawsand Bay contain different proportions of types of bacteria throughout the annual sampling programme. There is a fairly even distribution of Gram negative and Gram positive bacteria at this site, although there appear to be more rod-shaped bacteria than cocci at this site. Gram positive rods are present in every month except March at this site, and peak as a proportion of the bacterial assemblage in November and June. Gram positive cocci are absent from the assemblage in September, November, May and July but peak in August and December. Gram negative rods form a proportion of the assemblage in all months at this site, peaking as a proportion of the assemblage in September, April and July. Gram negative cocci form a proportion of the assemblage only from November to May, perhaps indicating that these bacteria have different environmental requirements from the others at this site. From Table 5.4 and Figure 5.5 it can be seen that the proportion of the bacterial assemblage which is Gram positive fluctuates throughout the annual sampling period, but generally appears to be above 50% during all months except during spring (March to May). Cocci-shaped bacteria only form greater than 50% of the assemblage during the months of August and December, indicating that rod-shaped bacteria dominate the bacterial assemblage at this site.

Table 5.5: Annual variation in stain and shape characteristics of bacteria from Drake's Island sediments 1993/1994.

Month	% Gram positive rods	% Gram positive cocci	% Gram negative rods	% Gram negative cocci	% Gram positive bacteria	% cocci
August	0	0	67	33	0	33
September	50	38	12	0	88	38
October	33	17	50	0	50	17
November	20	0	80	0	20	0
December	29	29	13	29	58	58
January	20	40	40	0	60	40
February	18	73	9	0	91	73
March	25	0	75	0	25	0
April	43	0	57	0	43	0
May	50	25	25	0	75	25
June	0	57	43	0	57	57
July	0	0	67	33	0	33

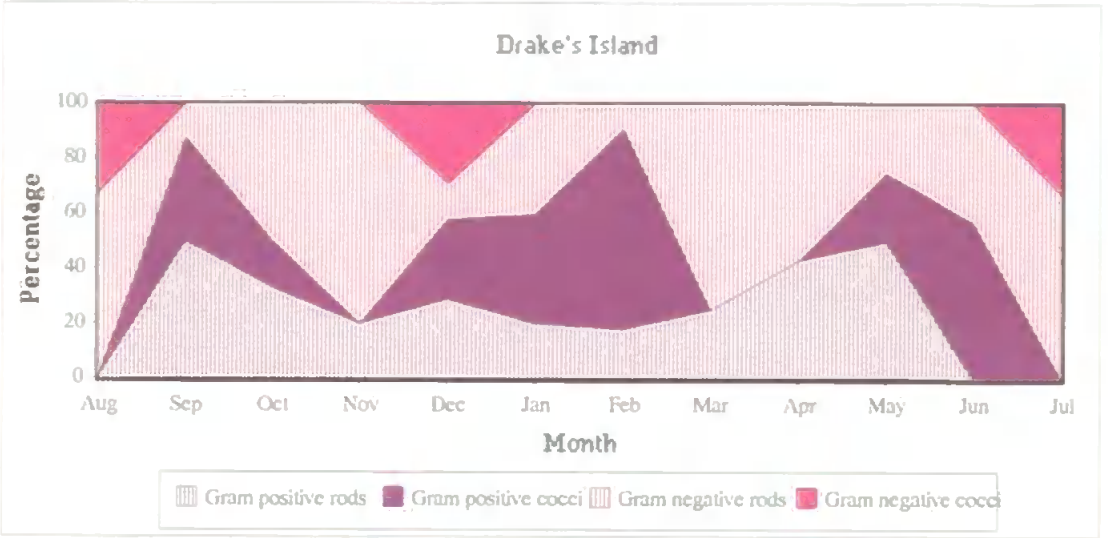


Figure 5.6: Temporal variation in percentage of stain and shape characteristics of bacteria from sediments from Drake's Island, 1993/1994.

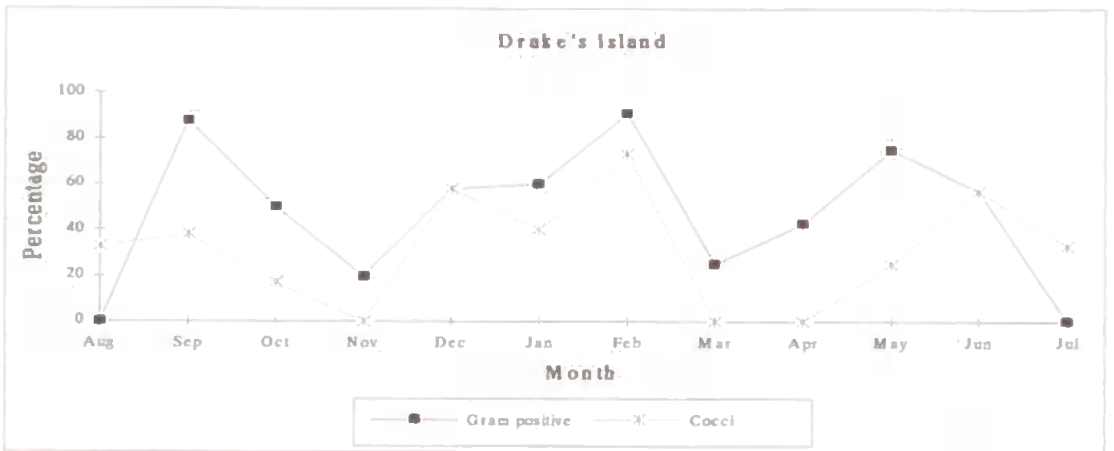


Figure 5.7: Temporal variation in percentage of total stain and shape characteristics of bacteria from sediments from Drake's Island, 1993/1994.

From Table 5.5 and Figure 5.6 it can be seen that the sediments of Drake's Island contain very varied proportions of types of bacteria throughout the annual sampling programme. The bacterial assemblage at this site appears to be dominated by rod-shaped bacteria, especially Gram negative rods. Gram positive rods are present in every month except August, June and July, and peak as a proportion of the bacterial assemblage in September and May, perhaps indicating a nutritional need for settled phytoplankton. Gram positive cocci are absent from the assemblage in August, November, March, April and July but peak in abundance in February. Gram negative rods form a proportion of the assemblage in all months at this site, peaking as a proportion of the assemblage in the months of November and March. Gram negative cocci form a proportion of the assemblage only in the months of

August, December and July, and just as with the Cawsand Bay Gram negative cocci, this may indicate that these bacteria have different environmental requirements than the other bacteria at this site. From Table 5.5 and Figure 5.7 it can be seen that Gram positive and cocci-shaped bacteria increase and decrease as a proportion of the bacterial assemblage cyclically. The pattern of these two types of bacteria is very similar indicating that, at this site, most of the Gram positive bacteria are also cocci-shaped. The two groups increase as a proportion of the assemblage in September and February.

Table 5.6: Annual variation in stain and shape characteristics of bacteria from White Patch sediments 1993/1994.

Month	% Gram positive rods	% Gram positive cocci	% Gram negative rods	% Gram negative cocci	% Gram positive bacteria	% cocci
August	75	25	0	0	100	25
September	78	11	11	0	89	11
October	57	43	0	0	100	43
November	33	0	50	17	33	17
December	36	46	0	18	82	64
January	25	50	12.5	12.5	75	62.5
February	38	50	12	0	88	50
March	0	17	66	17	17	34
April	30	10	60	0	40	10
May	50	25	25	0	75	25
June	0	67	33	0	67	67
July	12.5	37.5	37.5	12.5	50	50

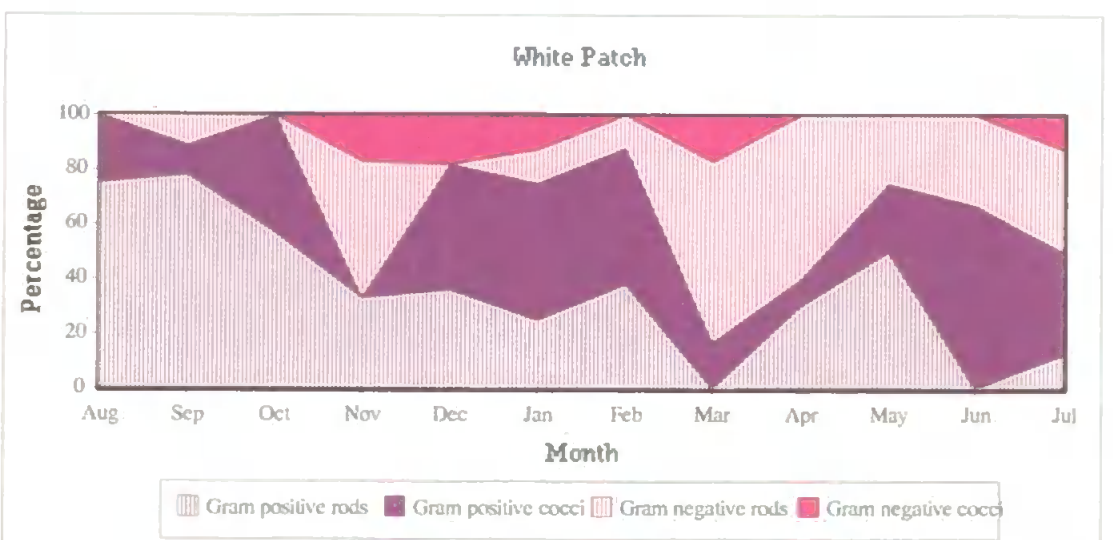


Figure 5.8: Temporal variation in percentage of stain and shape characteristics of bacteria from sediments from White Patch, 1993/1994.

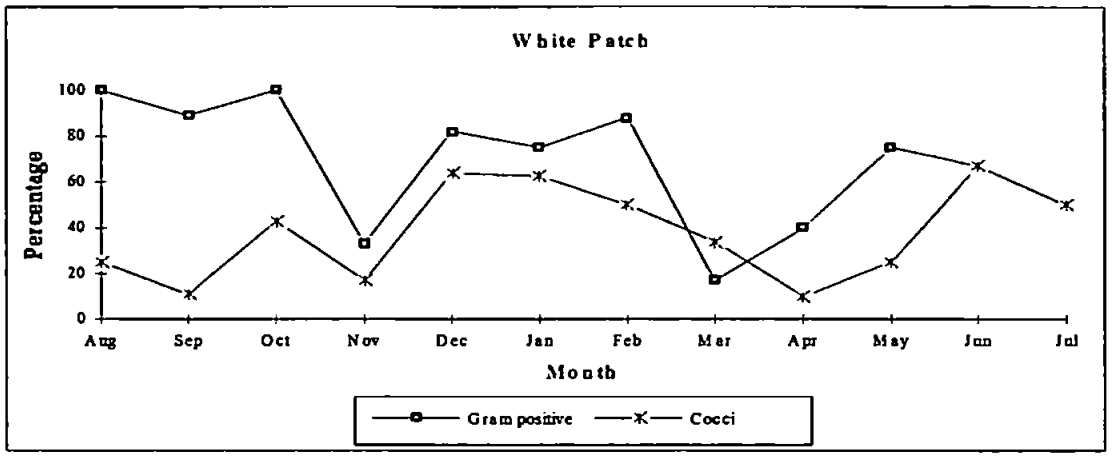


Figure 5.9: Temporal variation in percentage of total stain and shape characteristics of bacteria from sediments from White Patch, 1993/1994.

From Table 5.6 and Figure 5.6 it can be seen that the sediments of White Patch, like those of Cawsand Bay and Drake's Island, contain very varied proportions of types of bacteria throughout the annual sampling programme. The bacterial assemblage at this site appears to be mainly dominated by Gram positive bacteria, especially Gram positive rods. Gram positive rods are present in every month except March and June, and peak as a proportion of the bacterial assemblage in September. Gram positive cocci are absent from the assemblage in the month of November, but peak in abundance in the month of June. Gram negative rods form a proportion of the assemblage in all months at this site except October, peaking as a proportion of the assemblage in March. Gram negative cocci form a proportion of the assemblage in the months of August, September, October, February, April, May and June, and just as with the Cawsand Bay Gram negative cocci, may indicate that these bacteria have different environmental requirements from the other bacteria at this site. From Table 5.6 and Figure 5.9 it can be seen that the proportions of Gram positive and cocci-shaped bacteria have similar patterns of abundance, indicating that most Gram positive bacteria at this site are cocci. Gram positive bacteria increase as a proportion of the assemblage in August, September, October, December, February and May. The cocci-shaped bacteria increase as a proportion of the bacterial assemblage at this site in December, January and June.

Comparison of sites

All sites appear to be dominated by rod-shaped bacteria, but whereas Cawsand Bay and Drake's Island sediments have similar abundances of Gram positive and Gram negative bacteria, White Patch sediments are dominated by Gram positive bacteria. Gram negative rods are present at all sites in all months sampled.

Pigmentation

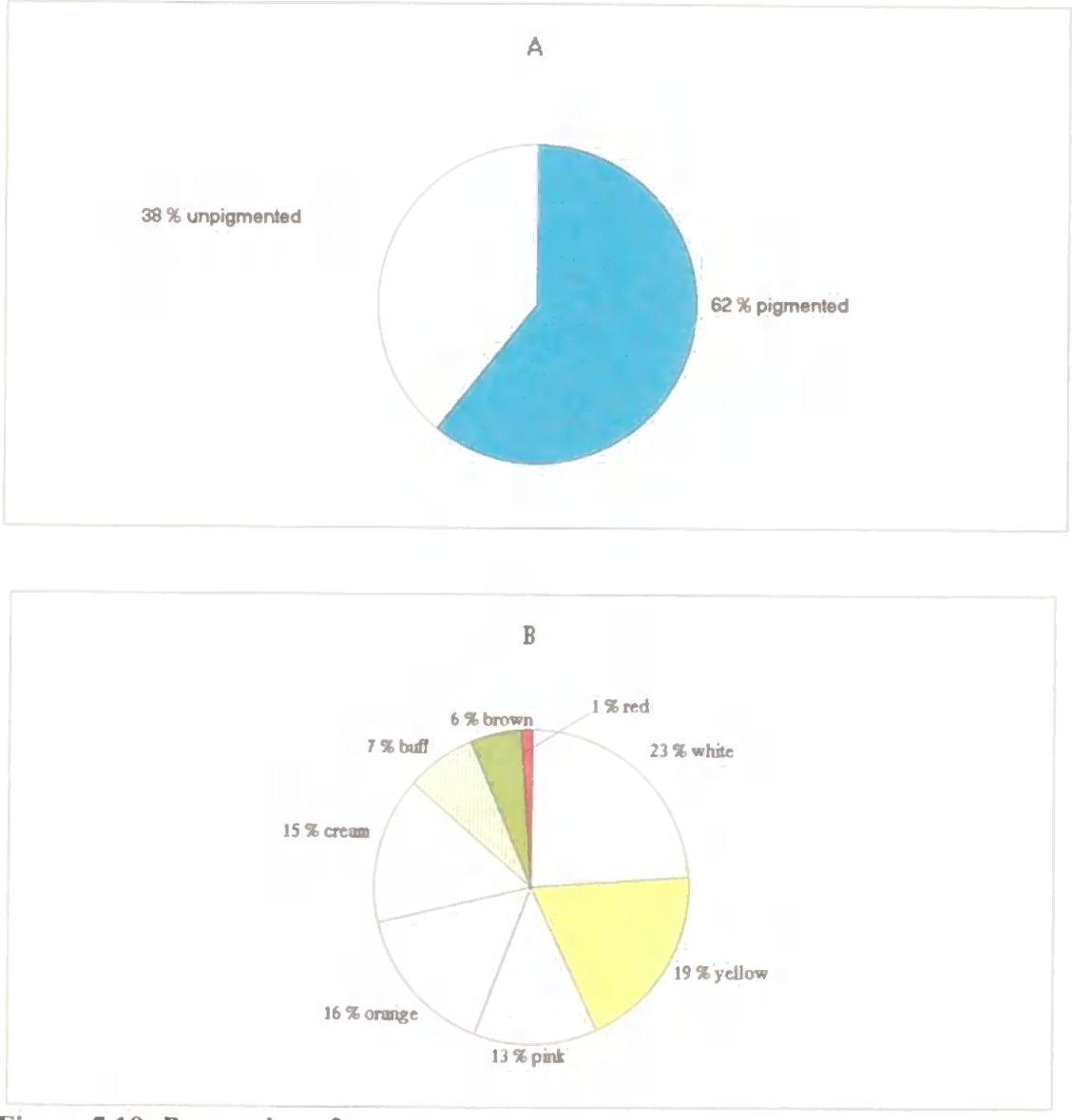


Figure 5.10: Proportion of
(A) pigmented bacteria and unpigmented (white/cream) bacteria
(B) pigmentation from all cfu's throughout the annual sampling programme.

Marine bacteria can be pigmented with a wide range of colours. From Figure 5.10 (A) it can be seen that all cfu grown from all sites throughout the annual sampling programme were

mainly pigmented, with 62% being coloured colonies and 38% of the colonies being white or cream in colour. From Figure 5.10 (B) it can be seen that colours recorded of the colonies grown included white, cream, yellow, pink, orange, buff, brown and red. Red bacteria are rare from the assemblages sampled with brown, buff, pink, cream, orange, yellow and white colonies forming increasing proportions of the total bacteria sampled.

5.3.4. DISCUSSION

Abundance

The abundance of bacteria in marine sediments have been connected with the spring and autumnal phytoplankton blooms (Rheinheimer, 1992) and, in winter months, with eroded macrophytes, re-suspended sediment and terrestrial material (Meyer-Reil, 1984; quoted by Rheinheimer, 1992). The peak in bacterial abundance at all sites in the month of October may, therefore, be due to the autumnal bloom of phytoplankton and detrital algae settling on the sea bed providing a rich nutrient source for the proliferation of benthonic bacteria. At Drake's Island the abundance of bacteria in the sediment is relatively high in the months of August to December (although the sand is well-sorted), which may indicate that the sewage input at this site controls the proliferation of bacteria at these times. The abundance of bacteria at all sites falls slightly in June, possibly reflecting predation upon bacteria by settled invertebrate spat. All sites show a rise from this fall in the month of July possibly indicating the death of juvenile predators. Whereas Drake's Island and White Patch sediments show a slight peak in abundance in January, Cawsand Bay sediments contained fewer bacteria than the previous month, perhaps reflecting the limited effects of rivers, sewage and detrital macroalgae at this site. Ellison (1984) shows that bacterial populations in mudflats at the mouth of the River Tamar are largest in February, April and May (1974), although the timing of this bacterial production does not seem to be reflected in any of the assemblages in the Sound. The maximum abundance of 2.0×10^9 bacteria per wet gram of sediment corresponds well with Fry's calculation of 1.6×10^{10} bacteria per ml for the top 1 cm of sediment assuming that the sediment consists of 60% water (Fry, 1982).

Although the abundance of bacteria per gram of wet sediment is not significantly different between sites, Drake's Island sediments often contained relatively high numbers of bacteria. According to Newell (1979), the number of microbes is related to particle size and the degradation of organic debris is governed by particle size and wave energy, perhaps indicating the possible reason for the differences in bacterial abundances at the three sites.

Scanning Electron Microscopy has shown that bacteria are mainly found in grooves and holes of sand grains where they are largely protected from the mechanical effects caused by movement of the sand (Rheinheimer, 1992). Surface bacteria have very effective adherent mechanisms to remain attached to the substratum, and sediments of coarse sand contain, as a rule, considerably fewer bacteria than do fine silts (Rheinheimer, 1992). This is not the case with the bacterial populations sampled within this study.

Number of cfu

The number of cfu at Cawsand Bay and Drake's Island increase in the months of February and in October and September respectively. The number of cfu at White Patch increase in the months of December and April. An increase in the number of cfu at the sites investigated may reflect the presence of several different types of organic matter at the times of increased abundance of different types of bacteria. The increase in number of cfu in October, September and December may rely upon the organics supplied by detrital macrophytes, whereas the increase in February may depend upon the re-suspension of organic matter by storms.

Types of bacteria

The composition of bacterial flora differs widely, and is influenced not only by the salt and organic content, the pH, turbidity and temperature, but also by the sources from which organics enter the water (Rheinheimer, 1992), as well as upon sediment location, rate of sedimentation, depth of water column, chemical nature of the sedimenting material and local hydrographic conditions (Battersby & Brown, 1982). Phytoplankton blooms are also known to affect bacterial numbers; algae produce substances which inhibit the growth and

respiration in Gram positive bacteria, whereas Gram negative bacteria are resistant (Rheinheimer, 1992). The effect of all these different factors upon the bacterial flora may help to explain why the sites differ in the temporal distribution of types of bacteria throughout the sampling period.

Moriarty & Hayward (1982) state that in the upper aerobic sediments marine benthonic bacteria consist of 90% Gram negative and 10% Gram positive bacteria and Atlas & Bartha (1981) state that over 95% of marine bacteria are Gram negative. Although all sites appear to be dominated by rod-shaped bacteria, Cawsand Bay and Drake's Island sediments have similar abundances of Gram positive and Gram negative bacteria, whilst White Patch sediments are dominated by Gram positive bacteria. This contradicts the above findings and may indicate that nearshore bacteria differ from the deeper marine bacteria sampled by the above authors. Gram positive bacteria are surrounded by a thick layer of peptidoglycan, whereas the layer of peptidoglycan surrounding Gram negative bacteria is relatively thin. This may indicate a difference in nutritional value to deposit-feeders, although the relative nutritional value of exudates produced by these two groups is unknown. Both Gram positive and Gram negative bacteria have extensive slime layers or envelopes and some of the external envelopes may contain other compounds such as protein in addition to polysaccharide, and thus be nutritionally important (Moriarty & Hayward, 1982).

Pigmentation

Rheinheimer (1992) states that yellow, orange, brown and red bacteria are the most frequent pigments of marine bacteria, whilst violet, blue, black or green are rare. This study largely supports this finding, although he ommits to mention the occurrence of pink bacterial colonies. Pigmented bacteria which contain carotenoids are light-tolerant to a large degree and are not inhibited by light of normal intensity (Rheinheimer, 1992) and, because all sampled sediments lie within the photic zone, this may be the reason why the majority of sampled cfu were pigmented.

5.4. OTHER MEIOFAUNA.

5.4.1. INTRODUCTION.

During the course of sampling the sediments for benthonic Foraminiferida, other meiofauna present in the samples have been isolated from the floated sediments. The method of processing the sediment for analysis of the foraminiferal content has resulted in the staining of live meiofauna with the protoplasmic stain Rose Bengal. Only those meiofauna with calcareous or chitinous tests which can withstand the rigorous drying and sieving techniques employed in this study were identifiable from the samples. Therefore, fragile meiofauna such as nematode worms and juvenile sea anemones, jelly-fish and nudibranchs will be unrepresented. The meiofauna present in the samples are only identified to the level of Classes and Orders.

The purpose of including within this study of Foraminiferida the abundance of the other meiofauna present is to evaluate if any of the other meiofauna compete with Foraminiferida for the resources the sites provide. All members of communities will be affected by both the abiotic and biotic factors present in their environment in different ways, and also interact together. Any organism in a habitat has particular needs for space and nutrition to allow growth and reproduction. These particular needs are termed the niche of that organism, and density dependent inter- and intra-competition of organisms within a habitat are known to occur. Ellison (1984) found that a rich and varied meiofaunal assemblage exists on a Cornish mudflat at the mouth of the River Tamar, consisting of Foraminiferida, harpaticoid copepods and nematodes in roughly equal numbers.

The meiofaunal groups recorded from the three sampling sites are Copepoda, Amphipoda, Ostracoda, Polychaeta, Bivalvia, Gastropoda, Scaphopoda and Acariformes. Bryozoa, sponge spicules and fragments of unidentified arthropods are excluded. The Class Copepoda consist of small crustaceans which are abundant in marine habitats, lack a carapace and may be planktonic or benthonic (Fish & Fish, 1989). Members of the Order

Amphipoda are generally benthonic, have laterally-compressed bodies, and feeding strategies include suspension feeding, scavenging and detritus feeding. Ostracoda have a bivalved calcareous carapace, are commonly benthonic and may be filter-feeders, scavengers, detritivores, herbivores or carnivores (Athersuch *et al.*, 1989). Polychaeta are annelid worms: only sedentary members of this class were recorded from this study. Polychaeta may be carnivorous, scavengers, deposit feeders or suspension feeders (Fish & Fish, 1989). The Class Bivalvia are mainly sedentary molluscs with two valves, and suspension-feed by passing a water current over their gills. The Class Gastropoda are also members of the phylum Mollusca, possessing a coiled shell in the subclass Prosobranchia; they may graze upon algae or detritus (Barnes *et al.*, 1988). The Class Scaphopoda secrete a calcareous tube and burrow into soft marine sublittoral sediments, and are known to prey upon Foraminiferida. The order of Acariformes consist of marine mites.

5.4.2. MATERIALS & METHODS.

Meiofauna were extracted from sediment samples analysed for Foraminiferida. The methods are exactly the same as those put forward in Chapter 2 (Section 2.4) and calculated to provide numerical abundance per grab of sediment to standardise abundance both within and between sample sites. (Counts of Bivalvia and Ostracoda were limited to specimens possessing both valves connected to each other). Residues of floats were examined to see if some groups were selectively not floated by this method. Residues from the August samples (when the floating technique was unfamiliar) were examined. Number of meiofauna per grab are recorded in Appendix V.

5.4.3. RESULTS.

Residues of "floats"

Table 5.7: Specimens of stained meiofauna not separated from the sediment by flotation from the quarter grab sample of August, 1993 from Cawsand Bay.

Type	> 63 µm	> 125 µm	> 250 µm	> 500 µm	> 1000 µm
Copepoda	10	45	3		
Ostracoda		2	7		
Gastropoda	2				

Table 5.8: Specimens of stained meiofauna not separated from the sediment by flotation from the quarter grab sample of August, 1993 from Drake's Island.

Type	> 63 µm	> 125 µm	> 250 µm	> 500 µm	> 1000 µm
Copepoda	4	1			
Ostracoda	2	3	1		
Gastropoda		1			
Bivalvia					1
Scaphopoda			2		
Acariformes		1			

Table 5.9: Specimens of stained meiofauna not separated from the sediment by flotation from the quarter grab sample of August, 1993 from White Patch.

Type	> 63 µm	> 125 µm	> 250 µm	> 500 µm	> 1000 µm
Copepoda	7	2			
Ostracoda			2		
Gastropoda	2				

All residues contained stained meiofauna not separated by flotation from all groups investigated except those of Amphipoda and Polychaeta. There were more specimens of meiofauna not floated at Cawsand Bay than at Drake's Island and White Patch respectively. The Cawsand Bay residue contained a large number of Copepoda (Boltovskoy {1964} found these mostly in the size range >125 µm), nine Ostracoda and two Gastropoda. The residue of Drake's Island contained five and six Copepoda and Ostracoda respectively with one or two representatives of Gastropoda, Bivalvia, Scaphopoda and Acariformes from all size ranges. The White Patch residue contained nine Copepoda (mostly in the >63 µm size range) with two specimens of Ostracoda and Gastropoda.

The omission of meiofaunal specimens from floats was not type-specific, with almost all types represented in residues. The Drake's Island residue contained un-floated meiofauna although it did not contain any un-floated Foraminiferida. Also, unlike Foraminiferida found in residues, other meiofauna not separated by the flotation technique were not confined to the smaller size ranges.

Copepoda.

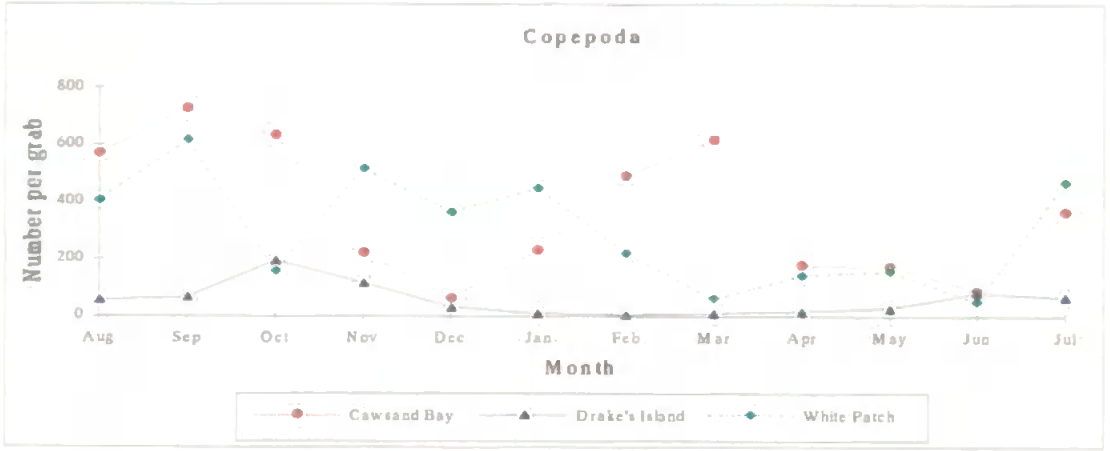


Figure 5.11: Comparison of abundance of Copepoda between the three sites sampled, 1993/1994.

From Figure 5.11 it can be seen that the absolute abundance of Copepoda at the three sites is relatively high and comparable to numbers of Foraminiferida (see Chapter 3). Cawsand Bay Copepoda have the highest abundances at this site in September and March, and have a very similar temporal distribution as Foraminiferida at this site. The Copepoda at Drake's Island occur in relatively low numbers, yet peak in abundance in October and January. White Patch sediments contain a fluctuating assemblage of Copepoda, which increase in abundance in September, November and July.

Amphipoda

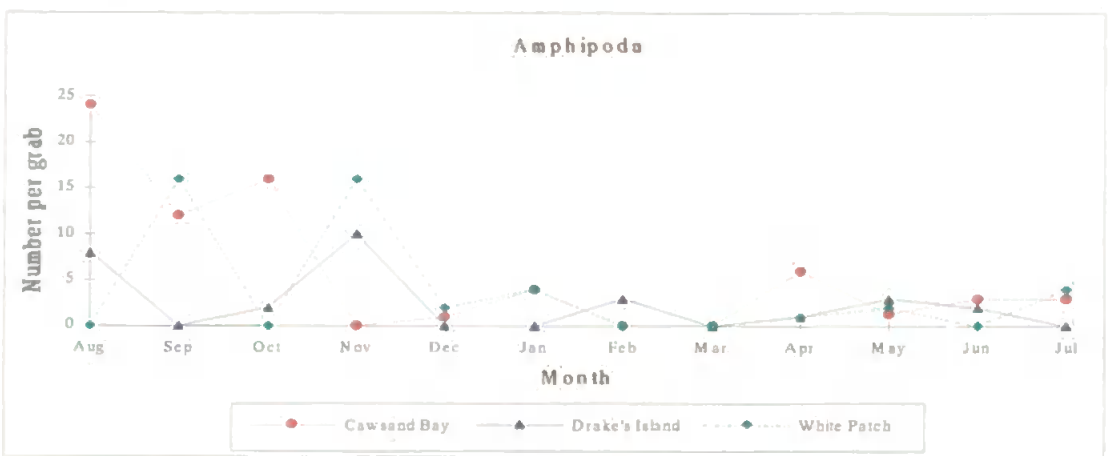


Figure 5.12: Comparison of abundance of Amphipoda between the three sites sampled, 1993/1994.

From Figure 5.12 it can be seen that although Amphipoda at all three sites have relatively low numbers, they generally peak in abundance in the late autumn and winter months. Amphipoda from Cawsand Bay peak in August, October and slightly in April. The sediments from Drake's Island contain comparable numbers of Amphipoda as the other sites and these peak in August, November and February. The Amphipoda retrieved from White Patch sediments peak in abundance in September, November and June.

Ostracoda

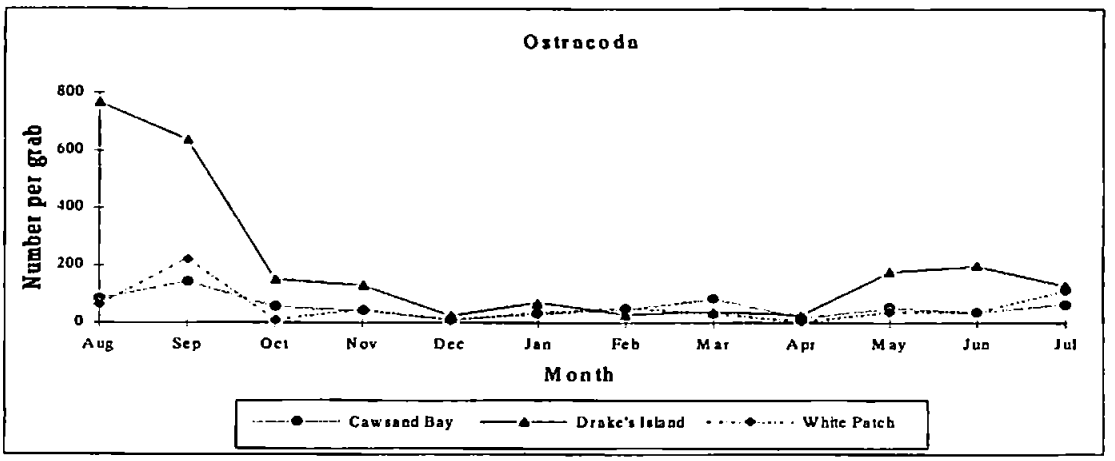


Figure 5.13: Comparison of abundance of Ostracoda (two connected valves and stained) between the three sites sampled, 1993/1994.

Figure 5.13 shows that Drake's Island sediments contain the highest numbers of Ostracoda of the three sites, having a very large peak in abundance in August, and slight peaks in the months of May and June. Sediments from both Cawsand Bay and White Patch contain relatively stable populations which both peak in September and in the months of March and July respectively.

Polychaeta

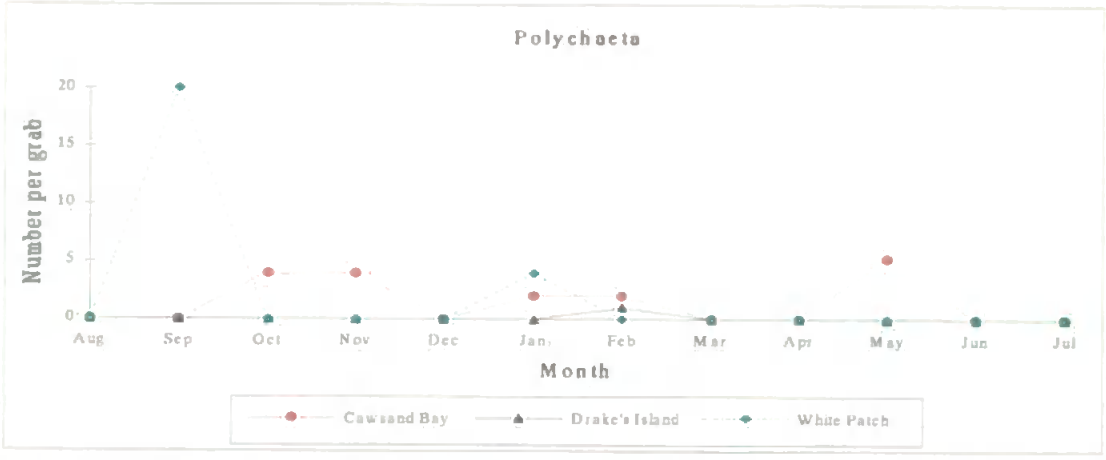


Figure 5.14: Comparison of abundance of Polychaeta between the three sites sampled, 1993/1994.

With reference to Figure 5.14 it can be seen that the abundance of Polychaeta at all sites is relatively low; they were virtually absent from Drake's Island. Cawsand Bay sediments contained a few specimens in October and November, January and February and May, whilst Polychaeta at White Patch peaked in abundance in September and January.

Bivalvia

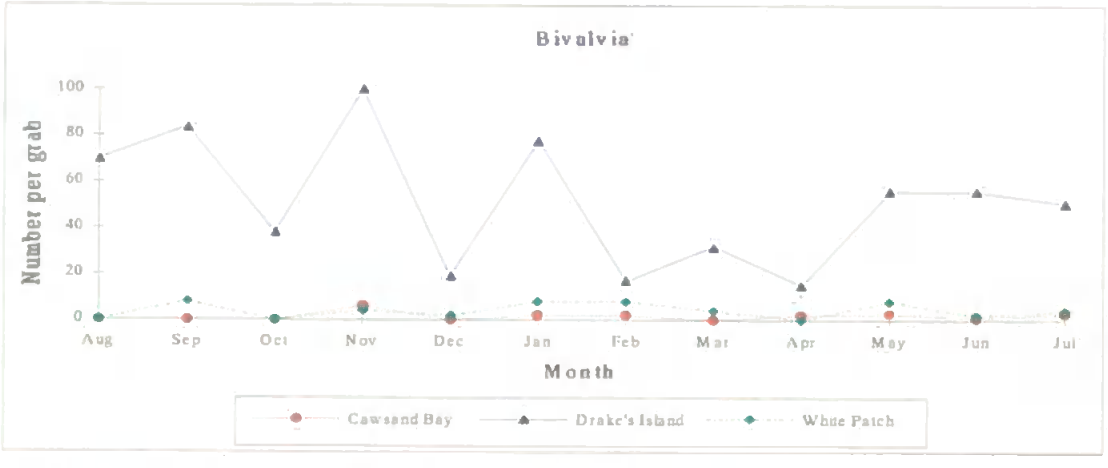


Figure 5.15: Comparison of abundance of Bivalvia (two connected valves and stained) between the three sites sampled, 1993/1994.

Figure 5.15 shows that the abundance of Bivalvia is very different at each of the three sites sampled. The sediments at Cawsand Bay and White Patch contain relatively constant populations of Bivalvia, whereas Drake's Island sediments contain Bivalvia which appear to increase and decrease in abundance on a monthly basis.

Gastropoda

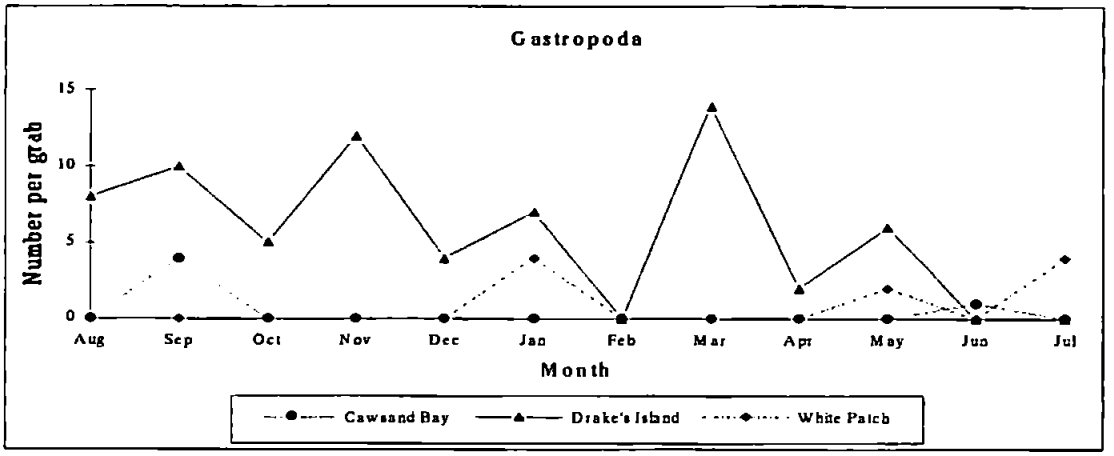


Figure 5.16: Comparison of abundance of Gastropoda between the three sites sampled, 1993/1994.

Figure 5.16 shows that sediments at Drake's Island contain more Gastropoda throughout the year than those of Cawsand Bay and White Patch. Gastropoda increase slightly in Cawsand Bay sediments in September and June, whereas in White Patch sediments Gastropoda increase slightly in January, May and July. The abundance of Gastropoda in Drake's Island sediments increases and decreases monthly.

Scaphopoda

Figure 5.17 shows that no specimens of Scaphopoda are recorded from Cawsand Bay sediments and only 4 specimens in the month of September from White Patch sediments. Drake's Island sediments contain fluctuating numbers of Scaphopoda which peak in September.

Scaphopoda

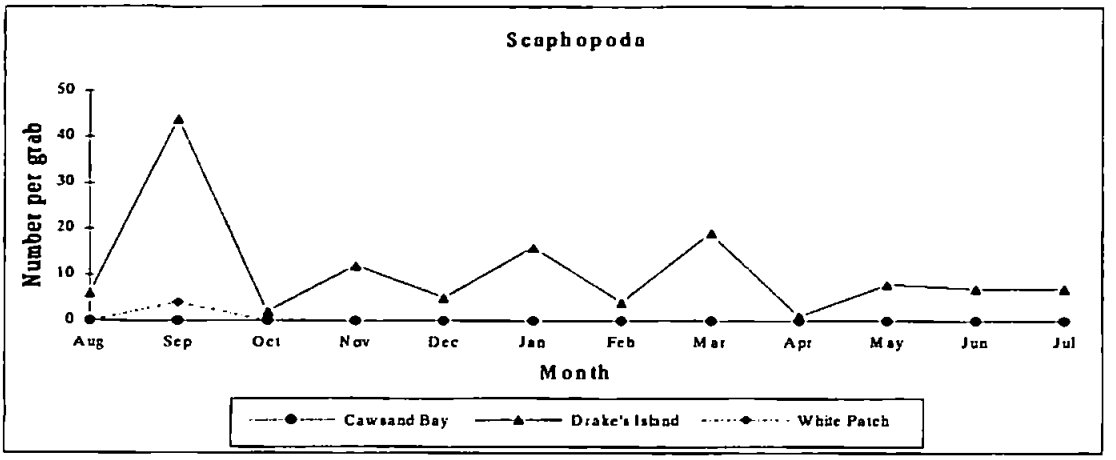


Figure 5.17: Comparison of abundance of Scaphopoda between the three sites sampled, 1993/1994.

Acariformes

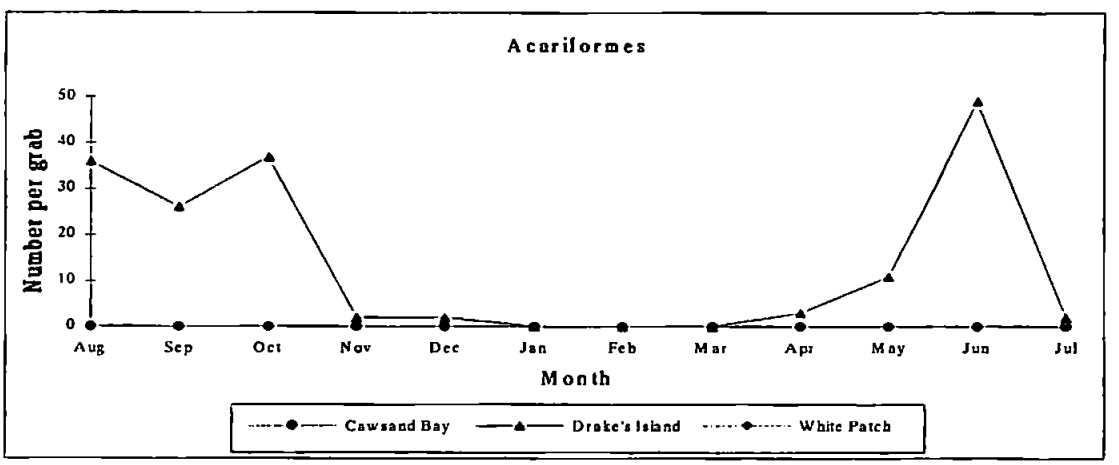


Figure 5.18: Comparison of abundance of Acariformes between the three sites sampled, 1993/1994.

From Figure 5.18 it can be seen that Acariformes are present at only one of the three sites, at Drake's Island. It may be that this group of marine mites benefit from the *Zostera* bed at this site, or from the different parameters this habitat provides. From Figure 5.18 it can be seen that Acariformes at Drake's Island peak in abundance in June and October.

Comparison of sites

Copepoda form two peaks in abundance at Cawsand Bay and Drake's Island, whereas at White Patch abundance of this group of meiofauna fluctuate greatly. The patterns of abundance of Amphipoda at all sites fluctuate greatly and generally are highest in the

months of August to December and numbers of Polychaeta are low at all sites. Ostracoda form two peaks of abundance at all sites, although patterns of abundance at Cawsand Bay and White Patch appear to have more relatively stable populations of these meiofauna than Drake's Island. Cawsand Bay and White Patch appear to have small, relatively stable populations of Bivalvia and Gastropoda compared to Drake's Island sediments. Scaphopoda are absent from Cawsand Bay and very few specimens are present in White Patch sediments, whereas Drake's Island sediments contain relatively high, fluctuating numbers. Acariformes are only present at Drake's Island, being entirely absent from the other two sites under investigation.

5.4.4. DISCUSSION.

The sedimentary characteristics of the sampling sites and the salinity of the water probably determine to a large extent the meiofauna able to survive at each site. Whereas Copepoda dominate the fauna at Cawsand Bay and White Patch, Ostracoda dominate the meiofaunal assemblage at Drake's Island. This may reflect the comparative abundance of organic matter a Drake's Island for the proliferation of Ostracoda and perhaps, Copepoda prefer the more stable substrata that Cawsand Bay and White Patch provide. Polychaeta and Scaphopoda require a sediment which is thixotropic to support their tests, and the dynamic environment of Drake's Island does not provide the correct conditions for this group, whereas the poorly-sorted sediment of White Patch does. The spat of Bivalvia and Gastropoda settle at all three sites, although the populations of these groups at Drake's Island fluctuate greatly, possibly reflecting the inability of these groups to successfully maintain stable populations in this dynamic environment with more fresh water input than the other two sites. The presence of Acariformes at Drake's Island only may reflect a need for this group for the sea grass *Zostera*.

5.5. BACILLARIOPHYCEAE.

5.5.1. INTRODUCTION.

The class Bacillariophyceae are diatoms; unicellular, eukaryotic micro-organisms. They probably comprise the most abundant group of plants on Earth (Round *et al.*, 1990). The diatoms are abundant in all aquatic ecosystems and even occur in moist terrestrial habitats (Round *et al.*, 1990). Most diatoms are pigmented and photosynthetic and there are at least 10,000 living species from all parts of the world (Wornardt, 1967).

Diatoms produce distinctive siliceous cell walls called frustules; the principal source of the soluble silicon used is orthosilicic acid (Boney, 1989). The diatom frustule is taxonomically important, as are the silicified internal structures. The external shape of diatoms can range from centric (circular), to panduriform (figure-of-eight), semi-lanceolate (orange segment), lanceolate (spear-shaped), sigmoid (S-shaped), elliptical (egg-shaped) and other shapes (rectangular, triangular *etc.*). Plate 2 (produced from Hendey, 1964) shows representative shapes of diatoms from this study. Atlas & Bartha (1981) state that the cell walls typically have bilateral or radial symmetry and cells may be unicellular or colonial. Reproduction of this group is by division with the formation of cells of unequal sizes, since each daughter cell reconstructs the smaller inside half of the frustula regardless of which half of the parental frustula it received (Atlas & Bartha). Auxospores (rejuvenescent cells larger than the cells which produced them) are occasionally produced to reverse the trend of decreasing size. Movement of these algal cells is possible, but is restricted to those which possess a raphe (a median line) and, therefore, not found in centric genera (Wornardt, 1967).

As diatoms are photosynthetic, the amount of light available is important and depends upon the sky light-level (a function of latitude, season, time of day and cloud cover) and the proportion of surface light which is able to penetrate the overlying water column; a function of water depth and turbidity (Pilgrim & Millward, 1989). The transmissive exponents of light vary for the different wavelengths, being smaller for blue and green than for violet and

red, with the result that blue and green penetrate to the maximum depths (Vaughan, 1940). The depth of penetration is also dependent on the amount of organic and inorganic matter suspended in the water (Vaughan, 1940), and turbidity linked to deposition of clays and its prolongation will produce a reduction in penetration of the photic zone (Goard, 1975).

Every element, with the exception of silicon, increases in concentration in the sea as compared to river waters; and so the relatively higher concentration of silicon in river waters allows diatoms to proliferate in the proximity of estuaries. Species of planktonic diatoms appear to react differently throughout the year; whilst some species maintain small populations in the euphotic zone, others have brief periods of abundance and then disappear. Ellison (1984) finds that diatoms on a mudflat at the mouth of the River Tamar (1974) produce much larger populations in May and July than in the period between December and April.

As diatoms are unicellular algae they serve to structure the habitat of meiofauna due to their trophic value and, apart from bacteria, diatoms are the most important food source (Giere, 1993). Vinogradov (1953) states that diatoms are rich in iodine, iron and possibly arsenic. Organic content has been found to increase abundance of diatoms and Round (1981) states that the supply of nutrients from land is essential to algal growth, with the main source of nitrate in agricultural areas being provided by excess of fertilisers, and with phosphate provided by the input of sewage. Phytoplankton (and zooplankton) are known to deplete nitrogen levels in sea water in early summer (Herbert, 1982). As well as organic content and light quality there appears to be an interaction between diatoms and bacteria. Provasoli (1960) quotes Waksman *et al.*, (1937) as stating that there is a close correspondence between the numbers of bacteria and the number of diatoms in the sea, perhaps due to the exchange of metabolites. Round (1981) states that the presence of bacteria is necessary for algae to grow, as the uptake of organic acids into algae is influenced by uptake into the associated bacterial flora. Giere (1993) finds that the production of mucus from diatoms promotes bacterial growth.

Diatoms raise the dissolved oxygen content of sediments (Newell, 1979) and Nisbet (1984) states that diatoms migrate vertically in the top 2 cm of silt, causing a considerable amount of variation in the amount of dissolved oxygen in interstitial water. Foraminiferida may well benefit from increased dissolved oxygen content of sediments, especially the infaunal forms. The direct benefit to Foraminiferida from diatoms is as a food source. Lee & Lee (1979) state that meiofauna are highly selective in feeding habits. Kitazato (1994) states that shallow infaunal benthonic Foraminiferida presumably feed selectively on benthonic diatoms that grow on the surface of sea weeds and/or the sediment surface and Lee (1974) states that Foraminiferida are very selective feeders and may gain different nutritive values from the food they do assimilate. Foraminiferida form lipid droplets when they consume large amounts of algae (Lee *et al.*, 1969) and although Round (1981) finds that the colour of foraminiferal cytoplasm is not always due to algae, Murray (1963) finds that *Elphidium crispum* fed upon *Phaeodactylum* formed brown cytoplasm and when fed upon *Tetraselmis* formed green cytoplasm.

Laboratory experiments have been carried out by Lee *et al.* (1966) who find that the algal prey of *Ammonia beccarii* changed with the ontogeny of the Foraminiferida, and that the young Foraminiferida eat young diatoms. Some species of Foraminiferida carry endosymbiotic algae within their tests and appear to be highly specific as to the algal species of chloroplast utilised. Round (1981) states that when an alga enters into a symbiotic relationship its growth rate slows down whilst the photosynthetic rate is unaffected, leading to an excess of carbohydrates which are leaked to the host. Akers (1983) states that in five species of larger Foraminiferida most specimens are hosts for only one species of endosymbiotic diatom at a time, which are small and usually pennate.

Field studies of both diatomaceous and Foraminiferidal content of sediments have been rarely carried out. Phleger (1954) identifies six species of diatoms in association with Foraminiferida from the Mississippi Sound and Buzas (1969) finds that regression coefficients for the chlorophylls a, b and c (measured 1 m off bottom) suggest that both the amount and kind of food available is important in determining foraminiferal species

densities. Matera & Lee (1972) find that the species composition of diatoms indicate that this important part of the community has a similar pattern to that of the Foraminiferida; they identify more than 225 species of diatoms, but state that, in general, most communities are composed of 1 or 2 species in large numbers whilst most species are represented by small populations. Walker (1976) states that diatoms such as *Navicula* sp. are often found permanently attached to the tests of Foraminiferida in tide pools. Frankel (1974) states that *Lepidodeuterammina ochracea* has a sessile infaunal habitat living attached over depressions in sand grains, within which are living diatoms which may provide food for the foraminiferid. De Rijk (1995) studied nine sediment samples for diatom and foraminiferal densities and finds that they do not correlate.

Many selective marine organisms have specialised mouth parts for the ingestion of prey, and Giere (1993) states that many ciliates, nematodes and oligochaetes have specialised mouth parts enabling utilisation of, and even differentiation between, various algal cells and shapes. The various apertural shapes displayed by Foraminiferida must have a functional role and may be adaptations to the shape of diatom species preferred as prey, although Lee (*pers. comm.*), Faber & Lee, 1991 and Lee *et al.*, 1991 {a} state that normally digestion of diatoms occurs outside of the test, within the pseudopodia.

The aim of this part of the study is to assess the seasonal variability in diatoms available, and, although not quantitative, will provide some insight into the change in shapes of diatoms present at each site each season.

5.5.2. MATERIALS & METHODS.

Seasonal samples of sediment were taken from each of the sampling sites simultaneously with the respective month's sampling of Foraminiferida. Samples for diatom identification were taken in the months of August, October, January and April, 1993/1994.

Extraction of diatoms from the sediment

The quantification of abundance of diatoms is very difficult (Dr. D. Harbour, PML; *pers. comm.*) and so the method of extracting diatoms from sediment samples is a compromise. Within 6 hours of collection each sediment sample was placed into a Petri dish with a little extra fresh sea water to cover the sediment and make it more thixotropic. The surface of the sediment was covered in 1 cm^2 pieces of doubled lens tissue and the Petri dish covered with a clear lid to prevent evaporation. The samples were placed in a north-facing window and left until the following morning so that living motile diatoms could move up towards the light, and become trapped within the lens tissue.

Cleansing of the diatoms

The lens tissues containing the diatoms were placed into separate sterile bijou bottles. An equal volume of concentrated sulphuric acid was added to the tissue and agitated gently to access all parts of the solution. Saturated potassium permanganate solution was added to the bottles until a slight purple tint could be perceived. Saturated oxalic acid was then titrated against the solution until it again became colourless. The solutions were centrifuged for 5 minutes at 1000 rpm. The supernatants were removed, and distilled water added; and the centrifuge process repeated 6 times.

Mounting of diatoms

The remaining cleansed solutions were mounted on glass coverslips by dropping a drop of the fluid from a height of approximately 30 cm and allowing it to dry by evaporation. (This method spreads the diatoms within the droplet evenly and prevents the over-lapping of specimens). Once dry, 3 drops of DPX mountant were placed on a microscope slide, and the coverslip inverted on to the mountant so that the diatom-rich droplet was embedded in the mountant. The slides were placed into an incubator to thoroughly dry overnight.

Examination of diatoms

Random selection of diatom-rich drops on slides was carried out. The diatoms were examined on a cardioid dark-field condenser with a X 40 lens. The specimens were

identified with direct reference to Hendey (1964) and recorded. Colonial species were excluded from this study. The identification of diatoms from each season at each site was continued until approximately 300 specimens had been noted. This method was used instead of examination directly by SEM, as this was tried and found to be unsuccessful. Photographs of each species were taken through the dark-field cardioid condenser, but due to the depth of field were unclear. Subsequent image analysis of the negatives was not successful. Abundances and relative abundances of diatoms from the three sites are given in Appendix V.

5.5.3. RESULTS.

Cawsand Bay

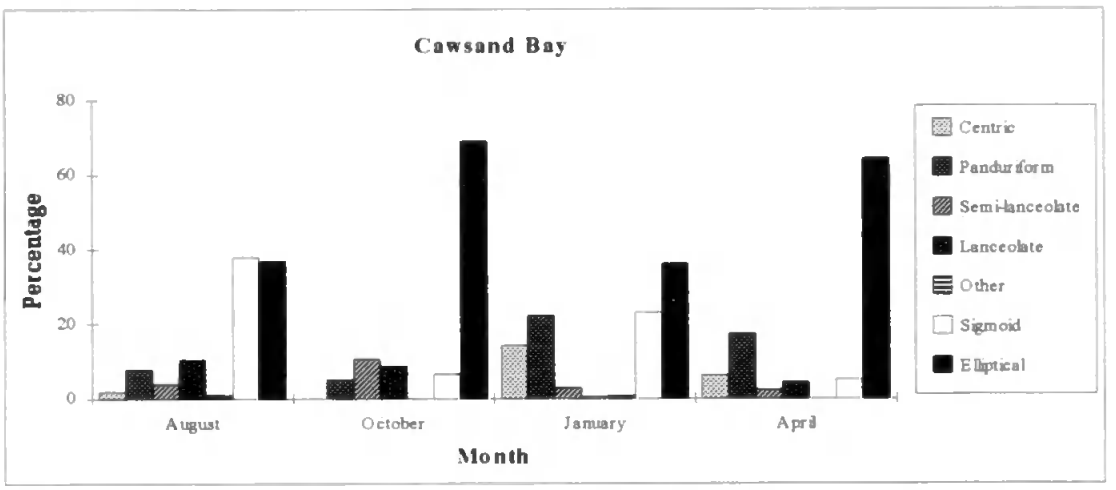


Figure 5.19: Temporal variation in relative abundance of differently-shaped diatoms at Cawsand Bay, 1993/1994.

From Figure 5.19 it can be seen that centric specimens are relatively few at this site; the proportion of this group increases in January and decline again in April. The panduriform specimens increase as a proportion of the assemblage in January and suffer a slight decline in April. Semi-lanceolate individuals are approximately 3% throughout the year except in October when this group rises to form approximately 10% of the assemblage. Lanceolate specimens form approximately 10% in August, 9% in October and decline to 0.4% in January and slightly rise to 4.5% in April. Diatoms of other shapes are relatively rare at this site, forming approximately 1% of the assemblage in August and January and 0% in October

and April. Sigmoid-shaped diatoms at Cawsand Bay are relatively abundant in August and January, whilst the diatom assemblage at this site is dominated by elliptically-shaped forms.

In August the assemblage at Cawsand Bay is dominated by sigmoid and elliptical forms with some lanceolate and panduriform specimens and other groups comprising a minor proportion of the assemblage. In October the assemblage mostly consists of elliptical forms followed by semi-lanceolate and lanceolate forms, whereas in January the assemblage at this site is comprised mostly of elliptical forms with fewer proportions of sigmoid and panduriform specimens and a lesser proportion of centric forms. In April the assemblage at this site is mostly of elliptical diatoms with a lesser proportion of panduriform specimens, and with other groups forming a minor proportion.

Drake's Island

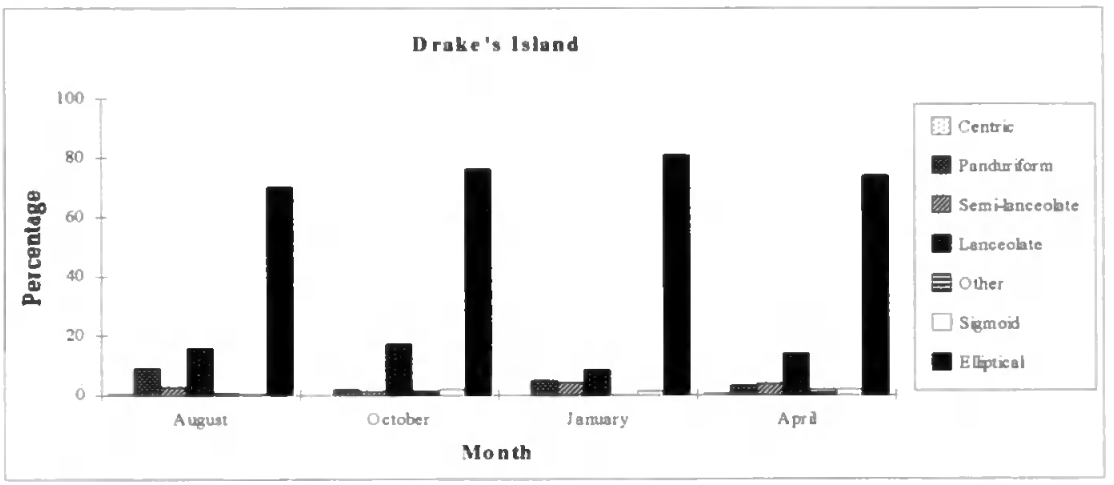


Figure 5.20: Temporal variation in relative abundance of differently-shaped diatoms at Drake's Island, 1993/1994.

Centric diatoms are few: they form 0.6% and 0.7% of the assemblage in August and April respectively with 0% in both October and January. Panduriform diatoms peak as a proportion of the assemblage in August forming approximately 9% of the diatom fauna and decrease to approximately 3% in the other months. Semi-lanceolate diatoms form a fairly constant small proportion of the assemblage at this site. Lanceolate diatoms form a relatively stable proportion of the assemblage at this site during the sampling period; forming between 8.5% and 17.2% of the assemblage at this site. Diatoms of other shapes

and sigmoid forms form minor proportions of the diatom assemblage throughout the year, whilst the percentage of elliptical specimens is always above 70% at this site.

White Patch

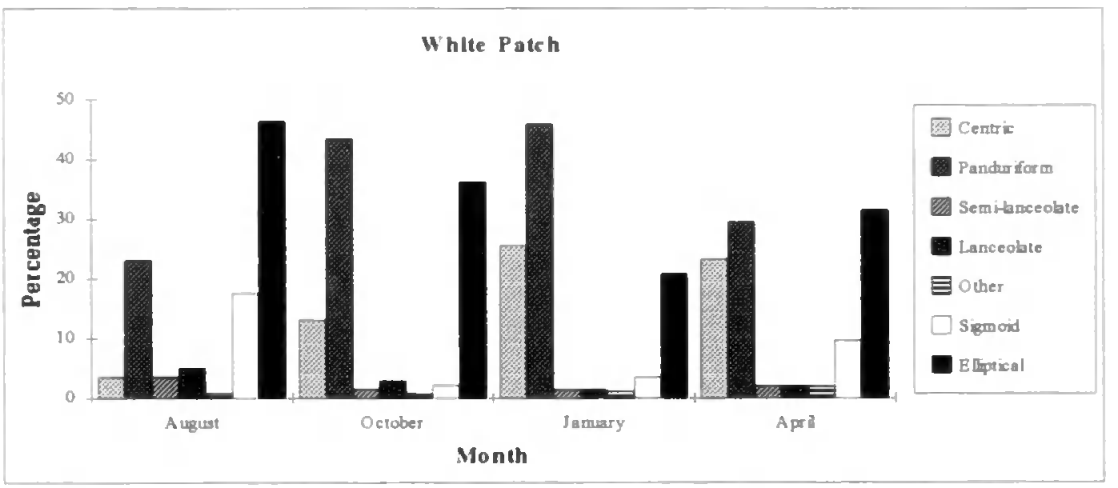


Figure 5.21: Temporal variation in relative abundance of differently-shaped diatoms at White Patch, 1993/1994.

From Figure 5.21 it can be seen that there is a much more even distribution of diatom shapes at this site in the seasonal samples taken than at either Cawsand Bay or Drake's Island. Centric diatoms rise from a percentage of 3.5% in August through October to reach a peak of 25.6% in January and only slightly decline from this to 23.3% in April. Panduriform specimens form a good percentage of the assemblage at this site throughout the year ranging from 23.1% in August to 46.0% in January. Semi-lanceolate, lanceolate and diatoms of other shapes form relatively small proportions of the assemblages at this site in the seasonal samples. Sigmoid diatoms range from 2.2% in October to 17.6% in August, whilst elliptical diatoms form over 20% of the assemblage every season and peak at 46% of the assemblage in August.

In August, the diatom assemblage at White Patch is dominated by elliptically-shaped diatoms followed by panduriform and sigmoid-shaped diatoms. In October the diatom assemblage is dominated by panduriform diatoms followed by elliptical diatoms. In January panduriform diatoms are relatively more numerous than centric and elliptical forms. In April

at this site elliptical, panduriform and centric specimens are roughly similar for percentage abundance.

Diversity

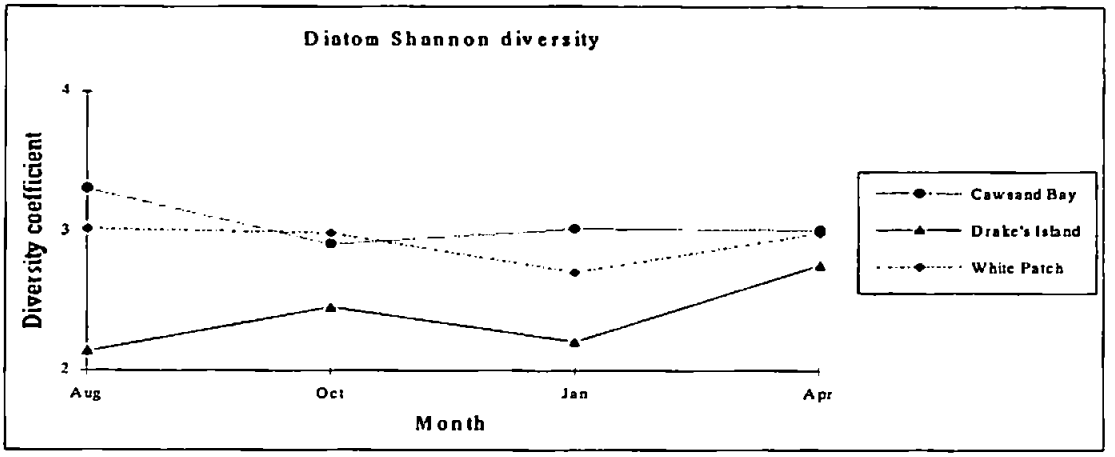


Figure 5.22: Comparison of Shannon diversity of diatoms at the three sampling sites, 1993/1994.

From Figure 5.22 it can be seen that the Shannon diversity measure was generally highest at Cawsand Bay, whilst diversity of diatoms at Drake's Island was lowest of the three sites and White Patch was intermediate between the other two sites.

Richness

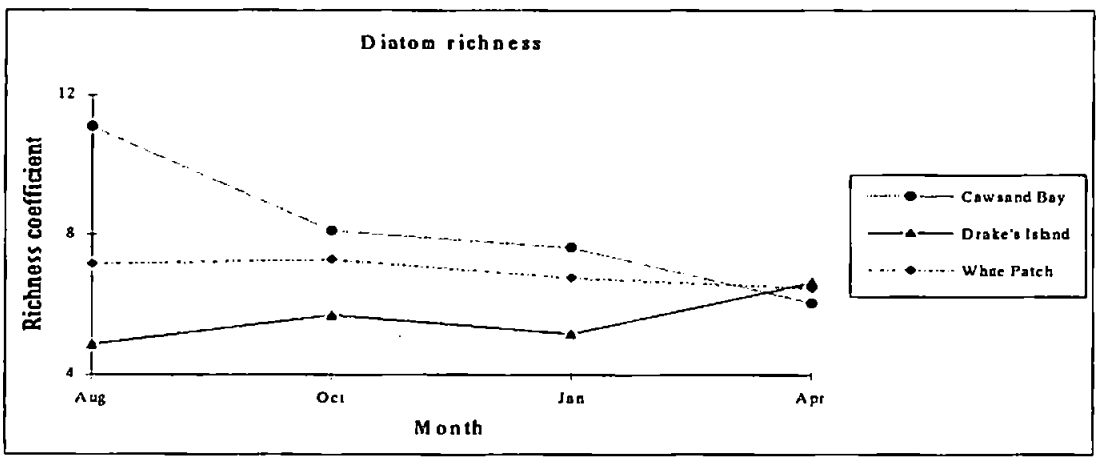


Figure 5.23: Comparison of Margalef's species richness of diatoms at the three sampling sites, 1993/1994.

From Figure 5.23 it can be seen that diatom richness of species is generally highest at Cawsand Bay, except for April; Drake's Island diatoms were generally lowest in terms of

species richness; and White Patch diatoms are fairly stable and intermediate between the two other sites.

Evenness

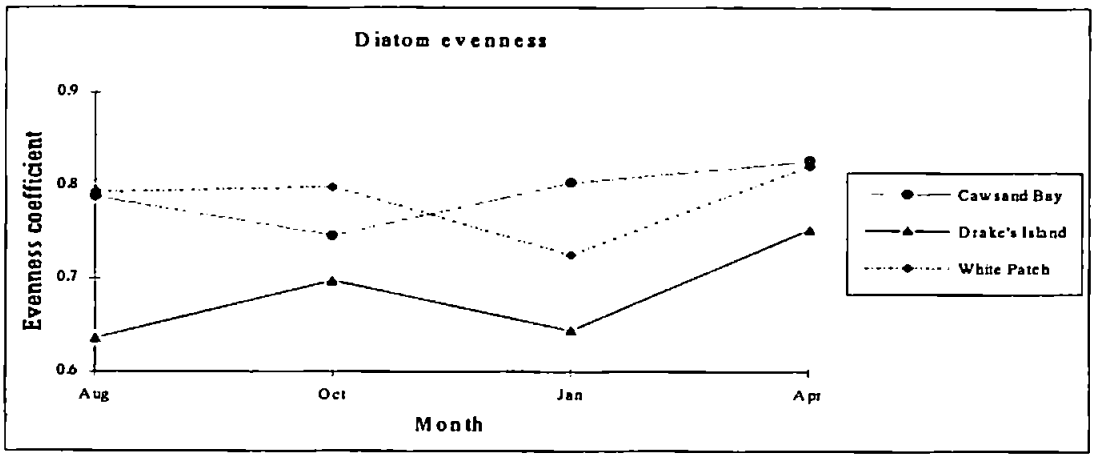


Figure 5.24: Comparison of Pielou's species evenness of diatoms at the three sampling sites, 1993/1994.

From Figure 5.24 it can be seen that Drake's Island diatoms have the lowest evenness values of the three sites, indicating that the assemblage at this site is dominated by a few species. Cawsand Bay and White Patch diatoms alternate in levels of evenness, with White Patch diatoms having a higher level of evenness in August and October, and lower levels than Cawsand Bay in January and April.

Comparison of sites

The three sites sampled contained very different assemblages of diatoms in the seasonal samples taken. White Patch assemblages contained the most even distributions of the different shapes of diatoms, with Cawsand Bay assemblages being the next most even in distribution, and Drake's Island assemblages being dominated by elliptical specimens. Centric, panduriform and other-shaped diatoms were most numerous at White Patch; semi-lanceolate and sigmoid diatoms were generally most numerous at Cawsand Bay; lanceolate and elliptical diatoms were most numerous at Drake's Island.

Drake's Island diatom assemblages had the lowest values for Shannon diversity, species richness and species evenness. Diatoms from Cawsand Bay had the highest values for

Shannon diversity and species richness and were highest for species evenness in January and April. White Patch diatoms were generally intermediate between the other two sites for Shannon diversity, and species richness and was highest for species evenness in August and October.

5.5.4. DISCUSSION.

Cawsand Bay diatoms had the highest values of the three sites sampled for Shannon diversity and species richness, and were highest for species evenness in January and April. This may reflect that this site was more marine in nature than the other two sites sampled, which appears to allow a high number of diatom species, and high equitability in abundance of each species which inhabits this site. Cawsand Bay assemblages were fairly even for distribution of different shapes of diatoms, being lower in evenness of shapes than White Patch, but more even than Drake's Island assemblages. Semi-lanceolate and sigmoid diatoms were generally more numerous at Cawsand Bay than at the other two sites, perhaps indicating a preference for these diatoms for more marine conditions.

The domination of the Drake's Island diatom fauna by elliptical specimens during the sampling months may reflect the inability of many other types of diatom to survive in the dynamic and variable habitat this site provides. This may also be the reason for the low values of species diversity, species richness and evenness at this site. This site contained the most numerous number of lanceolate and elliptical diatoms of the three sites, indicating that these shapes of diatoms can withstand the environmental factors at this site and so dominate the sampled assemblages.

The assemblage at White Patch had a more even distribution of shapes of diatoms than those of Cawsand Bay and Drake's Island respectively. This may reflect the fact that this site is intermediate between Cawsand Bay and Drake's Island for salinity and temperature, therefore allowing many different species of diatoms to be present at this site, whereas diatom species with specific salinity and temperature requirements may be unable to live at

the comparatively more marine Cawsand Bay or the comparatively more fresh-water site of Drake's Island. The poorly-sorted substratum at White Patch, together with high organic input from the Rivers Tamar and Plym, may also favour the proliferation of many shapes of diatoms at this site. White Patch diatoms were generally intermediate between the other two sites for Shannon diversity and species richness, and was highest for species evenness in August and October. The distribution of shapes of diatoms revealed that centric, panduriform and other-shaped diatoms were most numerous at White Patch.

5.6. SUMMARY.

The three sampling sites were different for all biotic variables sampled. The sediments at the sites contained different proportions of total organic content, with generally highest amounts at Drake's Island; then White Patch and Cawsand Bay respectively. The cyclic fluctuation of total organic content at Cawsand Bay could be the result of bacterial blooms and the high organic content at Drake's Island may be due to the variable discharge of organics from the River Tamar and the relatively high ability of water to flush organics from this well-sorted substratum. The sediments from White Patch were generally intermediate between Cawsand Bay and Drake's Island for organic content; the peak in May may be the result of the spring phytoplankton bloom settling on the sediment, or to unicellular algae proliferating in the River Plym and becoming deposited at White Patch.

Although the abundance of bacteria per gram of wet sediment is not very different between sites, Drake's Island sediments often contained relatively high numbers of bacteria. The peak in bacterial abundance at all sites in October may be due to excess detrital algae providing a rich nutritive substratum for the proliferation of benthonic bacteria, and the fall in bacterial abundance may perhaps reflect predation of bacteria by settled invertebrate spat. The increase in number of cfu at the sites probably depends upon organic matter: in winter months this is probably supplied by detrital macrophytes, whilst the increase in February may depend upon the re-suspension of organic matter by storms. The effect of the different environmental variables upon the bacterial flora may help to explain why the sites differ in

the temporal distribution of types of bacteria throughout the sampling period. Pigmentation of bacterial colonies probably reflects the position of the sampling sites within the photic zone.

Other meiofauna differ between sites; no Acariformes were found at Cawsand Bay or White Patch and Scaphopoda were absent from Cawsand Bay sediments. Copepoda and Ostracoda are constantly present at all sites and levels of Bivalvia and Gastropoda at Cawsand Bay and White Patch may reflect the more stable substrata these sites provide for these meiofauna and perhaps reflect the better salinity these environments provide. Numbers of Amphipoda were very variable at all sites and Polychaeta relatively rare. Copepoda form two peaks in abundance at Cawsand Bay and Drake's Island, whereas at White Patch abundance of this group of meiofauna fluctuates greatly. The patterns of abundance of Amphipoda at all sites fluctuate greatly and generally are highest in the months of August to December. Ostracoda form two peaks of abundance at all sites, although patterns of abundance at Cawsand Bay and White Patch appear to have more relatively stable populations of these meiofauna than Drake's Island. Cawsand Bay and White Patch appear to have small, relatively stable populations of Bivalvia and Gastropoda compared to Drake's Island sediments. Scaphopoda are absent from Cawsand Bay and very few specimens are present in White Patch sediments, whereas Drake's Island sediments contain relatively high, fluctuating numbers. Acariformes are only present at Drake's Island, being entirely absent from the other two sites under investigation.

The relatively high values for diversity, richness and evenness which the Cawsand Bay diatoms provide and the fairly equal distribution of shapes of diatoms at this site may indicate that the stable substratum and marine conditions appear to allow a high number of diatom species, and high equitability in abundance of each species to inhabit this site. The domination of Drake's Island diatoms by elliptical and lanceolate forms, and the low values for diversity, richness and evenness may reflect that few species of diatoms can withstand the dynamic, low-salinity environment of this site. White Patch diatoms had a more even distribution of shapes than those of the other two sites and was generally intermediate for

diversity, richness and evenness. This site is intermediate between Cawsand Bay and Drake's Island for salinity, temperature and organic content, and this may be reflected by the more even distribution of types of diatoms at this site.

PLATE 2.

Figures illustrating shapes of diatoms (after Hendey, 1964.)

Figure 1: Example of a centric diatom; *Coscinodiscus radiatus* Ehrenberg

Figure 2: Example of a panduriform diatom; *Diploneis crabro* Ehrenberg

Figure 3: Example of a semi-lanceolate diatom; *Amphora ventricosa* Gregory

Figure 4: Example of a lanceolate diatom; *Nitzschia angularis* Wm. Smith

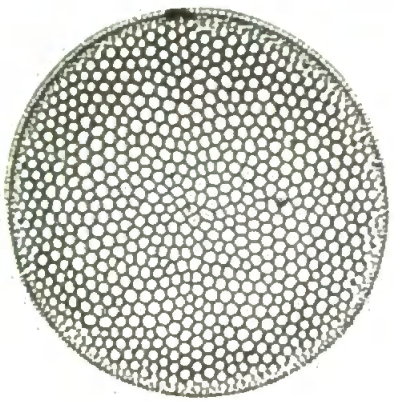
Figure 5: Example of other shapes of diatom; *Grammatophora serpentina* Ehrenberg

Figure 6: Example of a sigmoid diatom; *Pleurosigma aestuarii* (de Brébisson ex Kützing) Wm. Smith

Figure 7: Example of an elliptical diatom; *Diploneis littoralis* (Donkin) Cleve

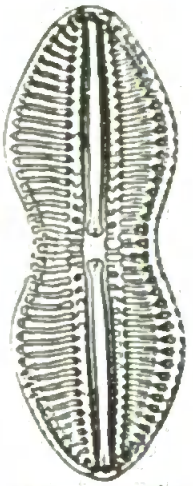
PLATE 2.

CENTRIC



Coscinodiscus radiatus

PANDURIFORM



Diploneis crabro

SEMI-LANCEOLATE

Amphora ventricosa

LANCEOLATE

Nitzschia angularis

OTHER

Grammatophora serpentina

SIGMOID

Pleurosigma aestuarii

ELLIPTICAL

Diploneis littoralis

CHAPTER 6.

CORRELATIONS OF ABIOTIC VARIABLES AND FORAMINIFERIDA.

6.1. INTRODUCTION.

Analysis of data by statistical methods was carried out to ascertain if any significant relationships exist between the data for Foraminiferida and those of the abiotic environmental variables. The statistical method used was correlation: a measure of the strength of the relationship between two variables. The value of the correlation coefficient always lies between minus one and plus one, and strong correlation coefficients are close to the extreme values. Positive coefficients are obtained if one variable rises as the other variable rises, whereas negative coefficients are obtained if one variable rises as the other falls. If there is a strong correlation between two variables this does not mean that there is necessarily a cause-and-effect relationship between them; *i.e.* correlation, unlike regression, is not a predictive tool. The correlation coefficients were calculated by use of MINITAB software package (Version 7.1) and analysed for Pearson's Correlation Coefficients. This correlation coefficient assumes that a plot of the X,Y variables would have a bivariate normal distribution which, because the measurements of variables in nature are from a continuous scale of measurements and not discrete values, makes this correlation test the most applicable. The null hypothesis is that there is no significant relationship between the X values and the Y values. The correlation coefficients differ as to whether the relationship between the variables is tested for being either positive or negative (a one-tailed test: α_1), or whether no assumption is made about the direction of the relationship (a two-tailed test: α_2). For this study no assumptions were made about the direction of relationships between variables. The correlation coefficient obtained is compared to values in statistical tables to obtain percentage values of significance; *e.g.* if a value of 0.7082 is obtained this is greater than the value obtained for 1% significance. This

means that the chances of getting that correlation coefficient by chance are less than 1%. It must be appreciated, however, that a significant relationship between variables and Foraminiferida may not be the result of a direct relationship but may be a common factor relying upon a variable not measured; *e.g.* a positive relationship between number of Foraminiferida and temperature may be due to phytoplankton blooming in higher-temperature waters leading to greater nutrients available to enable foraminiferid reproduction. Both the calculated number per grab (absolute abundance) and the percentage (relative abundance) of each foraminiferid group have been correlated with variables.

Table 6.1: Statistical table values for Pearson's Correlation Coefficients. All values from Neave (1981) except the correlation coefficient for 0.1 % significance which is provided by Murdoch & Barnes (1986).

Correlation coefficient (n = 12)	α_2 percentage value	description of relationship
0.823	0.1%	very strong correlation
0.7079	1.0%	strong correlation
0.6581	2.0%	good correlation
0.5760	5.0%	correlation

Correlation coefficients greater than 5% significance have been tabulated and only correlation coefficients greater than 0.1% (*i.e.* 0.823, or very strong correlations) have been plotted. Temperature at depth, salinity at depth, mean phi size of the sediment, sorting, skewness, kurtosis and percentage of the sediment less than 63 μm were recorded monthly, the samples being taken simultaneously with the foraminiferid samples. The measurement of salinity in May, 1993, was not taken due to instrument malfunction, and so the average salinities at the sites were used to correlate variables with Foraminiferida.

Table 6.2: Significant correlation coefficients between temperature and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Abundance	0.584	0.781	0.644
Richness		0.587	
Fisher coefficient		0.584	
Number of Spirillinina		0.609	
Number of Miliolina	0.611	0.825	0.747
Number of Lagenina	0.635	0.686	0.769
% Lagenina		0.604	0.583
Number of Rotaliina		0.681	0.582
Number of hyaline		0.697	0.594
Number of unilocular	0.664		0.821
% unilocular			0.658
Number of biserial		0.679	0.714
Number of planispiral	0.585	0.686	
Number of trochospiral		0.624	
Number of quinqueloculine		0.826	0.745
Number of round apertures	0.685	0.742	0.773
Number of arch apertures		0.764	0.615
Number of slit apertures	0.604	0.733	0.628
Number of epifaunal	0.644	0.805	0.637
Number of herbivores	0.584	0.811	0.604
Number of detritivores		0.632	0.683
Number of suspension-feeders		0.595	
Number >63 μm		0.765	0.791
Number >125 μm	0.634	0.614	0.583
Number >250 μm		0.692	
% >250 μm	-0.678		
Number >500 μm		0.718	

All correlation coefficients obtained between temperature and Foraminiferida are positive (except that for the percentage of the foraminiferid assemblage at Cawsand Bay which is greater than 250 μm), indicating that generally as temperature rises so does the number of the sub-groups of Foraminiferida having a significant relationship with this variable. This variable appears to be important at all sites for many groups of Foraminiferida.

The number of Foraminiferida is significantly correlated with temperature at all three sites and the higher correlation coefficient obtained for Drake's Island (1%) may either be because foraminiferid abundance at this site is comparatively low (and so an increase in numbers at this site would have more effect), or that there

are comparatively more species at this locality at their northern limit of distribution reproducing in response to higher temperatures. The abundance of Miliolina and Lagenina are significantly correlated with temperature at all sites, as are epifaunal and herbivorous Foraminiferida and the number of Foraminiferida with round and slit apertures and the number of Foraminiferida greater than 125 μm. Drake's Island and White Patch Foraminiferida increase in abundance as the temperature increases for the sub-groups of percentage of Lagenina, number of Rotaliina, biserial, quinqueloculine, detrivores and those with arch apertures and the number of Foraminiferida greater than 63 μm. Planispiral Foraminiferida at Cawsand Bay and Drake's Island increase in abundance as the temperature increases. The number of unilocular Foraminiferida at both Cawsand Bay and White Patch increases as the temperature increases, as does the percentage of unilocular forms at White Patch. Drake's Island Foraminiferida increase in both richness of species and Fisher diversity as the temperature increases, as do the numbers of Spirillinina, trochospiral and suspension-feeders. The Drake's Island Foraminiferida greater than both 250 μm and 500 μm bear positive relationships with temperature, whilst the percentage of Cawsand Bay Foraminiferida greater than 250 μm bears a negative relationship with temperature.

These correlations may be directly linked to the timing of reproduction, especially for species at their northern limit of distribution in the south-west of Britain, or may be indirectly related to the phytoplankton bloom or the benthonic bloom of diatoms. Sampled assemblages contain *Elphidium crispum* and *Ammonia beccarii*, which are known to be eurythermal (Alve & Nagy, 1990). Myers (1943) states that *Elphidium crispum* succeeds where summer surface sea temperatures range from 7°C to 30°C, although Jepps (1942) found that temperature does not affect the timing of schizogony in this species. Schnitker (1974) found that lowering temperature of laboratory-held *Ammonia beccarii* resulted in no growth or reproduction. *Elphidium crispum* and *Ammonia beccarii* are important members of all sampled assemblages and so temperatures affecting these two species may

well affect overall abundance of subgroups of Foraminiferida at the sites investigated.

Reproduction of these sub-groups is linked to temperature at depth, although proliferation of unicellular algae of shapes which can be carried through the above foraminiferid apertures and of epifaunal species may induce foraminiferid reproduction. It may also be that these significant correlation coefficients result from a relationship between temperature and composition of the sediment. Temperature is significantly correlated with the richness of foraminiferid species at Drake's Island; therefore as the temperature rises so does the number of foraminiferid species at this site. This may reflect a direct relationship of transportation into this site (from outside of the Breakwater) of species which are at the northern limit of their distribution and can survive at this site during warmer water temperatures, or an indirect relationship whereby higher temperatures occur at the time when unicellular algae reproduce and relatively rare species reproduce in response to this and are therefore represented in the fractions of the grab examined. Little is known of Lagenina, but it is possible that this group is parasitic upon other Foraminiferida and so may increase in numbers in response to a rise in the abundance of other Foraminiferida. There is a very strong relationship between quinqueloculine individuals and temperature at Drake's Island (0.1%) indicating that temperature is directly or indirectly important to this shape of test at this locality. Temperature may indirectly promote the reproduction of herbivorous species due to directly promoting the growth and reproduction of unicellular algae. Numbers of detritivorous individuals are correlated with temperature at Drake's Island and White Patch, indicating that at these two localities temperature bears a relationship with the abundance of detrital material. Temperature is highest in September when parts of old macroalgae break off from the fronds to become detrital particles; possibly providing an important food source for detritivorous Foraminiferida. The numbers of suspension-feeders are significantly correlated with temperature at Drake's Island, perhaps indicating that as temperature rises at

this site so does the amount of seston in the water column. Temperature also appears to be an important variable for sizes of Foraminiferida. The positive relationships with temperature and >63 μm Foraminiferida indicate that foraminiferid reproduction occurs when temperature is highest at these sites (including those species which never get greater than this size fraction). Significant correlations between >125 μm Foraminiferida and temperature may be because the juveniles of larger species such as *Elphidium crispum* or *Ammonia beccarii* are rarely present in the >63 μm fraction as juveniles but are present in the >125 μm fraction. The positive relationships between temperature and number of Foraminiferida of >125 μm size may therefore reflect the reproduction of these Foraminiferida of greater sizes. The relationship between temperature and number >250 μm Foraminiferida at Drake's Island may be indirect and reflect a good food supply when temperature of the water at depth is highest. Numbers of >500 μm Foraminiferida are positively strongly correlated with temperature at Drake's Island (+0.718: 1%) indicating that Foraminiferida at this site are mature when temperature is higher at this site and are, perhaps, ready to reproduce so that the offspring are produced when temperature is still relatively high. Percentage of Foraminiferida of >250 μm at Cawsand Bay is negatively correlated with temperature and it may be that perhaps as temperature was positively correlated to number of >63 μm Foraminiferida, that the growth of Foraminiferida to >250 μm occurs when temperature is lowest.

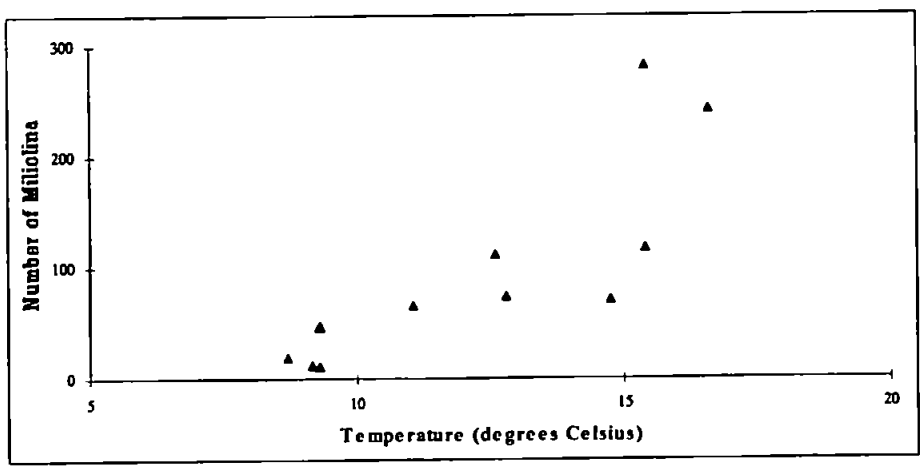


Figure 6.1: Scatter plot showing correlation between number of Miliolina per grab and temperature at Drake's Island (+0.825).

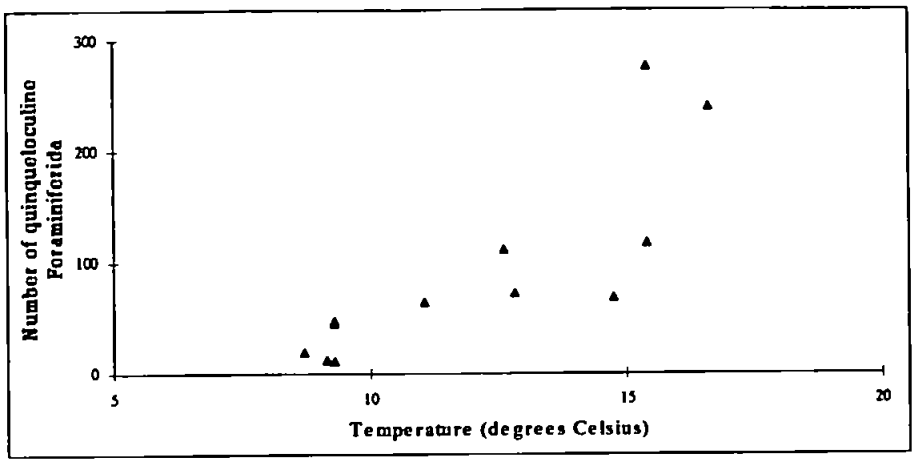


Figure 6.2: Scatter plot showing correlation of number of quinqueloculine Foraminiferida per grab and temperature at Drake's Island (+0.826)

6.3. SALINITY.

Table 6.3: Significant correlation coefficients between salinity and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of round apertures		0.626	
% round apertures		0.610	
% arch apertures			-0.584

Salinity here has very few significant correlations with the Foraminiferida, possibly because the salinity was generally good at all three sites. Salinity will have little effect upon euryhaline species such as *Ammonia beccarii* (Walton & Sloan, 1990) but will affect stenohaline species such as *Elphidium crispum* (Buzas, 1969). In addition, Myers (1943) states that Foraminiferida at Drake's Island have a maximum salinity tolerance between 26.6‰ and 34.9‰ at low and high tide respectively.

Salinity is positively correlated with both the number of, and percentage of, Foraminiferida with round apertures at Drake's Island. This may be a direct relationship, with round-apertured forms reproducing when salinity at depth is higher, or may be indirectly related to stenohaline unicellular algae reproducing at high salinities and providing a good food source for these Foraminiferida. Percentage of Foraminiferida with arch apertures is negatively correlated with salinity at White Patch indicating that as salinity increases the percentage of Foraminiferida with arch apertures falls. These Foraminiferida appear to reproduce

when salinity is low, and may be the response of euryhaline opportunistic species reproducing when other stenohaline species are prevented from reproducing by the low salinity.

6.4. MEAN PHI SIZE OF THE SEDIMENT.

Table 6.4: Significant correlation coefficients between mean phi size of the sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Abundance	0.886		
Fisher coefficient	-0.613		
Number of Miliolina	0.841		
Number of Lagenina	0.775		
Number of Rotaliina	0.791		
Number of Hyaline	0.794		
Number of unilocular	0.755		
Number of biserial	0.879		
Number of triserial	0.816	0.684	
Number of planispiral	0.742	0.579	
Number of trochospiral	0.798		
Number of quinqueloculine	0.794		
Number of other coiling		0.617	
Number of round apertures	0.819		
Number of arch apertures	0.929		
Number of slit apertures	0.760		
Number of pore apertures	0.727	0.618	
Number of other apertures	-0.602		
Number of infaunal	0.806	0.641	
Number of epifaunal	0.884		
Number of herbivores	0.889		
Number of detritivores	0.842		
Number >63 µm	0.797		
Number >125 µm	0.883	0.721	
Number >250 µm	0.873		
Number >500 µm	0.769		

Mean phi size of the sediment appears to be an important variable for many groups of Foraminiferida at Cawsand Bay, although it is not correlated with many groups of Foraminiferida at Drake's Island and bears no significant relationship with any foraminiferid group at White Patch. An increase in the mean phi size of sediment means that the sediment is composed of finer particles in mm size diameter and most of the significant relationships at this site are positive. Mean phi size of the sediment may be more important to Foraminiferida at Cawsand Bay as the sediment at this site is usually well-sorted throughout the annual cycle, whereas it is moderately-sorted at Drake's Island and poorly-sorted at White Patch. The

sediment at Cawsand Bay is mainly, therefore, of one size and a reduction in mean grain size is of benefit to the foraminiferid community at this site.

This finding contradicts that of Goard (1975) who states that coarser substrata support higher populations of Foraminiferida due to them being less prone to predation in coarser sediments. Whereas some species, such as *Ammonia beccarii*, are found in both fine and coarse sediments (Walton & Sloan, 1990), other species appear to have more specific requirements. Myers (1943) states that sublittoral *Elphidium crispum* is most numerous on firmly packed sand or a mixture of coarse sand and shell gravel; Sliter (1965) states that fine sands between 125 μm and 250 μm favour the grazing of *Rosalina globularis* and Buchanan & Hedley (1960) state that medium sand of 250 μm to 500 μm with less than 10% silt and 2% clay favours *Astrorhiza limnicola*. Murray (1986) states that muddy sand favours *Fursenkoina fusiformis* and shelly sand favours *Textularia truncata*.

The mean phi size of the sediment is positively correlated with all groups of Foraminiferida at Cawsand Bay except those of Shannon diversity, richness of species, Textulariina, Spirillinina, uniserial and suspension-feeders; and bears negative relationships with Fisher diversity and number of Foraminiferida with other types of apertures. Drake's Island Foraminiferida are positively correlated with abundance of triserial and planispiral forms, those of other coiling, pore apertures and infaunal forms.

Positive relationships indicate that Foraminiferida reproduce when the sediment becomes finer: this may indicate a preference for a more stable substratum and, because finer substrata are more nutritionally rich, this perhaps allows the growth necessary before reproduction can occur. The numbers of both epifaunal and infaunal Foraminiferida are strongly positively correlated with mean phi size at Cawsand Bay; however, the coefficient obtained for those which are epifaunal is higher than that for infaunal forms. Numbers of infaunal species are correlated with mean phi size at Drake's Island. Both epi- and in-faunal species probably benefit from the sediment being more stable as it becomes finer, and being able to support more unicellular algae and bacteria. The reproducing infaunal Foraminiferida at Drake's Island will probably not suffer from a lack of oxygen as the sediment

becomes finer in composition, due to the sediment being well-sorted at this site. The numbers of both herbivorous and detritivorous Foraminiferida are very strongly positively correlated with mean phi size at Cawsand Bay. South-westerly gales in the area during both autumn and spring probably result in high mean phi sizes at these times and would also be the time of bloom for unicellular algae and the deposition of detrital particles of macro-algae, allowing the reproduction of both groups without competition. This partitioning of feeding strategies reflects that there is little competition between the two groups, or species within the two groups. It appears that an increase in mean phi size at Cawsand Bay favours the growth of all sizes of Foraminiferida (specimens greater than 1000 μm are absent from this site). The >125 μm Foraminiferida at Drake's Island may prefer, more than other sizes, the stability and nutrition that a finer sediment may provide, or reflect the reproduction of larger species of Foraminiferida at this time.

There is a negative correlation between foraminiferid diversity and mean phi size at Cawsand Bay, indicating that as the sediment becomes finer the number of different species per number of Foraminiferida reduces. This relationship may be due to the increase in abundance of Foraminiferida which would reduce the Fisher α diversity index, and does not necessarily reflect a fall in the number of species present.

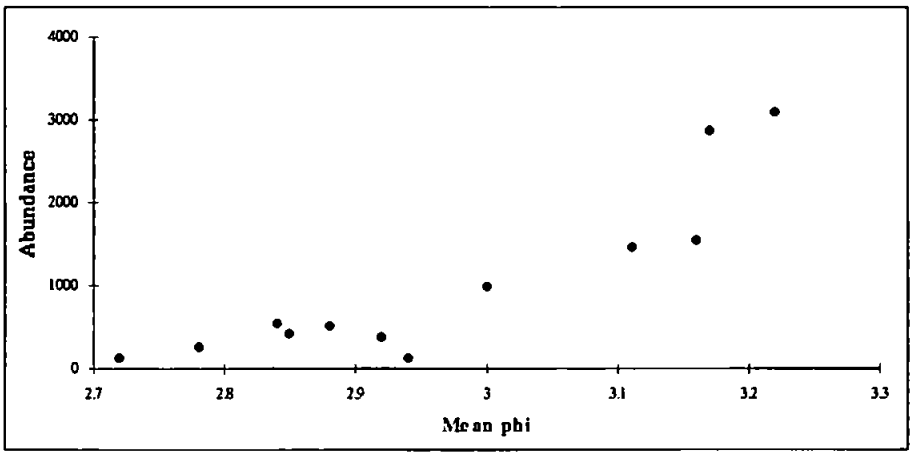


Figure 6.3: Scatter plot showing correlation of number of Foraminiferida per grab and mean phi size at Cawsand Bay (+0.886).

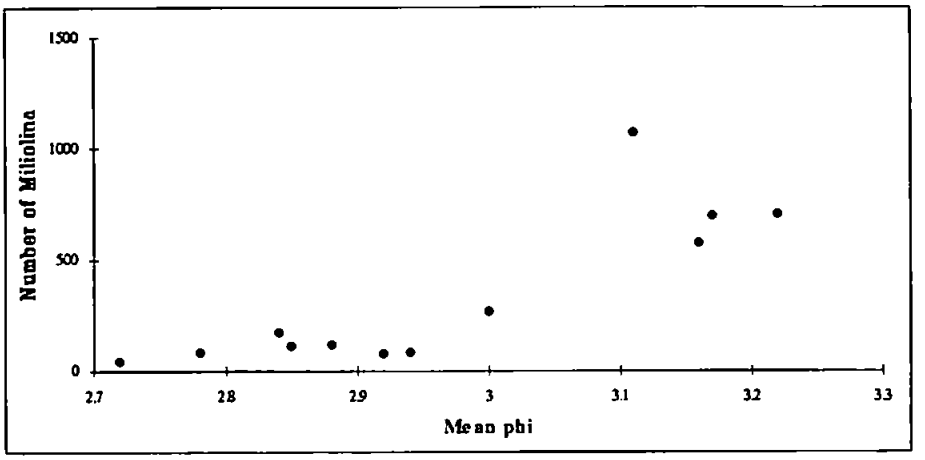


Figure 6.4: Scatter plot showing correlation of number of Miliolina per grab and mean phi size at Cawsand Bay (+0.841).

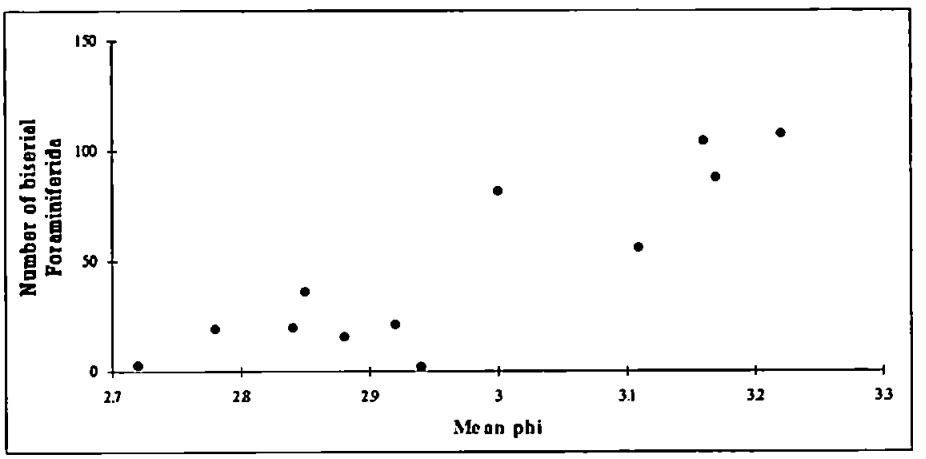


Figure 6.5: Scatter plot showing correlation of number of biserial Foraminiferida per grab and mean phi size at Cawsand Bay (+0.879).

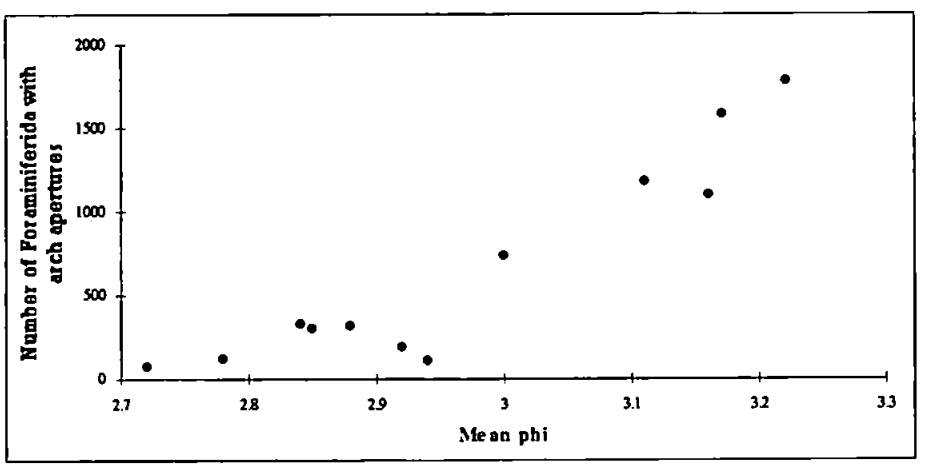


Figure 6.6: Scatter plot showing correlation of number of arch-shaped apertures per grab and mean phi size at Cawsand Bay (+0.929).

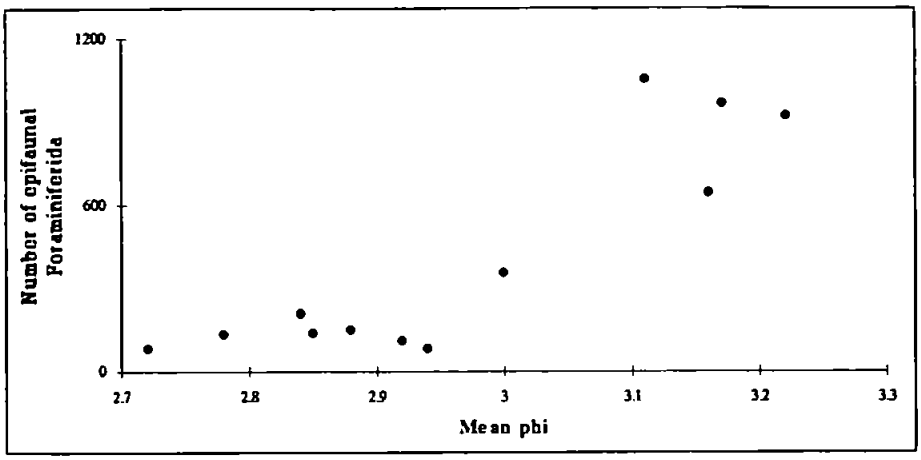


Figure 6.7: Scatter plot showing correlation of number of epifaunal Foraminiferida per grab and mean phi size at Cawsand Bay (+0.884).

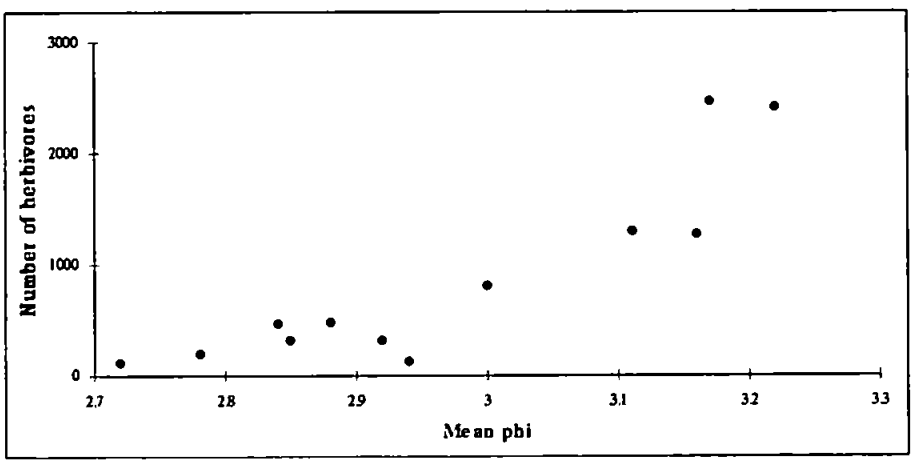


Figure 6.8: Scatter plot showing correlation of number of herbivorous Foraminiferida per grab and mean phi size at Cawsand Bay (+0.889).

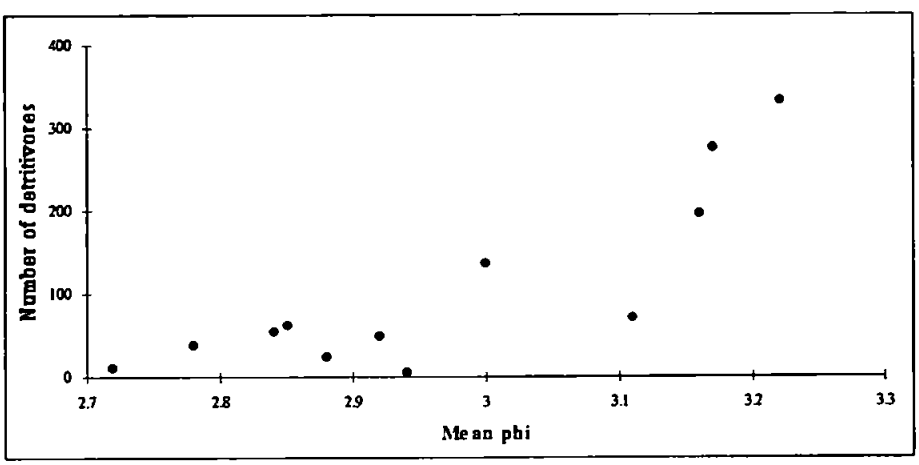


Figure 6.9: Scatter plot showing correlation of number of detritivorous Foraminiferida per grab and mean phi size at Cawsand Bay (+0.842).

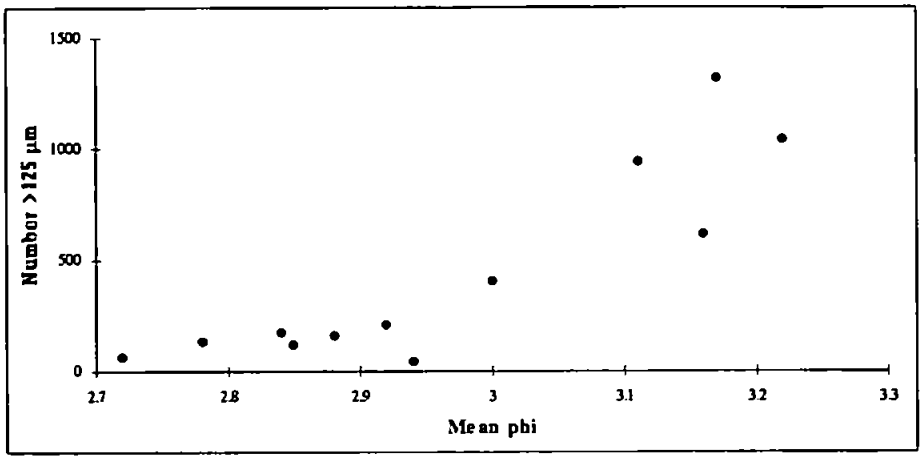


Figure 6.10: Scatter plot showing correlation of number of >125 µm Foraminiferida per grab and mean phi size at Cawsand Bay (+0.883).

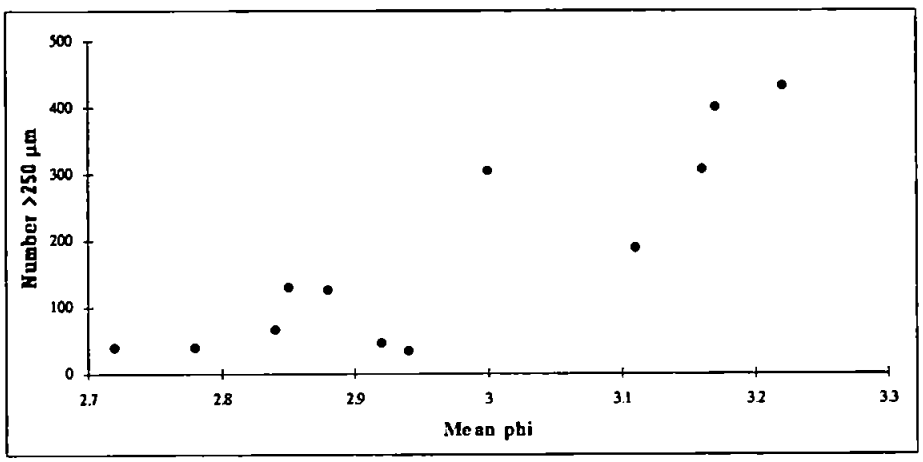


Figure 6.11: Scatter plot showing correlation of number of >250 µm Foraminiferida per grab and mean phi size at Cawsand Bay (+0.873).

6.5. SORTING OF THE SEDIMENT.

Table 6.5: Significant correlation coefficients between sorting of the sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of Spirillinina		0.832	
% Spirillinina	-0.768	0.753	
% trochospiral	-0.598		
% other apertures		0.870	
% >63 µm	-0.636		
% >125 µm	0.944		
Number > 500 µm		0.723	

Negative relationships between Foraminiferida and sorting of the sediment mean that as the sorting coefficient reduces (the sediment becomes better-sorted) the numbers of Foraminiferida rise. Strong currents and wave-action sort the sediment by placing the grains into suspension; the larger particles fall out of suspension closer to the area, whereas smaller particles may be transported by the current to be deposited further away. An increase in sorting of the sediment results in sediment that is mainly of one size. Sand-sized sediments are more easily transported and therefore better-sorted than finer or coarser sediments. Well-sorted sediments of particles greater than 63 μm are loosely-compacted and well-oxygenated, and toxins are more easily flushed from the sediment. Positive relationships between Foraminiferida and sorting indicate that Foraminiferida prefer the sediment to be less well-sorted and therefore more stable, and the mixture of particle sizes may include finer particles which will provide more attachment sites than coarser particles for unicellular algae and bacteria.

Foraminiferida at Drake's Island significantly correlated with sorting of the sediment (the number of Spirillinina, percentage of Spirillinina, percentage of other apertures and number > 500 μm) all bear positive relationships with this variable. Cawsand Bay percentage of Spirillinina, trochospiral forms and Foraminiferida > 63 μm are negatively correlated with sorting of the sediment, whilst the percentage of Foraminiferida > 125 μm are positively very strongly correlated with sorting of the sediment.

The negative correlation of percentage >63 μm sized Foraminiferida at Cawsand Bay with sorting may be the response to larger, mature Foraminiferida reproducing when the sediment is better sorted and oxygenated, and therefore juveniles of this size are present. Frankel (1972) states that some Foraminiferida reproduce below the sediment surface, and if the sediment is better sorted this would increase the oxygenated layer of the sediment, perhaps allowing sub-surface reproduction; and so the appearance of >63 μm Foraminiferida at the times of better-sorting of sediments. The very strong positive correlations between the percentage of the

assemblage at Cawsand Bay which is >125 µm, and the number of Foraminiferida at Drake's Island >500 µm, with sorting of the sediment indicate that these Foraminiferida are abundant when the sediment is poorly sorted. The negative correlations recorded may indicate that these foraminiferids benefit from the increased stability and nutritional value provided by a more poorly-sorted sediment, and the timing of reproduction in Foraminiferida may be to take advantage of these conditions. Positive correlations with sorting may indicate a preference for a more oxygenated, toxin-free sediment.

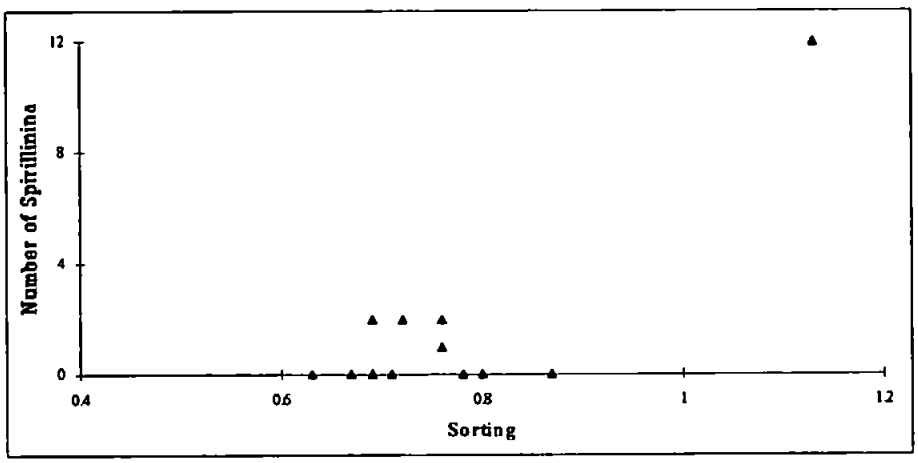


Figure 6.12: Scatter plot showing correlation of number of Spirillinina per grab with sorting at Drake's Island (+0.832).

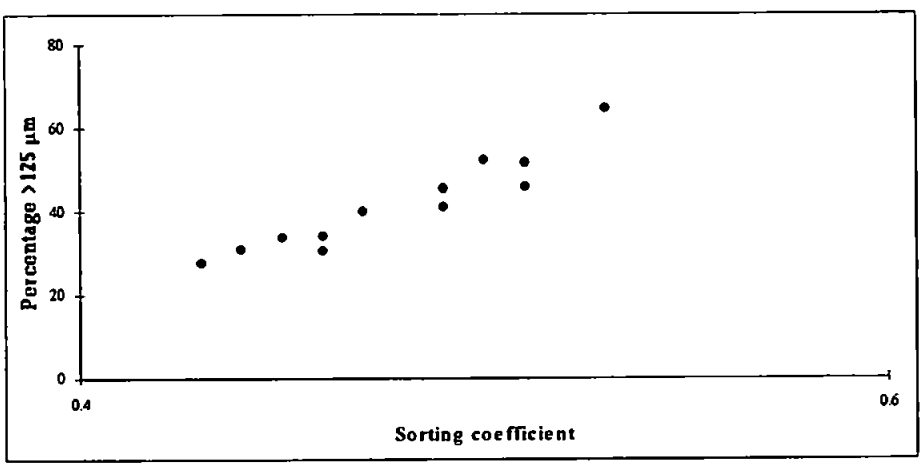


Figure 6.13: Scatter plot showing correlation of percentage of >125 µm Foraminiferida with sorting at Cawsand Bay (+0.944).

6.6. SKEWNESS OF THE SEDIMENT.

Table 6.6: Significant correlation coefficients between skewness of the sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Abundance	-0.897	-0.700	
Number of Textulariina	-0.639		
Number of Spirillinina		-0.826	
% Spirillinina		-0.737	
Number of Miliolina	-0.789	-0.673	
Number of Lagenina	-0.690	-0.592	
% Lagenina			-0.704
Number of Rotaliina	-0.828	-0.580	
Number of hyaline	-0.827	-0.610	
Number of unilocular	-0.678		
Number of uniserial	-0.699		
Number of biserial	-0.786	-0.719	
Number of triserial	-0.735		
Number of planispiral	-0.810		
Number of trochospiral	-0.812	-0.723	
Number of quinqueloculine	-0.742	-0.679	
Number of round apertures	-0.829		
Number of arch apertures	-0.896	-0.669	
Number of slit apertures	-0.693	-0.681	-0.612
Number of pore apertures	-0.821		
Number of epifaunal	-0.877	-0.712	
Number of infaunal	-0.838		
Number of herbivores	-0.912	-0.657	
Number of detritivores	-0.829		
Number of suspension-feeders		-0.767	
Number >63 μm	-0.790	-0.644	
Number >125 μm	-0.927		
Number >250 μm	-0.842	-0.807	
Number >500 μm	-0.778	-0.759	

Skewness of the sediment appears to be a very important variable for most groups of Foraminiferida at Cawsand Bay and for several groups at Drake's Island, whilst only having a significant relationship with two groups of Foraminiferida at White Patch. All significant correlations are negative, showing that as numbers of Foraminiferida within the groups increase the skewness coefficients fall. A reduction in skewness coefficients mean that the sediments become more coarsely-tailed in distribution; consisting of coarse particles. The negative correlations between groups of Foraminiferida and skewness indicate that numbers of Foraminiferida rise as sediments at the sites become coarser.

All data of Foraminiferida at Cawsand Bay, except Shannon and Fisher diversity measures, richness, evenness and those of other coiling and aperture types, are negatively correlated with skewness of the sediment. This means that almost all groups of Foraminiferida at Cawsand Bay reproduce when the sediment has a coarse tail of distribution. Drake's Island Foraminiferida (except Shannon and Fisher diversities, richness, evenness, Textulariina, unilocular, uniserial, triserial, planispiral, other coiling types, round apertures, pore apertures, infaunal and detritivores) are also negatively correlated with skewness of the sediment. The percentage of Lagenina and those with slit apertures at White Patch are negatively correlated with skewness.

These negative correlations may indicate that these types have sub-surface reproduction and/or benefit from the greater oxygenation a coarser sediment provides. Infaunal Foraminiferida would benefit from coarser sediment by having better oxygenated interstitial pore water, whereas epifaunal Foraminiferida may reproduce when the sediment is better flushed of toxins. The numbers of herbivores and detritivores are very strongly correlated with skewness at Cawsand Bay and numbers of herbivores and suspension feeders are correlated with skewness at Drake's Island. The correlation coefficients for Cawsand Bay are higher for herbivores than for detritivores indicating that skewness of the sediment is more important for the reproduction of herbivores than detritivores at this site. As the sediment becomes coarser these Foraminiferida reproduce and increase in numbers. The positive relationship between suspension feeders at Drake's Island and skewness of the sediment may indicate that although most suspension feeders are epilithic or epiphytic, having no direct contact with the sediment, the faster currents which better sort the sediment may provide the suspension feeders with a greater quantity of particles upon which to feed. The stronger relationship for >125 μm and >250 μm at Cawsand Bay, rather than for the >63 μm and >500 μm sizes, perhaps indicates that the >63 μm Foraminiferida are scarce due to larger species reproducing when the sediment is negatively skewed. The relatively weak

correlation between Cawsand Bay specimens of >500 μm and skewness may indicate that reproduction of this size of Foraminiferida occurs when the skew of the sediment is negative and so the parental Foraminiferida are lost from the live assemblage.

Cawsand Bay sediments are generally symmetrically distributed or positively-skewed, whereas sediments at Drake's Island are mainly symmetrical or negatively-skewed and White Patch sediments are generally negatively-skewed; and this may explain the number of relationships between Foraminiferida and skewness at each of these sites.

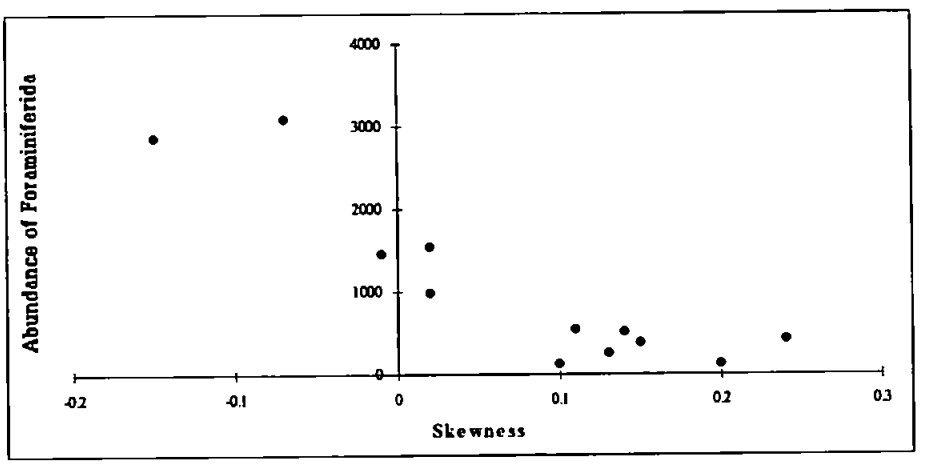


Figure 6.14: Scatter plot showing correlation of number of Foraminiferida per grab and skewness at Cawsand Bay (-0.897).

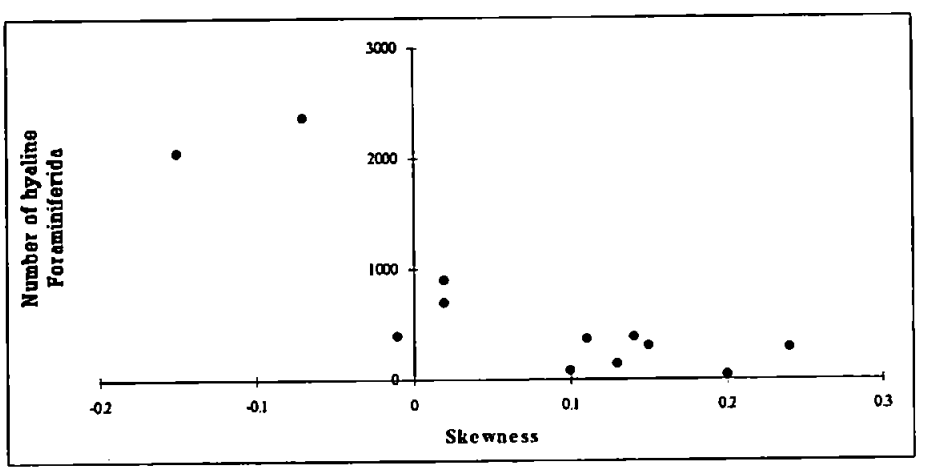


Figure 6.15: Scatter plot showing correlation of number of hyaline Foraminiferida per grab and skewness at Cawsand Bay (-0.827).

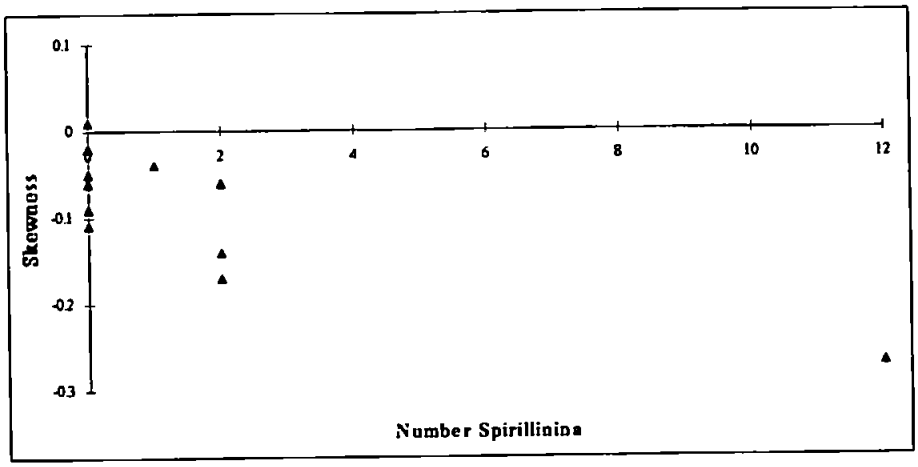


Figure 6.16: Scatter plot showing correlation of number of Spirillinina per grab and skewness at Drake's Island (-0.826).

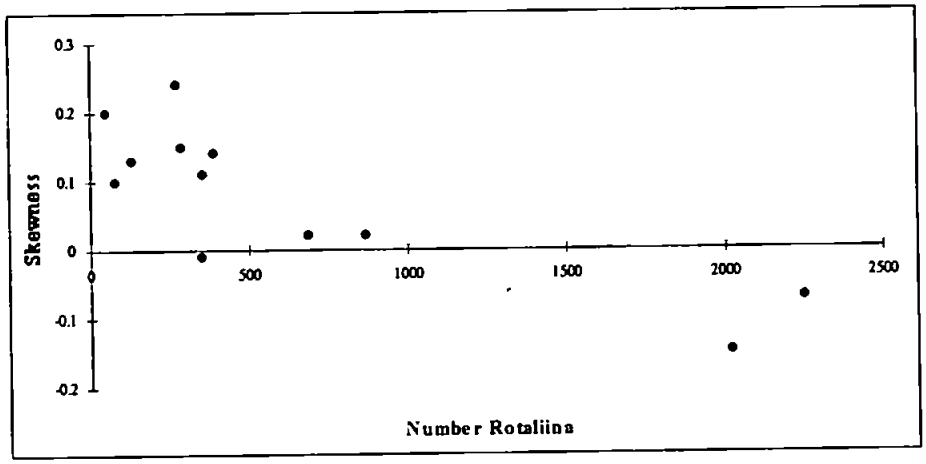


Figure 6.17: Scatter plot showing correlation of number of Rotaliina Foraminiferida per grab and skewness at Cawsand Bay (-0.828).

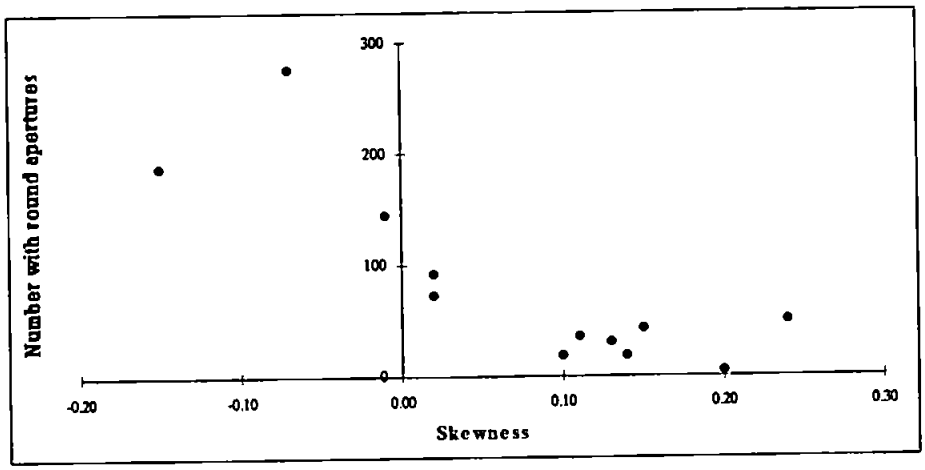


Figure 6.18: Scatter plot showing correlation of number of Foraminiferida with round apertures per grab and skewness at Cawsand Bay (-0.829).

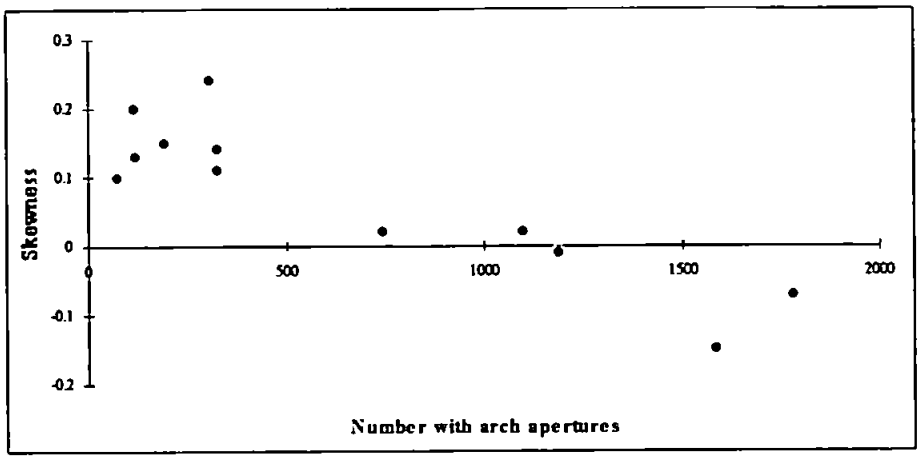


Figure 6.19: Scatter plot showing correlation of number of Foraminiferida with arch-shaped apertures per grab and skewness at Cawsand Bay (-0.896).

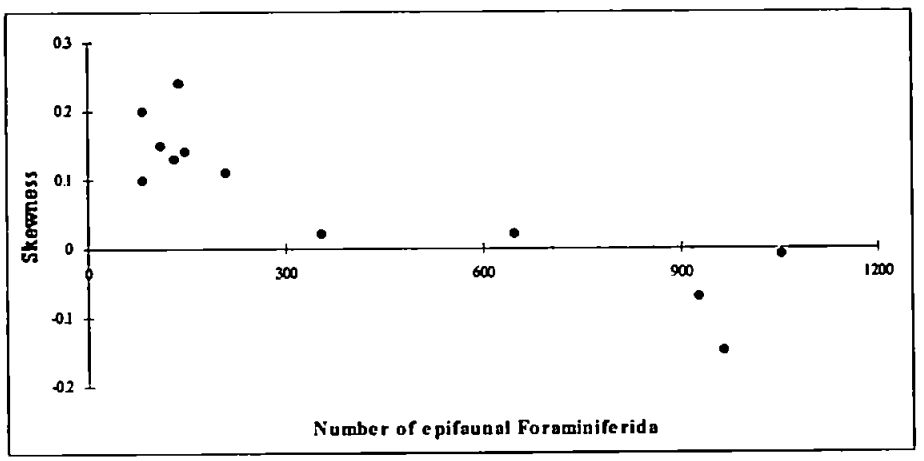


Figure 6.20: Scatter plot showing correlation of number of epifaunal Foraminiferida per grab and skewness at Cawsand Bay (-0.877).

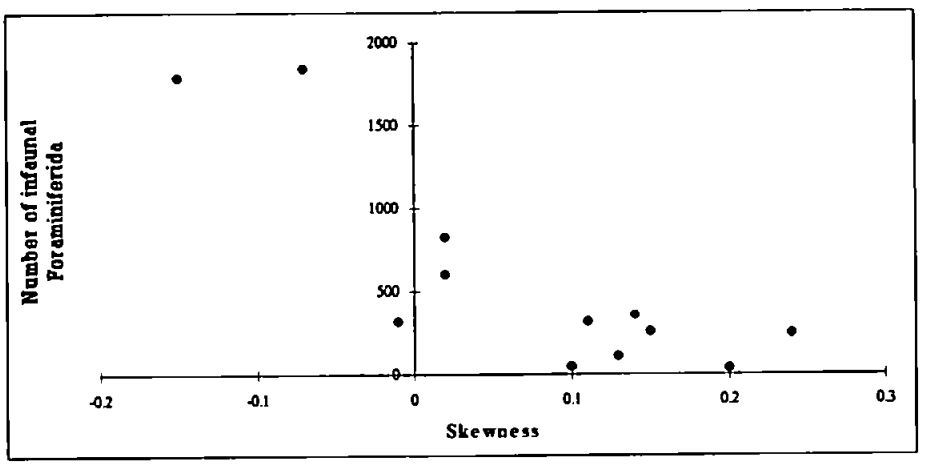


Figure 6.21: Scatter plot showing correlation of number of infaunal Foraminiferida per grab and skewness at Cawsand Bay (-0.838).

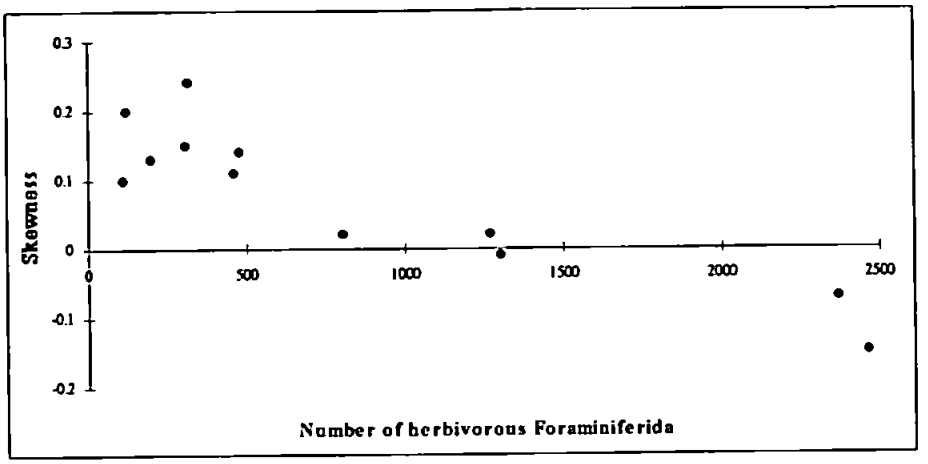


Figure 6.22: Scatter plot showing correlation of number of herbivorous Foraminiferida per grab and skewness at Cawsand Bay (-0.912).

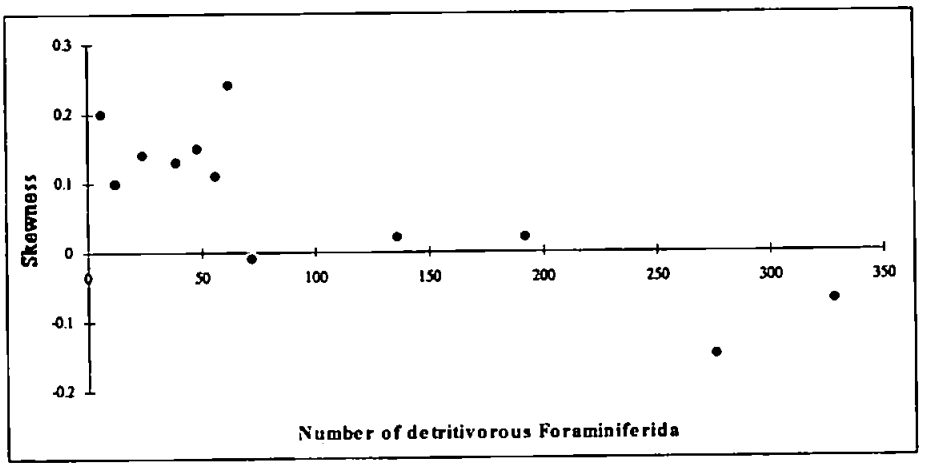


Figure 6.23: Scatter plot showing correlation of number of detrivorous Foraminiferida per grab and skewness at Cawsand Bay (-0.829).

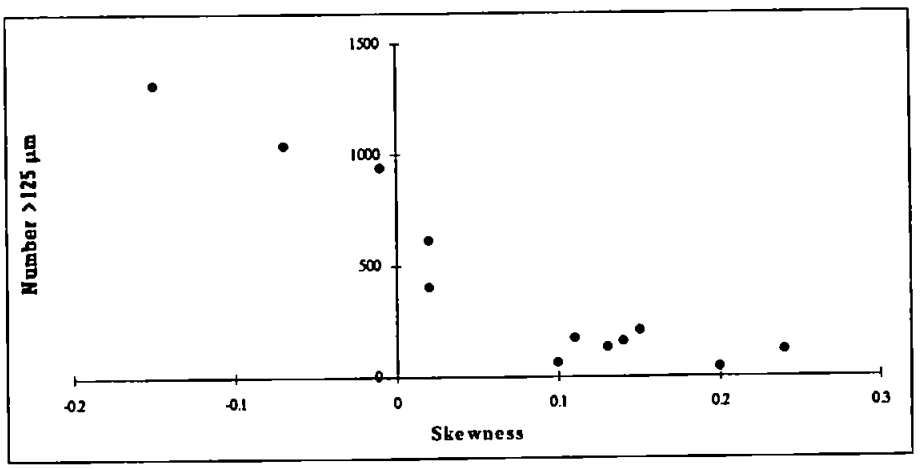


Figure 6.24: Scatter plot showing correlation of number of >125 µm Foraminiferida per grab and skewness at Cawsand Bay (-0.927).

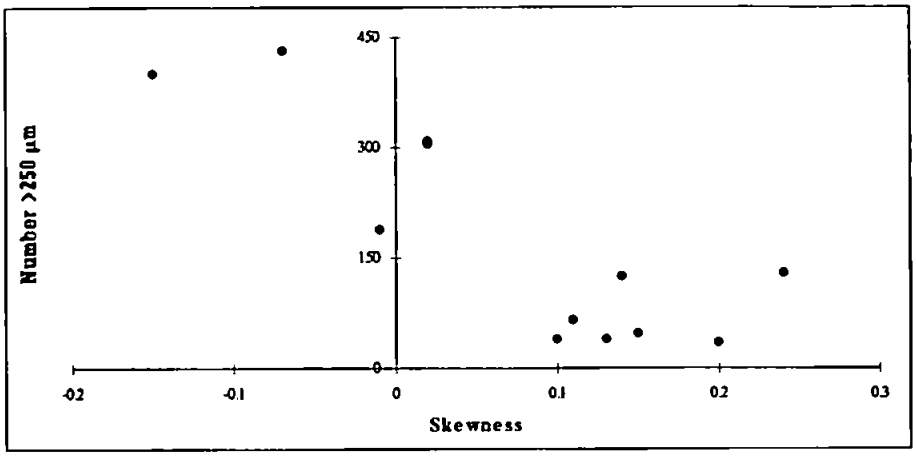


Figure 6.25: Scatter plot showing correlation of number of >250 µm Foraminiferida per grab and skewness at Cawsand Bay (-0.842).

6.7. KURTOSIS OF THE SEDIMENT.

Table 6.7: Significant correlation coefficient between kurtosis of the sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
% trochospiral		-0.623	

Kurtosis has only one significant correlation with Foraminiferida from the three sites. The relationship is negative, which means that means that the foraminiferid group increases as the sediment becomes less peaked than a normal distribution. The percentage of trochospiral Foraminiferida at Drake's Island is negatively correlated with kurtosis of the sediment and these individuals form a significant proportion of the assemblage, whilst the central portion of the sediment is poorly-sorted.

6.8. PERCENTAGE OF THE SEDIMENT LESS THAN 63 μm.

Fine sediment less than 63 μm provides a rich nutrient source for Foraminiferida, as unicellular algae and bacteria adhere to these fine particles in greater numbers than on coarser particles. Clay will also increase the laminar flow of water over the sediment, resulting in less disturbance of the sediment surface and to epifaunal Foraminiferida. Murray (1963) shows that Foraminiferida will ingest particles of kaolinite and he hypothesised that it was the size of the particle which is primarily important for selection and not the nutritional value. Kaolinite, however, will have proportionally greater numbers of unicellular algae and bacteria attached to it than coarser particles and, therefore, may be selected for digestion. An excess of fine sediment will reduce the oxygenated layer of sediment and may adversely affect infaunal Foraminiferida; Goard (1975) states that too much fine sediment may result in the coating of Foraminiferida and unicellular algae, thereby retarding metabolism. The percentage of the sediment less than 63 μm appears to be a very important variable for groups of Foraminiferida at Drake's Island. There are no significant relationships between White Patch Foraminiferida and the percentage of the sediment below 63 μm. This lack of relationship at this site probably reflects that there is sufficient clay at this site throughout the year (hence the name "White Patch", due to china clay settling here from the River Plym). There are very few significant relationships between Cawsand Bay specimens and percentage of fine sediment; here, too, perhaps there is sufficient fine sediment at this site throughout the annual cycle. At Drake's Island there are significant positive relationships between almost all groups of Foraminiferida and the percentage of fine sediment, reflecting the low proportion of the sediment which is fine (mean 4.26%). Almost all correlations (except one), are positive, indicating that groups of Foraminiferida reproduce in response to a more stable, nutrient-rich, substratum.

Table 6.8: Significant correlation coefficients between the percentage of the sediment less than 63 μm and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Abundance		0.763	
Number of Textulariina		0.661	
Number of Spirillinina		0.653	
% Spirillinina		0.653	
Number of Miliolina		0.676	
Number of Lagenina		0.611	
Number of Rotaliina		0.765	
Number of hyaline		0.769	
Number of unilocular		0.648	
Number of biserial		0.690	
Number of planispiral		0.814	
Number of trochospiral		0.707	
Number of quinqueloculine		0.677	
Number of round apertures		0.734	
Number of arch apertures		0.676	
Number of slit apertures		0.724	
Number of pore apertures		0.692	
Number of other apertures	0.582		
Number >63 μm		0.712	
Number >125 μm		0.629	
Number >250 μm		0.705	
Number >500 μm		0.580	
Percentage >500 μm	-0.584		
Number of epifaunal		0.719	
Number of infaunal		0.653	
Number of herbivores		0.741	
Number of detritivores		0.669	
% detritivores	0.678		
Number of suspension-feeders		0.819	

This variable is very important to most groups of Foraminiferida at Drake's Island (except for Shannon and Fisher diversities, evenness, richness, uniserial and triserial forms and those of other coiling). Cawsand Bay Foraminiferida of other apertures and the percentage of detritivores are positively correlated with the proportion of the sediment less than 63 μm. The percentage of Foraminiferida >500 μm are negatively correlated with the proportion of the sediment less than 63 μm. White Patch Foraminiferida bear no significant correlations with this variable.

The positive correlations may indicate that the increased nutritional value of silts and clay probably allows growth and subsequent reproduction of Foraminiferida, and may also indicate the importance of fine sediment providing additional stability

of the sediment. The correlation coefficients are slightly higher for epifaunal specimens than for infaunal specimens at Drake's Island, indicating that although the percentage of fine sediment is an important variable to both groups, then perhaps the increased laminar flow which fine sediment provides is important to epifaunal Foraminiferida. This finding contradicts Goard (1975), who states that infaunal forms depend more upon the amount of fine grains within the substratum, as most organic matter is concentrated with finer materials and supplements unicellular plants. The numbers of suspension feeders at Drake's Island increase in response to higher levels of fine sediment, perhaps because the levels of seston and phytodetritus at this site would be highest when the percentage of fine sediment is high. All sizes of Foraminiferida except those >1000 μm at Drake's Island are positively correlated with the percentage of fine sediments. It appears that most sizes at this site benefit from the increased nutrition the fine sediment provides for growth and reproduction. Specimens >1000 μm may not be correlated with fine sediment due to reproduction and death, however there is not a negative correlation, indicating that growth to this size and death through reproduction are balanced. The percentage of >500 μm Foraminiferida is negatively correlated with fine sediment at Cawsand Bay, indicating that, as Foraminiferida do not increase past this size at this site, the increased nutrients may induce reproduction and, therefore death in this size of Foraminiferida here.

6.9. SUMMARY.

Temperature is a very important variable for most groups of Foraminiferida at all sites. Most relationships are positive, indicating that reproduction of Foraminiferida occurs when temperature is relatively high. These relationships may also be linked to the bloom of the benthonic and planktonic unicellular plants, which also occur when temperature is high.

Salinity is not an important variable for the Foraminiferida at the three sites, producing only two significant correlations at Drake's Island. Salinity does not appear to affect the abundance of the sub-orders of Foraminiferida at the sites under investigation, probably because the sea water is of relatively good salinity, however, the influence of the River Tamar bringing fresh water to Drake's Island probably accounts for the correlations at this site.

Mean phi size of the sediment has no significant relationships with Foraminiferida at White Patch, and few at Drake's Island, but it is a very important variable for Foraminiferida at Cawsand Bay. This is a marine site with little organic input from the land, and therefore mean phi would be important for nutrition and stability of the sediment. Sorting is not an important variable for Foraminiferida at White Patch, but is positively correlated with some foraminiferid groups at Cawsand Bay and Drake's Island. The relationship between an increase in sorting coefficients and number of Foraminiferida indicates that some Foraminiferid groups benefit from greater oxygenation of the sediment. Skewness of the sediment appears to be important for Foraminiferida at Cawsand Bay, less so at Drake's Island, and only correlates with Foraminiferida at White Patch twice. All significant relationships with skewness are negative, indicating that Foraminiferida, especially at Cawsand Bay, prefer coarser sediments. Kurtosis of the sediment is not an important variable with only two significant correlations with Foraminiferida. Percentage of the sediment less than 63 μm is not an important variable for Foraminiferida at White Patch or Cawsand Bay, although it is a very important variable at Drake's Island. These relationships reflect the amount of fine material at these sites and it appears that at Drake's Island the fine material might provide more stability and nutrients to enable the Foraminiferida to reproduce.

Abiotic variables appear to be important to the Foraminiferida investigated and seem to dictate the timing of reproduction of many groups. These factors may influence biotic factors in the vicinity and therefore indirectly drive foraminiferid reproduction. Due to using correlation instead of regression techniques, it is

unclear as to whether increases in abiotic factors would further increase reproduction of the foraminiferid groups positively correlated with Foraminiferida.

CHAPTER 7.

CORRELATIONS OF BIOTIC VARIABLES AND FORAMINIFERIDA.

7.1. INTRODUCTION.

The data obtained from samples were analysed by statistical methods to ascertain if any significant relationships exist between the data for Foraminiferida and those of the biotic environmental variables at the three sampling sites. The statistical method used was correlation (see Chapter 6.0.). Correlation coefficients greater than 5% significance have been tabulated and only correlation coefficients greater than 0.1%, (*i.e.* 0.823; very strong correlations), have been plotted. Variables analysed were organic content of the sediment, number of bacteria per gram, number of colony-forming units per gram, percentage Gram positive rod-shaped bacteria, percentage Gram positive cocci bacteria, percentage Gram negative rods, percentage Gram negative cocci, percentage of the bacteria which are Gram positive, percentage of the bacteria which are cocci and numbers of Copepoda, Amphipoda, Ostracoda, Polychaeta, Bivalvia, Gastropoda, Scaphopoda and Acariformes per grab. Due to the great number of very strong correlations between Foraminiferida and other meiofauna at the sites investigated, plots between these groups are omitted. Four seasonal samples of diatoms were also taken from each site as part of the sampling suite, and because correlations are not valid for less than five data points, there are no site correlations. The diatom data set was correlated to that of the foraminiferid data set corresponding to the months and sites sampled for diatoms.

7.2. PERCENTAGE TOTAL ORGANIC CONTENT.

Table 7.1: Significant correlation coefficients between percentage organic content of the sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Eveness		0.670	
% biserial		0.738	
% other coiling		0.697	
% pore apertures	-0.644		
% arch apertures		0.622	
% >250 µm		0.616	

Organic content of the sediment should be an important variable by providing direct nutrition for detrivores and suspension feeders, whilst providing indirect nutrition for herbivores by providing nutrition for unicellular algae upon which the herbivorous species feed. Giere (1993) states that much of the detritus in sediments is the result of phytoplankton; and Thiel *et al.* (1988, 1989) state that an abundance of phytodetritus leads to a significant increase in meiofaunal abundance and diversity. There are few significant correlations, however, between total organic content of the sediment and Foraminiferida. This is doubtless because the measurement of the Total Organic Content of the sediments is not a true reflection of the available nutrients for Foraminiferida to utilise, as it incorporates sources of carbon not necessarily of nutrient material. The relationships at Drake's Island are positive, whilst at Cawsand Bay the single significant correlation is negative. No significant correlations were found at White Patch. Sediments from Drake's Island generally contained more organic material than at the other two sites and so the number of correlations between Foraminiferida and organic content at this site is unexpected. It may be, however, that because the sediment at this site is well-sorted medium sand that the nutrients are flushed from the sediment regularly, and although present at the time of sampling, are unstable and therefore not a true reflection of the proportion of nutrients available to the Foraminiferida at this site.

Evenness of Foraminiferida is positively correlated with percentage organic content of the sediment at Drake's Island. Percentage of biserial types and

Foraminiferida of other coiling are positively correlated with organic content at Drake's Island, as are the percentages of Foraminiferida with arch apertures and those >125 μm. The percentage of Foraminiferida with pore apertures is negatively correlated with organic content at Cawsand Bay.

The positive relationship between evenness of the fauna at Drake's Island and organic content of the sediment may reflect that when food is abundant species cannot dominate others and out-compete them. Biserial Foraminiferida such as the bolivinids and brizalinids (which generally have arch apertures) have been correlated with sediments high in organic content (Sieglie, 1968; Sen Gupta & Machain-Castillo, 1993), and it appears that at this site there is also such a positive correlation (as well as with the percentage of Foraminiferida with arch apertures). The increase in Foraminiferida >250 μm when organic content of the sediment rises perhaps indicates that relatively large species of Foraminiferida reproduce when the organic content of the sediment is high, so producing more individuals of this size range. The negative relationship between the percentage of pore-apertured Foraminiferida and organic content at Cawsand Bay may indicate that the pore-apertured elphidiids may suffer from oxygen deficiency if organic content is too high. The elphidiids have a high requirement for oxygen (Hannah *et al.*, 1994; Schafer *et al.*, 1995) and organic content is a factor which governs the depth at which sediments become anoxic (Fenchel, 1987). Altenbach (1992) finds that the biomass and reproductive cycles of *Elphidium excavatum clavatum* are directly related to the development and sedimentation of phytoplankton biomass over the year.

Although various authors have found that organic content of the sediment could be limiting to the distribution of Foraminiferida (see Uchio, 1962; Ansari *et al.*, 1980; Ajao *et al.*, 1991; Steinsund *et al.*, 1991) there is little evidence that organic content is limiting at the sites investigated. Bernhard (1986) states that there is a strong correlation between test morphology and total organic carbon in Jurassic to

Holocene Foraminiferida; and this is supported by the positive relationships between the percentages of biserial and other coiling forms at Drake's Island. Whilst Alve & Nagy (1986) state that agglutinated taxa have an affinity for increased organic content, this was not found at these nearshore locations. Setty & Nigam (1982) state that although *Ammonia* species have a positive tendency towards organic carbon and miliolids have a negative tendency; the positive relationship between Foraminiferida with arch apertures at Drake's Island may partially be caused by *Ammonia batavus*, although there is no evidence for a negative relationship between miliolids and organic content.

7.3. NUMBER OF BACTERIA PER GRAM OF SEDIMENT.

Table 7.2: Significant correlation coefficients between number of bacteria per gram of sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Evenness	-0.598		
Number of Miliolina	0.683		
% Miliolina	0.746		
% Rotaliina	-0.706		
% hyaline	-0.703		
% Lagenina			0.762
% unilocular			0.830
Number of quinqueloculine	0.744		
% quinqueloculine	0.735		
% arch aperture	0.689		
% infaunal	-0.624		
% epifaunal	0.608		
% >125 μm	0.665		

From laboratory experiments, Foraminiferida have a definite indispensable need for bacteria in their environment. It would be expected, therefore, that perhaps there would be more significant correlations between Foraminiferida and number of bacteria in the sediment, although the requirement for bacteria may be met by less bacteria than are present in the sediments at the localities investigated. More significant correlations are found at Cawsand Bay than at White Patch, with none present at Drake's Island. The numbers of bacteria at Drake's Island were usually a magnitude higher than at the other sites, perhaps explaining why there are no

significant correlations at this site. The numbers of bacteria at Cawsand Bay and White Patch are generally similar, however, reflecting that Cawsand Bay Foraminiferida react to the abundance of bacteria differently to those at White Patch.

Evenness of Foraminiferida at Cawsand Bay is negatively correlated with number of bacteria at this site, indicating that the evenness of foraminiferid species rises as the number of bacteria in the sediment falls. Numbers of Miliolina, and percentage Miliolina, are positively correlated with number of bacteria per gram at Cawsand Bay, whilst the percentage of Rotaliina and hyaline Foraminiferida are negatively correlated with the numbers of bacteria at this site. The percentage of Lagenina and unilocular specimens at White Patch are positively strongly correlated to the number of bacteria in the sediment. Both the number of, and percentage of, quinqueloculine Foraminiferida at Cawsand Bay are strongly positively correlated with bacterial numbers, as is the percentage of Foraminiferida with arch apertures. The percentage of epifaunal Foraminiferida at Cawsand Bay is positively correlated with number of bacteria per gram, whereas the percentage of infaunal Foraminiferida is negatively correlated with number of bacteria per gram of sediment at this site. The percentage of Foraminiferida >125 μm at Cawsand Bay is significantly correlated with number of bacteria in the sediment.

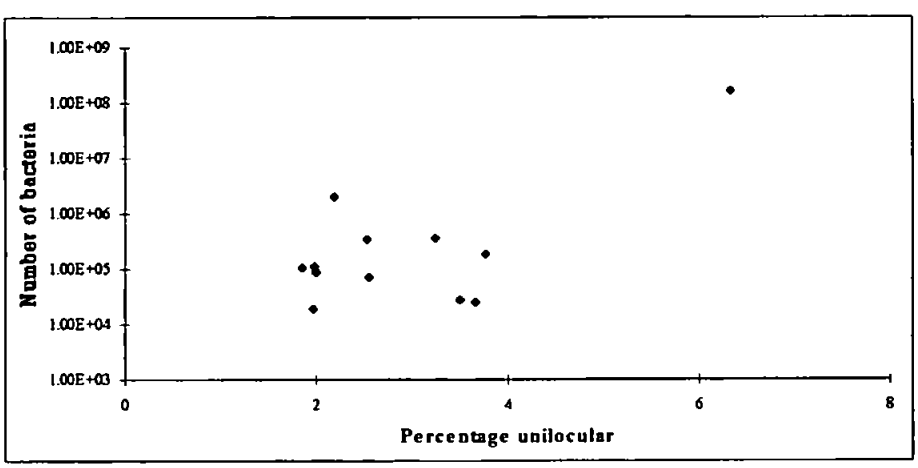


Figure 7.1: Scatter plot showing correlation of percentage of unilocular Foraminiferida per grab and number of bacteria per gram at White Patch (+0.830).

The negative relationship between evenness of Foraminiferida and number of bacteria present at Cawsand Bay may reflect that dominance by species through reproduction, which depend more upon bacteria for nutrition, take place when the bacteria are more numerous. It appears that the Miliolina at this site also reproduce when the bacteria in the sediment are more numerous, whereas the negative correlations between the percentages of both hyaline Foraminiferida and Rotaliina may indicate that as the number of, and percentage of, Miliolina rise in response to number of bacteria the percentage of hyaline and Rotaliina suffer a relative decline. The percentage of both unilocular Foraminiferida and Lagenina at White Patch are very strongly positively correlated with number of bacteria in the sediment, so that as the numbers of bacteria rise so the proportion of the assemblage which is unilocular also rises, as do Lagenina. The correlations of quinqueloculine coiling are slightly greater than the correlation between percentage of Miliolina and bacterial abundance at this site, indicating that the quinqueloculine miliolids have a stronger relationship with bacteria than the miliolids of other test shapes. As most miliolids have arch-shaped apertures, this correlation may also be linked to the response of this sub-order at this site to bacterial abundance. From the correlation coefficients, the percentage of epifaunal Foraminiferida shows a slightly stronger relationship with bacteria than that of the infaunal forms, perhaps suggesting that the relationship between bacteria and epifaunal specimens is the true relationship, and that the correlation with infaunal forms is in response to the epifaunal relationship. It appears, therefore, that epifaunal Foraminiferida reproduce when the number of bacteria in the sediment is high and the bacteria may provide direct nutrition, and/or indirectly provide vitamins and other metabolites which enable these Foraminiferida to reproduce. The bacteria may similarly promote the growth of >63 μm sized Foraminiferida to >125 μm.

7.4. BACTERIA: NUMBER OF MORPHOLOGICALLY DIFFERENTIATED COLONY FORMING UNITS PER GRAM OF SEDIMENT.

Table 7.3: Significant correlation coefficients between number of morphologically differentiated colony forming units per gram of sediment and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Evenness	-0.633		
% planispiral	-0.826		
% arch apertures	0.759		
% pore apertures	-0.815		
Number of infaunal		-0.583	

The number of morphologically differentiated colony forming units (cfu) which the bacteria form gives an indication of the diversity of bacteria at each site each month. This factor is significantly correlated with groups of Foraminiferida at Cawsand Bay, whilst only being significantly correlated with one group at Drake's Island.

Pielou's evenness of Foraminiferida is significantly negatively correlated with the number of different bacterial colony forming units at Cawsand Bay, as is the percentage of planispiral Foraminiferida. The percentage of Foraminiferida with pore apertures is very strongly negatively correlated with the number of cfu per gram of sediment at Cawsand Bay, whereas the percentage of arch-apertured Foraminiferida at this site increases as a proportion of the assemblage as the number of cfu rises. The numbers of infaunal Foraminiferida at Drake's Island are negatively correlated with the number of cfu at this site.

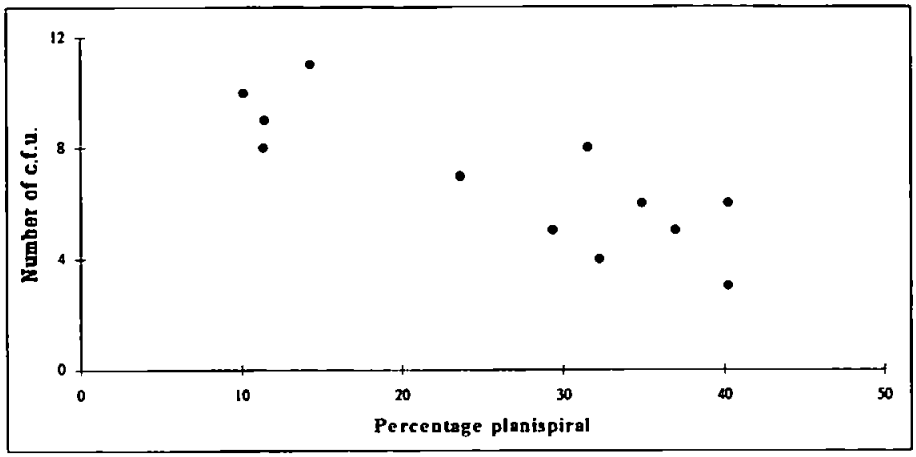


Figure 7.2: Scatter plot showing correlation of percentage planispiral Foraminiferida per grab and number of cfu per gram at Cawsand Bay (-0.826).

The negative correlation between Pielou's evenness of the foraminiferal fauna at Cawsand Bay and the number of cfu present at this site may show that when the diversity of the bacteria is high those species which rely upon bacteria as a food source, or benefit from their metabolites, reproduce when other species do not and therefore dominate the assemblage. The percentages of the assemblage at Cawsand Bay which have pore apertures and are planispiral are both negatively correlated with number of cfu. This may indicate that the percentage of planispiral forms (many of which have pore apertures) decrease as a proportion of the assemblage as those Foraminiferida with arch apertures reproduce and take advantage of the greater diversity of bacteria. The negative correlation with infaunal Foraminiferida at Drake's Island with number of cfu perhaps indicates that as the diversity of bacteria at this site rises the number of infaunal Foraminiferida suffer from the presence of some bacteria. It may be that some species of bacteria cause disease to Foraminiferida, especially infaunal forms.

7.5. BACTERIA: PERCENTAGE OF GRAM POSITIVE RODS.

Table 7.4: Significant correlation coefficients between percentage of Gram positive rods and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of Rotaliina			0.594
Number of Lagenina			0.633
Number of hyaline			0.597
Number of biserial			0.695
Number of triserial			0.688
Number of other coiling	0.638		
% other coiling	0.638		
Number of round apertures			0.688
% round apertures			0.688
Number of arch apertures			0.591
Number of infaunal			0.620
% herbivores			-0.642
Number of detritivores			0.689
% detritivores			0.623
Number suspension feeders			0.640
Number >63 μm			0.699
% >63 μm			0.581

The shape and type of bacteria present in the environment may be important nutritionally and/or for causing diseases of Foraminiferida. The percentage of the bacterial flora which are Gram positive rods are mainly correlated with Foraminiferida at White Patch, but form two significant correlations with Foraminiferida at Cawsand Bay. The percentage of Gram positive rods is comparatively high at White Patch in August and September, when the number of Foraminiferida at this site is maximal. None of these correlations is very strong, perhaps indicating that these correlations are happenstance. All correlations except one are positive, indicating that most groups of Foraminiferida benefit from the presence of Gram positive rod-shaped bacteria at White Patch.

The numbers of Rotaliina, Lagenina and hyaline Foraminiferida are all significantly positively correlated with percentage of Gram positive rods at White Patch. The numbers of both biserial and triserial Foraminiferida are also positively correlated with this group of bacteria at White Patch, as are the number and percentage of Foraminiferida with round apertures and the number of Foraminiferida with arch

apertures. Both the number and percentage of Foraminiferida of other types of coiling are positively correlated with percentage of Gram positive rods at Cawsand Bay. The number of infaunal Foraminiferida at White Patch is significantly positively correlated with percentage of Gram positive rod bacteria, as is the percentage of detritivorous Foraminiferida and the number of suspension feeders, whilst the percentage of herbivorous Foraminiferida at this site is negatively correlated with Gram positive rods. Both the numbers of, and percentage of, Foraminiferida >63 μm are positively correlated with Gram positive rods at White Patch.

The positive relationships indicate that numbers of these groups of Foraminiferida increase as the percentage of Gram positive rods increases. It may be possible that these bacteria provide, directly or indirectly, valuable nutrition, metabolites or vitamins which enable these groups of Foraminiferida to reproduce. It also may be that the shape of these bacteria benefits certain Foraminiferida of specific apertural shapes. These bacterial types also appear to benefit infaunal Foraminiferida, perhaps because these bacteria are infaunal themselves, thus providing nutrition for infaunal specimens rather than for epifaunal individuals. It appears that the detrivores and suspension feeders at this site prefer a high abundance of Gram positive rods; the detritivores will depend more upon bacteria as a food source than herbivores, perhaps explaining the negative relationship with herbivores at this site. The positive relationship between suspension feeders and percentage of Gram positive rods may be related to these bacteria multiplying in response to seston falling from the water column. This type of bacteria may also, by aiding foraminiferid reproduction, produce specimens of >63 μm, or indicate that reproduction of species which do not grow greater than this size has occurred.

7.6. BACTERIA: PERCENTAGE OF GRAM POSITIVE COCCI.

Table 7.5: Significant correlation coefficients between percentage of Gram positive cocci and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of other apertures	-0.584		
% round apertures			-0.665
% detritivores			-0.651
% >63 μm	-0.625		
% >125 μm			0.710

From Table 7.5 it can be seen that significant correlation coefficients between Foraminiferida and the percentage of Gram positive cocci are relatively few and mostly negative. No significant coefficients are produced for Drake's Island Foraminiferida and this variable, with two between Cawsand Bay Foraminiferida and three produced between White Patch Foraminiferida and this variable.

The number of Foraminiferida with other apertures is significantly negatively correlated with percentage of Gram-positive cocci at Cawsand Bay, whilst the percentage of Foraminiferida at White Patch with round apertures is negatively significantly correlated with this variable. At White Patch the percentage of detritivores is negatively correlated with these bacteria. The percentage of Foraminiferida >63 μm at Cawsand Bay is negatively correlated with the percentage of Gram positive cocci at this site, whilst the percentage of White Patch foraminiferid fauna >125 μm is positively correlated with the percentage of Gram positive cocci.

The negative relationships demonstrated between Foraminiferida and these bacteria may indicate that these Foraminiferida may be directly adversely affected by an increase in these bacteria through disease or the metabolites they produce, or may be adversely affected by the conditions in which this type of bacteria proliferate. The positive relationship may indicate that the foraminiferid group benefits directly, or indirectly from the presence of these bacteria.

The White Patch fauna bears opposing coefficients for the same two groups of Foraminiferida and the percentage of the bacterial fauna which is Gram positive cocci and rods. The percentage of Foraminiferida at this site with round apertures and those which are detritivores are negatively correlated with Gram positive cocci whilst being positively correlated with Gram positive rods. The positive relationships have slightly higher coefficients than the negative relationships and so it may be inferred that the positive relationships are the most likely to affect these groups.

7.7. BACTERIA: PERCENTAGE OF GRAM NEGATIVE RODS.

Table 7.6: Significant correlation coefficients between percentage of Gram negative rod-shaped bacteria and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
% Textulariina		-0.601	
Number of other apertures	0.629		

These types of bacteria have very few significant correlation coefficients with groups of Foraminiferida from the sites investigated. One relationship is positive and the other is negative, so no suggestions as to whether their presence is generally beneficial or detrimental to Foraminiferida can be made. The percentage of Textulariina is negatively correlated with the percentage of Gram-negative rod-shaped bacteria at Drake's Island and the number of Foraminiferida with other types of apertures is positively correlated with percentage of Gram-negative rod-shaped bacteria at Cawsand Bay. It may be that the Textulariina increase as a proportion of the foraminiferid assemblage at Drake's Island when other types of bacteria proliferate, although no positive significant coefficients have been produced for this group and any other group of bacteria identified. The positive relationship between Foraminiferida of other types of apertures may be the result of the positive relationship between this group and the percentage of Gram positive cocci already discussed.

7.8. BACTERIA: PERCENTAGE OF GRAM NEGATIVE COCCI.

Table 7.7: Significant correlation coefficients between percentage of Gram negative cocci and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
% round apertures		-0.589	

From Table 7.7 it can be seen that only one weak significant relationship exists between Foraminiferida at the three sites and the percentage of Gram negative cocci. This may reflect the limited relative abundance of this type of bacteria at the three sites (reaching maxima of 40% at Cawsand Bay in May; 33% at Drake's Island in August and July, although frequently 0%; 18% at White Patch in December). The percentage of Foraminiferida with round apertures is negatively correlated with percentage of Gram negative cocci at Drake's Island. It may be for this group of Foraminiferida at this site, that a proliferation of Gram negative cocci causes a detrimental environment, or these foraminiferids proliferate when other types of bacteria dominate the bacterial assemblage.

7.9. BACTERIA: PERCENTAGE OF GRAM POSITIVE.

Table 7.8: Significant correlation coefficients between percentage of Gram positive bacteria and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of Spirilinina			-0.646
% Spirilinina			-0.617

From Table 7.8 there are only two significant correlations with the percentage of the bacterial fauna which is Gram positive; both relationships are between Spirillinina at White Patch and the bacteria, and both are negative. It appears that Spirillinina, therefore, benefit from the presence of Gram negative bacteria and are detrimentally affected by a predominance of Gram positive bacteria. It would be expected that there would be many significant coefficients with reference to Tables

7.5 and 7.6, and the relative lack of significant coefficients indicates that the shape of the bacteria is an important factor to the Foraminiferida.

7.10. BACTERIA: PERCENTAGE OF COCCI.

Table 7.9: Significant correlation coefficients between percentage of cocci shaped bacteria and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of other apertures	-0.679		
% >63 μm			-0.599

The number of Foraminiferida with other apertures at Cawsand Bay is negatively correlated with cocci-shaped bacteria. Foraminiferida with this type of aperture will be positively correlated with rod-shaped bacteria, therefore, and perhaps benefit from their presence and allow reproduction of these foraminiferid groups. The percentage of Foraminiferida >63 μm at White Patch is negatively correlated with cocci-shaped bacteria at White Patch; therefore, the rod-shaped bacteria may promote the reproduction of Foraminiferida at this site.

The relative lack of significant correlations between cocci-shaped bacteria and, from Table 7.8 the percentage of Gram positive bacteria, indicate that both the stain and the shape of bacteria within the environment are important factors to the Foraminiferida in the habitat.

7.11. OTHER MEIOFAUNA: ABUNDANCE OF COPEPODA.

Table 7.10: Significant correlation coefficients between numbers of Copepoda and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab	0.852		0.717
Number of Miliolina	0.866		0.719
Number of Lagenina	0.783		0.714
Number of Rotaliina	0.734		0.692
Number of hyaline	0.740		0.696
Number of unilocular	0.774		0.730
Number of biserial	0.921		0.778
Number of triserial	0.764		
Number of planispiral	0.674		
Number of trochospiral	0.750		0.578
Number of quinqueloculine	0.827		0.709
Number of round apertures	0.844		0.716
Number of slit apertures	0.756		0.650
Number of arch apertures	0.913		0.739
Number of pore apertures	0.650		
Number of epifaunal	0.900		0.615
Number of infaunal	0.742		0.699
Number of herbivores	0.850		0.692
Number of detritivores	0.828		0.723
% Suspension-feeders		-0.693	
Number >63 μm	0.748		0.705
Number >125 μm	0.864		0.592
Number >250 μm	0.862		0.577
Number >500 μm	0.721		

The abundance of Copepoda is significantly positively correlated to almost all groups of Foraminiferida from both Cawsand Bay and White Patch. The almost complete lack of relationships between Copepoda and Foraminiferida at Drake's Island reflects that this site is dominated by Ostracoda, whilst Cawsand Bay and White Patch are dominated by Copepoda throughout the annual sampling period. The positive correlations obtained probably indicate that Copepoda reproduce when the Foraminiferida do, although they do not compete for food or space resources in the environment. The correlation coefficients produced from the data are all positive with the exception of the only significant coefficient between Foraminiferida from Drake's Island and Copepoda.

The number of Foraminiferida at Cawsand Bay has a very strong relationship with the number of Copepoda at this site, and the number of Foraminiferida at White

Patch also has a strong relationship with the abundance of Copepoda. These relationships indicate that Copepoda reproduce at the same time as the Foraminiferida, and probably in response to the same environmental cues. Numbers of Miliolina, Lagenina, Rotaliina and hyaline Foraminiferida are correlated with number of Copepoda at both Cawsand Bay and White Patch. The correlation coefficients at both sites increase from Rotaliina to hyaline taxa to Lagenina and Miliolina. The number of unilocular, biserial, triserial, planispiral, trochospiral and quinqueloculine Foraminiferida are all positively correlated with number of Copepoda per grab at Cawsand Bay, whilst at White Patch unilocular, biserial, trochospiral and quinqueloculine Foraminiferida are positively correlated with these organisms. The number of Foraminiferida with round, slit and arch apertures are correlated with number of copepods at both Cawsand Bay and White Patch, whilst the number of Foraminiferida with pore apertures at Cawsand Bay is also correlated positively with Copepoda. The numbers of both infaunal and epifaunal Foraminiferida at Cawsand Bay and White Patch are positively correlated with number of Copepoda. These correlations probably form part of the relationships between Foraminiferida and Copepoda and further demonstrate the synchronised reproduction of Foraminiferida and Copepoda in these areas. The numbers of herbivores and detritivores are correlated with numbers of Copepoda; the correlations are good at White Patch and very strong at Cawsand Bay. The numbers of all test sizes present at Cawsand Bay are strongly correlated with the number of Copepoda, whilst at White Patch all test sizes except those of >500 μm and >1000 μm are correlated with Copepoda. This may indicate that at White Patch, although the growth of Foraminiferida may be relatively quick after reproduction, there is a slowing-down of the growth rate so that those individuals of >500 μm and >1000 μm are not part of the correlation for reproduction of these two groups of benthonic meiofauna. Copepoda collected are rarely greater than the size range between 250 μm and 500 μm, and therefore might not correspond with the larger species of Foraminiferida at White Patch for this reason, although growth rates of the two groups may differ considerably. These groups of

Foraminiferida must reproduce at the same time as the Copepoda, and it appears that neither group of these benthonic meiofauna suffers from competition.

7.12. OTHER MEIOFAUNA: ABUNDANCE OF AMPHIPODA.

Table 7.11: Significant correlation coefficients between number of Amphipoda and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab	0.741		
Number of Miliolina	0.722		
Number of hyaline	0.651		
Number of Rotaliina	0.651		
Number of uniserial	0.741		
Number of biserial			0.679
Number of planispiral	0.701		
Number of trochospiral	0.594		
Number of quinqueloculine	0.687		
Number of round apertures	0.719	0.599	
Number of arch apertures	0.716		
Number of pore apertures	0.717		
Number of epifaunal	0.782		
Number of infaunal	0.658	0.577	
Number of herbivores	0.772		
Number >63 μm	0.632		
Number >125 μm	0.842		

The number of Amphipoda per grab was relatively low at all sites sampled, but the abundance of these meiofauna corresponded well with abundance of Foraminiferida at Cawsand Bay, reflecting the more numerous significant correlations at this site than at the other two sites. All correlations are positive meaning that these two groups of meiofauna probably reproduce at the same time and do not compete for food or space.

The number of Foraminiferida per grab and the number of Amphipoda per grab are strongly correlated at Cawsand Bay as are the numbers of Miliolina, Rotaliina and hyaline Foraminiferida. The numbers of uniserial, planispiral, trochospiral and quinqueloculine Foraminiferida are all correlated with the numbers of Amphipoda at Cawsand Bay, whilst the numbers of biserial forms are correlated with Amphipoda at White Patch. Foraminiferida with arch and pore apertures are

correlated with the number of Amphipoda at Cawsand Bay, and the number of Foraminiferida with round apertures are correlated with Amphipoda at both Cawsand Bay and at Drake's Island. The number of epifaunal Foraminiferida is correlated strongly with Amphipoda at Cawsand Bay, whilst the number of infaunal Foraminiferida is correlated with Amphipoda at both Cawsand Bay and Drake's Island. The number of herbivores is strongly correlated with the abundance at Cawsand Bay. Amphipoda feed upon seston, detritus and scavenge amongst the sediment and so do not compete with herbivorous Foraminiferida for food. The number of Foraminiferida of both >63 μm and >125 μm size are correlated with number of Amphipoda at Cawsand Bay. This re-inforces the assumption that these two groups of benthonic meiofauna reproduce at the same time at this site. At this site the Amphipoda reproduce when the Foraminiferida reproduce, probably in response to the same environmental cues.

7.13. OTHER MEIOFAUNA: ABUNDANCE OF OSTRACODA.

Table 7.12: Significant correlation coefficients between number of Ostracoda (two connected valves and stained) and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab	0.845	0.956	0.837
Richness			0.578
Number of Textulariina		0.701	
Number of Miliolina	0.613	0.966	0.778
Number of Spirillinina	0.759	0.658	
Number of Lagenina	0.884	0.960	0.869
% Lagenina		0.751	
Number of Rotaliina	0.837	0.883	0.821
Number of hyaline	0.844	0.904	0.827
Number of unilocular	0.885		0.881
Number of uniserial			0.589
Number of biserial	0.790	0.953	0.872
Number of triserial	0.898		0.723
Number of planispiral	0.834	0.811	0.685
Number of trochospiral	0.801	0.864	0.643
Number of quinqueloculine		0.965	0.780
Number of other coiling		0.880	
Number of round apertures	0.859	0.746	0.885
Number of slit apertures	0.885	0.966	0.860
Number of arch apertures	0.811	0.967	0.817
Number of pore apertures	0.792		0.667
Number of other apertures			0.786
Number of epifaunal	0.712	0.971	0.717
Number of infaunal	0.823	0.712	0.819
Number of herbivores	0.815	0.951	0.798
Number of detritivores	0.885	0.909	0.867
Number suspension-feeders	0.747	0.883	
Number >63 µm	0.880	0.963	0.823
Number >125 µm	0.743	0.668	0.787
Number >250 µm	0.755	0.887	0.580
Number >500 µm	0.705	0.805	
Number >1000 µm		0.732	
% > 1000 µm		0.732	

Ostracoda are strongly correlated with the number of almost all groups of Foraminiferida from all sites. This means that Ostracoda share the same reproductive period of all groups of Foraminiferida and as there is no evidence of negative relationships between these two groups of meiofauna it seems likely that Ostracoda and Foraminiferida do not compete for food resources or for space in the sites investigated.

All sites investigated have very strong correlation coefficients between abundance of Ostracoda and Foraminiferida. The numbers of Ostracoda are significantly positively correlated to the richness of foraminiferid species at White Patch; therefore, as numbers of Ostracoda rise, so do number of foraminiferid species. It may be possible that more species of Foraminiferida provide different metabolites benefiting Ostracoda directly or indirectly, or *vice versa*. The often very strong correlations of Ostracoda and groups of Foraminiferida at all sites indicate that these two groups of benthonic meiofauna suffer no detrimental effects of the presence of each other. Ostracoda are detritivores and it would be expected that the detrivorous Foraminiferida would compete with the Ostracoda for this food source; this does not occur and perhaps indicates that these meiofauna utilise different components of the detrital organic matter which is available at the sites investigated.

7.14. OTHER MEIOFAUNA: ABUNDANCE OF POLYCHAETA.

Table 7.13: Significant correlation coefficients between number of Polychaeta and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab			0.603
Number of Lagenina			0.653
% of Lagenina	0.594		
Number of Rotaliina			0.659
Number of hyaline			0.661
Number of unilocular			0.656
% unilocular	0.599		
Number of biserial			0.798
Number of trochospiral			0.621
% trochospiral		0.578	
Number of round apertures			0.764
Number of arch apertures			0.625
Number of slit apertures			0.578
% slit apertures	0.620		
Number of other apertures			0.661
Number of infaunal			0.737
Number of detritivores			0.719
% suspension-feeders		0.621	
Number >63 μm			0.696

Polychaeta are relatively rare components of the meiofauna at the sites investigated. Only one specimen was found at Drake's Island, reflecting that the unstable substratum at this site is unsuitable for Polychaeta to form their tube-shaped burrows, and indicates that the significant correlations found for percentage of trochospiral Foraminiferida and suspension-feeders at this site are untenable. Polychaeta are present at Cawsand Bay only in five months of the year and always less than five specimens per sample. This site only has few significant correlations with the percentage of the foraminiferid fauna which is Lagenina, unilocular and those with slit apertures. White Patch Polychaeta are present only in two months of the sampling period; 20 specimens in September and 4 specimens in January. The correlation with abundance of Foraminiferida and number of >63 μm Foraminiferida at White Patch shows that the Polychaeta probably reproduce at this site when the Foraminiferida do, and, in particular, when the Lagenina, Rotaliina and hyaline forms do. Significant correlations are also found for unilocular, biserial and trochospiral Foraminiferida, as well as those Foraminiferida with round, arch, slit and other types of apertures. Strong correlations are found at White Patch for number of infaunal Foraminiferida and detritivores indicating that these Foraminiferida and the Polychaeta share both life-position and feeding strategies. All correlations are positive, indicating that both groups increase in abundance at the same time; probably the Polychaeta, which are predators of Foraminiferida, benefit from the increased abundance of Foraminiferida.

7.15. OTHER MEIOFAUNA: ABUNDANCE OF BIVALVIA.

Table 7.14: Significant correlation coefficients between number of Bivalvia (two connecting valves and staining) and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab		0.661	
Shannon diversity		0.705	
Number of Miliolina		0.619	
Number of Rotaliina		0.699	
Number of hyaline		0.686	
Number of unilocular		0.595	
Number of planispiral		0.690	
Number of trochospiral		0.680	
Number of quinqueloculine		0.622	
Number of other coiling		0.642	
Number of round apertures		0.747	
Number of arch apertures		0.600	
Number of pore apertures		0.657	
Number of infaunal		0.663	
Number of epifaunal		0.619	
Number of herbivores		0.679	
Number suspension-feeders		0.683	0.583
Number >63 μm		0.586	
Number >125 μm		0.762	
Number >250 μm		0.609	

The numbers of Bivalvia at Cawsand Bay and White Patch are relatively few, but at Drake's Island Bivalvia are present in relatively large numbers throughout the year. This is reflected by the number of correlations between Bivalvia and Foraminiferida at the sites. Abundance of all Foraminiferida is correlated at Drake's Island with abundance of Bivalvia, as are the abundance of Miliolina, Rotaliina, hyaline, unilocular, planispiral, trochospiral, quinqueloculine and Foraminiferida of other coiling. The numbers of Foraminiferida with round, slit, arch and pore apertures, as well as those of >63 μm, >125 μm and >250 μm, are correlated with Bivalvia at Drake's Island. Numbers of Bivalvia at Drake's Island are also correlated with the Shannon diversity of the Foraminiferida at this site; this may indicate that the seston providing food for the suspension-feeding Bivalvia provides nutrients for suspension-feeding Foraminiferida at this site, so increasing the diversity of Foraminiferida. The numbers of both infaunal and epifaunal Foraminiferida at Drake's Island are correlated with Bivalvia, although the coefficient for the infaunal forms is slightly higher than that for the epifaunal forms.

Although herbivores are correlated with Bivalvia at Drake's Island, the numbers of suspension-feeders are correlated with Bivalvia at both Drake's Island and White Patch; reflecting that Bivalvia are both herbivorous and suspension-feeders, and that both groups increase in abundance to capitalise upon the seston and unicellular algae available in the environment.

7.16. OTHER MEIOFAUNA: ABUNDANCE OF GASTROPODA.

Table 7.15: Significant correlation coefficients between the number of Gastropoda and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number of Spirillinina	0.803		
% Spirillinina		0.629	
Number of Lagenina	0.811		
Number of Rotaliina	0.625		
Number of hyaline	0.635		
Number of unilocular	0.809		
Number of uniserial			0.637
% uniserial			0.723
Number of triserial	0.689		
Number of planispiral	0.635		
Number of trochospiral	0.612		
Number of round apertures	0.681		
Number of slit apertures	0.823		
Number suspension-feeders	0.842		
Number of detritivores	0.590		
Number >63 μm	0.706		

Gastropoda are relatively rare at Cawsand Bay and White Patch, although at Drake's Island numerous specimens were present in most of the samples. Only one gastropod was found at Cawsand Bay, bringing all significant correlations at this site into doubt. The correlation with Drake's Island Foraminiferida, however is probably valid.

7.17. OTHER MEIOFAUNA: ABUNDANCE OF SCAPHOPODA.

Table 7.16: Significant correlation coefficients between the number of Scaphopoda and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Number per grab			0.604
Number of Spirillinina		0.867	
% Spirillinina		0.839	
Number of Lagenina			0.690
Number of Rotaliina			0.648
Number of hyaline			0.652
Number of unilocular			0.678
Number of biserial			0.812
Number of triserial			0.583
Number of trochospiral			0.577
Number of round apertures			0.782
Number of arch apertures			0.620
Number of slit apertures			0.617
Number of other apertures			0.621
Number infaunal			0.724
Number detritivores			0.745
Number suspension-feeders		0.633	
Number >63 µm			0.726
Number >500 µm		0.743	

There were no Scaphopoda found at Cawsand Bay throughout the sampling period, hence the lack of correlations. Scaphopoda were only found in one month at White Patch, probably making these correlations at this site invalid. Scaphopoda were found throughout the year at Drake's Island, so these correlations with Spirillinina, suspension-feeders and Foraminiferida of >500 µm are probably true relationships. Scaphopoda are selective predators of Foraminiferida and probably reproduce at Drake's Island in order to take advantage of the Foraminiferida reproducing at this site.

7.18. OTHER MEIOFAUNA: ABUNDANCE OF ACARIFORMES.

Table 7.17: Significant correlation coefficients between the number of Acariformes and Foraminiferida.

Foraminiferida	Cawsand Bay	Drake's Island	White Patch
Evenness		-0.594	
Number of Miliolina		0.592	
% Miliolina		0.588	
% Rotaliina		-0.702	
% hyaline		-0.627	
Number of quinqueloculine		0.591	
% infaunal		-0.638	
% suspension-feeders		-0.722	
Number >500 μm		0.588	

Acariformes were only found at Drake's Island, hence the lack of correlations at the other two sites investigated. Acariformes are one of the few groups of other meiofauna to produce negative correlation coefficients with Foraminiferida. Negative relationships exist between Acariformes and the evenness of Foraminiferida, the percentage of Rotaliina, hyaline Foraminiferida, infaunal and suspension-feeders. The number of Foraminiferida of >500 μm are positively correlated with the number of Acariformes at Drake's Island, however. The number of Acariformes per grab being negatively correlated to evenness at Drake's Island indicates that as the number of Acariformes increases, evenness falls and dominance by a few species of Foraminiferida occurs. This may indicate that Acariformes may compete for a food source utilised by some species of Foraminiferida and deplete the area of these food items when Acariformes reproduce. The negative relationships between Acariformes and Foraminiferida may indicate that these two groups compete for food resources or for space; both commodities are very important to benthonic meiofauna.

7.19. BACILLARIOPHYCEAE.

Multi-variate analysis was carried out upon the diatom assemblages from the three sites to investigate if the diatoms form discrete assemblages at the sampling sites. The data were transformed by natural logarithms. The inclusion of colour-coded lines around the samples is to easily distinguish the geographical areas and is not intended to influence the interpretation of the plots. From Figure 7.3 it can be seen that the sites sampled contain different assemblages of diatoms as the sites can be grouped together. The diatom assemblage for Cawsand Bay in April appears to be more similar to the White Patch diatom assemblages than to assemblages at Cawsand Bay in other months.

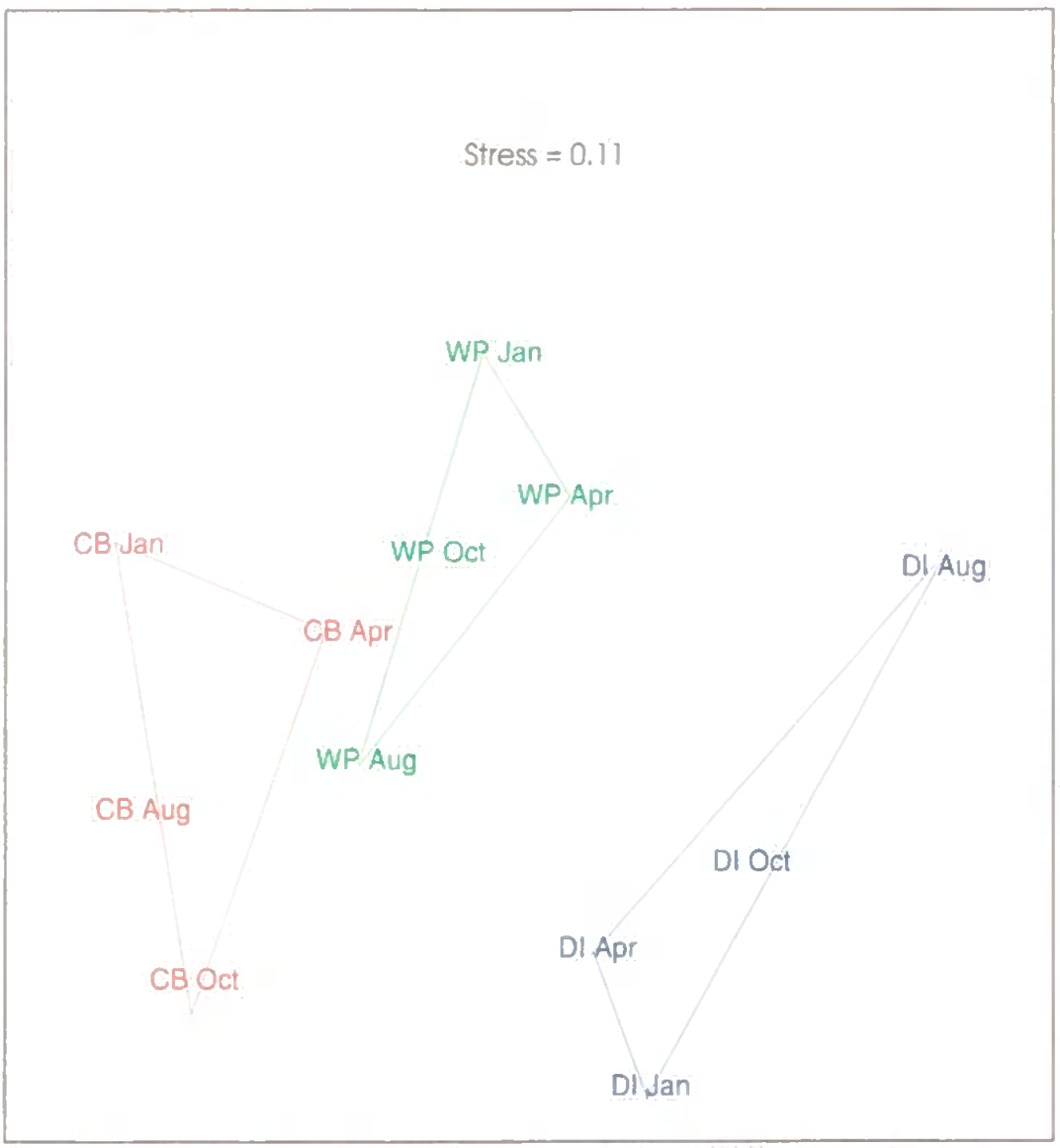


Figure 7.3: Multi-dimensional scaling plot of diatom assemblages from the three sampling sites, 1993/1994.

Figure 7.4: Multi-dimensional scaling plot of foraminiferidal assemblages from the three sampling sites, 1993/1994

The multi-dimensional scaling plot of Foraminiferida at the three sites for the months of August, October, January and April (the months sampled for diatoms) show that the Foraminiferida for these months are not as discrete in terms of site as the diatoms, although the Drake's Island assemblage in April appears to be quite different to the other samples. By comparison of Figures 7.3 and 7.4, it can be inferred that the diatom assemblages at the sites sampled do not dictate the species of Foraminiferida present.

7.19.1. PERCENTAGE CENTRIC DIATOMS.

Table 7.18: Significant correlation coefficients between centric diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% Rotaliina	0.6471
% Hyaline	0.6566
% trochospiral	0.7577
% quinqueloculine	-0.5800
Number of other apertures	0.7109
% other apertures	0.6577
% infaunal	0.6404
% epifaunal	-0.6289
% 250 µm	0.8993
% 500 µm	0.5775

Centric diatoms are positively correlated with both percentage Rotaliina and percentage of hyaline specimens, although the coefficient for hyaline forms is slightly higher than that for Rotaliina, indicating that centric diatoms reproduce when hyaline forms as a whole form a higher proportion of the assemblages sampled. The negative correlation between quinqueloculine Foraminiferida and centric diatoms could indicate that when centric diatoms and hyaline taxa are high the proportion of quinqueloculine forms is relatively small. The percentage of trochospiral Foraminiferida and both the number of and percentage of Foraminiferida with other apertures rise when the proportion of centric diatoms is also high. Both the percentage of >250 µm and of >500 µm Foraminiferida rise as the proportion of centric diatoms rise at the sites. Whilst the proportion of infaunal Foraminiferida rises as the proportion of centric diatoms rises, there is a subsequent fall in the proportion of epifaunal forms; the coefficient for infaunal forms is slightly higher than the coefficient for epifaunal forms, perhaps indicating that this is the true relationship.

The positive relationships between groups of Foraminiferida and centric diatoms may indicate that these groups reproduce at the same time, or may indicate that one group reproduces in response to the other. Negative relationships between centric diatoms and groups of Foraminiferida indicate that as the proportion of

centric forms in the diatom assemblage increases the foraminiferid group decreases. This may reflect competition between diatom shapes and perhaps indicates that the centric diatoms out-compete some other shape of diatom which would benefit the foraminiferid group.

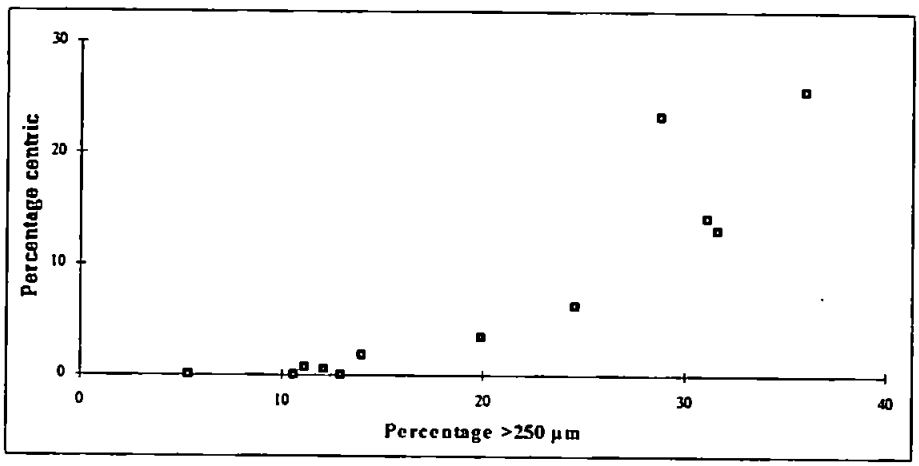


Figure 7.5: Scatter plot showing correlation of percentage centric diatoms and percentage of foraminiferid fauna >250 µm (0.8993).

7.19.2. PERCENTAGE PANDURIFORM DIATOMS.

Table 7.19: Significant correlation coefficients between panduriform diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% Miliolina	-0.6883
% Rotaliina	0.7307
% hyaline	0.7606
% trochospiral	0.8547
% quinqueloculine	-0.6919
Number of other apertures	0.8017
% other apertures	0.7341
% infaunal	0.6563
% epifaunal	-0.6682
% >63 µm	-0.6030
% >250 µm	0.9196

From Table 7.19 it can be seen that most of the relationships with panduriform diatoms and groups of Foraminiferida are positive. As the proportions of hyaline forms and Rotaliina rise with the proportion of panduriform diatoms, there is a negative relationship between these diatoms and percentage of Miliolina, and with quinqueloculine-coiled Foraminiferida. The percentages of trochospiral forms and

both the number of and percentage of Foraminiferida with other types of apertures have positive relationships with panduriform diatoms. Whilst the percentage of Foraminiferida >63 μm is negatively correlated with this shape of diatoms, the percentage of Foraminiferida >250 μm has a very strong positive relationship with these diatoms. As with the centric diatoms, the percentage of infaunal Foraminiferida increases as the proportion of panduriform diatoms rises and the percentage of epifaunal Foraminiferida falls as this group of diatoms increases.

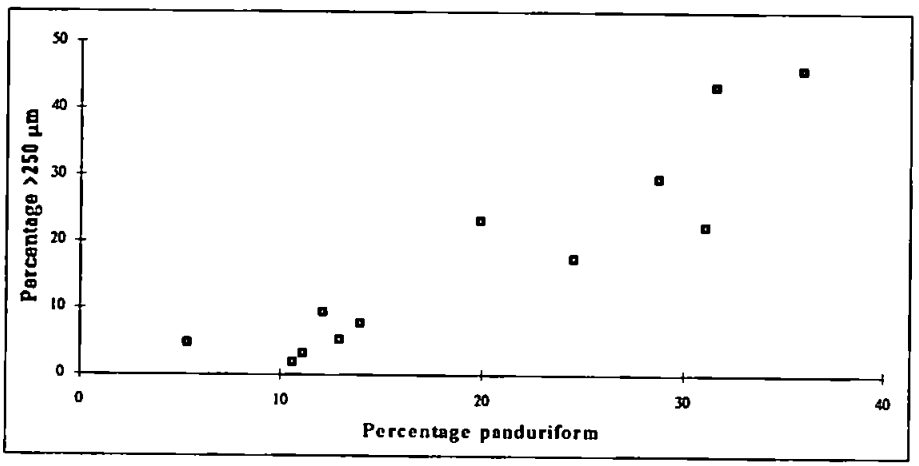


Figure 7.6: Scatter plot showing correlation of percentage panduriform diatoms and percentage of foraminiferid fauna >250 μm (+0.9196).

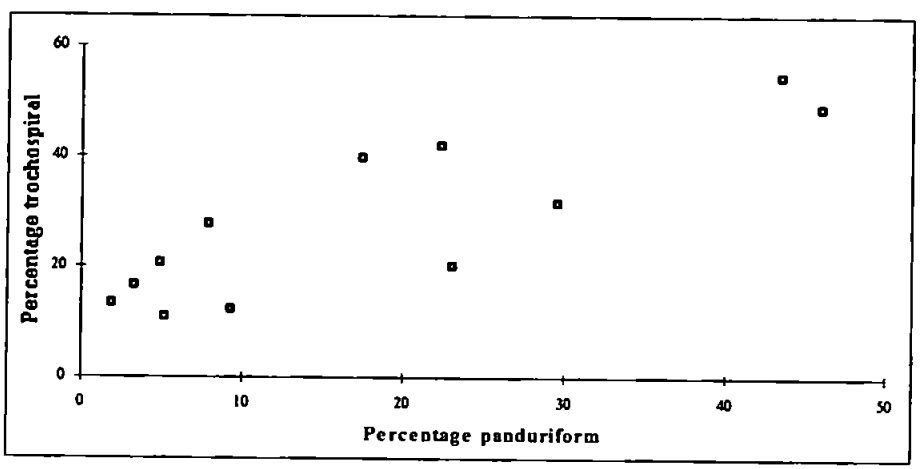


Figure 7.7: Scatter plot showing correlation of percentage panduriform diatoms and percentage of trochospiral Foraminiferida (+0.8547).

7.19.3. PERCENTAGE SEMI-LANCEOLATE DIATOMS.

Table 7.20: Significant correlation coefficients between semi-lanceolate diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
Number Miliolina	0.6124
% Miliolina	0.6027
Number quinqueloculine	0.6276
% quinqueloculine	0.5831
% >125 μm	0.6866

Semi-lanceolate diatoms are positively correlated with number and percentage of both Miliolina and quinqueloculine-coiled forms. There is not a consequent negative correlation between this diatom group and Rotaliina, however, indicating that the increased presence of Miliolina and quinqueloculine Foraminiferida is not at the expense of rotalinids. This group of diatoms is also positively correlated with the percentage of Foraminiferida >125 μm.

7.19.4. PERCENTAGE LANCEOLATE DIATOMS.

Table 7.21: Significant correlation coefficients between lanceolate diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% Miliolina	0.7006
% Rotaliina	-0.7518
% hyaline	-0.7634
% trochospiral	-0.7907
% quinqueloculine	0.7019
% other apertures	-0.6273
% infaunal	-0.7646
% epifaunal	0.7756
% >63 μm	0.6964
% >250 μm	-0.8396

From Table 7.21 it can be seen that lanceolate diatoms have more negative correlations with Foraminiferida than positive. As the proportion of lanceolate diatoms increases so do the percentage of Miliolina and quinqueloculine forms; whereas the percentages of Rotaliina, hyaline, trochospiral and those with other apertures fall. The proportion of infaunal Foraminiferida is negatively correlated

with lanceolate diatoms and the proportion of epifaunal forms is correspondingly positively correlated with these diatoms, perhaps indicating the preference of epifaunal Foraminiferida for this group of diatoms. The percentage of Foraminiferida >63 μm is positively correlated with lanceolate diatoms and the percentage of Foraminiferida >250 μm is strongly negatively correlated with lanceolate forms perhaps indicating the reproduction of Foraminiferida when lanceolate diatoms reproduce.

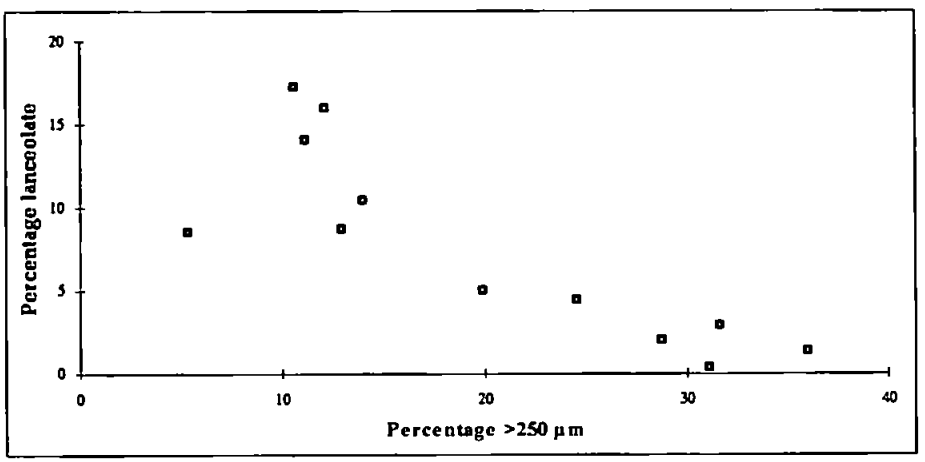


Figure 7.8: Scatter plot showing correlation of percentage lanceolate diatoms and percentage of foraminiferid fauna >250 μm (-0.8396).

7.19.5. PERCENTAGE SIGMOID DIATOMS.

Table 7.22: Significant correlation coefficients between sigmoid diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
Number of Textulariina	0.6794
Number of Rotaliina	0.5908
Number of hyaline	0.5875
Number of uniserial	0.7033
Number >125 μm	0.6558

From Table 7.22 it can be seen that all significant correlations between sigmoid diatoms and Foraminiferida are positive. Sigmoid diatoms appear to reproduce at the same time as Textulariina, Rotaliina, hyaline, uniserial and Foraminiferida of >125 μm, whilst not causing a subsequent decrease in other foraminiferid groups.

7.19.6. PERCENTAGE ELLIPTICAL DIATOMS.

Table 7.23: Significant correlation coefficients between elliptical diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% Miliolina	0.6942
% Rotaliina	-0.7540
% hyaline	-0.7778
Number of trochospiral	-0.6844
% trochospiral	-0.7445
% quinqueloculine	0.7104
Number of other apertures	-0.6417
% other apertures	-0.6468
% infaunal	-0.6990
% epifaunal	0.6989
% suspension feeders	0.5989
% >63 μm	0.6405
Number >250 μm	-0.5999
% >250 μm	-0.8531

From Table 7.23 it can be seen that the proportion of Miliolina rises together with the proportion of elliptical diatoms as the proportions of both Rotaliina and hyaline specimens fall. Similarly, both the number and proportion of trochospiral Foraminiferida, which in part form part of the relationship between both Rotaliina and hyaline forms, are negatively correlated with elliptical diatoms, whereas the proportion of quinqueloculine forms, which form a major part of the relationship between Miliolina, is positively correlated with elliptical diatoms. Both the number and percentage of Foraminiferida with other apertures are negatively correlated with elliptical diatoms. Whereas the proportion of epifaunal Foraminiferida increases as a proportion of the assemblage when elliptical diatoms increase as a proportion of the diatom assemblage, the percentage of infaunal Foraminiferida falls. The percentage of suspension-feeding Foraminiferida increases with an increase in epifaunal forms, perhaps indicating that this group benefits from elliptical diatoms as a food source. The percentage of >63 μm Foraminiferida is positively correlated with this group of diatoms, indicating that reproduction of most Foraminiferida occurs when elliptical diatoms proliferate, whereas both the number and percentage of Foraminiferida >250 μm are negatively correlated with this diatom group.

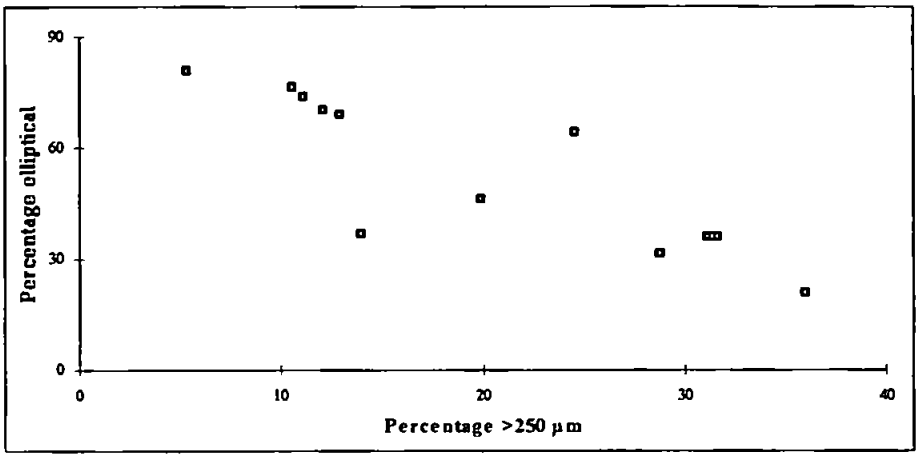


Figure 7.9: Scatter plot showing correlation of percentage elliptical diatoms and percentage of foraminiferid fauna >250 µm (-0.8531).

7.19.7. PERCENTAGE OTHER TYPES OF DIATOMS.

Table 7.24: Significant correlation coefficients between other types of diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% round apertures	0.5805
% >125 µm	-0.6836

Correlations with other types of diatoms are very few, perhaps reflecting the limited abundance of this type of diatom at the sampling sites. Foraminiferida with round apertures increase as a proportion of the foraminiferid fauna together with other types of diatom, whereas the proportion of Foraminiferida >125 µm falls.

7.19.8. SHANNON DIVERSITY OF DIATOMS.

Table 7.25: Significant correlation coefficients between Shannon diversity of diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
Fisher diversity	-0.658
Richness	-0.585
% Textulariina	-0.675
% other coiling	-0.824
% arch apertures	-0.615
% suspension feeders	-0.610

All significant correlations with Foraminiferida and the Shannon diversity of diatoms are negative. As the diversity of diatoms rises the diversity of Foraminiferida, richness of species of Foraminiferida, the percentage of agglutinated, of other coiling, arch apertures and suspension-feeders decreases. The decrease in foraminiferid diversity as diversity of diatoms rises indicates that only a limited number of species of diatom are useful as food or symbiotic chloroplasts to Foraminiferida and as the diversity of diatoms rises there are, perhaps, fewer useful diatoms for the foraminiferid assemblages. Similarly it appears that Textulariina, Foraminiferida with other coiling, arch apertures and suspension feeders suffer in the same way from an increase in diversity of diatoms.

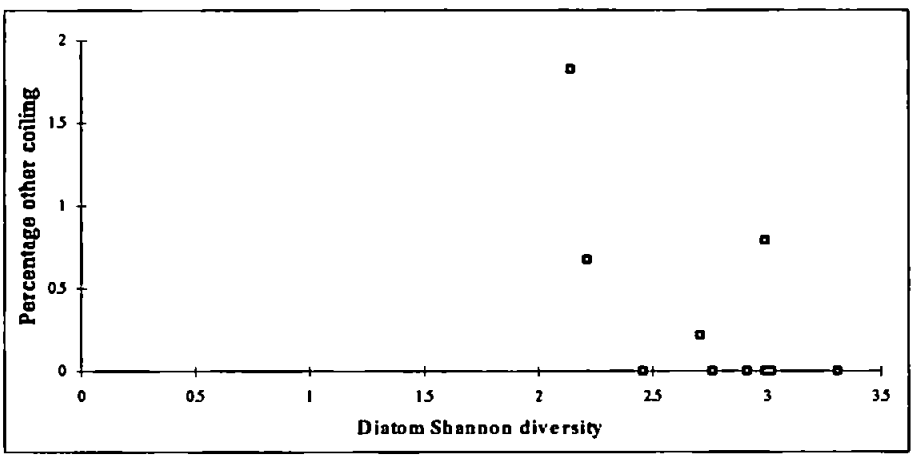


Figure 7.10: Scatter plot showing correlation of Shannon diversity of diatoms and percentage of foraminiferid fauna of other coiling (-0.8240).

7.19.9. MARGALEF'S RICHNESS OF DIATOMS.

Table 7.26: Significant correlation coefficients between richness of diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
Abundance	0.586
Number of infaunal	0.704
Number of herbivores	0.648

All significant correlations between richness of species of diatoms and foraminiferid abundance, number of infaunal and herbivorous specimens are

positive, indicating that as the number of diatom species increases these groups benefit from a varied food source.

7.19.10. PIELOU'S EVENNESS OF DIATOMS.

Table 7.27: Significant correlation coefficients between evenness of diatoms and Foraminiferida.

Foraminiferida	Correlation coefficient
% Textulariina	-0.728
% other coiling	-0.792
% arch apertures	-0.618
% slit apertures	0.591
% infaunal	0.626

The evenness of diatom species is positively correlated with the percentage of Foraminiferida with slit apertures and with infaunal specimens, whilst being negatively correlated with the percentage of Textulariina, other coiling and Foraminiferida with arch apertures. This may indicate that Textulariina and Foraminiferida with other coiling and arch apertures are more selective for diatom species and therefore benefit from dominance of certain diatom species.

7.19.11. DIATOM SHAPE AND FORAMINIFERID GROUPS.

The percentage of Textulariina is positively correlated with sigmoid diatoms, and may benefit directly from an increased abundance of this diatom shape. The percentage of Rotaliina and hyaline types share the same correlations with diatoms and are positively correlated with centric, panduriform and sigmoid diatoms, whilst being negatively correlated with lanceolate and elliptical diatoms. Correlations for Miliolina for panduriform, lanceolate and elliptical diatoms are opposite to those of hyaline and Rotaliina, and, in addition, are positively correlated with semi-lanceolate forms.

Trochospiral and quinqueloculine-coiled Foraminiferida produce opposing correlations; trochospiral forms are positively correlated to centric and

panduriform diatoms and negatively correlated with lanceolate and elliptical diatoms, whereas quinqueloculine Foraminiferida are negatively correlated with centric and panduriform diatoms and positively correlated with lanceolate and elliptical diatoms, and semi-lanceolate diatoms. There are similar relationships between trochospiral and hyaline types and Rotaliina (with the exception of sigmoid diatoms) and Miliolina and quinqueloculine Foraminiferida (with the exception of centric diatoms) indicating that quinqueloculine Foraminiferida form the major constituent of the Miliolina, and that the abundance of trochospiral forms dictates the abundance of Rotaliina and hyaline forms.

The number of Foraminiferida with other apertures is positively correlated with centric and panduriform diatoms, whilst being negatively correlated with elliptical forms, and the percentage of Foraminiferida with other apertures is positively correlated with panduriform diatoms whilst being negatively correlated with lanceolate and elliptical diatoms. Foraminiferida with round apertures are positively correlated with other-shaped diatoms. These correlations of minor groups of aperture type indicate that the apertural shape of Foraminiferida is not an adaptive feature for the ingestion of unicellular algae into the test. This supports the finding of Lee (*pers. comm.*) that digestion of diatoms occurs outside of the test.

Life position of Foraminiferida is correlated with diatom shape; infaunal forms are positively correlated with centric and panduriform diatoms and negatively correlated with lanceolate and elliptical forms. Epifaunal forms have opposite correlations to infaunal forms. This may indicate that infaunal Foraminiferida and centric and panduriform diatoms reproduce when environmental variables favour this and may indicate that these diatoms benefit from the environment at this time. Epifaunal Foraminiferida are correlated positively with lanceolate and elliptical diatoms and may indicate that these diatoms are also strongly epifaunal.

It was expected that the feeding strategies of Foraminiferida would be correlated with diatom shape, especially amongst herbivores. Only suspension-feeders are correlated with diatoms of a shape (elliptical), and whilst suspension-feeders may be selective feeders of this shape of diatom, other Foraminiferida appear to be unselective for shape of diatom.

Sizes of Foraminiferida are correlated with shapes of diatoms. Foraminiferida between 63 μm and 125 μm are positively correlated with lanceolate and elliptical diatoms and negatively correlated with panduriform diatoms. Foraminiferida between 125 μm and 250 μm are positively correlated with semi-lanceolate and sigmoid-shaped diatoms and negatively correlated with other shapes of diatoms. Foraminiferida between 250 μm and 500 μm are positively correlated with centric and panduriform diatoms and negatively correlated with lanceolate and elliptical diatoms. Specimens between 500 μm and 1000 μm are positively correlated with centric diatoms. The correlations between the 63 μm-125 μm and 125 μm-250 μm Foraminiferida and shape of diatom are common to correlations between the Miliolina and diatom shape. The correlations for Foraminiferida of 250 μm-500 μm and 500 μm-1000 μm are common to the correlations between the Rotaliina and shape of diatom. This may indicate that the correlations between the smaller sizes of Foraminiferida and diatom shapes reflect the reproduction of Miliolina and the correlations between the larger sizes of Foraminiferida and shapes of diatom reflect the reproduction of Rotaliina.

7.20. SUMMARY.

Organic content of the sediment appears to be an important variable to certain groups of Foraminiferida at Drake's Island, whilst only being significantly correlated with one group at Cawsand Bay and having no significant correlations with the White Patch fauna. The number of significant correlations at the sites may reflect the differences in the energy of the environments; the poorly-sorted

sediment of White Patch would hold organic matter, the fine sand sediment of Cawsand Bay will probably hold organic matter well, whilst the well-sorted medium sand of Drake's Island will be more easily flushed of organic content. Most significant relationships are positive indicating that reproduction of foraminiferid groups occurs when organic content is relatively high. These relationships may also be linked to the bloom of the benthonic and planktonic unicellular plants or to bacterial blooms or the deposition of detrital macroalgae.

The number of bacteria per gram of wet sediment is significantly negatively correlated with 4 groups of Foraminiferida at Cawsand Bay and significantly positively correlated with 1 group at Cawsand Bay and 2 groups at White Patch. These relationships may indicate that there is a limited number of bacteria at Cawsand Bay and slightly more at White Patch, and sufficient bacteria at Drake's Island which do not adversely affect the Foraminiferida. The diversity of bacteria, measured by the number of cfu (colony forming units) appears to be less important to Foraminiferida than the number of bacteria present: 1 positive correlation exists between the number of cfu and a group of Foraminiferida at Cawsand Bay, 3 negative correlations exist between Foraminiferida and number of cfu at Cawsand Bay and 1 negative correlation between cfu and Foraminiferida at Drake's Island. The shapes and types of bacteria do not appear to be very important to Foraminiferida at the sites, with relatively few significant relationships noted above. At Cawsand Bay there are two positive correlations with Gram positive rods, 2 negative relationships with Gram positive cocci, 1 positive correlation with Gram negative rods, and 1 negative relationship with that percentage of the bacteria which are cocci. At Cawsand Bay the fauna appears to reproduce when bacterial rods are abundant. The Foraminiferida at Drake's Island have few correlations with types of bacteria, having 1 negative correlation with Gram negative rods and 1 negative correlation with Gram negative cocci and may prefer an abundance of Gram positive bacteria in order to reproduce. White Patch Foraminiferida are positively correlated with Gram positive rods (14 groups), and

Gram positive cocci (1 group), whilst being negatively correlated with Gram positive rods (1 group), Gram positive cocci (1 group), Gram positive bacteria (2 groups) and cocci-shaped bacteria (1 group). These correlations indicate that most foraminiferid groups at this site reproduce when Gram positive rods are abundant. These correlations between Foraminiferida and types of bacteria present in the environment indicate that rod-shaped bacteria at Cawsand Bay are important, Gram positive bacteria are important at Drake's Island and Gram positive rods are important to the foraminiferid fauna at White Patch.

The presence of other meiofauna appears to be beneficial to Foraminiferida at all sites, with the exceptions of Acariformes (5 groups) and Copepoda (1 group) at Drake's Island. In general, the other meiofauna appear to reproduce at the same time as the Foraminiferida at the sites, probably in response to the same environmental cues or just perhaps because excreta produced by the Foraminiferida is beneficial to them, or their excreta is beneficial to the Foraminiferida. There appears to be little competition (with the exception of Acariformes) between other meiofauna and Foraminiferida.

The correlations with shapes of diatom present and Foraminiferida indicate that the major sub-orders of Foraminiferida (Miliolina and Rotaliina) are correlated with specific shapes of diatoms, and the correlations of foraminiferid shapes and sizes reflect these relationships. The relative lack of correlations between foraminiferid apertural shape and shape of diatoms indicate that the apertural shape of Foraminiferida is not an adaptive feature to allow entry of particular shapes of diatom into the foraminiferid test. Infaunal and epifaunal Foraminiferida are correlated with specific diatom shapes, whilst amongst feeding strategies only the suspension-feeders are correlated with shape of diatom.

The correlations between Foraminiferida and biotic variables appear to have been worth investigating. The correlations between Foraminiferida and organic content,

abundance and types of bacteria, other meiofauna and diatoms reveal that, as with abiotic variables, the differences between sites lead to different correlations, but are important to the reproduction of foraminiferid groups. Further work should be carried out between foraminiferid species and the variables investigated to truly understand the importance of variables to the Foraminiferida present in the habitats studied.

CHAPTER 8.0.

CULTURE EXPERIMENTS.

8.1. INTRODUCTION.

According to Boltovskoy & Wright (1976), the first published accounts of the examination of live Foraminiferida are provided by Blainville (1825) and d'Orbigny (1826). The latter believed them to be a part of the life-cycle of Cephalopoda. Boltovskoy & Wright (1976) also state that Ehrenberg (1839), and almost simultaneously Dujardin (1841), managed to maintain Foraminiferida in the laboratory. Since these initial investigations many workers have made observations of Foraminiferida in the laboratory, and have described their behaviour, reproduction and structural organisation, notably the reticulose pseudopodial networks. Although much of the basic understanding of the biology of Foraminiferida has been obtained from these laboratory studies, to what extent these observations reflect events in the natural environment remains unclear.

Nutritional requirements of Foraminiferida maintained under laboratory conditions have been undertaken on a limited number of species by various authors. Studies on the quality of algal prey have been carried out (see Lee *et al.*, 1961; Murray, 1963; Hedley & Wakefield, 1967; Schnitker, 1974). Lee *et al.* (1966) carried out tracer experiments and determined that the algal needs of *Ammonia beccarii* changed with ontogeny. Nutritional needs of Foraminiferida vary from species to species, but diatoms and other unicellular algae appear to provide a good nutritional basis for most species (Arnold, 1974). The quantity of food has also been investigated by authors such as Lee (1980), Bé *et al.* (1981) and Lee *et al.* (1991{b}). Lee *et al.* (1966) related feeding to food density and found that food uptake was directly proportional to concentrations between 10^3 and 10^6 individual cells per 10 ml of medium, becoming erratic at lower concentrations. Studies on feeding frequency (Bé *et al.*, 1981) showed that this varied inversely to survival time and that smaller, starved, individuals may resorb their chambers. Ecological experiments have also

been carried out upon a proteinaceous testate allogromid (Bradshaw, 1955, 1961; Kitazato, 1981), *Haliphysema* (Hedley, 1958; Lee & Pierce, 1963), *Heterostegina depressa* d'Orbigny (Röttger & Berger, 1972), *Astrorhiza limicola* Sandahl (Buchanan & Hedley, 1960) and *Allogromia laticollaris* Arnold (Lee *et al.*, 1969). In addition, Moodley (1990 {b}) observed that "soft" Foraminiferida would move into empty tests of other species; and Schnitker (1974) observed ecotypic variation in *Ammonia beccarii* kept under differing conditions in the laboratory.

Reproduction of some species maintained in the laboratory has been observed and described for *Patellina corrugata* (Myers, 1934, 1938), *Allogromia laticollaris* Arnold (Lee & McEnery, 1970), *Discorbis* (Myers, 1940), *Elphidium crispum* (Jepps, 1942), *Amphistegina madagascariensis* d'Orbigny (Muller, 1974), *Trochammina inflata* (Montagu) (Angell, 1990) and *Rotaliella elatiana* Pawlowski & Lee (Pawlowski, 1991). These observations have provided vital information on the appearance and production of gametes, on schizogony and on the subsequent calcification of offspring. The observation of the reproduction of Foraminiferida in the laboratory is of vital importance to micro-palaeontologists, as stages of development in the past have been described, occasionally, as separate species.

Chamber formation has also been observed in some species and has provided a useful insight to the processes involved. In 1967 Angell observed chamber formation in the calcareous *Rosalina floridana* (Cushman). Arenaceous species, such as *Textularia candeina* d'Orbigny (Bender, 1992) and *Trochammina inflata* (Angell, 1990), have been observed forming and mineralising chambers, and Bé *et al.* (1981) found that rate of chamber formation and test size was proportional to feeding frequency. Pseudopodial functions and arrays have been described by many authors. Sandon (1934) described pseudopodial movements and the two-way movement of granules within a single pseudopodium. The pattern of pseudopodial networks has been described for many species (see Jepps, 1942; Jahn & Rinaldi, 1959; Knight, 1986). The movement of various Foraminiferida both upon and within sediments is described by Kitazato (1988).

Whilst observations on Foraminiferida maintained in the laboratory have proved to be vital in the understanding of the basic requirements and responses to environmental variables, it is only by culturing species that one can ascertain the variety of responses through ontogeny in terms of habitat, nutritional requirements and the natural alternation of reproductive strategies. General culture methods for marine invertebrates are plentiful (*e.g.* Galtsoff, 1937) and methods for the culture of Foraminiferida have been detailed by authors such as Myers (1935, 1937) and Arnold (1954 {b}). A laboratory system designed specifically for the culture of Foraminiferida is described by Arnold (1966), although a lathe and a great deal of patience must have been necessary to make the equipment.

Many investigations of live Foraminiferida have been carried out at the Marine Biological Association (MBA), Plymouth using Foraminiferida from collections in the region. Jepps (1942) maintained *Elphidium crispum* in the laboratory and describes the feeding requirements and the reproduction of this species. Myers (1935) made similar observations for *Elphidium crispum*, and he also observed the alternation of generations and the morphology of the gametes in 1943. Murray (1963) maintained *Elphidium crispum* and found that this species prefers live food, and that it selects food on a size basis. He also found that a reduction in salinity causes a reduction in feeding frequency in this species. Hedley & Wakefield (1967) maintained *Rosalina leei* Hedley & Wakefield collected from Plymouth, and record observations on its reproduction and feeding requirements. Bryan (*pers. comm.*) successfully maintained *Elphidium crispum* on a shell/gravel substratum in a recirculating marine aquarium at the MBA prior to their use in radiological experiments (Bryan, 1963).

Although many authors have maintained Foraminiferida under laboratory conditions for a limited period, there are few accounts of the successful culture of these organisms. Any organism in culture must demonstrate its complete life-cycle throughout several generations (Anderson *et al.*, 1991). Amongst those who have carried out extended studies, there are three notable exceptions who have managed to culture Foraminiferida: Professor John Lee, of the City College, (New York); Dr. Hiroshi Kitazato of Shizuoka University, (Japan) and

Dr. Jan Pawlowski of the University of Geneva, (Switzerland). Professor Lee has cultured *Allogromia laticolaris* for long periods (Lee & McEnery, 1970); Dr. Kitazato has observed most of the life cycle of *Trochammina hadai* Uchio (oral presentation, Proceedings of the Fourth International Workshop on Agglutinated Foraminifera, Kraków, Poland, 1993); Dr. Pawlowski has kept *Rotaliella elatiana* Pawlowski & Lee in culture for several years (Pawlowski, 1991). To date there are no records of any species of planktonic Foraminiferida which have completed their life-cycle in culture. Of those maintained in the laboratory, Bijima *et al.* (1990) discovered the temperature and salinity limits for some species, and discovered that some species reproduce according to the lunar cycle.

Agnotobiotic cultures (that is those which contain other organisms) were tried first, as these would be the most simple to initiate and maintain. Lee *et al.* (1966) found that gnotobiotic cultures resulted in greatly reduced fecundity. Bacteria are essential to the viability of Foraminiferida in the laboratory (Muller & Lee, 1969); and those workers who have attempted to maintain Foraminiferida have found that growth and fecundity are greatly reduced in systems which used antibiotics to limit bacterial growth. Benthonic Foraminiferida have traditionally been maintained in vessels containing sediment or algal substrata; this approach would be disadvantageous to later work involving heavy metals, due to the ubiquitous chelation of heavy metals to organic materials, and therefore attempts were made to culture Foraminiferida in high-quality glass vessels without substrata. Although the preliminary system was a mixture of foraminiferal species, the assemblage was dominated by *Elphidium crispum*; the two subsequent attempts to culture native benthonic Foraminiferida involved only *Elphidium crispum*. This species is readily available in Plymouth Sound, and has been studied by many authors.

The aim of this study was to establish benthonic Foraminiferida in culture throughout the life-cycle as a basis for further studies on the possible relationship between pollutants and deformation of the test.

8.2. MATERIALS & METHODS.

8.2.1. ALGAL CULTURE.

Pure cultures of three marine algal species were established as a source of food for indigenous Foraminiferida. The algal species, a motile Chlorophyte *Dunaliella praemolecta*, a motile Phaeophyte *Isochrysis galbana* and a benthonic diatom *Phaeodactylum tricornatum*, were maintained in sterile media following the methods utilised by Plymouth Marine Laboratory (PML). Starter cultures, obtained from PML, were each inoculated into 250 ml conical flasks containing 100 ml of sterile "K" medium (Appendix VI) following standard microbiological sterile procedures. The cultures were placed in a constant-temperature room of 15°C, approximately 30 cm below two 40 Watt fluorescent lights, and gently agitated every other day. Subculturing was carried out approximately every two weeks to prevent senescence of the algae as the youth of the culture was considered to be important (Lee *et al.*, 1966; Lee, 1974). The algae were fed live to the Foraminiferida because, whilst some authors advocate the use of heat-killed algae, Arnold (1974) found that this led to bacterial multiplication. A mixture of the three algal species was added to each culture of Foraminiferida to provide a concentration of between 10^3 and 10^6 food organisms per 10 ml of sea water (Lee *et al.*, 1966); these were counted using a haemocytometer (Laing, 1991).

8.2.2. COLLECTION AND ISOLATION OF INDIGENOUS FORAMINIFERIDA.

Sediment containing Foraminiferida was collected from the MBA Research Vessel *Sepia* with the use of a small Naturalist's Dredge, or the "Murray Grab". Upon collection, the sediment was placed into plastic containers in the ratio of approximately 20% sediment, 60% sea water and 20% air (Lee, 1974; Anderson *et al.*, 1991) and placed into a cool box. Within four hours of collection the sediment was emptied into a shallow polypropylene trough containing aerated sea water at approximately 2°C below that recorded at the collection site, to reduce stress (Muller, 1974), with a daylight-fluorescent light situated

20 cm above the trough. The Foraminiferida were extracted either by direct removal on a sable brush or by allowing them to migrate up microscope slides held vertically in the sediment by perspex racks (Arnold, 1974), and identified to species level.

8.2.3. MAINTENANCE OF INDIGENOUS FORAMINIFERIDA.

Density of Foraminiferida within vessels was limited to approximately ten specimens to each Petri dish of 50 mm diameter and each "finger bowl" of 90 mm diameter (Arnold, 1954 {b}). Sea water of high quality was supplied by PML: this was collected from a deep trench within Plymouth Sound. The sea water in the cultures was changed twice daily for a period of three days; then once daily for a period of a week; and thereafter every other day (following Arnold, 1966). Foraminiferida were maintained as simply as possible with no prior cleansing of the specimens. Light was provided by a single fluorescent light of 40 Watts, and the culture vessels situated approximately 25 cm from it. When contaminated specimens were noted, the bases of the containers were brushed with a sable brush every other day, and a jet of sea water directed against the walls of the dish to help remove debris (Myers, 1935) before removing the sea water.

8.2.4. CRITERIA FOR SUCCESS.

Individual Foraminiferida were examined prior to changing the media, using dark-field microscopy on a Swift Instruments International microscope, for indications of healthiness. The extension of the pseudopodia for feeding or locomotion; the presence of a feeding cyst encapsulating, or adjacent to, an individual; or vertical movement were taken as indications of healthiness. Inactivity, together with loss of colour and the visible adherence of contamination were indications of unhealthiness. Dead or contaminated specimens were removed from the culture containers and placed into separate containers to prevent contamination of healthy individuals.

8.3. EXPERIMENTS AND RESULTS.

The purpose of conducting these experiments was to evaluate the best method of maintaining indigenous benthonic Foraminiferida. The first experiment was to investigate the survivability of benthonic Foraminiferida with time taken to emerge from the sediment, following collection using Petri dish culture at 10° C. The second experiment was to investigate the survivability of specimens of *Elphidium crispum* held in a continuous-flow system with temperature fluctuations. The third experiment was carried out at a constant temperature, involved the use of anti-biotics within the sea water, and investigated the survivability and fecundity of *Elphidium crispum*.

8.3.1. PETRI DISH CULTURE AT 10°C.

Indigenous benthonic Foraminiferida for this experiment were collected on the 17th of November, 1992, from the areas of "White Patch" (off Jennycliff Bay) and Drake's Island, both within Plymouth Sound, and from Cawsand Bay outside of the Breakwater. Only Foraminiferida which migrated on to slides were used in this investigation. The species involved were mainly *Elphidium crispum* (Linné), with four *Quinqueloculina seminulum* (Linné), four *Ammonia beccarii* (Linné) and one *Quinqueloculina oblonga* (Montagu). These were removed from slides on days 3, 6, 9, and 12 (Table 8.1), following the initial collection of the sediment, and maintained separately in Petri dishes in unsterile sea water as described above. These specimens were maintained at 10° C because this temperature was slightly lower than that of the natural environment when collected. A total of 76 un-lidded Petri dishes were placed into a tray containing wet tissue to create a humidifying chamber. The Foraminiferida were examined every three days for vitality for a maximum period of 54 days.

Table 8.1: The number of specimens in each group from the three sampling sites and the time taken for each group to emerge from the sediment after collection for 10°C experiment.

Collection site	Number emerging with day following collection				Total
	3	6	9	12	
Cawsand Bay	58	111	119	64	352
Drake's Island	6	7	15	10	38
White Patch	79	103	60	106	348
Total	143	221	194	180	738

The data for this experiment constitutes Appendix VI and consists of activity and contamination levels for each group from each collection site every three days. The speed at which individuals had migrated on to the vertical slides might indicate the health of the specimens and possibly immunity to bacterial contamination.

It was noted that the specimens collected for this study were green, whilst those collected from White Patch in December, a month later, were rust-brown. Ciliated protozoa were noted on the bases of the containers on the 14th December, 1992, and appeared to preferentially colonise the empty feeding cysts left by the Foraminiferida. No reproduction occurred in this experimental group, even when transferred to a 20°C Constant Temperature room. The specimens which became contaminated (transferred to a separate container) periodically appeared to become less coated in the contaminant. Although largely inactive, some contaminated specimens formed feeding pseudopodial nets and feeding cysts, whilst still appearing devoid of colour and covered in the contaminant. On the 11th of January (1993) one contaminated specimen was removed and placed on a cover-slip for examination; it withdrew its cytoplasm into the test and the contaminant was then no longer visible. Frequently small specimens of living *Elphidium crispum* were observed floating on the meniscus of the sea water in the containers, although the larger specimens did not display this behaviour. The Foraminiferida were maintained in this system for three months, until the 18th of February (1993) when the few specimens not contaminated with bacteria were transferred to a constant-temperature room of 20°C in an attempt to induce reproduction.

8.3.2. CONTINUOUS-FLOW CULTURE

Specimens for the continuous-flow system were collected from the "White Patch" area off Jennycliff Bay on the 30th of March, 1993. One hundred and twenty *Elphidium crispum* (greater in size than 500 µm diameter) were selected from the sediment and washed over a 500 µm nylon sieve. This system was terminated on the 30th of June (1993) when the number of specimens contaminated with bacteria was in excess of those that were healthy, and showed no sign of recovery. Groups of twelve *Elphidium crispum* were transferred into glass finger bowls. The culture containers were placed into two perspex aquaria filled with sea water, with an outlet pipe situated 10 cm above the height of the finger bowls. The aquaria were placed into a trough containing sea water to minimise temperature fluctuations; this trough was placed into a larger trough. Sea water and algae were held in a header tank, cooled to approximately 10-14°C by a Hetofrig cooler and pumped by a peristaltic pump (H.R. Flow Inducer: Watson-Marlow Ltd., Falmouth, England) into both aquaria, with a water replacement rate of approximately four litres per aquarium every 24 hours. The water from the outlet pipes went to waste in the trough. In this way the containers were constantly covered in sea water and supplied with fresh sea water and nutrients in a continuous-flow system. The temperature of the water surrounding the Foraminiferida fluctuated with room temperature, however, and to minimise these fluctuations both the external trough and the aquaria were covered with small, floating, polystyrene particles.

From Figure 8.1 (A) it can be seen that the specimens in the continuous-flow system were initially very active and gradually decreased in activity as time progressed. The decrease in activity was mirrored by an increase in contamination. Figure 8.1 (B) demonstrates how the temperature ranged temporally within the medium of this system. The temperature rose to a maximum of 14°C three times and fell to a minimum of 2°C. There was no apparent relationship between the wide fluctuation in temperature in this system with either activity or contamination levels of the experimental specimens.

Table 8.2: Activity and contamination levels of *Elphidium crispum* in the continuous-flow experiment.

Day	Temperature °C	Percentage active	Percentage contaminated
2	10	75.83	0.83
3	11.5	88.33	0.83
5	11	86.67	0.83
7	11.5	79.17	0.00
9	14	80.00	0.83
11	10	84.17	0.83
15	11	84.17	3.33
17	11	72.50	11.67
18	11	59.17	5.83
21	11.5	61.67	14.17
23	10.5	63.33	12.50
25	11	63.33	8.33
28	11	55.83	24.17
30	13	55.00	19.17
32	14	51.67	39.17
35	12	53.33	35.00
38	14	52.50	36.67
39	12	47.50	42.50
42	5	45.83	40.83
44	7	44.17	39.17
46	8	51.67	40.83
49	2	45.83	43.33
51	7	55.00	40.00
53	7	47.50	50.83
56	8.5	53.33	45.00
58	11	46.67	48.33
60	11	47.50	41.67
63	11.5	46.67	50.00
65	11	40.00	54.17
67	11	39.17	53.33
70	13	42.50	53.33
72	12	36.67	52.50

Two adult *Elphidium crispum* within this experimental group reproduced. On the 28th April (1993) {day 9} an adult became colourless and extruded a brown protoplasmic mass from its test. On the 30th April (1993) {day 11} another specimen became colourless and extruded several brown spheres from the test. This specimen was transferred to a small Petri dish to be examined, but the globular masses of cytoplasm extruded lost their spherical nature and disintegrated. By the 10th May (1993) {day 21} the parental *Elphidium crispum* had regained its colour and formed a pseudopodial feeding net by the 12th May (1993) {day 23}. Stalked protozoa were noted attached to the tests of the Foraminiferida on the 14th May (1993) {day 25} and holotrichous ciliated protozoa were noted on the bases of the containers on the 17th May (1993) {day 28}. Figure 8.2 shows a specimen whose test is clearly covered in a contaminant and Figure 8.3 shows a specimen with stalked protozoa

attached to the exterior of its test; these were identified as *Vorticella* sp. (Jahn & Jahn, 1949).

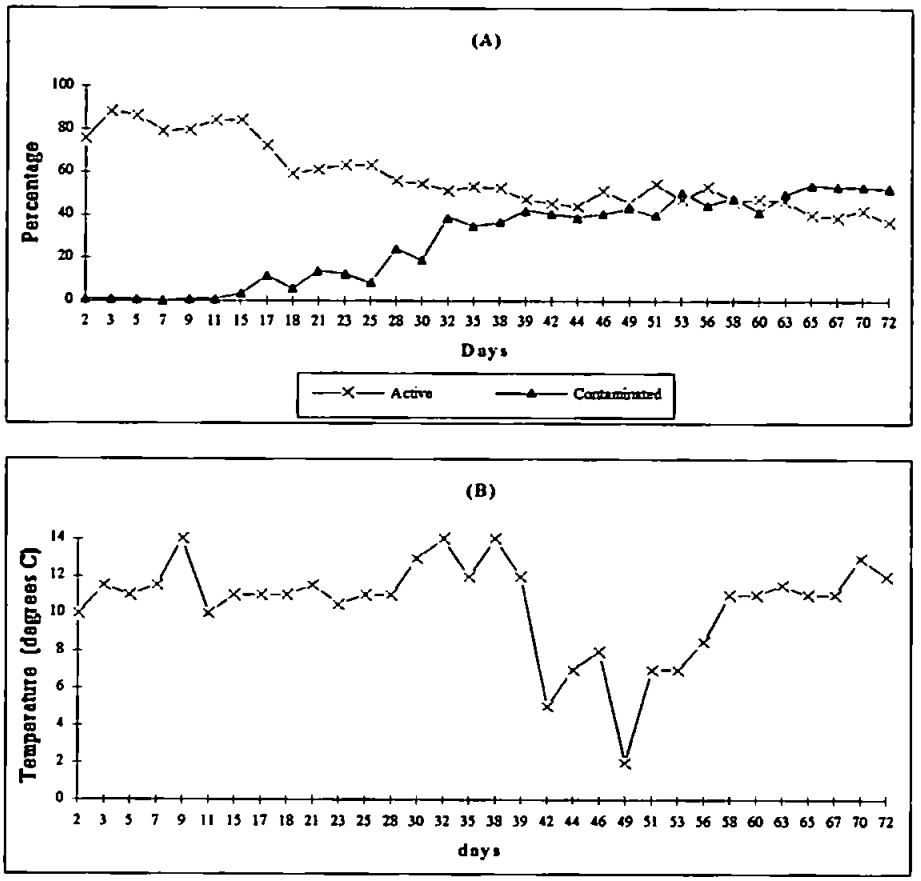


Figure 8.1: (A) Temporal fluctuations in activity and contamination of *Elphidium crispum* in the continuous-flow experiment
(B) Temporal fluctuations in temperature of the medium within the continuous-flow experiment.

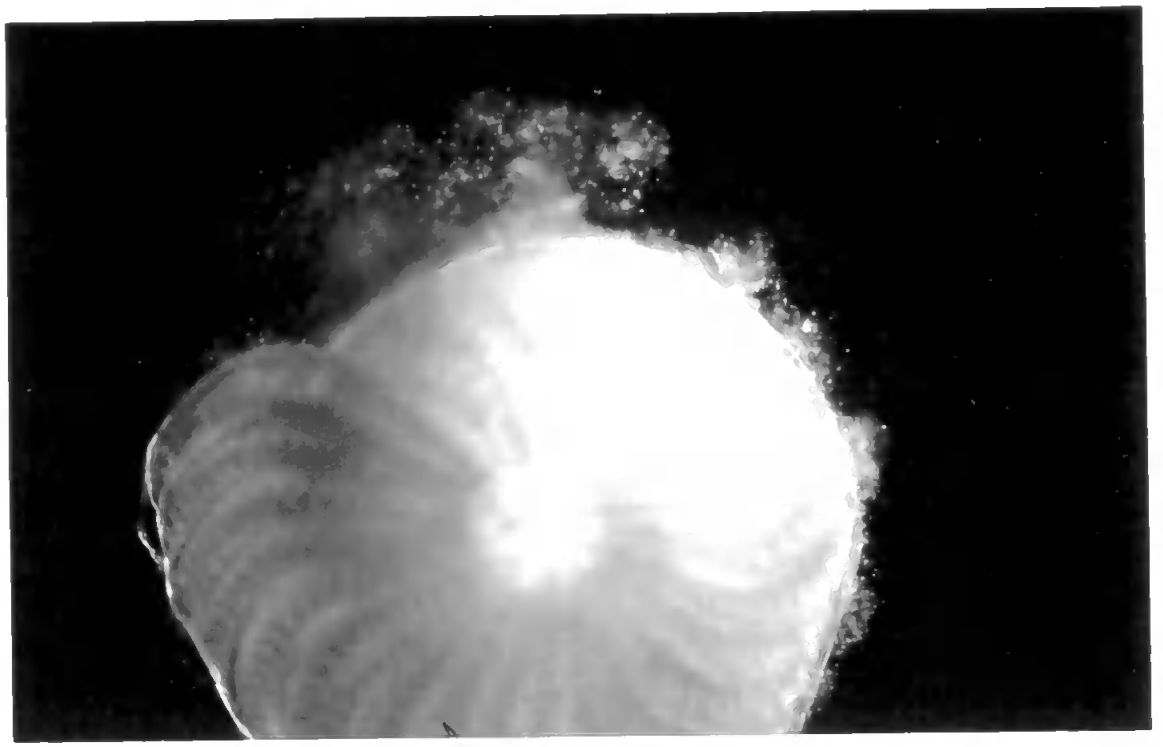


Figure 8.2: Contaminated *Elphidium crispum* from the continuous-flow experiment.

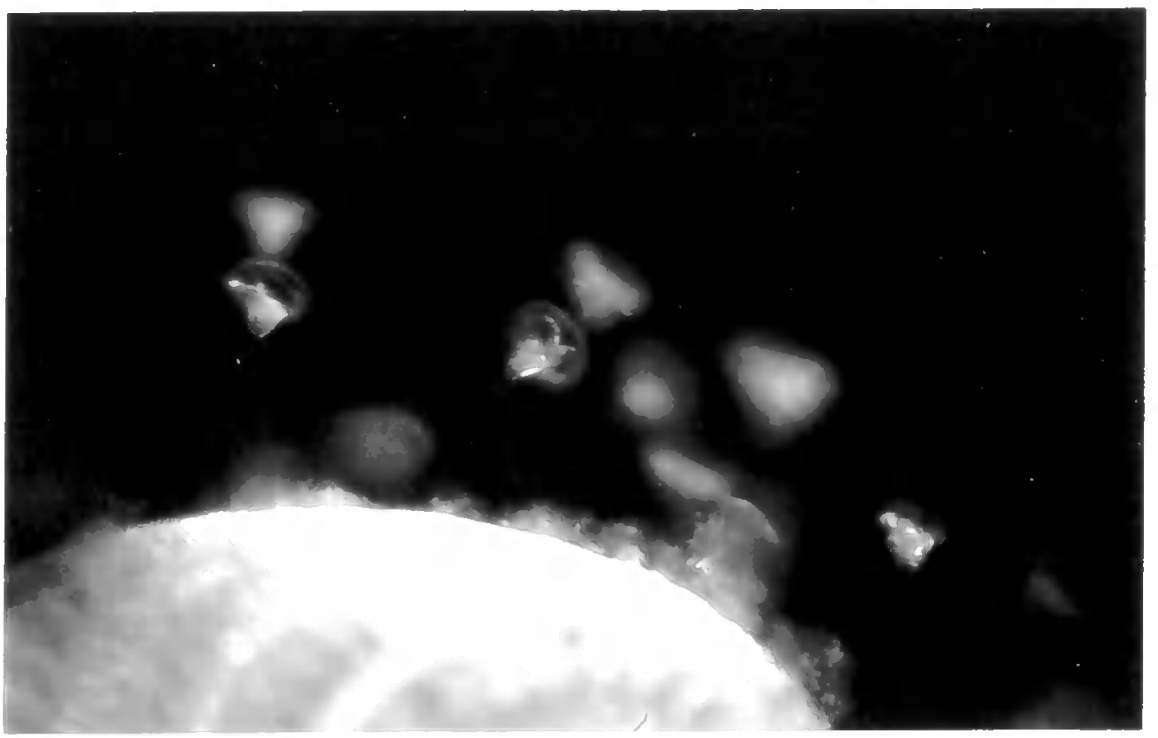


Figure 8.3: Continuous-flow *Elphidium crispum* with *Vorticella* attached to the test.

8.3.3. CONSTANT-TEMPERATURE EXPERIMENT.

The Foraminiferida were maintained in sterile Petri dishes in a constant-temperature room of 15°C and each container was supplied with 10 ml aerated, ambient-temperature sea water which had been filtered through a cellulose-nitrate Millipore filter of 45 µm pore size. Two antibiotics were added to the sea water to reduce bacterial contamination; Chloramphenicol at a concentration of three mg per litre and Streptomycin at a concentration of two mg per litre (Arnold, 1967). Streptomycin binds with the 30s subunit of the bacterial ribosome to inhibit protein synthesis and cause misreading of mRNA; Chloramphenicol binds to the 50s ribosomal subunit and blocks peptide bond formation through inhibition of peptidyl transferase (Prescott *et al.*, 1996). This system was run simultaneously with the continuous-flow system. Specimens were collected from the "White Patch" area off Jennycliff Bay on the 30th of March, 1993. One hundred *Elphidium crispum* (greater than 500 µm diameter) were extracted from the sediment and washed over a 500 µm nylon sieve.

When the specimens became contaminated on the 6th of May (1993) the contaminant was tested to establish whether it was bacterial or fungal in nature. Selective nutrient agar plates were prepared; four of Tryptone Soy Agar plus added salt, and four of Malt Agar plus added salt. The Malt Agar plates have a relatively low pH and allow fungi to grow and proliferate; the Tryptone Soy Agar plates are suitable for the growth of bacteria. Of the four plates of each media, two were designated as duplicate assays for Control and two were designated as duplicate assays for Contaminant Growth. 0.1 ml of sea water was extracted from the proximity of a contaminated specimen four times and spread on to each of the four Contaminant Growth plates, and 0.1 ml of sea water was extracted from the proximity of a healthy specimen and spread on to the four Control plates. The grown contaminant was then subjected to further identification procedures. This system was terminated on the 30th of June (1993) when contaminated specimens were in excess of healthy specimens and showed no sign of recovery.

From Table 8.4 and Figure 8.4 (A) it can be seen that activity was variable in this system. Activity initially declined sharply, oscillated until day 42 and then gradually decreased until the end of the experimental period. The levels of activity were almost mirrored by contamination levels. Figure 8.4 (B) and (C) illustrate that activity was consistently higher and contamination was generally lower in the continuous-flow experiment than in the constant-temperature experiment.

Table 8.3: Contaminant growth on selective media.

Nutrient Agar Plates		Average number of bacterial colonies per ml of medium
Tryptone Soy Agar:	Control	4600
Tryptone Soy Agar:	Contaminant Growth	4650
Malt Agar:	Control	0
Malt Agar:	Contaminant Growth	0

Contaminant growth only occurred on the Tryptone Soy Agar plates, indicating that the contaminant was bacterial in nature. The colonies from both the Control plates and from the Contaminant Growth plates were subjected to Gram-Stain analysis. The Control plates yielded Gram-negative rods, whilst the Contaminant Growth plates yielded both Gram-positive and Gram-negative rods. Holotrichous ciliated protozoa were observed in this system on 23rd June, 1993, and it was noted that they appeared to feed on the masses of contamination, with the result that the few containers which lacked ciliated protozoa were more contaminated than the rest.

Table 8.4: Records of the activity and contamination levels in the constant-temperature experiment.

Day	Percentage active	Percentage contaminated
2	77	0
3	70	0
5	38	1
7	58	0
9	48	0
11	57	3
15	37	26
17	28	33
18	24	31
21	40	39
23	27	42
25	56	32
28	48	37
30	47	39
32	41	45
35	31	47
38	52	37
39	35	38
42	38	45
44	27	46
46	29	40
49	21	46
51	32	44
53	24	53
56	15	62
58	26	63
60	20	59
63	16	65
65	14	64
67	13	74
70	7	77
72	10	80

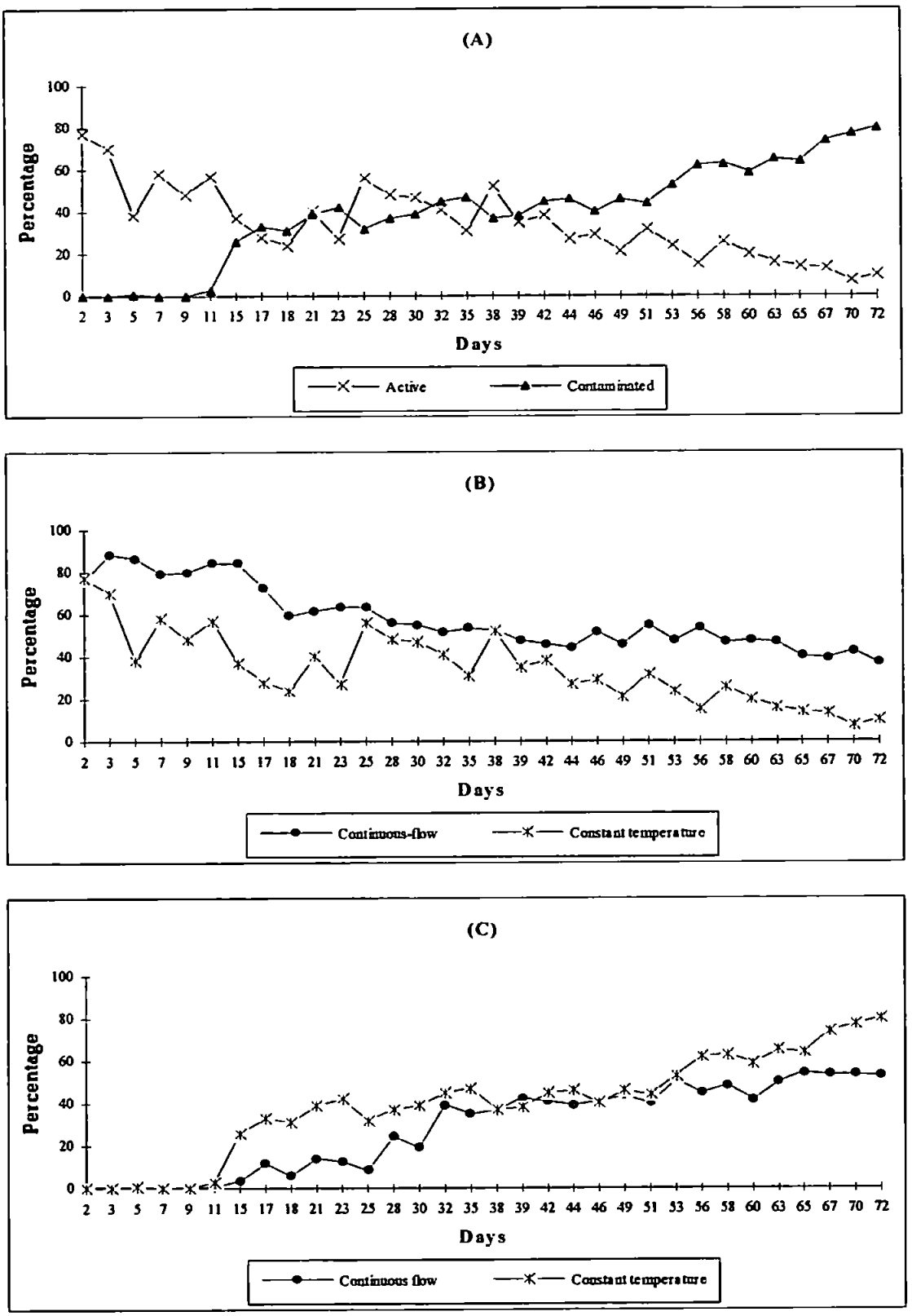


Figure 8.4: (A) Relationship between activity and contamination in constant temperature flow experiment
(B) Comparison of activity levels between continuous-flow and constant-temperature specimens
(C) Comparison of contamination levels between continuous-flow and constant-temperature specimens

One specimen reproduced in this system on the 17th May (1993) {day 28} and produced 97 offspring. The parent died on 21st May (1993) {day 32}. The offspring initially actively fed and moved, but by the 7th June (1993) {day 49} approximately 20 were white in colour and failed to form pseudopodial nets and were therefore assumed to be dead. This assumption was proved to be incorrect by the juveniles becoming devoid of contamination and actively feeding again by the 21st June (1993) {day 63}. On the 9th June (1993) {day 51} it was thought that the offspring had calcified sufficiently to be safely transferred, and 19 juveniles were transferred to clean containers. The offspring were again transferred on 14th June (1993) {day 56}. By the 30th June (1993) {day 72} all had become inactive and colourless. It was noted that by the 10th May (1993) {day 21} the pseudopodial nets of all specimens had become notably thinner, indicating a loss in vitality of all specimens.

Figures 8.5 and 8.6 show offspring leaving the parental test; Figure 8.5 gives some scale to the size of the proloculi, whilst Figure 8.6 clearly shows that the test had partially de-calcified, especially in the terminal chamber. Figure 8.7 shows that cytoplasmic filaments connected the proloculi of the offspring upon release from the parental test. Figure 8.8 shows two proloculi, in the centre of the picture, which apparently secreted one chamber between them. Figure 8.9 shows that the juveniles formed feeding pseudopodial nets and cysts at a very early stage in their development. Figure 8.10 shows that, at a later stage of chamber addition, the pseudopodia had become morphologically different, becoming both thicker and longer. Figure 8.11 shows a nine-chambered juvenile with stalked protozoa attached to the exterior of its test. The stalked peritrichous protozoa were identified as *Vorticella* sp. (Jahn & Jahn, 1949).

Figure 8.5: *Elphidium crispum* offspring leaving parental test.

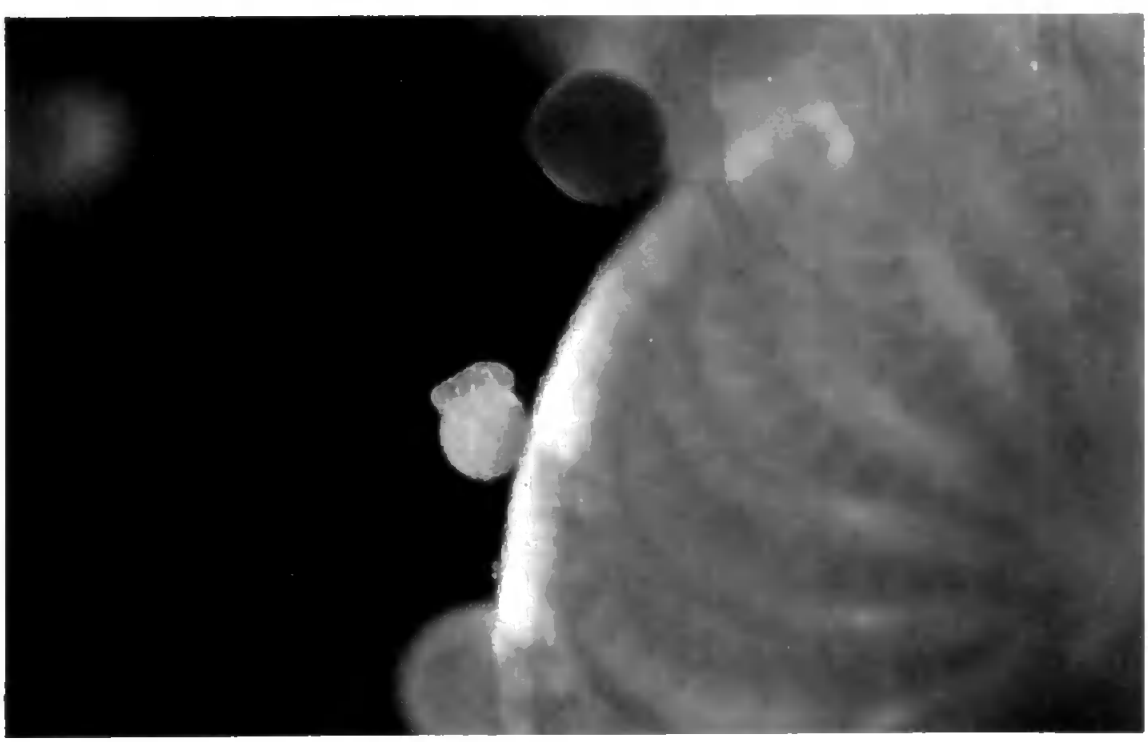


Figure 8.6: Partial de-calcification of parental test.

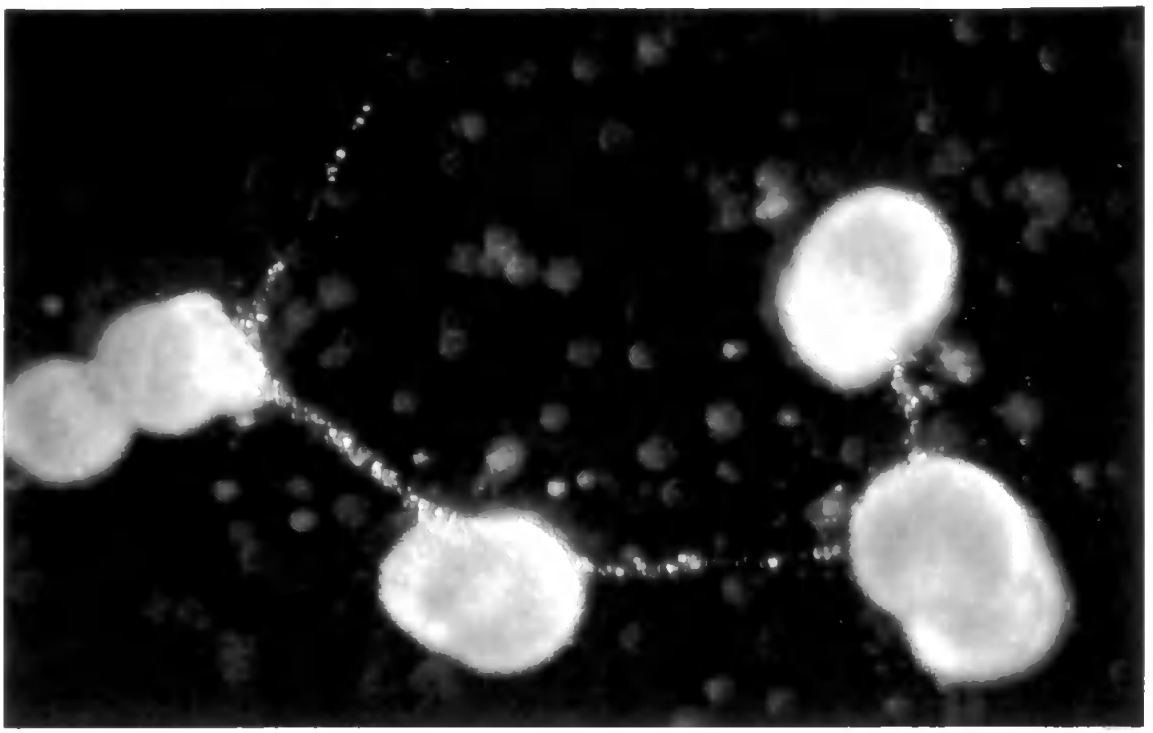


Figure 8.7: Cytoplasmic filaments connecting proloculi of offspring.

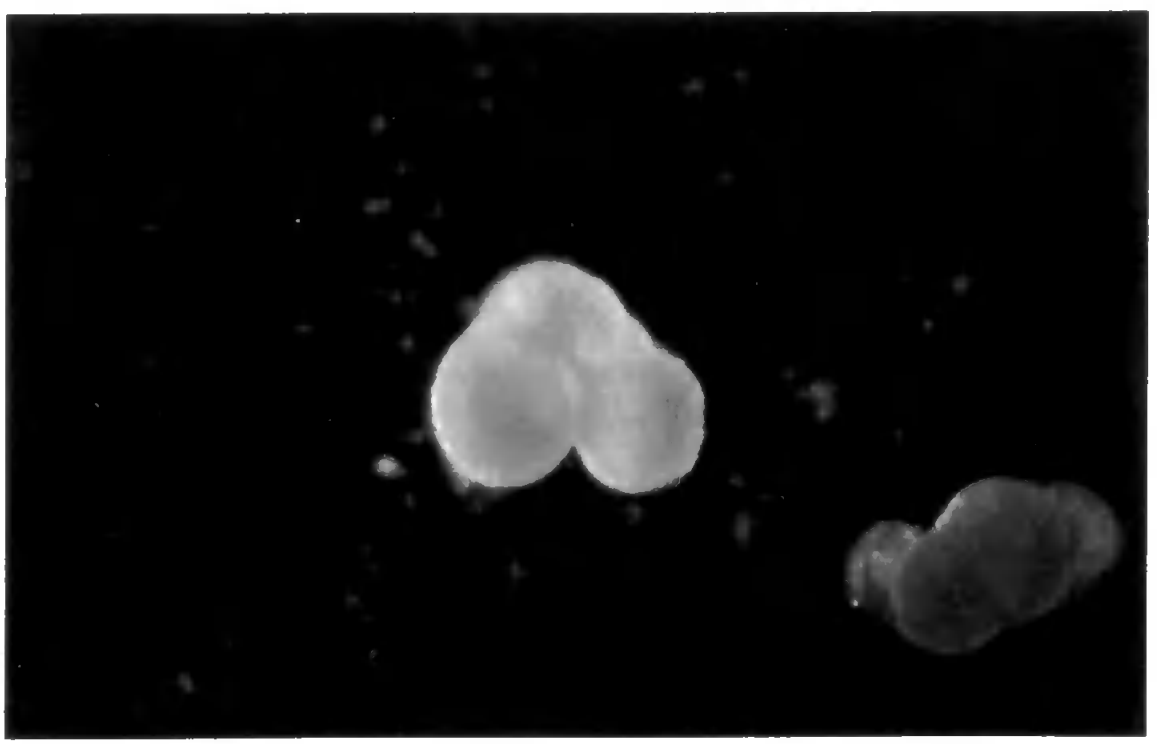


Figure 8.8: The secretion of a common chamber between two proloculi.

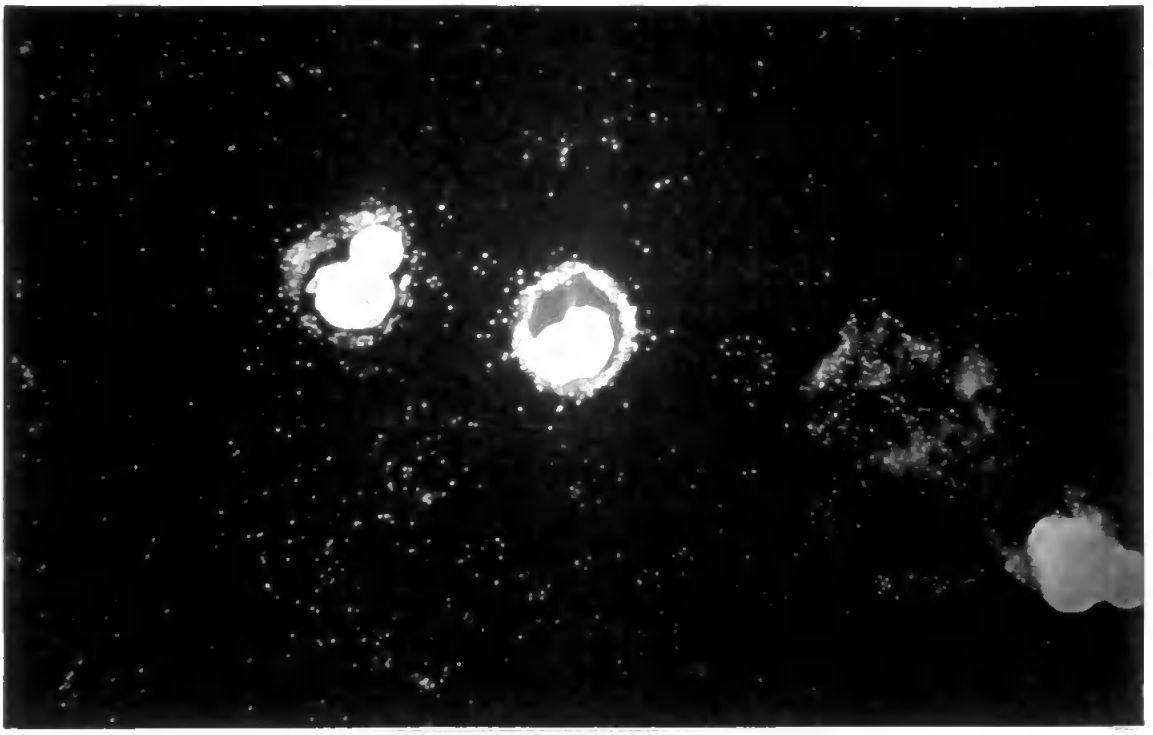


Figure 8.9: Juveniles forming pseudopodial nets and feeding cysts.

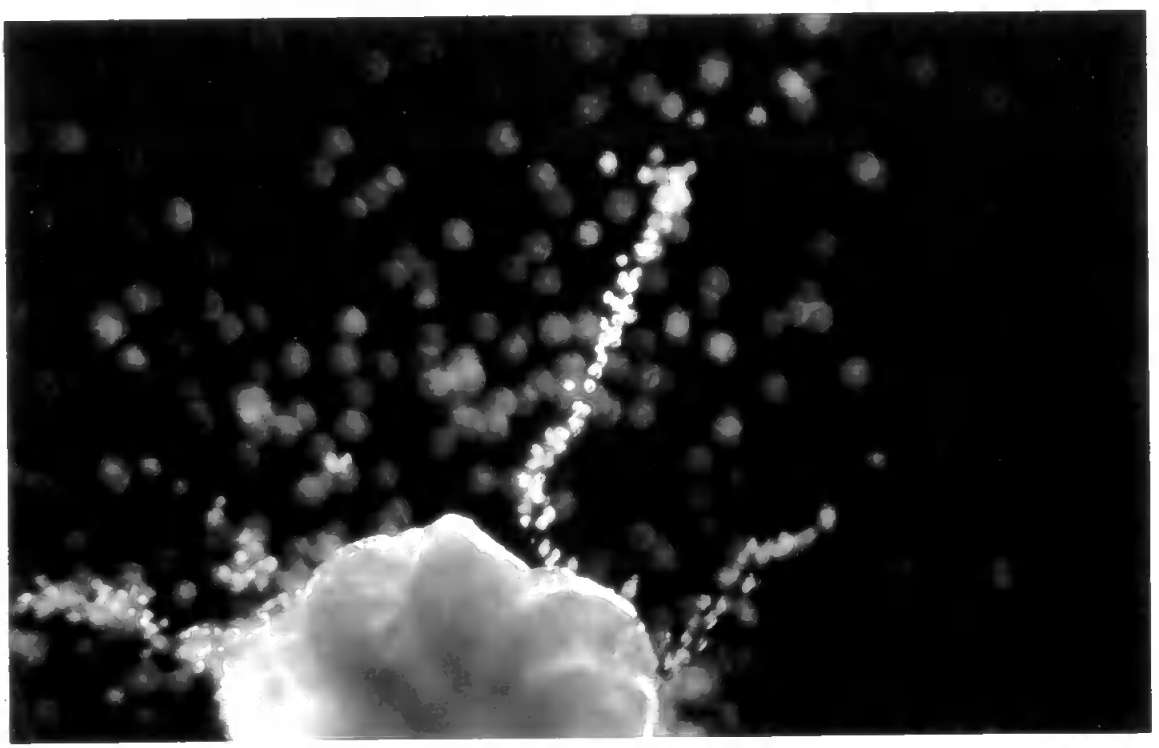


Figure 8.10: Morphologically different pseudopodia produced from an older juvenile.

Figure 8.11: Nine chambered juvenile with attached *Vorticella* sp.

8.4. DISCUSSION.

Number of Foraminiferida collected in samples

There was good extraction of *Elphidium crispum* for the Petri dish culture at 10°C from the sediment by using the microscope slides held vertically in racks, but this method was not viable for other species of Foraminiferida. Murray (1991) describes species of *Elphidium* and *Quinqueloculina* as epifaunal and those of *Ammonia* as infaunal. It would be expected therefore that only *Ammonia beccarii* would not have migrated onto the vertical slides. *Elphidium crispum* has, however, been described as negatively geotaxic (Murray, 1963: Arnold, 1974) and positively phototaxic (Kitazato, 1981), possibly explaining why it mounted the vertical slides in larger numbers than the other species present in the sediment. *Elphidium crispum* was abundant in samples collected in March, 1993, for the second and third experiments, probably corresponding with the Spring bloom of Foraminiferida at White Patch following the bloom of phytoplankton.

Vitality of specimens

From the Petri dish culture at 10°C there was no significant difference in activity and contamination levels between specimens which emerged at different times from the sediment, except for Group 3 from Drake's Island. It was expected that perhaps the first specimens to emerge from the sediment would be more active and less susceptible to contamination than the specimens which were collected later, but this was not so. There appears to be no link between speed of migration on to the microscope slides and resistance to contamination, possibly because speed of migration was probably more dependent upon burial in the sediment than healthiness.

Elphidium crispum in the continuous flow experiment appeared to have higher activity levels than those in the constant temperature experiment indicating that this system was more beneficial to the Foraminiferida than that of the third experiment. Contamination levels were also significantly lower in the continuous-flow specimens, supporting Anderson *et al.* (1991), who claim that Foraminiferida thrive in circulating and recirculating aquaria.

Benthonic Foraminiferida have a high requirement for oxygen and respire ten times more rapidly than naked amoebae of equivalent size (Hannah *et al.*, 1994). Although not a true comparison of "like with like" due to factors other than the flow of the media being different (higher temperature, added anti-biotics and smaller containers used in the constant-temperature system), the continuous-flow specimens were more vital than the constant-temperature specimens; perhaps benefitting from increased oxygenation of the media a continuous-flow system provides.

Contamination

There was no clear pattern of differences in contamination between sites in those maintained at 10°C. From subsequent sampling of the sites (see Chapter 5), the sediment from Drake's Island generally held bacterial numbers a magnitude higher than those of White Patch and Cawsand Bay. Therefore, it was to be expected that specimens collected from Drake's Island might become contaminated more quickly than those from other sites and, as this did not occur (except in Group 3), it must be concluded that the contaminant originated from the sea water supplied to the laboratory.

There was an inverse relationship in the continuous flow experiment between activity and contamination levels, strongly indicating that contamination was the major cause of the decline in activity levels. Contamination of the Foraminiferida appeared to affect the ability to form pseudopodial feeding nets and cysts, and to move.

The presence of holotrichous ciliated protozoa indicates that the contaminant was bacterial in nature, as ciliates are major consumers of bacteria; and once present, they did not disappear. These ciliated protozoa also probably originated from the sea water supplied to the laboratory. The periodic loss of visible contamination of the separated Foraminiferida might have been linked to fluctuations in the ciliated protozoan population and therefore to their consumption of the bacteria. Although the contaminated specimens were devoid of colour and obviously covered in contaminant, some still occasionally formed pseudopodial nets and feeding cysts; this confirmed that the contaminant did not colonise only dead

Foraminiferida. It may be that the metabolites of the contaminant were toxic to the Foraminiferida. The contaminated specimen from amongst those maintained at 10°C placed on a coverslip for examination withdrew its cytoplasm and the contaminant was no longer visible, indicating that the contaminant had not attached to the exterior of the test, but was present on the foraminiferal cytoplasm.

Activity levels were an inverse relationship of contamination levels in the constant temperature experiment, further supporting the theory that the contaminant adversely affected the Foraminiferida. It was noted in this experimental system that badly-contaminated specimens were adjacent to specimens devoid of contamination, suggesting that differences amongst individuals governed their potential for contamination.

Holotrichous ciliated protozoa were noted in the constant temperature experiment on the 23rd June (1993); they appeared to feed on masses of contaminant and reduce its abundance. Tests carried out on the contaminant showed that it consisted of two species of bacteria. Samples taken from the vicinity of a healthy specimen yielded Gram-negative rods, whereas media from the vicinity of a contaminated specimen yielded both Gram-negative and Gram-positive rods. Seiglie (1973) states that bacteria invade foraminiferal protoplasm as a type of disease, and it appears from the results obtained that the Gram-positive rods were responsible for the loss in activity and overgrowth of the Foraminiferida. It was hoped that the two antibiotics added to the medium of this experiment would have prevented bacteria from affecting the vitality of the Foraminiferida, although there are many microbial populations which are tolerant to antibiotics and are capable of degrading them (Atlas & Bartha, 1981). The lowering in activity is comparable to Schnitker's (1974) experience with cultures of *Ammonia beccarii* which had reproduced through 9 generations before a water change introduced a "mold infection" which killed nearly all specimens. Although many authors have reported the presence of bacteria in containers whilst trying to maintain Foraminiferida (see Myers, 1940; Sliter, 1965 and Lee, 1974), usually sediment and algal substrata have also been present. The sediment would provide a natural community of bacteria and other protozoa which would regulate themselves, whilst still providing

Foraminiferida with a food source. It is also possible that the epifaunal *Elphidium crispum* could remove contaminants from its test by locomotion through sediment in the natural environment, or in laboratory cultures containing a sedimentary substratum. In the third experimental system it appeared that only two species of bacteria were tolerant to the antibiotics and only one species was detrimental to the vitality of the Foraminiferida through over-production. It has also been noted in other systems that antibiotics inhibited foraminiferal growth and increased mortality (Bradshaw, 1961).

Buzzati-Traverso (1960) states that there is a great need for studies on diseases of marine organisms which may well be responsible for the rise and fall of large populations in the oceans. He also quotes Lucas (1947) as saying that substances having antibiotic activity might be responsible for the survival of delicate forms of planktonic plants and animals during the most critical periods in their life cycles, and it is known that antibiotic metabolites are produced by bacteria and algae. Rheinheimer (1992) states that bacteria and fungi may settle, at least temporarily, on surfaces of many plants and animals and there produce a fairly dense layer of growth called aufwuchs: animals shed excreta and bits of tissue which serve as nutrients for the aufwuchs flora on their surface. Fry (1982) states that the external surfaces of aquatic invertebrates are potentially an ideal habitat for bacterial colonisation and will benefit from organic material excreted by the invertebrate. In the marine environment the natural antibiotics produced by algae may prevent the detrimental effects of bacteria upon Foraminiferida observed in the laboratory experiments.

Colour of cytoplasm

Elphidium crispum harbours algal chloroplasts throughout its ontogeny (Lee, *pers. comm.*) and although this is not a true symbiotic relationship, the chloroplasts are generally of one specific algal species. Foraminiferida collected in November for the 10°C experiment were green in colour, whereas those collected in December for another purpose were rust-brown. This change in colour may be related to the Foraminiferida feeding upon Phaeophyte algae rather than Chlorophyte algae, or may indicate a change in chloroplasts harboured by this species.

Dispersal mechanism

Small specimens of *Elphidium crispum* in the first experiment were frequently found floating on the meniscus of the sea water in the containers and it may be that this represents a potential dispersion mechanism in calm waters or intertidally in the natural environment.

Temperature

The fluctuation in temperature experienced by *Elphidium crispum* in the continuous-flow system was likely to have affected both the activity of the Foraminiferida and the contaminant. It was expected that foraminiferid metabolism would be greatly affected by the fall in temperature; whilst a background temperature above that experienced in the natural environment for this species may have caused damage to enzymes and tissues and allowed bacteria to proliferate. This did not occur, however; and neither foraminiferid activity nor the contaminant was affected. The temperature dropped to a minimum of 2°C, which would not be experienced by *Elphidium crispum* under natural conditions and yet it appeared that the experimental specimens were not adversely affected by this extreme of temperature.

Reproduction

Placing specimens from the first experiment into a constant-temperature room of 20°C did not induce reproduction, indicating that possibly time of year rather than temperature governs reproduction. Two specimens reproduced in the second experiment in late April, consistent with observations by Jepps (1942) that maximum sporulation occurred just before the bloom of diatoms in the natural habitat. Although Myers (1935) advocated that transfer of the offspring is possible a day after reproduction, the offspring that were transferred did not survive and were obviously transferred at too early a stage. It was not known which type of reproduction had taken place: Jepps (1942) reported that this species became pale or white before the production of gametes, which usually occurred at 2 am. The mode of reproduction was likely to have been schizogony, as Lee *et al.* (1966) state

that schizogony is less sensitive to feeding than gamogony and Lee *et al.* (1969) found that often when daughter schizoids are released they are contacted to the parental test by thick pseudopodia. Myers (1943) states that reproduction results in death because all the protoplasm and almost all of the calcium carbonate goes to the new generation or gametes. One of the parental *Elphidium crispum* did not die, but regained its colour and started to feed after a few days, discounting the accepted maxim that all Foraminiferida die after reproduction.

Although Lee (1980) states that antibiotics inhibit reproduction, one specimen reproduced in the constant temperature experiment and produced 97 offspring. As Jepps (1942) states that up to 200 young can be produced from the asexual reproduction of this species, the fecundity may have been lowered by the antibiotics (Lee, 1974). Jepps (1942) states that the protoplasm from asexual reproduction issues from small openings in the canal near the last chamber and probably also from terminal openings. From Figure 8.6 it can be seen that the terminal chamber had become partially de-calcified, perhaps to allow emergence of the proloculi and to provide the proloculi with a source of dissolved calcite to secrete their tests. The difference in morphology of pseudopodia with ontogeny may relate to increased locomotion; Kitazato (1990) correlated different morphologies of pseudopodia with the mode of life.

By the end of June, 1993, it had been established that maintaining a thriving culture of *Elphidium crispum* was far more difficult than had first appeared. Three distinct approaches had been tried, and all three had failed due to bacterial contamination. A year, then, had been virtually wasted as attempts to successfully culture indigenous benthonic Foraminiferida had failed.

8.5. SUMMARY.

Attempts to culture indigenous Foraminiferida should be carried out with the sediment collected with the Foraminiferida in the natural environment, so that natural communities of bacteria and holotrichous ciliated protozoa are present and will regulate their populations so

that the Foraminiferida are not subject to bacterial overgrowth. Sediment might also provide a possible means of foraminiferid cleansing, if they became contaminated. The use of antibiotics is to be avoided, as it reduces fecundity and growth in Foraminiferida, and does not prevent the overgrowth of those pathogenic bacteria which are tolerant to antibiotics. The media should also be well supplied with oxygen.

CHAPTER 9.

GEOTAXIS AND PHOTOTAXIS IN *ELPHIDIUM CRISPUM* (LINNÉ).

9.1. INTRODUCTION.

Sedentary photosynthetic organisms are capable of detecting sunlight and can usually orientate themselves with respect to this stimulus: this is termed a tropic response. Tropic responses are common amongst terrestrial plants which orientate their leaves to follow the path of the sun to gain the most energy possible for photosynthesis. Some motile organisms are capable of detecting changes in their environment and move towards or away from the stimulus: this is termed a taxic response. If the organism moves towards the stimulus, this is regarded as a positive response, whereas if the organism moves away from the stimulus it is regarded as a negative response (Lincoln *et al.*, 1982).

The zonation of intertidal marine invertebrates often relies upon the ability to respond to light and gravity: for example, intertidal marine gastropods may use a combination of negative geotaxis and negative phototaxis to climb up rock faces, travelling vertically up the rock face in response to negative geotaxis, and then crawling into crevices under the influence of negative phototaxis. This alternation of the two types of taxis is repeated until the gastropod reaches the appropriate height for settlement. Geotaxic and phototaxic responses are well-documented in marine invertebrates and in the settlement behaviour of intertidal marine larvae and the phenomena of phototaxis and cyclic rhythms are very frequent among marine organisms (Buzzati-Traverso, 1960). Positive phototaxis of pelagic larvae facilitates their return to the shore as they rise close to the sea surface in the day when the wind is predominantly landward (Tait, 1981). Responses to light and gravity also aid the dispersion of larvae from marine invertebrates: the newly released larvae of corals (planulae) are geonegative and photopositive and enter

surface waters to be carried in currents; the planulae of most species studied reverse their response to gravity and light within two days, to settle on the sea bed (Barnes & Hughes, 1988).

Micro-organisms also display taxic responses to stimuli and may display thermotaxis (heat), geotaxis (gravity), aerotaxis (oxygen), thigmotaxis (mechanical force), or magnetotaxis (magnetic field) (Atlas & Bartha, 1981). These taxic responses to stimuli generally allow micro-organisms to move to sites that are favourable for growth and survival and even some non-photosynthetic micro-organisms, such as some protozoa, may exhibit phototaxic responses (Atlas & Bartha, 1981). Round (1981) states that all the major components of the epipelon are actively motile and positively phototaxic so they can move rapidly back to the surface after disturbance and burial.

Each foraminiferid species can be either epifaunal or infaunal in soft substrata. The reason for the vertical distribution of a species is unknown, but may be related to its feeding strategy or upon its requirement for oxygen. A mechanism is therefore necessary to allow each species to maintain the correct vertical distribution in sediments for its maximal growth and reproduction. It has been noted that when samples of sediment containing Foraminiferida have been returned to the laboratory by researchers and placed into a container of aerated sea water then some foraminiferal species appear at, and remain upon, the surface of the sediment. The mechanism for this behaviour has been poorly understood, and often reported as negative geotaxism or positive phototaxism: Verworn, 1889 (*fide* Boltovskoy and Wright, 1976) and Jepps (1942) note that *Elphidium crispum* is attracted to light and Myers (1943) observes that most Foraminiferida are positively phototaxic which, combined with negative geotaxis, allows the organism to reach the best position to release gametes. Lankford (1959) states that living Foraminiferida at the sediment-water interface may keep from being buried by crawling up through the fall of detritus and Murray (1991) states that some species living at the surface

may become buried by sediment during storms and because they are negatively geotaxic, they crawl upwards. Severin *et al.* (1982), found that the velocity of movement was inversely correlated with the depth of burial in *Quinqueloculina impressa* Reuss and suggest that higher velocities in surface layers may allow Foraminiferida to escape from a rising anoxic layer and may also allow for increased foraging rates.

Elphidium crispum is a shallow-water epifaunal species (Murray, 1991), which harbours chloroplasts throughout its ontogeny (Lee, *pers. comm.*). Lee & Lee (1989) find that this species, collected from the Plymouth area, carry approximately 150 chloroplasts when first captured. Many authors have noted that *Elphidium crispum* has appeared at the surface of collected sediment and Arnold (1974) used vertical microscope slides to harvest this species from the sediment. Myers (1943) states that buried *Elphidium crispum* individuals can escape from burial to a depth of 5-7 times their diameter and authors have variously described this species as being negatively geotaxic or positively phototaxic. Kitazato (1981) states that this species is positively phototaxic, whilst Murray (1963) states that *Elphidium crispum* is negatively geotaxic and (*ibid* 1979 {a}) that isolating Foraminiferida by allowing them to climb up the sides of the containing dish is feasible by reason of this taxism. Sheehan & Banner (1972) find in experiments upon *Elphidium incertum* (Williamson) from floating weed that 80% of the group displayed positive phototaxism and 20% of a group collected from sediment displayed negative geotropism when kept in the dark for four days.

In samples collected to extract Foraminiferida from sediment it was noted that the specimens of *Elphidium crispum* would migrate to the surface of the sediment within a few days; this response was variable, however, and in two winter samples this species had to be extracted with the aid of a stereoscopic microscope, showing that although present in the samples, they had not migrated to the sediment surface. Myers (1943) claims that in late autumn Foraminiferida become negatively

phototaxic and retreat into crevices, especially in the microspheric generation. The study of tactic responses is complex as responses may differ between individuals, through ontogeny, reproductive cycles, or be modified by the external environment or by the condition of the animal (Tait, 1981).

Despite various authors claiming that *Elphidium crispum* is phototaxic or geotaxic, no experiments have been carried out to distinguish which mechanism enables this species to remain epifaunal. This work was designed to study the mechanism by which *Elphidium crispum* remains epifaunal, geotaxism, phototaxism, temporal influence and response of the species through ontogeny.

9.2. MATERIALS AND METHODS.

9.2.1. COLLECTION & ISOLATION.

Foraminiferida were collected from the MBA Research Vessel *Sepia* from the White Patch area of Plymouth Sound, either by Naturalist's Dredge or by the Murray Grab. The temperature on the sea bed was assessed by use of a Temperature/ Salinity Bridge, type M.C.5 {manufactured by Electronic Switchgear (London) Ltd} and licensed by the National Institute of Oceanography. The probe was weighted and lowered until the sea bed was reached, so that temperature at depth could be measured. Upon collection, the sediment was placed into plastic containers in the ratio of approximately 20% sediment 60% sea water and 20% air (Lee, 1974; Anderson *et al.*, 1991) and placed into a cool box. Within four hours the sediment was emptied into a shallow polypropylene trough containing aerated sea water at room temperature. Specimens of *Elphidium crispum* were extracted by the use of a stereoscopic microscope and a sable brush. Viable specimens (assessed by movement and the production of pseudopodia) were washed in sea water over a set of nylon sieves, to produce specimens of different size classes without causing damage to their tests. The sieves were of aperture sizes 1 mm,

710 μm, 500 μm, 355 μm, 250 μm, 125 μm and 63 μm. The abundance of different size classes in the samples fluctuated throughout the year, and this was reflected in the size-classes tested. Half of the representatives of each size-class each month were designated as Control Specimens and the other half were designated as Experimental Specimens.

9.2.2. PRELIMINARY EXPERIMENTS.

Maintenance

Specimens of *Elphidium crispum* collected in July, October and November, 1993, formed the Preliminary Experimental Organisms. They were placed into lidded perspex Petri dishes of 47 mm diameter, together with 10 ml of aerated sea water. A mixture of the three unicellular algal species kept in culture (*Phaeodactylum tricornatum*, *Isochrysis galbana* and *Dunaliella praemolecta*) was added to the sea water to provide a concentration of 10^3 to 10^6 organisms per 10 ml of sea water (Lee, *et al.*, 1966). After the experimental period, the bases of the containers were cleaned with a sable brush, and the sea water and food organisms replaced. The Foraminiferida were maintained and tested within a Fison's Fi-totron 600 H Environmental Chamber at the temperature measured at the time of sampling. Light was provided by a 40 W fluorescent tube, with a photoperiod of 12 hours light/12 hours dark. The specimens within this preliminary system were tested for response to light above them, light below them (placed under the light source in a random manner) and to a sloped base for the months of July, 1993 and November, 1993. The tests for the month of October, 1993, were only carried out for gravity and for a light source below, as evaporation and the resultant salinity stress made the test for response to a light source above them inoperable.

Geotaxis

The containers used to test for response to gravity, for both experimental and control specimens, had black-painted bases and clear lids. The experimental specimens were placed on a perspex sheet, elevated at one end to provide a slope of 12°, and with a line ruled widthways across it. The control specimens were placed on a perspex sheet lying horizontally in the environmental chamber. The foraminiferal specimens were manoeuvred with a sable brush to lie along the line ruled across the sloping sheet or, in the case of the control specimens, to lie along a line drawn across a diameter of the base; in all cases, the orientation of the apertures was random. Individual movements were assessed as into one semi-circle or the other in the control samples and up or down the slope in the experimental cases. A positive geotactic response was recorded if individual specimens had moved down the slope; negative response was recorded if individual specimens moved up the slope.

Phototaxis

The containers used to test for response to a light source above the experimental specimens were modified: the bases were painted black, so that no extraneous light from below the specimens would affect their behaviour, and half of the lid was painted black to differentiate between a response into or out of the lit area. It is not thought that there was a temperature difference under the clear perspex half of the container lid and the black half of the lid due to differential absorption of thermal radiation, as the distance of the containers from the fluorescent light source was probably great enough to negate this effect. The intercept between the clear perspex and the painted area of the lid was oriented to correspond with a line drawn along the diameter of the base. The containers used for the control specimens had painted bases and clear lids. The foraminiferal specimens were manoeuvred with a sable brush to lie along the line drawn across the base; the orientation of the apertures was random. The positions of the control and experimental specimens were recorded every day, at the end of the experimental

period, on a piece of clear acetate on to which the diameter and the circumference of the Petri dish containers had been photocopied.

The containers used to test for response to a light source situated below the experimental specimens had painted black lids, to exclude light from above the specimens affecting their response and half of the base was painted black. The containers used for the control specimens had painted lids and clear bases. The individual specimens were manoeuvred with a sable brush to lie along a line drawn across the diameter of the base; the orientation of the apertures was random.

Positive phototaxic response was recorded for the light-source-above-the-specimens experiment if individual specimens had moved into the area beneath the clear half of the lid; negative response was recorded if individual specimens moved into the area covered by the painted half of the lid. Positive phototaxic response was recorded for the light-source-below-the-specimens experiment if individuals had moved into the area of the clear half of the base; negative response was recorded if individual specimens moved into the area covered by the painted half of the base.

Statistics

The experiments were repeated for five days with the same individuals and the total number of specimens which were positively or negatively active over that period was recorded. The null hypothesis was that the specimens of *Elphidium crispum* of each size-class for each month were neither phototaxic nor geotaxic. The results were analysed using a Chi-square (χ^2) contingency table test, with a continuity correction applied (for a 2 x 2 table). The resultant χ^2 value was compared to the critical values obtained from χ^2 tables (Murdoch & Barnes, 1986).

9.2.3. SECONDARY EXPERIMENTS.

Specimens collected for these experiments were not tested for response to a light source below them. The experimental technique was refined for testing the Secondary Experimental Specimens in 1994. Food organisms were removed from the containers prior to the experimental period by brushing the bases of the containers and rinsing with fresh sea water and then filling the containers with sea water. This minimised the risk of evaporation and removed the possibility that the Foraminiferida were following the motile unicellular algae in the containers, as the algae were themselves quite possibly phototaxic or geotaxic. The photoperiod was adjusted to correlate with Civil Twilight times (Nautical Almanac, 1993) for each month, so that the photoperiod would correspond to that of the natural environment. The Civil Twilight times were given for Greenwich (Latitude 50° N), and a correction for Plymouth (plus 5° W) was calculated as an added 20 minutes. The size-class pairs of experimental and control specimen containers were placed in a linear pattern beneath the fluorescent tube; within each pair the containers were set equidistant from the centre of the tube, to eliminate the possibility of different responses to differing light intensities. For the testing of a response to gravity the light-tube in the environmental chamber was replaced by two short tubes. The tube above the experimental specimens was hung 20 cm parallel to the elevated perspex sheet; the tube above the control specimens was hung 20 cm horizontally above the (unelevated) specimens (Figure 9.1). The slope was increased to 25° from the horizontal for the month of April, 1995.

Response to gravity was tested for March and April, 1994 (denoting Spring responses), June and July, 1994 (denoting Summer responses) and the month of September, 1994 (denoting Autumn response). Response to light above was also tested as above; except for September, 1994, when the Environmental Chamber failed, and this behavioural experiment was terminated. A schematic diagram of the experimental system is given in Figure 9.1.

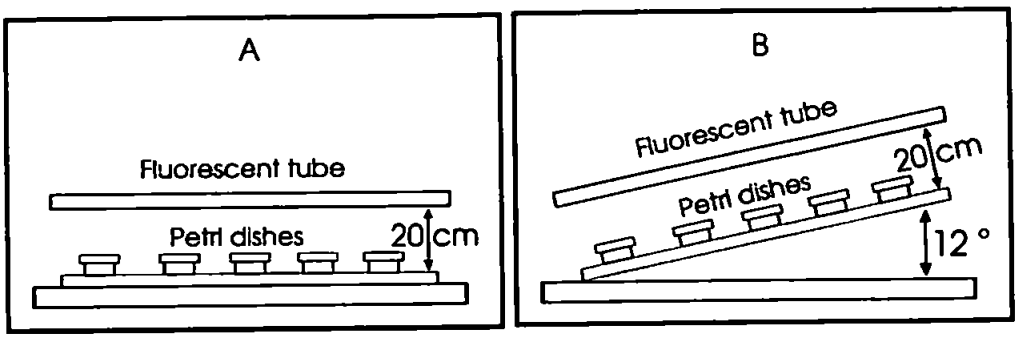


Figure 9.1: Schematic diagram of equipment to test geotaxis.

9.3. RESULTS.

The raw data of these experiments is contained in Appendix VII.

9.3.1. PRELIMINARY EXPERIMENTAL SPECIMENS.

Geotaxis

From Table 9.1, significant results were obtained for this experiment for the month of November, 1993, for size-classes of 500 µm-710 µm and 710 µm-1000 µm and the null hypothesis that *Elphidium crispum* of these sizes were not geotaxic, was rejected. The geotaxis demonstrated in the above specimens was negative, with movement upwards in both cases.

Table 9.1: Response of preliminary experimental specimens to gravity.

Month, year	Size (µm)	Number	Significant	Test statistic	p-value
July, 1993	250-500	200	X	0.321	-
July, 1993	500-1000	600	X	0.027	-
October, 1993	250-500	60	X	3.675	-
October, 1993	500-710	500	X	2.650	-
October, 1993	>1000	60	X	1.697	-
November, 1993	500-710	300	√	10.752	<0.005
November, 1993	710-1000	300	√	9.284	<0.005
November, 1993	>1000	150	X	0.459	-

Phototaxis

From Table 9.2 significant results were obtained for responses to a light source above the specimens for all size-classes and months; the null hypothesis was rejected and hence a significant phototaxic response was present. A comparatively high test statistic (108.338) and p-value (<0.001) was calculated for July, 1993 for individuals of 500 μm-1000 μm. The phototaxis demonstrated in the above specimens was positive, with all groups in both months moving into lit areas.

Table 9.2: Response of preliminary experimental specimens to a light source above them.

Month, year	Size (μm)	Number	Significant	Test statistic	p-value
July, 1993	250-500	200	√	5.664	<0.02
July, 1993	500-1000	600	√	108.338	<0.001
November, 1993	500-710	300	√	10.387	<0.005
November, 1993	710-1000	300	√	6.283	<0.02
November, 1993	>1000	150	√	10.446	<0.005

From Table 9.3 significant results were obtained for responses to a light source below the specimens for the months of July and November, 1993, for two size-classes. The null hypothesis, that *Elphidium crispum* of 500 μm-1000 μm in July, 1993, and 500 μm-1000 μm in November, 1993 were not phototaxic was rejected. From the p-values obtained the response to light from below the specimens was stronger in November, 1993. The phototaxis demonstrated in the above specimens was positive, with individuals moving into lit areas in both cases.

Table 9.3: Response of preliminary experimental specimens to a light source below.

Month, year	Size (μm)	Number	Significant	Test statistic	p-value
July, 1993	250-500	200	X	1.758	-
July, 1993	500-1000	600	√	4.878	<0.05
October, 1993	250-500	60	X	1.0774	-
October, 1993	500-710	500	X	0.0	-
October, 1993	>1000	60	X	1.313	-
November, 1993	500-710	300	√	14.901	<0.001
November, 1993	710-1000	300	X	0.480	-
November, 1993	>1000	150	X	1.318	-

9.3.2. SECONDARY EXPERIMENTAL SPECIMENS.

Geotaxis

From Table 9.4, significant geotaxic responses were observed on just three occasions. The null hypothesis that *Elphidium crispum* individuals were not geotaxic was rejected for the following: March, 1994, 250 μm-355 μm ($p<0.001$); June, 1994, 350 μm-500 μm ($p<0.02$); and September, 1994, 500 μm-1000 μm ($p<0.005$). For all other months and size-classes there was no evidence against the null hypothesis. The geotaxis for individuals in March, 1994, was positive, with individuals moving down from the horizontal; whilst in June and September, 1994, the geotaxis response was negative, with individuals moving up from the horizontal.

Table 9.4: Response of secondary experimental specimens to gravity.

Month, year	Size (μm)	Number	Significant	Test Statistic	p-value
March, 1994	250-355	80	√	11.509	0.001
March, 1994	355-500	400	X	1.001	-
April, 1994	355-500	400	X	0.041	-
April, 1994	500-1000	60	X	0.267	-
June, 1994	250-355	100	X	0.160	-
June, 1994	355-500	200	√	6.512	0.02
June, 1994	500-1000	500	X	2.89	-
June, 1994	>1000	200	X	2.016	-
July, 1994	355-500	60	X	0.067	-
July, 1994	500-1000	500	X	0.806	-
July, 1994	>1000	40	X	0.11	-
September, 1994	355-500	40	X	3.609	-
September, 1994	500-1000	400	√	10.3	0.005

Phototaxis

Significant results were obtained for this experiment for all size-classes and months, except April, 1994, when there was no evidence that *Elphidium crispum* specimens of 500 μm-1000 μm were phototaxic. For all other months and size-classes, the null hypothesis was rejected and hence a significant phototaxic response was present. The p-values were below 0.001 for all significant phototaxic responses, except March, 1994 250 μm-355 μm ($p<0.025$) and July, 1994 355 μm-500 μm ($p<0.01$). The greatest phototaxic responses were for individuals of

500 μm-1000 μm for the months of June and July, 1994. The phototaxis demonstrated in the above specimens was positive, with all moving into lit areas.

Table 9.5: Response of secondary experimental specimens to a light source above them.

Month, year	Size (μm)	Number	Significant	Test Statistic	p-value
March, 1994	250-355	80	√	5.158	<0.025
March, 1994	355-500	400	√	25.79	<0.001
April, 1994	355-500	400	√	13.964	<0.001
April, 1994	500-1000	60	X	1.736	-
June, 1994	250-355	100	√	16.536	<0.001
June, 1994	355-500	200	√	14.583	<0.001
June, 1994	500-1000	500	√	61.756	<0.001
June, 1994	>1000	200	√	34.396	<0.001
July, 1994	355-500	60	√	7.05	<0.01
July, 1994	500-1000	500	√	114.94	<0.001
July, 1994	>1000	40	√	16.41	<0.001

9.4. DISCUSSION.

9.4.1. MECHANISM BY WHICH *ELPHIDIUM CRISPUM* REMAINS EPIFAUNAL.

Positive phototaxis appears to be an important mechanism for *Elphidium crispum* to remain epifaunal in Summer months. The positive phototaxism demonstrated would be a mechanism for bringing a lightly-buried individual to the sediment-water interface, and maintaining it there. This is probably connected with providing the algal chloroplasts harboured by this species with sufficient light to photosynthesise.

The specimens of size-class 250 μm to 355 μm in March, 1994, showed strong evidence of being both geopositive ($p<0.001$) and photopositive ($p<0.025$). These opposing responses would counteract each other. It is possible that this might allow *Elphidium crispum* to avoid storms. If buried at this time of year by storm-produced sediment, or if the turbidity of the water increased due to waxing storm action, the organism would be unable to detect light and a geopositive response to move deeper into the sediment could well be advantageous. If light could still be

detected at this time of year, then the positive phototaxism displayed would enable the organisms to remain at the sediment/water interface.

In November, 1993, the specimens of size-class 500 µm to 710 µm were geonegative and photopositive (in response to light source situated both above and below the specimens) and the size-class 710 µm to 1000 µm were both geonegative and photopositive (in response to light source above the specimens only). In June, 1994 (Secondary Experimental Specimens) the size-class of 355 µm to 500 µm individuals was geonegative and photopositive; as was the size-class of 500 µm to 1000 µm individuals in September, 1994. These two types of taxism would act together to ensure that the species would move to the sediment surface.

It appears from the data that negative geotaxism is a useful secondary mechanism to remain at the surface if light cannot be detected, but in March, 1994, positive geotaxis may have helped *Elphidium crispum* to avoid storms and being carried out of the area by strong currents.

9.4.2. GEOTAXISM.

Negative geotaxis was demonstrated in only two of eight tests in the Preliminary Experiments; both of which were in November, 1993, for two different size-classes. Geotaxism was significant in only three of the thirteen tests of the Secondary Experiments. The slope was increased from 12° to 25° for April, 1994 to ascertain if this would lead to an increased response; both size-classes tested were not significant for geotaxis, however, indicating that the gradient was probably not important in April for the response to occur.

Moodley (1990 {b}) discovered from laboratory experiments that benthonic Foraminiferida exhibited negative geotaxis and Langer *et al.* (1989) observed elphidiid and ammoniid species digging into the sediment (positive geotaxis). This

study showed that positive and negative geotaxis was demonstrated in *Elphidium crispum* at different times of the year. Geotaxis in protozoa has been largely discounted as no organelle has been found, although vacuole contents could act as a statolith (Fenchel, 1987). Fenchel (1987) states that true geotaxis is only present in the ciliated protozoan *Loxodes* which contains a Müller vesicle which serves as a gravity sensor informing this geotaxic ciliate of its vertical positioning. Fenchel & Finlay (1984) determined that geotaxis in *Loxodes* is sensitive to dissolved oxygen tension: in low oxygen tensions it swims up, and in high oxygen tensions it swims down.

Positive phototaxis was demonstrated in Preliminary and Secondary Experimental individuals with no correlation to water temperature, but it may be possible that the temperature of the water acts as a trigger for geotaxic behaviour in *Elphidium crispum*. Negative geotaxis was observed in November, 1993, and June and September, 1994, when the water temperature was rising; whereas positive geotaxis was observed in March, 1994, when the temperature of the water was at a minimum. If the contents of vesicles are the mechanisms of the geotaxic behaviour observed, the density of the contents would be affected by water-temperature, and perhaps lead to the observed change in response.

Geotaxism was variable, both in terms of significance and whether it was positive or negative. It is possible that the temperature of the water acts as a trigger for the opposing geotaxic behaviour in *Elphidium crispum*. The media within the experimental containers was not agitated within the experimental period, and so possible sensory input by the reticulopodes to induce geotaxism was not possible. In addition, the media was uniformly oxygenated before filling of the containers, so movement in response to varying oxygen concentrations was not possible.

9.4.3. PHOTOTAXIS.

Comparison of the phototaxic data from the light above the specimens and the light source below the specimens shows that *Elphidium crispum* reacted more consistently to the experiment of the light source situated above the specimens. All size-classes of all months tested for response to a light source above the specimens in the Preliminary Experiments were positively phototaxic. The test statistic value for specimens of 500 μm-1000 μm in July, 1993 was comparatively much higher than that of other size-classes and months tested.

Only two of the eight tests carried out for response to a light source below the specimens in the Preliminary Experiments yielded significant positive phototaxic responses. It would be assumed that if the *Elphidium crispum* had followed the motile food source into light, then all tests would have been significant. It seems likely, therefore, that either the algae did not preferentially move into the lit area, or that the foraminiferid specimens did not follow the food source. This is substantiated by Murray's work (1963), who finds that *Elphidium crispum* did not follow the positively phototropic *Tetraselmis suecica* alga into the light side of the culture dish, although Sliter (1965) finds in his experiments upon *Rosalina globularis* that this species did follow diatoms to the light side of the culture dish.

In the Secondary Experiments all size-classes for all months tested were positively phototaxic except for April, 1994, for the size class 500 μm to 1000 μm. The p-values for the phototaxic responses were all 0.001 except for the size class of 250 μm to 355 μm specimens in March, 1994, when it was 0.025. Specimens between 500 μm to 1000 μm tested in June and July, 1994, produced comparatively very high Test Statistics.

This study concurs with that of Lee (1990) who observed phototaxis in three species of Foraminiferida which contained endosymbionts, and Murray (1991) who

stated that as the symbionts require light, symbiont-bearing benthonic Foraminiferida are responsive to this. Fenchel (1987) put forward the idea that ciliated protozoa containing symbiotic photosynthetic cells which accumulated in the light were not demonstrating a true taxic behaviour. He found that *Paramecium bursaria* which normally contain symbiotic *Chlorella* cells are attracted to light, but if no symbionts are present there is no response to light. It is likely that the positive movement towards light observed in the above study is a behavioural response to maintain the chloroplasts harboured by *Elphidium crispum* in the light; however, it is maintained that this is a motile response to a stimulus, and as such, is a taxic behaviour.

By comparison of results from the experiments carried out upon the Preliminary and Secondary experimental specimens, it appears that the *Elphidium crispum* in the Preliminary experiments were little affected by the presence of the unicellular algae in the containers, although in the natural environment their behaviour may well be mediated by the unicellular algae in their habitat.

9.4.4. TEMPORAL INFLUENCE.

Both geotaxis and phototaxis appeared to be affected by the time of year tested. In the Preliminary Experiment for geotaxis only two size-classes were significantly geonegative, both in November, 1993; and in the Secondary Experiment for geotaxis specimens were geopositive in Spring (March, 1994) and geonegative in Summer (June, 1994), Autumn (September, 1994) and Winter (November, 1993). Positive phototaxism appears to be an important mechanism for *Elphidium crispum* to remain epifaunal in Spring (March and April, 1994), Summer (June, 1994; July, 1993; July, 1994) and Winter (November, 1993).

9.4.5. ONTOGENY.

Individuals of greater than 250 µm demonstrated geotaxis and phototaxis. Stage of development appears to be important for phototaxis in *Elphidium crispum* as strong significant test statistics were obtained in the months of July, 1993, and June and July, 1994, for individuals of 500 µm to 1000 µm. This increase in response was probably not due to natural variability or sampling error, and it is tentatively assumed that phototaxis is more important to the larger, adult *Elphidium crispum* in these Summer months; perhaps to facilitate the release of gametes. Although Jepps (1942) stated that culture *Elphidium crispum* gametes settle with no orientation to light or to gravity, individuals of greater than 250 µm were capable of geotaxis and phototaxis.

The quality and intensity of the light were not altered during the experimental period and this would possibly have affected the responses observed. Intensity of light at depth is a complex variable, which may change by the hour in the natural environment. Although the quality of the light could have been approximated by the use of coloured screens over the fluorescent tube, it was not possible to accurately reflect the changes in intensity in the natural environment.

Additional research needs to be carried out to test the responses of this species to light and gravity throughout an annual cycle, and to test whether the temperature of the water is the fundamental factor which renders the geotaxism positive or negative. It would also be necessary to determine the mechanism of geotaxism and phototaxism. The positive geotaxism observed must be reversed at some stage (when light is not detected) and may, in the natural environment, be related to available oxygen within the sediment: the trigger for this change in behaviour needs to be assessed. In addition, it would be useful to determine the responses of this species to gravity at night.

9.5. SUMMARY.

Positive phototaxism appears to be an important mechanism to maintain harboured chloroplasts in the photic zone, and, combined with negative geotaxism, both responses ensure that *Elphidium crispum* remains epifaunal. The observed combination of positive geotaxism and positive phototaxism in March might be a mechanism to avoid storms and being carried out of the area on high currents. Specimens as small as 250 μm demonstrated the ability to respond to light and gravity, although there appeared to be a very strong response to light for large specimens in Summer, perhaps to facilitate reproduction. The time of year appears to affect whether geotaxism is positive or negative perhaps indicating the possible mechanism of geotaxis (density of vesicles). A light source above the specimens appeared to induce a phototaxic response, perhaps demonstrating that a photoreceptor exists on the dorsal side of the organism.

CHAPTER 10.

DEFORMATION OF THE TEST.

10.1. INTRODUCTION.

Stress and morphological differentiation

Organisms under environmental stress may become morphologically different from members of their own species not subject to stress. This response is known to occur amongst marine algae (both amongst micro-algae and macro-algae) and amongst marine invertebrates. Organisms with higher levels of tissue complexity and compartmentalisation are generally able to excrete or secrete excess pollutant materials. Free-living Foraminiferida, in general, form very regular, symmetrical tests, which allows relatively easy identification of the taxa, although attached epiphytic and epilithic forms often form tests distorted to allow easier attachment. Miller *et al.* (1982) find that the morphological variation in the *Elphidium excavatum* group is a function of natural physical variables.

The test of Foraminiferida is believed to act as an effective barrier against stressful conditions. The separation of the series of chambers by narrow openings, (Marszalek, 1969; Marszalek *et al.*, 1969; Murray, 1991) and the observed withdrawal of protoplasm into inner chambers, (Marszalek, 1969; Marszalek *et al.*, 1969; Hottinger & Dreher, 1974; Murray, 1991) are both thought to be mechanisms to protect the organism from unfavourable changes in environmental chemistry. These mechanisms are thought to be important to miliolids and planispiral Foraminiferida and the genera of *Sorites*, *Planorbulina*, *Bolivina* and *Discorbis*. Arnold (1954 {a}) finds that the pore plugs of *Discorinopsis aguayoi* might act as valves to allow the escape of pseudopodia and then close as soon as the pseudopodia are retracted, and Pierce *et al.* (1968) state that the organic matrix of calcareous and arenaceous tests and organic tests of "tectinous" Foraminiferida have a vital role in regulating the entrance of various elements in the environment into the interior of the test. Behaviour of Foraminiferida may also be affected

by the environment, as Sieglie (1975) observed *Ammonia catesbyana* burying in sediments, which he states may be a form of defence against sudden and unfavourable conditions.

Micropalaeontologists have discovered from sedimentary cores that a proportion of foraminiferid tests examined are sometimes morphologically deformed. The cause of deformation of tests of Foraminiferida is unknown. Examination of foraminiferid tests from living assemblages have sometimes also revealed a proportion of the assemblage to have deformed tests, and many authors have suggested a relationship between deformed foraminiferid tests and particular environmental variables from field collections. Murray (1979 {b}) states that although growth is genetically controlled in some environments, abnormalities are "not uncommon" and range from reduced chamber size to changes in coiling direction. Deformation of foraminiferid tests is believed to occur in response to extremes of food items, salinity, temperature, organic content and heavy metal content of the sediment.

Nutrition

It is believed that food deficiency in winter results in the formation of chambers smaller, or longer and thinner, than those produced before and after the shortage of food organisms (Myers, 1943; Alve, 1991), producing tests of uneven peripheries. Setty (1976) states that *Ammonia beccarii* living in an environment high in organic content are high spired, with crooked, bent or curved terminal whorls. Sieglie (1975) finds that high organic content causes *Ammonia catesbyana* to produce a high-spired form (and some specimens may also possess a protruding proloculus); whilst *Quinqueloculina rhodiensis* may develop an abnormal form in response to organic pollution. Sieglie (1975) also finds *Ammonia catesbyana* to be mostly megalospheric, indicating that sexual reproduction provides a quick way to adapt to the organic pollution. Sieglie (1973) finds that living pyritised specimens are found at organically polluted sites, especially amongst variants of *Ammonia tepida*, and suggests that pyrite may be produced by sulphate-reducing bacteria and may invade foraminiferal protoplasm as a type of disease. High organic pollution, caused by the Amoco Cadiz oil spillage, resulted in malformed Foraminiferida (especially *Protelphidium*

paralium), possibly due to affected growth rates and modes of calcification which might affect foraminiferal resistance to parasitic attack (Vénéc-Peyré, 1981).

Salinity

The morphology of Foraminiferida is also believed to be affected by the salinity of the water within the habitat. Murray (1973 {a}) states that specimens which reproduce near the limits of favourable salinities commonly have more chambers and are slightly larger than those reproducing under favourable conditions; and Malmgren (1984) identifies three morphotypes of *Ammonia beccarii* from salinas samples ranging from 7‰ to 92‰. Almogi-Labin *et al.* (1992) observe in a hypersaline pool (ranging from 39.7‰ to 54.5‰) that abnormal tests were formed in *Ammonia beccarii* as a result of seasonal stress conditions and the ionic composition of the water. Deformities due to hypersalinity ranged from deformed chambers smaller than previous chambers to changes in coiling direction and the presence of twinned forms, with some specimens having abnormal early stages with no further growth. Aberrant calcareous specimens have been observed from both hypersaline and hyposaline environments, indicating possible interference with the precipitation of the test.

Temperature

Temperature also affects the morphology of some calcareous Foraminiferida; this may be because the solubility of calcium carbonate is increased at lower temperatures and pressures. Overall size, as well as thickness of the wall and strength of ornament, may vary with changes in salinity and temperature (Haynes, 1981). Boltovskoy & Wright (1976) quoted Lutze (1962) as observing that benthonic specimens of *Bolivina spissa* varied morphologically, from being narrow at 1000m depth in cold water to becoming broader and more highly ornamented in warmer and shallower waters. It is also possible that this may be due to hydrodynamic activity rather than to temperature. The benthonic species *Ammonia beccarii* seems to have physiological races based on temperature optima (Matera & Lee, 1972), and cultured *Ammonia beccarii* grown at lower temperatures produce larger tests (Bradshaw, 1961). Planktonic Foraminiferida also demonstrate morphological variations

based on temperature, with asymmetry and aperture losses in colder water (Boltovskoy, 1962). Bé (1968) related the porosity of planktonic Foraminiferida to temperature with warm, tropical, species having a 20% porosity while those from cold polar waters have a 5% porosity. This may indicate that porosity of the test is related to different buoyancy requirements of planktonic Foraminiferida in waters of different temperatures; those from warmer waters requiring a higher porosity of the test. Sieglie (1975) states that thermal pollution results in *Ammonia tepida* having distorted chamber arrangement and tumour-like outgrowths of chambers in larger specimens, and that *Quinqueloculina rhodiensis* develops an abnormal form in response to thermal pollution.

Heavy metals

Although marine Foraminiferida show only a very small proportion of the population to be abnormal, some fossilised Foraminiferida have shown abnormalities in test morphology (Arnal, 1955). Sharifi *et al.* (1991) are the first authors to directly correlate foraminiferid test deformation in core samples with the presence of heavy metals in the surrounding sediment. They find that the distributions of some Foraminiferida are altered by some heavy metals, and, whilst some species are able to tolerate this type of pollution, others form deformed tests. Examination of core material reveals that prior to higher levels of copper and zinc there are no foraminiferid deformities, but that deformations are apparent in specimens associated with these higher levels of heavy metals. Since their paper, other authors have also attempted to correlate deformation of foraminiferid tests in field collections with the concentration of heavy metals in the substrata at the time of collection (see Stubbles, 1993; Yanko *et al.*, 1994) . To substantiate the hypothesis that heavy metals were causing the observed deformities, Sharifi *et al.* (1991) maintained living *Ammonia beccarii*, and exposed them to levels of copper between 10 and 20 parts per billion; specimens formed deformed tests after 12 weeks. Types of deformation observed from this trial included producing a high spiral side, additional chamber development, twisting and twinning. Unfortunately, laboratory Foraminiferida are known to show aberrances in the absence of metals (Hedley & Wakefield, 1967), and, as the number of specimens tested was only a maximum of six, the results are not statistically viable. However, unlike other

authors, Sharifi *et al.* (1991), by carrying out laboratory experiments under controlled conditions, attempted to prove that heavy metals were capable of causing the observed deformation.

It is necessary to fully understand the chemistry and properties of heavy metals before attempting to theorise the possible cause of test deformation. A heavy metal is distinguished from a metal if it has a density greater than 5g cm^3 and has the chemical properties of a metal. There are 32 heavy metals which often occur with the metalloids of arsenic, antimony and bismuth. Most heavy metals are transition elements, which means that they can move a newly-gained electron to the penultimate shell. This ability alters the chemical properties of the element. Its reactivity is changed, and up to 5 electrons can be moved into the inner shell, making the element pentavalent. There is no re-distribution of valence electrons during bond formation; the degree of covalent bonding between two atoms is determined to a significant extent by the relative energies of the valence orbitals (Whitfield & Turner, 1983). Similarity between heavy metals is expressed along the vertical axis of the periodic table *e.g.* zinc, cadmium and mercury, because as each electron shell is added to the transition elements, the mass and reactivity is increased. Heavy metals chelate easily with other elements, and even gases. Because they are transition elements, when the electron is moved to the inner shell by loose bonding, the heavy metal may attract another element. This characteristic means that heavy metals can be used to transport an element from the place of uptake to the place of use, and this is why they are common components of respiratory pigments. Although heavy metals transport elements without oxidising them, they have no method of control. Many heavy metals readily adhere to organic matter and, if the organic content in the environment is high, there is a high rate of heavy metal chelation.

Heavy metals are important aquatic pollutants, which are both naturally and anthropogenically introduced into the marine environment. These elements are subject to biogeochemical cycling as a natural part of the ecosystem. The particles settle out as dust from magma eruptions and the vapours condense on particulate materials in the atmosphere. Fumaroles on the sea bed may also release heavy metals. By the processes of vulcanism and

fumaroles, the marine system receives particles or vapours of heavy metals by precipitation. The erosion of igneous rocks also releases heavy metals, as all igneous rocks contain them, although erosion may be at widely different rates. Natural localised high concentrations of heavy metals may be due to the local biology or geology. Biogenic rocks are generally fine sediments with high organic content, which chelate heavy metals into the sediment; and estuarine muds generally carry a high heavy metal content (Atlas & Bartha, 1981). The activity of man can place naturally-occurring heavy metals at problem levels into the marine ecosystem; the drainage of mine works frequently results in the release of acid water which has leached heavy metals from the rocks mined; and the extraction or spillage of oil places these heavy metals into the marine ecosystem in unnatural concentrations. If the activity of man distributes high concentrations of heavy metals into areas which were previously not subjected to them, this is pollution. The unnatural release of heavy metals occurs by many processes, and includes: the mining of rock which accelerates the erosional process and places heavy metal laden dust into the atmosphere to be carried in all types of water courses; smelting of ores; the use of pesticides, fungicides and metals as supplements for livestock feed; car emissions which release lead into the air; photographic laboratories which release silver into discharge points *etc*. Cadmium is present in phosphate-bearing rocks, and therefore in phosphate-based fertilisers (Atlas & Bartha, 1981). Jones & Johnson (1991) state that cadmium, chromium, copper, nickel, lead and zinc are associated with sewage input and Balogh (1988) states that an adult man excretes between 7 and 20 mg of zinc daily. Ramelow (1985) finds that shipping and sewage elevate levels of zinc, but reduce levels of nickel and cadmium.

Factors which affect the transportation of heavy metals also affect their uptake and toxicity. The aquatic system ensures that metals exist in a variety of physical and chemical forms. The chemical form is variable and is largely dependent upon the chemistry of the receiving waters, which affects metals and changes their chemical state. The two major transport phases are either dissolved or in suspension: if dissolved, the metal is usually in the form of a free ionic salt, or associated with a soluble organic molecule, whereas if the metal is in suspension, it may be adsorbed on to or into organic or inorganic particles, or be

precipitated as a salt of the metal. Most metals exist in the dissolved state and this affects their uptake by organisms. In suspension, the particles are adsorbed on to the surface of materials, which makes them relatively easily adsorbed by digestion (due to pH changes in the gut changing their state from the particulate to the soluble form). If heavy metals are incorporated into organic particles, they may not be fully available, and may be excreted.

Uptake of heavy metals may occur either *via* the surrounding water or from food items taken into the body. Interstitial waters which have low levels of oxygenation generally are highly acidic, and act as reservoirs for heavy metals; this results in deposit-feeders generally suffering more heavy metal uptake from the medium than suspension-feeders. Active uptake may also occur *via* the cellular pumps for sodium and potassium. Uptake *via* food organisms is the major route of heavy metal passage into an organism, except for those which are small and have a high surface-area-to-volume ratio. Bacteria are known to have highly anionic walls and, in the few species of bacteria studied, the outer membrane of Gram positive bacteria was more effective at binding heavy metals than the walls of Gram negative bacteria (Beveridge, 1984). Although Boyle (1984) states that bioaccumulation of heavy metals by algae may be important through food chains to consumer organisms, and Abel (1989) states that heavy metals in the tissues of prey may form a threat to long-lived organisms at higher trophic levels, metals do not appear to accumulate through the trophic chains to the top predators of a community, with the exception of methyl mercury (Bryan & Langston, 1992).

Life evolved with heavy metals present, and at naturally-occurring levels they are normally harmless. Many heavy metals are incorporated into the biochemistry of many organisms, and are vital to much of the life on the planet. Vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, molybdenum and tin are all essential elements. Manganese, iron, copper, zinc and molybdenum are essential for plants, whilst iron is important in vertebrate respiration. Zinc is present in DNA, and copper and vanadium are important in molluscan and ascidian respiration respectively. These heavy metals are termed "essential" if the lack of them causes a process to be less efficient. Dale (1991) quotes Curd (1982) that some

metals, such as copper, zinc, iron and cobalt are micronutrients and are, therefore, needed at very small concentrations, whereas metals such as lead, cadmium, mercury and arsenic are not needed at all. Many authors have published upon the requirements of organisms for metals, and include: Sunda & Gillespie (1979) on the requirements of bacteria and marine algae for copper; Arnon (1960) on the requirements of green plants for heavy metals; Knauer & Martin (1983) on the role of copper, manganese and zinc in primary production; White & Rainbow (1985), who discuss the enzymatic requirements for molluscs and crustaceans and Fries (1982), who states that additional vanadium in culture media increased the fresh weight of the green marine alga *Enteromorpha compressa* by 90%. White and Rainbow (1985) calculated that for molluscs and crustaceans, the number of copper- and zinc-containing enzymes, RNA and DNA polymerases, malate and lactate dehydrogenases, plus cytochromes and haemocyanin mean that these organisms have a requirement of 26.3 μg per g dry weight of copper and 34.5 μg per g dry weight of zinc.

The concentration of heavy metals in sediments usually exceeds those of over-lying waters by between three and five times (Bryan & Langston, 1992), and due to physical adsorption and chemical bonds, pollutants become highly enriched in sediments and are only slowly released into the water column (Giere, 1993). In addition, trace contaminants that are not easily degraded (such as polychlorinated biphenyls, chlorinated pesticides and metals) are adsorbed on to the surfaces of the bacteria or sludge particles (Capuzzo *et al.*, 1985). In order for a metal to be taken up by organisms, it is important that the metal is in a form which is readily incorporated. The most readily available forms are those of the free ions; Bryan & Langston (1992) state that the free ions of copper and cadmium are the most bioavailable inorganic forms, although they only account for a small proportion of total dissolved copper, and the most bioavailable form of zinc is Zn^{++}, which is often the most abundant dissolved form. The principal forms of cadmium are as chlorides in sea water, although the available free ions of this metal increase with decreasing salinity (Bryan, 1985; Bryan & Langston, 1992). Amdurer *et al.* (1983) state that iron probably forms $Fe(OH)_3$ in sea water; zinc probably forms Zn^{++}, $ZnCl^+$, $ZnCl_2$, $Zn(OH)_2$, $ZnCO_3$; and cadmium

probably exists as $CdCl_2$, $CdCl^+$, $CdCl^{- \cdot \cdot}$. Kremling & Wenck (1983) state that numerous studies have indicated the association of copper with dissolved organic matter.

Although no work has been published upon the heavy metal requirements of Foraminiferida, it is known that most marine invertebrates have essential requirements for zinc and copper (White & Rainbow, 1985), whereas cadmium is usually toxic. It is known that iron is bound to the organic tests of Foraminiferida (Hedley, 1960) and is incorporated into foraminiferal calcite (Izuka, 1988). The incorporation of iron into agglutinated tests is believed to be a secondary feature of chelation of this metal to the tests after the chambers are formed in *Jadammina macrescens* (Brady) (K. Allen, *pers. comm.*). Iron is probably the agent responsible for the golden-tan coloration of agglutinated tests. Boyle (1980) states that Foraminiferida may be significant carriers in the oceanic cycling of zinc, and McCrone & Schafer (1966) state that in their study, the sediments containing Foraminiferida at low salinities were highly undersaturated with the common metallic ions that are usually important in nutrition.

Whether a metal is essential or not, all trace metals are potentially toxic at a threshold bioavailability (Rainbow *et al.*, 1990). Pollutants may cause genetic derangement or chromosomal damage resulting in morphological abnormalities (Capuzzo *et al.*, 1985). Segar *et al.* (1971) state that the heavy metal content of eleven species of mollusc varied greatly both inter- and intra-specifically. Rheinheimer (1992) states that copper and mercury entering the water *via* sewage and waste can completely destroy natural living communities; and Lande (1977) finds that the sessile marine fauna and flora of areas adjacent to mining communities were found to be considerably reduced in quality and quantity. In addition, once wastes are sedimented out of suspension, the action of bioturbation, erosion and bottom currents can resuspend them (Capuzzo *et al.*, 1985). Both particle size of the substratum and organic content can affect trace metal concentration (Jaffé & Walters, 1977); and McClusky *et al.* (1986) state that increased temperatures and salinities increase the toxicity of metals to molluscs. Microbial production of chelators and acids can reverse adsorption and remobilise toxic heavy metals, and is capable of transferring methyl groups

on to various heavy metals, thus increasing toxicity. Diatoms are known to suffer marked effects in fine structure with the addition of heavy metals to culture media (see Berland *et al.*, 1977; Canterford *et al.*, 1978; Coccetti & Lee, 1979; Thomas *et al.*, 1980; Rueter & Morel, 1981; Smith, 1983; Stauber & Florence, 1990) and to incorporate heavy metals into polyphosphate bodies during phosphate uptake (Sicko-Goad & Lazinsky, 1982). Copper and iron are associated with the silica frustules of diatoms (Lindahl *et al.*, 1983), and it has been established by Sunda *et al.* (1981) that copper competes with manganese in phytoplankton, whilst Moore & Ramamoorthy (1984) state that copper is toxic to plants, as it inhibits the electron transport of photosynthesis. The absorption of zinc by the macro-alga *Laminaria digitata* increases in older parts of the frond (Bryan, 1969), perhaps suggesting that for macro-algae exposure time rather than metal concentration is important. It is thought that heavy metals probably inhibit enzyme systems in macrofauna (Bryan, 1971; Verriopoulos & Hardouvelis, 1988), due to the binding of the sulphydryl groups of enzymes (Rheinheimer, 1992). This concurs with Harvey & Luoma's study (1985) of the clam *Macoma balthica*, which exhibited feeding avoidance with increased metal availability. McClusky *et al.* (1986) state that the sublethal effects of cadmium upon crustaceans include limb regeneration, moulting of the exoskeleton, osmoregulation problems and greater oxygen consumption. The occurrence of two or more metals together in the environment greatly modifies their effect upon the organisms present; zinc and copper suppress the bioavailability of cadmium by competing for metal-binding sites in *Fucus vesiculosus* (Bryan & Hummerstone, 1973), whereas other metals may act as synergists. Moore & Ramamoorthy (1984) find that cadmium displaces zinc in many vital enzymatic reactions, causing disruption or cessation of activity in plants. Competition also exists between metals such as copper and silver, and zinc and cadmium for uptake sites in organisms. Bryan (1969) states that copper and manganese inhibit the uptake of zinc in *Laminaria digitata*. Bryan & Langston (1992) state that the level of iron oxides in the sediment determines the availability of sediment-bound copper. In addition, Moore & Ramamoorthy (1984) state that zinc and cadmium, and zinc and copper, act as synergists to inhibit plant growth. Toxicity of metals may depend upon the stage of development of an organism, as embryonic and larval stages are usually more sensitive (often by orders of magnitude) than adults

(Bryan & Langston, 1992); and the reproductive cells of sea weeds are often the most vulnerable link in the algal life cycle (Levine, 1984). The timing of heavy metal pollution can also affect an organism; Alliot & Frenet-Piron (1990) state that seasonal pollution occurs in spring and summer, due to the activity in a harbour, whilst sampled shrimps appear to detoxify during winter.

The release of dissolved organic matter by living organisms serves to detoxify the environment of heavy metals by chelation (Atlas & Bartha, 1981) and chelators can decrease rates of accumulation of copper by competing with membrane ligands (Zamuda & Sunda, 1982). It is thought that the exudation of polyphenols from brown macro-algae may also contribute to the natural chelating capacity of inshore sea water (Ragan *et al.*, 1980), and Bryan (1971) states that the alginates in brown sea weeds have a high affinity for divalent metals. Salinity of the water can also affect the levels of metals; high salinity reduces levels of ionic copper (Bryan & Langston, 1992), and Sunda & Ferguson (1983) find that copper added to low-salinity coastal water was more highly complexed and, therefore, less toxic. Zinc is generally better regulated than other metals by organisms (Bryan, 1985) and there is great biological evidence that a wide range of organisms can develop a genetic resistance to heavy metals (Bellinger & Benham, 1978; Gower *et al.*, 1994). The polysaccharide coating of bacteria may bind heavy metals, and prevent their entry into cells (Moriarty & Hayward, 1982). The primary production of the oceans relies on keeping heavy metals at levels between toxicity and deficiency and, as some phytoplankton live in a wide range of metal concentrations, it is clear that some species have evolved mechanisms of adaptation to permit growth at both high and low concentrations (Rao & Sivasubramanian, 1985). Blue-green algae and diatoms appear to be more tolerant of zinc, copper, lead, nickel, cobalt and manganese ions than Chlorophyceae (Reddy & Venkateswarlu, 1985); and it may be that the incorporation of metals such as copper, zinc and cadmium into excreted photosynthetically-fixed carbon from diatoms relies upon the activity level of the cells (Fisher & Farris, 1982). The Chlorophycean *Enteromorpha compressa* appears to have genetically-determined tolerance to copper, and this may be due to internal detoxification (Reed & Moffat, 1983). Ciliated protozoa may

gain tolerance from calcium or magnesium chelators and Jones & Johnson (1991) quote Curd and Cockburn (1970) that there is no evidence that sewage containing heavy metal-laden industrial wastes had any detrimental effects on the protozoan populations of percolating filters. Macrofauna are able to regulate and detoxify their bodies of heavy metals due to having both better internal compartmentalisation and the production of proteins which bind the metal in a harmless state until excreted. Decapod crustaceans possess these proteins (Rainbow *et al.*, 1990), called metallothioneins, and, in addition, it is thought that the calcium deposits in the exoskeleton can sequester divalent cations (Weis, 1985) or that the organism can deposit metals in the exoskeleton (White & Rainbow, 1985). The primary function of metallothioneins is in regulating normal metal metabolism (Engel and Brouwer, 1984); and metallothionein-bound metals may concentrate the metal, but in this state it does not diffuse back into the environment. Each metallothionein is specific for one metal, and may be used to store metals for use in times of metal scarcity. Rainbow & White (1989) state that decapod crustaceans can regulate zinc at a level of 79 μg per g , until regulation breaks down and accumulation begins; and that no crustacean is capable of regulating non-essential metals such as cadmium. Nott & Nicolaidou (1989) have found that molluscs are able to form inert metal-containing granules, and it is thought that this group may have adapted the mechanism for the storage of calcium ions in granules to form the exoskeleton. Bryan (1976) finds that in molluscs temporary protection from metals may be afforded by binding the metal to proteins, polysaccharides and amino acids; and in scallops the excretion of metalliferrous granules from the kidneys and in spheres pinched off from digestive cells occurs. Bryan (1976) also states that in molluscs translocation and detoxification of metals are carried out by leucocytes.

The uptake of radioactive caesium and potassium by Foraminiferida has been investigated by Bryan (1963). He found that *Elphidium crispum*, which had been maintained in a recirculating aquarium (*pers. comm.*), absorbed ^{137}Cs more slowly than ^{42}K although it reached a higher concentration. Boltovskoy (1956) states that the lead present in the tests of Foraminiferida from the Argentinean shelf and the general impoverishment of both foraminiferal and other invertebrate fauna is probably due to lead brought into the area by

Andean streams. Boltovskoy (1956) also states that specimens are smaller, and that both abundance and diversity are affected; and that Lagenidae and Nonionidae display a tendency towards asymmetry. Boyle (1986) states that certain trace elements such as cadmium are highly correlated with oceanic nutrients such as phosphorus in the oceanic water column; and so, because they are incorporated into foraminiferal tests in proportion to the concentration in the water, these trace elements can be used as tracers of past oceanic nutrient distributions. Takashi Toyofuku working at the Shizuoka University upon *Quinqueloculina yabei* finds that as temperature rises the concentration of magnesium calcite decreases, which may cause problems with the calcification of the test in this species H. Kitazato, *pers. comm.*). Alve (1991) states that test malformation in both fossilised and living Foraminiferida are the result of environmental stress, and the action of both salinity and metals. She identifies seven deformation types from stressed assemblages, in which between 1-3% of the assemblage produce deformations: double apertures, small chambers, protuberances, twisted chambers, enlarged apertures, aberrant chamber shapes and twinned forms. Yanko *et al.* (1994) state that, because of heavy metal contamination, Foraminiferida produce smaller tests which are frequently pyritised; and that up to 2-3% of the Foraminiferida sampled were deformed (comprising 16 species including both calcareous and agglutinated taxa). Chang & Kaesler (1974) found that in *Ammonia beccarii* both temperature and salinity are important controls of morphological variations, and that there is a higher correlation with temperature plus salinity than with either characteristic separately. Although Stubbles (1993) states that the number of deformed living specimens of Foraminiferida in Restronguet Creek decreases with increasing distance from a discharge point of acid mining water, she does not indicate whether the ratio of undeformed/deformed individuals changes with distance. Somerfield *et al.* (1994 {a}) state that the concentration of heavy metals in this estuary before and after the mine discharge was not significantly different, and the overflow had no significant effect on the benthonic infauna in the estuary, although nematodes are more affected by heavy metals than copepods (Somerfield *et al.*, 1994 {b}). Abnormal growth of Foraminiferida is usually defined by authors as specimens forming additional chambers, enlarged final or penultimate chambers, protruding chambers, multiple distorted chambers, twinned tests, and uneven chamber or suture shape. Although

some authors analyse the heavy metal content of foraminiferid tests, Boyle (1979) advises that it is first necessary to remove iron and manganese contaminants. Despite many authors stating that heavy metals in greater-than-background levels are harmful to Foraminiferida causing deformations of the test and/or faunal shifts, it should be recognised that at least one type of foraminiferid community prospers upon deep-sea manganese nodules rich in many types of heavy metals (copper, cobalt and nickel) and may be responsible for their formation (Riemann, 1983).

Much of the published work on the relationship between heavy metals and deformations in living Foraminiferida is restricted to studies of estuarine species. An estuary is one of the most variable habitats in the world with the salinity, pH, suspended matter, organic content and temperature extremes experienced by organisms fluctuating daily. The movement and accumulation of heavy metals within estuarine systems is, therefore, very complex. Estuaries, due to the change in pH of fresh waters to sea water of pH 8.1, cause a rapid change of the transport phase, and metals move from being dissolved into their particulate form, and settle out of solution. This results in the escape of small, low-density particles from an estuary, whilst larger, denser particles are trapped (Duinker, 1983). There is also more particulate material for the heavy metals to adsorb on to, and so estuaries become highly contaminated with heavy metals. Martin & Whitfield (1983) state that more than 90% of the river-suspended matter settles with its associated colloidal material produced when river water mixes with sea water. It is vitally important, therefore, that any estuarine study intended for the study of trace-metals' geochemical cycles should include suspended matter content and important water parameters, especially pH (Bourg, 1983). The concentration and bioavailability of metals in estuarine sediments depends upon many different processes: mobilisation of metals to interstitial waters and chemical speciation; transformation; the control exerted by major sedimentary components (*e.g.* oxides of iron and organics) to which metals are preferentially bound; competition between metals for uptake sites in organisms; and the influence of bioturbation, salinity, redox or pH on these processes (Bryan & Langston, 1992). Schafer & Cole (1974) find that the pH of bottom sediments

seems to be important in controlling the establishment of foraminiferal populations in polluted environments.

Experimentation upon organisms to test their resistance to heavy metal contamination commonly uses a standardised test, based upon the concentration of a metal which causes 50% mortality in a set time (usually 96 hours). The measurement of the sublethal toxic effects is more representative of natural environments, however, and toxic effects can include the depression of fecundity, viability of sperm, behavioural changes and percentage survival of offspring.

Indicators

Marine biologists have searched for many years for organisms which deform in specific ways to pollution of different kinds, so that simple examination of the morphology of organisms will provide definitive proof of pollution in the area under investigation without the need to carry out expensive and time-consuming analytical tests of the substratum or water. An indicator of pollution must, therefore, be an organism which can suggest the presence or absence of a particular environmental variable (Whitton, 1984). Increased interest amongst foraminiferologists has occurred recently with the realisation that Foraminiferida may be such important indicators of pollution. Bandy *et al.* (1964) state that the use of Foraminiferida as indicators of pollution is possible because tests are abundant, reflect growth patterns, are left after death, and their small size means that it is relatively easy to collect and preserve large numbers; so making statistical analyses of the data possible. Yanko *et al.* (1994) state that Foraminiferida make useful biological monitors as they are ubiquitous in marine environments and live on, or in, sediment which receives and stores many pollutants. In addition, Foraminiferida have a wide range of taxonomic diversity; the relatively small, hard tests are preserved in the environment making statistics feasible, and they have short reproductive cycles, so they are capable of showing a rapid response to a factor. Setty (1982) also states that Foraminiferida are good indicators of pollution; and Seiglie (1975) states that test deformation, size ratios of the tests of living and dead individuals, change of morphological characteristics with time, and specific

content of assemblages (in cores) are tools which cannot be used with other taxa. Seiglie (1975) also states that Foraminiferida are sensitive *in situ* monitors of coastal pollution.

Despite the above authors suggesting that Foraminiferida would make important indicators of pollution due to deformation of the test, Röttger & Berger (1972) suggest that there exists a lag between the growth response and environmental change and possible slowing or cessation of growth during stress, resulting in minor changes in morphology. Watkins (1961) finds that the sensitivity of Foraminiferida is highly variable and related to both the type and the nature of the pollutant. Röttger & Berger (1972) also find that siblings vary in response to the same stimulus. Correlation of deformations in Foraminiferida from field collections with environmental variables measured at the time of collection, does not allow authors to state that a particular variable has caused the Foraminiferida to deform. It is equally likely that an unmeasured variable may be responsible for the deformations observed, or that deformation of the test is a natural response of the population to unstable conditions, or a predominance of sexual reproduction leading to more genetic variability and more mutations. Bryan & Langston (1992) concur with this and state that under field conditions deleterious effects on benthonic organisms cannot be attributed to specific metals as the effects are ameliorated by induction of metal-tolerance mechanisms in some species and in others by tolerant strains.

Changes in assemblage composition

Important work on the correlation of environmental variables (including pollutants) and populations living in a habitat has been carried out by some authors. Warwick (1984) states that the abundance and diversity of foraminiferid species are often used as indicators of "pollution", "disturbance" or "stress"; and Setty (1976) observes that certain living foraminiferid species restrict themselves to the least polluted zones of an area, and thereby are useful in establishing zones of effects of pollutants in a region. Seiglie (1975) finds that low foraminiferal species-diversity and high intraspecific polymorphism are characteristic of stressed and polluted environments. Alve (1991) states that a faunal shift occurs in response to the presence of heavy metals; *Verneuilina media* gives way to *Eggerelloides scabrum*,

and, if assemblages are stressed, then the abundance of Foraminiferida decreases and some shallow-water-tolerant species may extend their habitat to deeper waters. Ellison *et al.* (1986) state that zinc, chromium and vanadium present in cores resulting from municipal and industrial pollution, produce large populations of a few opportunistic species of Foraminiferida in a "subnormal zone", where the concentration of pollutants is below the critical level. Rao & Rao (1979) state that species diversity nearby a titanium plant is low in comparison to other sites.

Aims

The proportion of deformed Foraminiferida from a year-long sampling program of three sites in Plymouth Sound (see Chapter 2.0) is recorded together with the types of deformities exhibited. The heavy metal content of the substrata (five metals) and water samples is given for four summer months at each site. In order to clarify whether heavy metals do cause deformation of the test, it is necessary to expose a statistically significant number of individuals to varying regimes of metal toxicity. The phenotype of an organism is caused partly by its genotype and partly by its environment, and in order to eliminate genetic variability when subjected to experimental conditions, it was hoped to culture a species of Foraminiferida until asexual reproduction occurred, and then to use the offspring of a single parent to show response to the metal contaminants. In this way genetic variability would be negligible, and only the morphological response to the contaminant would be expressed. Attempts were made to induce reproduction of *Elphidium crispum* in the laboratory in order to expose the offspring of asexual reproduction to heavy metals (see Chapter 8). Failure to have offspring survive long enough in the laboratory to experiment upon, resulted in obtaining a foraminiferid species already successfully cultured for use in laboratory experiments. The use of the rapidly-reproducing and morphologically stable *Rotaliella elatiana* means that the action of the three main heavy metals (copper, zinc and cadmium) could be investigated and compared to the action of salinity extremes. In order to understand the action of heavy metals upon indigenous Foraminiferida it was decided to investigate the action of zinc upon the test formation of *Ammonia batavus* to complement the work of Sharifi *et al.* (1991), and to see if the same types of deformation are caused by

a different metal. It is hoped that these tests will reveal if deformations of the test are induced by short-term experiments; if deformation is specific to metals or salinity; or if deformation is metal-specific. The deformed specimens recorded from samples from Plymouth Sound will provide an insight into types and proportions of deformity produced by natural assemblages of Foraminiferida.

10.2. TEST DEFORMATION IN FORAMINIFERIDA COLLECTED FROM PLYMOUTH SOUND.

10.2.1. INTRODUCTION.

The input of heavy metals into Plymouth Sound varies for each of the three sites sampled. The Breakwater isolates the body of water enclosed by it until flushed from the area by tidal activity, making the Sound a catchment area for fluvial waters. This isolation of water between tides may allow toxic materials to be deposited within the area and allow heavy metals to become chelated to organic detritus within the substratum. Plymouth Sound is dominated by the River Tamar and, to a lesser extent, the River Plym. The Plym carries waste washings of china clay from English China Clay works. The Tamar, with its two tributaries of the Lynher and Tavy, flows from west Dartmoor over Devonian and Carboniferous rocks, with the Tavy rising among the peat bogs overlying the Dartmoor granite (Butler & Tibbitts, 1972). The Tavy probably carries heavy metals from the peat bogs into the River Tamar, and Bland *et al.* (1982) state that the high metal content of sediments from the River Lynher is probably due to run-off from the metalliferrous catchment area, coupled with a high mercury content from local sewage input. The increase in the number of marinas in the area will also serve to elevate the content of heavy metals due to the spillage of diesel and oil from yacht engines.

There is much input of sewage into the Sound; and sewage is laden with heavy metals such as zinc. From NRA (National Rivers Authority) data for 1993, the upper Tamar tidal catchment area between Gunnislake and Ernesettle contains ten sewage treatment works

and three waste-disposal sites. The lower estuary contains seven sewage treatment works, twenty-nine outfalls and fifty-six consented discharge points (mainly Ministry of Defence and Dockyard). NRA data also shows that the number of bacterial coliforms (enteric bacteria) per 100 ml of water measured at a monitoring point near to the Dockyard is within the range of 2.1×10^3 and 2.1×10^4 and is always higher when measured at low tide than at high tide. This indicates that the river Tamar has a greater input of sewage to the Sound than *vice versa*. NRA data for 1993 also shows that the catchment area encompassing the Rivers Plym and Meavy contains seven sewage treatment works, five waste-disposal sites and four China-clay works. NRA data supplied shows that the number of coliform bacteria per 100 ml water measured at a monitoring point in Jennycliff Bay contained between 4×10^2 and 3.1×10^3 coliforms. In addition to the above sources of heavy metals to Plymouth Sound, there are numerous outfalls along the front of Plymouth Hoe.

Cawsand Bay lies outside of the Breakwater and has relatively little local sewage input or industrial waste compared to the other two sites, although an area just off Cawsand Bay has regularly been used by the Navy as a de-gaussing site (correcting the magnetic field of shipping). Drake's Island, as well as being subject to high sewage input from the River Tamar, also lies just off the large Devil's Point outfall. The Dockyard lies just up-river from Drake's Island and may subject this site to sea water containing heavy metal based anti-fouling paints, wastes from electro-plating, filings and turnings of heavy metals, and possibly radiation from work upon nuclear submarines. The acquirement of heavy metal based anti-fouling paints has been banned (due to documented deleterious effects upon molluscs), although stocks held by organisations are allowed to be used. It is also possible that shipping not refitted and painted since the ban may come into the Dockyard. The change of pH as fresh water from the River Tamar becomes mixed with more alkaline sea water will precipitate metals in solution into particulate forms at this site. White Patch is also subject to a change of pH as the fresh water of the Plym becomes mixed with sea water and subject to heavy metals from sewage, leachate from Chelson Meadow waste-disposal site, and discharges from Sutton Harbour.

The aim of this part of the study is to record the number of, and types of, foraminiferid test deformation from the assemblages sampled at Cawsand Bay, Drake's Island and White Patch (see Chapter 2), to check upon deformation in natural habitats. The heavy metal content of sediments from these sites has also been recorded for four months, to ascertain the amounts of heavy metals present in the foraminiferid habitats during summer months.

10.2.2. MATERIALS & METHODS.

Collection of Foraminiferida

The methods utilised in the collection and isolation of living Foraminiferida from the three study sites are detailed in Sections 2.3 and 2.4. Sample site descriptions are given in Section 2.5.

Identification of deformed tests

Foraminiferida which exhibited chamber growth not in the same plane as previous chambers, of excessive size, of reduced size, or with un-uniform surface details are recorded. The presence of "twinned" tests and specimens with two apertures was also recorded, as were individuals of abnormal length. Only living/stained individuals have been isolated from samples, so that only those living in the habitat at the time of collection, and therefore subject to the environmental variables acting upon fauna at that site at the time of sampling, have been recorded. It should be noted that identification of test deformation is a very subjective process and Plate 3 provides representative specimens showing deformation types found in this part of the study.

Preparation of water samples

Duplicate sea water samples were collected from each site in 10 cm^3 plastic bottles. Due to the problems of chelation and possible contamination, the bottles had previously been placed into a bath of concentrated nitric acid for a period of not less than 12 hours, twice rinsed in de-ionised distilled water, and then filled with de-ionised distilled water and lidded until use. Upon return to the laboratory, the sea water samples were placed into a

refrigerator at 4°C until acidification of the sample could be performed by the addition of 1 ml of concentrated nitric acid. The cooling and subsequent acidification prevents microbiological activity in the sample which may affect the concentration of heavy metals.

Preparation of sediment samples

Sediment samples from each of the three sites were obtained in the months of April, May, June and July, 1994, simultaneously with the collection of Foraminiferida at these sites. All equipment used was previously bathed in concentrated nitric acid, twice rinsed in de-ionised distilled water, and filled with de-ionised distilled water until use. Following practical methods outlined by Dr. G. Wigham (Biological Sciences, University of Plymouth) approximately 25 g of wet sediment was dried in an oven at 60°C. The dry sediment was cooled and sieved over an Endacott sieve of aperture size 250 μm. This method splits the sediment into a coarse (>250 μm) and fine (<250 μm) fraction. Extraction of heavy metals was carried out using both EDTA and hydrochloric acid: EDTA chelates metals so that the biologically available heavy metals can be measured, whilst hydrochloric acid dissolves the total amount of heavy metals from the sediment samples. Both coarse and fine fractions of each sediment sample were analysed, using both fluids. The raw data are contained in Appendix VIII.

EDTA extraction

1 g of coarse sediment and 1 g of fine sediment were separately placed into centrifuge tubes containing 10 cm^3 of 0.25% of EDTA. The tubes were vigorously shaken for two minutes so that the EDTA could access all particles, and centrifuged for 5 minutes. The supernatant liquid was decanted into a 25 cm^3 volumetric flask; the residue was resuspended in 10 cm^3 of de-ionised distilled water, and recentrifuged for 5 minutes. The supernatant was added to that in the 25 cm^3 volumetric flask and the process repeated with 5 cm^3 of de-ionised distilled water. The volume of supernatant was adjusted to 25 cm^3 by the addition of de-ionised distilled water, and filtered through Whatman Number 1 filter paper.

Hydrochloric acid extraction

1 g of coarse sediment and 1 g of fine sediment were separately placed into 100 cm^3 conical flasks. 10 cm^3 of 0.5M hydrochloric acid were added to each flask and the mixture heated upon a hot-plate to boiling point. The mixture was then boiled for a further 20 minutes and allowed to cool. The sediment and acid were centrifuged for 5 minutes and the supernatant decanted into a 50 cm^3 volumetric flask. The residue was resuspended in 10 cm^3 of de-ionised distilled water and the supernatant was again decanted into the volumetric flask. This process was repeated with a further 10 cm^3 of de-ionised distilled water. The volume of supernatant was adjusted to 50 cm^3 with the addition of de-ionised distilled water and filtered through Whatman Number 1 filter paper.

Atomic Absorption Spectrophotometry

The processed sediment supernatants and the water samples were analysed for the concentration of copper, zinc, cadmium, lead and iron by Alex Fraser (Biological Sciences; University of Plymouth) using a Varian AA-975 Atomic Absorption Spectrophotometer. The produced concentrations of these metals in parts per million referred to water samples and were converted to micrograms per gram for the sediment samples by multiplying the metal ppm by the volume and dilution factor and dividing by the dry weight of the sample.

10.2.3. RESULTS.

Total number of deformed Foraminiferida from each site

Species exhibiting abnormal forms from each of the sample sites are detailed below, together with descriptions of the type of deformity.

Cawsand Bay

August:	1 x *Quinqueloculina aspera*; 2 apertures at opposite ends of the test, with only one stained.
October:	1 x *Quinqueloculina aspera*; 2 apertures at the same end, with both stained.
November:	1 x *Ammonia batavus*; irregular coiling in latter part of test.
December:	1 x *Ammonia batavus*; asymmetrical terminal chamber, too bulbous on umbilical side.
	1 x *Ammonia batavus*; terminal chamber has excess test material.
March:	1 x *Ammonia batavus*; coiling slightly twisted.
April:	2 x *Buliminella elegantissima*; very elongate.
June:	1 x *Buliminella elegantissima*; very elongate.
	1 x *Quinqueloculina aspera*; 90° bend in terminal chamber so that the aperture lies bent over preceding chambers.
July:	2 x twinned *Bulimina elongata*.

Drake's Island

August	1 x *Quinqueloculina seminulum*; chamber and aperture wrapped over base.
September:	1 x *Quinqueloculina aspera*; terminal chamber shorter than previous, therefore the aperture is adjacent to, not above, the previous chamber.
October:	1 x *Quinqueloculina aspera*; terminal chamber "buckled".
November:	1 x *Quinqueloculina aspera*; terminal chamber wrapped one-third around the previous chamber.
March:	1 x *Quinqueloculina aspera*; "buckled".
May:	1 x *Quinqueloculina aspera*; bulbous chambers.
July:	1 x *Quinqueloculina oblonga*; outer chamber "buckled".

White Patch

August: 1 x *Bulimina elongata*; chamber mis-aligned.
3 x *Ammonia batavus*; two twinned forms and one with an inflated terminal chamber.
1 x *Quinqueloculina* sp.; with mis-aligned coiling direction.
1 x *Elphidium crispum*; one twinned form.

September: 2 x *Ammonia batavus*; one twinned form and one with a chamber produced from the terminal chamber at 90°.
1 x *Quinqueloculina cliarensis*; distended proloculus.
1 x *Quinqueloculina seminulum*; inflated inner chamber.

October: 5 x *Ammonia batavus*; 2 with chamberlets produced off the proloculus, one twinned form, and two with irregular coiling.

November: 2 x *Ammonia batavus*; one with irregular coiling and one with multiple chamberlets produced from the proloculus.
1 x *Quinqueloculina cliarensis*; disproportionately long chamber which coils around towards the proloculus.
1 x *Quinqueloculina lata*; shortened terminal chamber so that the aperture is only half way up the adjacent chamber.

December: 2 x *Quinqueloculina* sp.; both have short terminal chambers so that the aperture is only half way up the adjacent chamber.

January: 4 x *Ammonia batavus*; 3 of irregular coiling and one with an additional stained chamber attached to the penultimate chamber

February: 1 x *Ammonia batavus*; chamber produced from the proloculus in the same plane, but 100° from the stained terminal chamber.

April: 1 x *Ammonia batavus*; additional chamberlet on the terminal chamber.

June: 1 x *Ammonia batavus*; coiling irregular.

July: 5 x *Ammonia batavus*; two have a double prolocuIi and 3 have irregular coiling.
1 x *Adelosina* sp.; one twinned form.
1 x *Quinqueloculina* sp.; one twinned form.

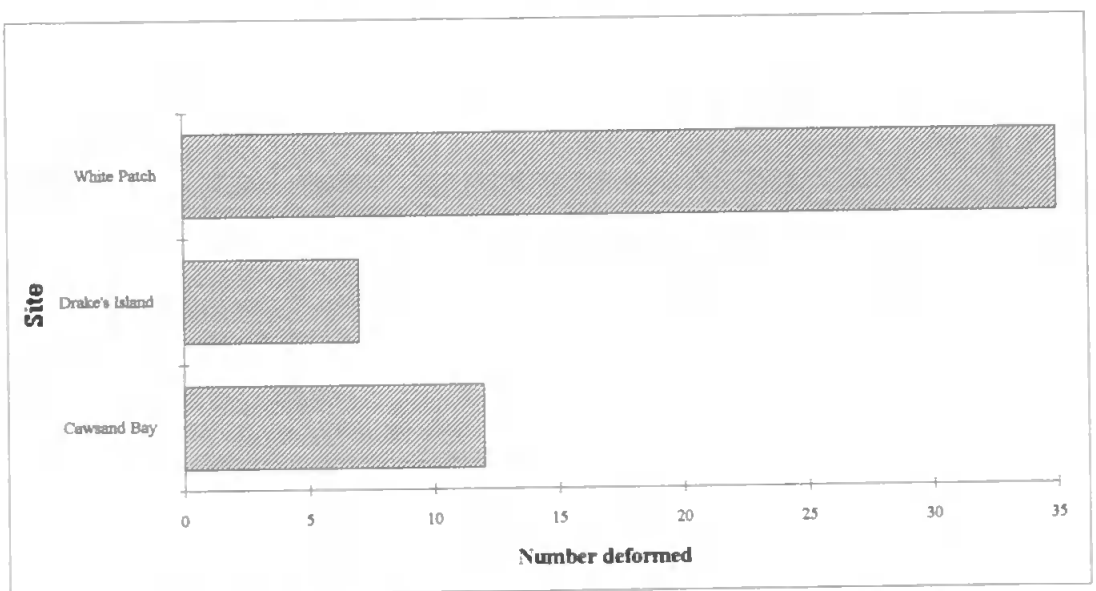


Figure 10.1: Comparison of sampling sites for the number of deformed Foraminiferida.

From the above descriptions and Figure 10.1 it is apparent that test deformation of living Foraminiferida is relatively rare at the sampling sites. A total of 54 deformed individuals was identified from the sample suites of the three sampling sites under investigation. As the total number of Foraminiferida examined from the three sites over the period of a year was 12,205, the percentage of individuals showing deformation is 0.44%. From Figure 10.1 it can be seen that individuals from Drake's Island included only 7 deformed specimens; the total number of Foraminiferida examined from this site was 1,632, and so the deformation percentage for Drake's Island fauna is 0.43%. From Figure 10.1 it can be seen that individuals from Cawsand Bay included 12 deformed specimens; the total number of Foraminiferida examined from this site was 4,192, and so the deformation percentage for Cawsand Bay fauna is 0.29%. White Patch-collected Foraminiferida contained 35 deformed specimens; the total number of Foraminiferida examined from this site was 6,381 and so the deformation percentage is 0.55%. From these calculations it can be seen that although the number of deformed individuals appears to increase from Drake's Island to Cawsand Bay to White Patch fauna, the percentage of deformations increases from Cawsand Bay to Drake's Island to the White Patch fauna.

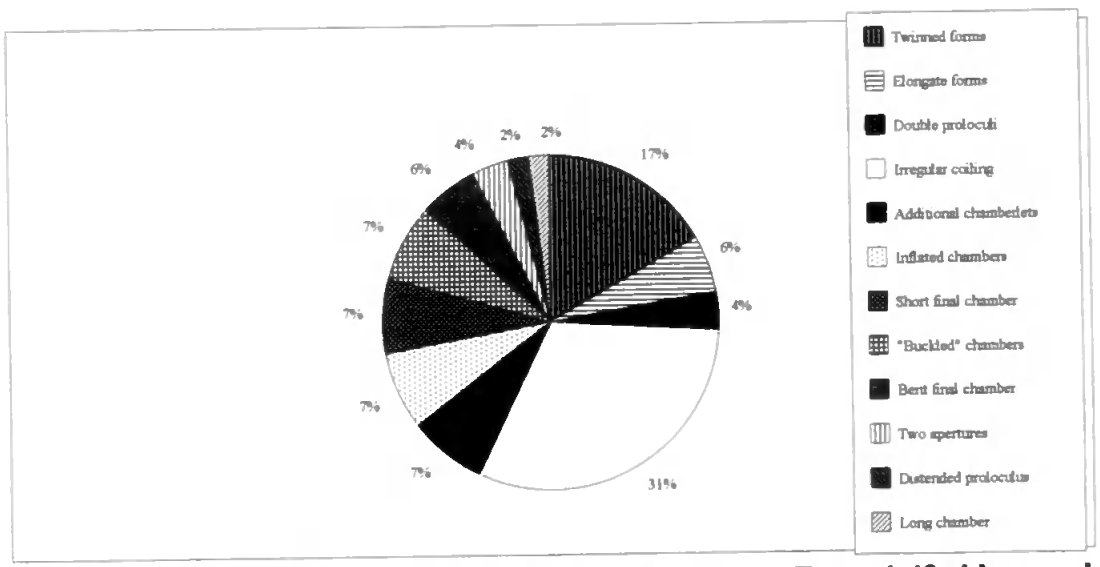


Figure 10.2: Comparison of types of deformity shown by Foraminiferida sampled 1993/1994.

From Figure 10.2 it can be seen that the main deformation type exhibited is that of irregular coiling followed by "twinned" forms. Irregular coiling is exhibited mainly by the species *Ammonia batavus* (14 of 17 specimens), whereas "twinned" specimens are produced by five

different species. The next most numerous types of deformation include the groups producing additional chamberlets, inflated chambers, a short final chamber and buckled chambers: these are all equally represented. Additional chamberlets are only produced by *Ammonia batavus* in this study; those producing a short final chamber are represented only by species of the genus *Quinqueloculina*; and both *Ammonia batavus* and *Quinqueloculina* species produce specimens with inflated and buckled chambers. The next most numerous types of deformation include the groups which are elongate and those which produce a bent final chamber: elongate forms are represented solely by the species *Buliminella elegantissima*, whereas species producing a bent final chamber are *Ammonia batavus* and *Quinqueloculina aspera*. Two specimens of *Ammonia batavus* produced two proloculi in each test, and two specimens of *Quinqueloculina aspera* were found each possessing two apertures. A specimen of *Quinqueloculina cliarensis* exhibited a distended proloculus and another exhibited an abnormally long chamber.

Table 10.1: Number of individuals of each species showing deformations from all three sampling sites, 1993/1994.

Species	Number deformed
Adelosina sp.	1
Quinqueloculina aspera	8
Quinqueloculina cliarensis	2
Quinqueloculina lata	1
Quinqueloculina oblonga	1
Quinqueloculina seminulum	2
Quinqueloculina sp.	4
Buliminella elegantissima	3
Bulimina elongata	3
Ammonia batavus	28
Elphidium crispum	1

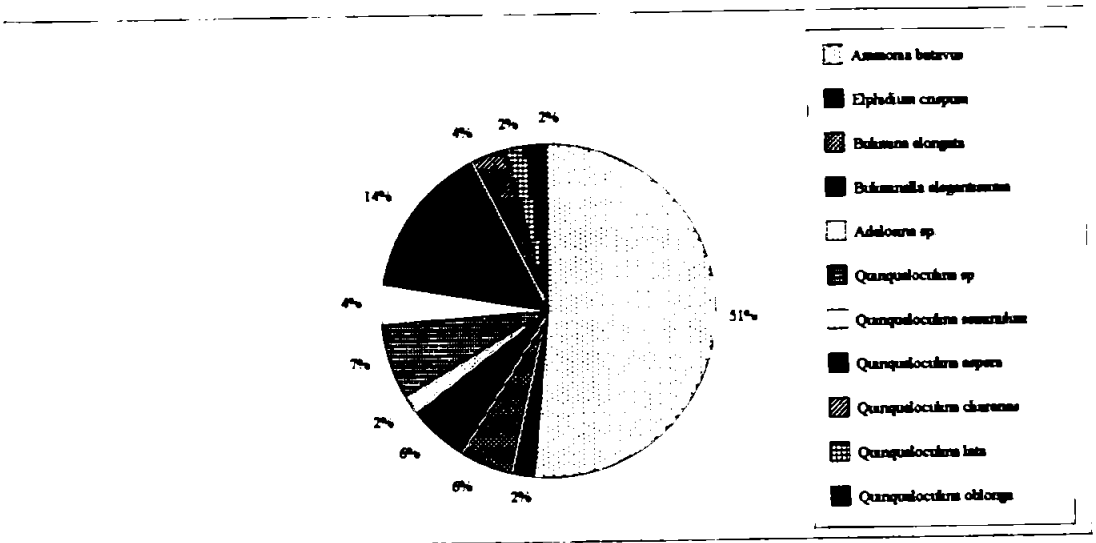


Figure 10.3: Species composition of test deformities exhibited in samples of Foraminiferida 1993/1994.

From Figure 10.3 and Table 10.1 it can be seen that only 11 species of Foraminiferida collected from the three sampling sites included deformed individuals. Although *Ammonia batavus* composed 51% of the deformed fauna, the genus *Quinqueloculina* seems to be morphologically unstable, forming a third (33%) of all deformed specimens identified and is the only genus exhibiting deformations in the Drake's Island fauna.

Deformations with possible natural causes

The occurrence of "twinned" Foraminiferida (two adult foraminiferid tests of the same species apparently cemented together), is probably to allow the transfer of gametes during sexual reproduction. Myers (1933) states that it is not unusual to find two or more tests of some species cemented together so that their apertures are roughly opposed to each other, and suggests that this is for reproduction. Frankel (1972) also believes that abutting tests are the remains of Foraminiferida which have completed gamogony below the sediment surface. Foraminiferida which are twinned and form part of this deformation set include four *Ammonia batavus*, two *Bulimina elongata* and one each of *Elphidium crispum*, *Adelosina* sp. and *Quinqueloculina* sp.

The two specimens of *Ammonia batavus* with double proloculi are believed to be the result of failure to separate as they were issued from the parental test, and, as such, are unlikely to be the result of adverse environmental conditions. *Elphidium crispum* maintained in the

laboratory also exhibited individuals in which two proloculi secreted a single chamber between them (see Figure 8.8).

The three elongate forms of *Buliminella elegantissima* described are thought to be the natural response of a species to natural conditions, and are possibly an adaptation to increased hydrodynamic activity. All three elongate forms of this species occurred in the samples from Cawsand Bay: two in the month of April and one specimen in the month of June.

Deformations with possible adverse environmental causes

When the deformations with possible natural causes are removed from the data set the proportions of sites producing deformed specimens and the species exhibiting deformities change. It is also possible that some of the deformations below have natural causes and are not the product of adverse environmental variables.

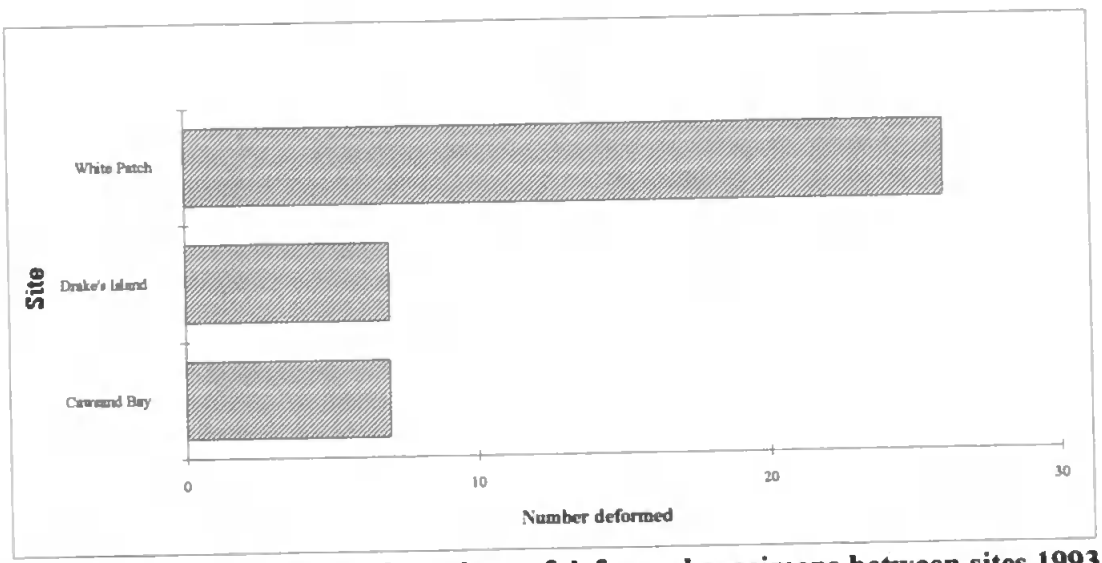


Figure 10.4: Comparison of numbers of deformed specimens between sites 1993/1994, after removal of the believed-naturally-deformed individuals.

Form Figure 10.4 it can be seen that Cawsand Bay and Drake's Island produced the same number of deformed specimens (7) over the sampling period, but White Patch produced far more deformed specimens (26). When compared to the total number of Foraminiferida examined from the sites (12,205) the production of aberrant forms is 0.33%; with Cawsand

Bay producing 0.167% aberrant forms, Drake's Island producing 0.43% aberrant forms and White Patch producing 0.41% aberrant forms.

Table 10.2: Comparison of number of individuals within species exhibiting types of aberrant test deformation from all sites 1993/1994, after removal of the believed-naturally-deformed individuals..

Type of deformation	Species	Number
Irregular coiling	*Ammonia batavus*	14
	Bulimina elongata	1
	Quinqueloculina seminulum	1
	Quinqueloculina sp.	1
Additional chamberlets	*Ammonia batavus*	4
Inflated chamber/s	*Ammonia batavus*	2
	Quinqueloculina aspera	1
	Quinqueloculina seminulum	1
Short final chamber	*Quinqueloculina* sp.	2
	Quinqueloculina aspera	1
	Quinqueloculina lata	1
"Buckled" chamber/s	*Quinqueloculina aspera*	2
	Ammonia batavus	1
	Quinqueloculina oblonga	1
Bent final chamber	*Quinqueloculina aspera*	2
	Ammonia batavus	1
Two apertures	*Quinqueloculina aspera*	2
Distended proloculus	*Quinqueloculina cliarensis*	1
Long chamber	*Quinqueloculina cliarensis*	1

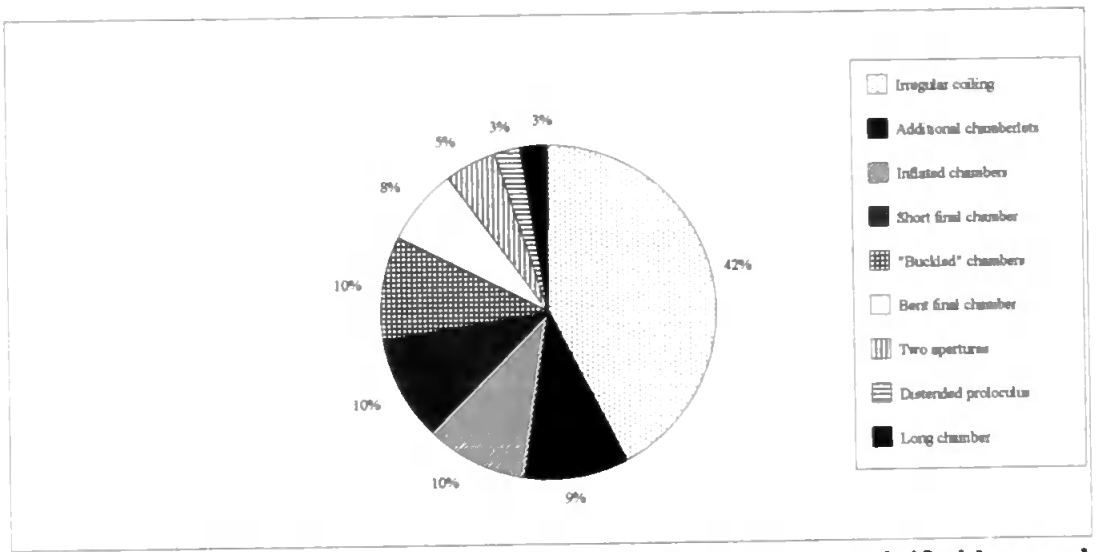


Figure 10.5: Comparison of types of deformity shown by Foraminiferida sampled 1993/1994, after removal of the believed-naturally-deformed individuals.

From Table 10.2 and Figure 10.5 it can be seen that the principal cause of aberrant tests is that of irregular coiling exhibited mainly by *Ammonia batavus* with single specimens of *Bulimina elongata*, *Quinqueloculina seminulum* and *Quinqueloculina* sp. Aberrances of

inflated chambers, short final chambers and "buckled" chambers are next in abundance. Inflated chambers were produced by two specimens of *Ammonia batavus* and singular specimens of *Quinqueloculina aspera* and *Quinqueloculina seminulum*, short final chambers were only produced by species of the *Quinqueloculina* genus (two specimens of *Quinqueloculina* sp. and single specimens of *Quinqueloculina aspera* and *Quinqueloculina lata*), whilst "buckled" chambers were produced by two *Quinqueloculina aspera*, one *Ammonia batavus* and one specimen of *Quinqueloculina oblonga*. Only specimens of *Ammonia batavus* were found to produce additional chamberlets. The production of a bent final chambers was exhibited by two specimens of *Quinqueloculina aspera* and one specimen of *Ammonia batavus*, two specimens of *Quinqueloculina aspera* produced two apertures per test and *Quinqueloculina cliarensis* produced one specimen with a distended proloculus and one with an abnormally long chamber.

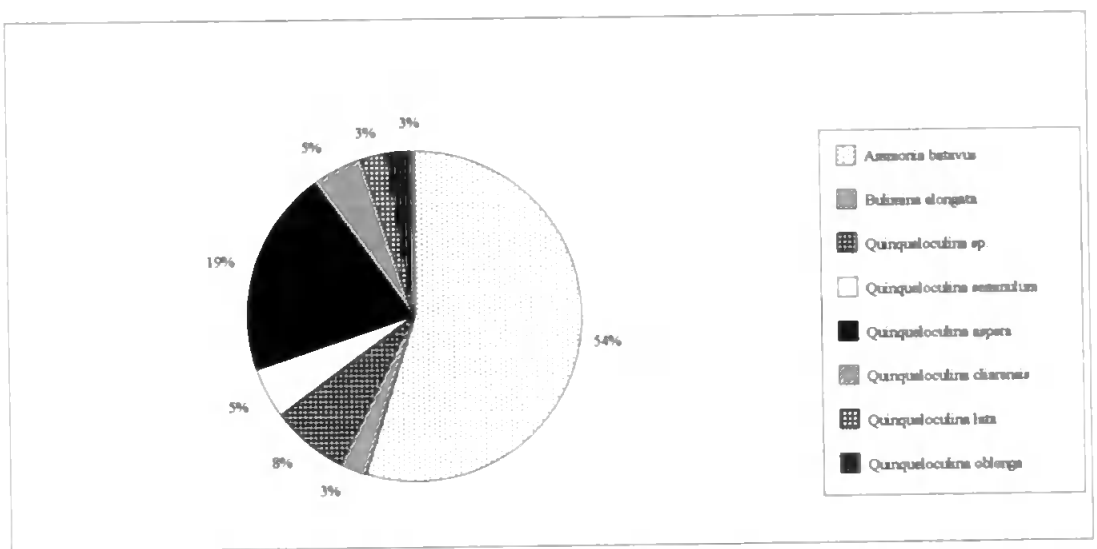


Figure 10.6: Species composition of aberrant test deformities exhibited in samples of Foraminiferida 1993/1994, after removal of the believed-naturally-deformed individuals.

Nine categories of test deformation in Foraminiferida collected have been identified. From Table 10.2 and Figure 10.6 it can be seen that *Ammonia batavus* produced most aberrant tests (22) with reducing abundances of *Quinqueloculina aspera* (8), *Quinqueloculina* sp. (3), *Quinqueloculina seminulum* and *Quinqueloculina cliarensis* (2 each) and single specimens of *Bulimina elongata*, *Quinqueloculina lata* and *Quinqueloculina oblonga* forming aberrant tests from the sample suite.

PLATE 3.

Examples of deformation types in natural assemblages sampled

Figure 1: Example of twinned forms; *Elphidium crispum*

Figure 2: Example of forms with two apertures; *Quinqueloculina aspera*

Figure 3: Example of forms with distended proloculus; *Quinqueloculina cliarensis*

Figure 4: Example of forms with inflated chambers; *Ammonia batavus*

Figure 5: Example of forms with short final chambers; *Quinqueloculina lata*

Figure 6: Example of forms with irregular coiling; *Ammonia batavus*

Figure 7: Example of double proloculi forms; *Ammonia batavus*

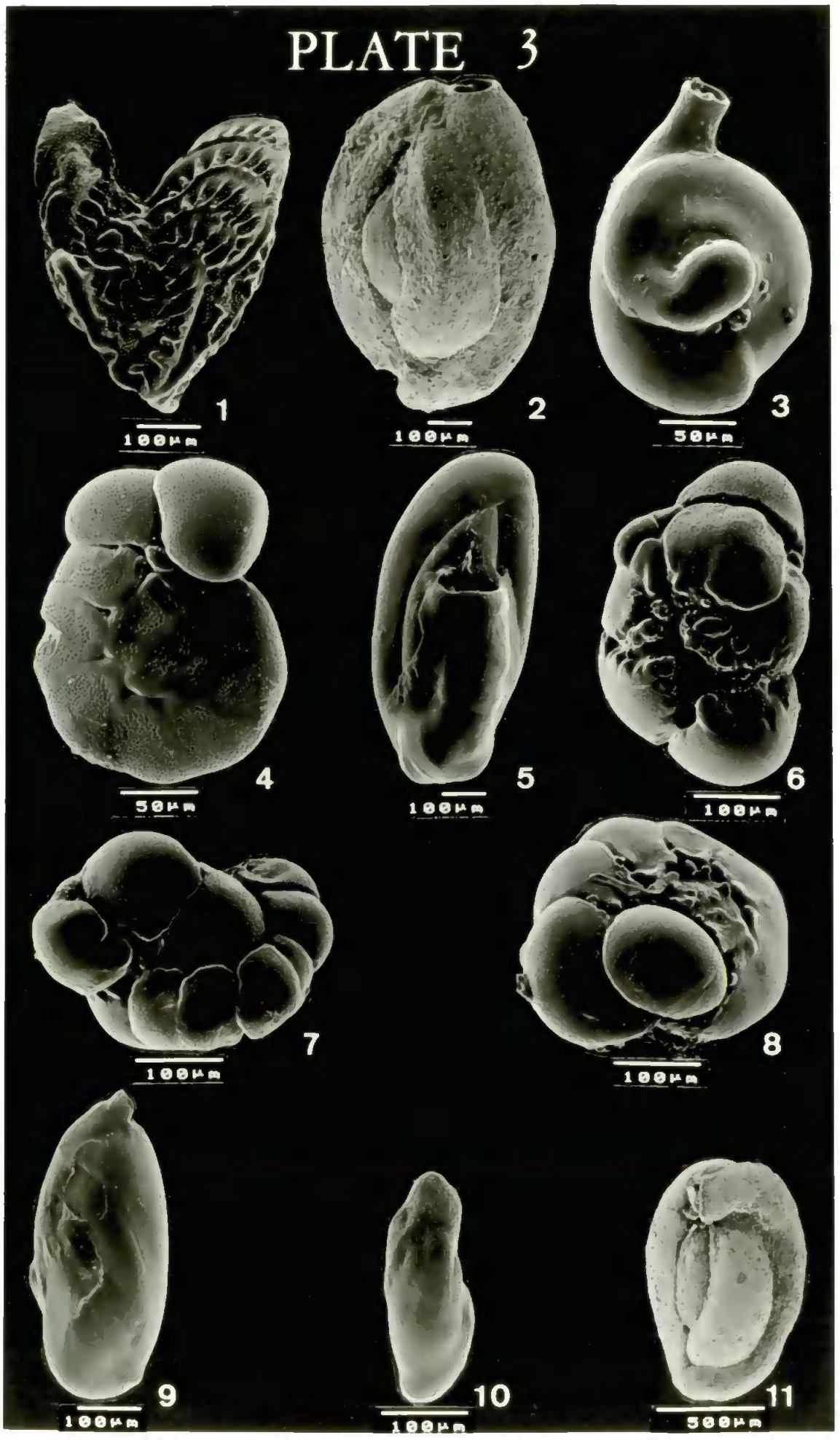
Figure 8: Example of forms with additional chamberlets; *Ammonia batavus*

Figure 9: Example of forms with buckled chambers; *Quinqueloculina oblonga*

Figure 10: Example of elongate forms; *Buliminella elegantissima*

Figure 11: Example of forms with bent final chambers; *Quinqueloculina aspera*

PLATE 3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11
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Table 10.3: Mean values of heavy metals in sea water samples from the three sites in parts per million (n = 4).

Site	Copper	Zinc	Cadmium	Lead	Iron
Cawsand Bay	1.595	0.335	0.198	0.928	0.815
Drake's Island	0.853	0.315	0.175	0.948	0.480
White Patch	0.545	0.098	0.150	0.740	0.468

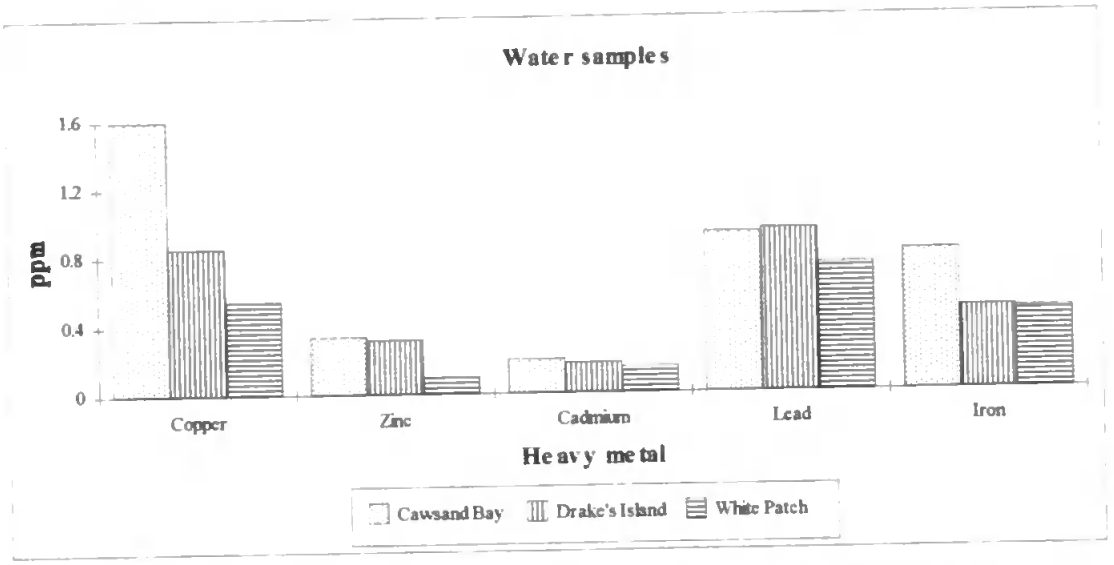

Figure 10.7: Comparison of mean heavy metal content of sea water samples from the three sampling sites April to July, 1994.

From Table 10.3 and Figure 10.7 it can be seen that the mean values for the five heavy metals investigated are fairly similar at the three sites sampled. Despite having similar values (especially for concentration of cadmium) the concentration of the metals copper, zinc, cadmium and iron all decrease from Cawsand Bay to Drake's Island to White Patch, whereas the concentration of lead in the water samples decreases from Drake's Island to Cawsand Bay to White Patch. The mean concentrations of metals in sea water samples at the three sites all have different distributions. The concentrations of the metals in sea water at Cawsand Bay have decreasing values of cadmium, zinc, iron, lead and copper respectively; those of Drake's Island decrease from cadmium, zinc, iron, copper to lead and those at White Patch decrease from zinc, cadmium, iron, copper to lead. These values are relatively low compared to the sediment concentrations.

Table 10.4: Comparison of mean values of copper in fine and coarse sediment samples from the three sites extracted by EDTA and hydrochloric acid in µg per g dry sediment (n = 4).

Site	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm
Cawsand Bay	13.870	15.357	13.457	24.619
Drake's Island	5.014	4.098	9.529	8.805
White Patch	15.450	8.107	118.521	63.427

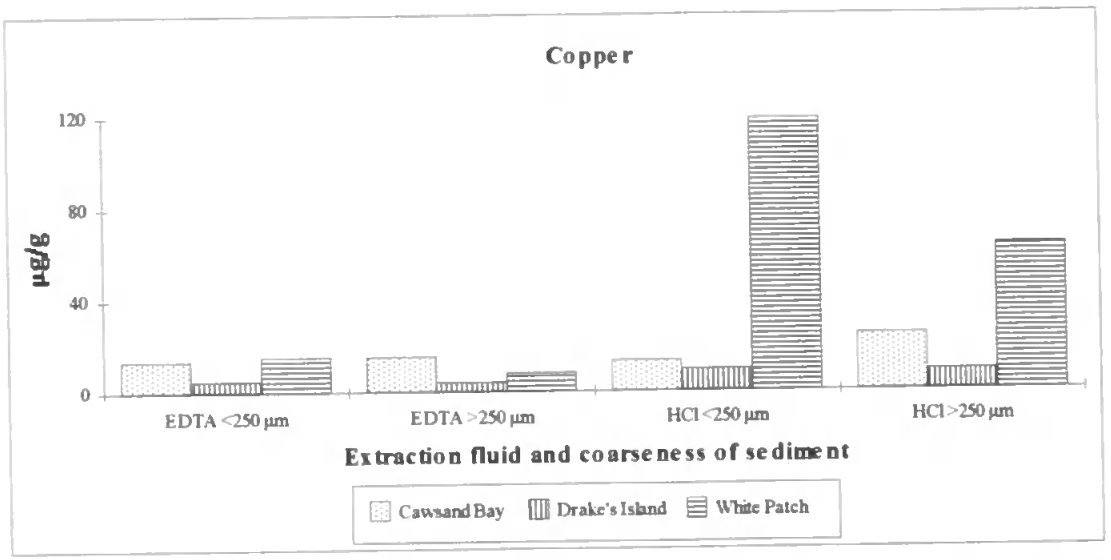

Figure 10.8: Comparison of mean total and bioavailable copper content of coarse and fine sediments from the three sampling sites April to July, 1994.

From Table 10.4 and Figure 10.8 it can be seen that fine and coarse sediments from Cawsand Bay extracted with EDTA and the fine fraction of sediment extracted with hydrochloric acid contain similar amounts of copper, whereas the coarse fraction of sediment extracted with hydrochloric acid contains approximately 10 µg per g more copper. Copper in Drake's Island sediments is lower than that of Cawsand Bay sediments and values are higher in fine sediments than in coarse sediments from this site by both extraction methods. Extraction of copper from White Patch sediments reveals that the fine fraction contains more copper than the coarse fraction when extracted with EDTA and much more copper in the fine fraction than the coarse fraction when extracted with hydrochloric acid. The total amount of copper in sediments is highest at White Patch and bioavailable copper is highest at White Patch in the fine fraction of sediment and highest in Cawsand Bay coarse sediments.

Table 10.5: Comparison of mean values of zinc in fine and coarse sediment samples from the three sites extracted by EDTA and hydrochloric acid in µg per g dry sediment (n = 4).

Site	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm
Cawsand Bay	8.579	13.798	38.308	52.443
Drake's Island	8.904	9.349	34.217	24.882
White Patch	12.473	9.211	42.989	33.990

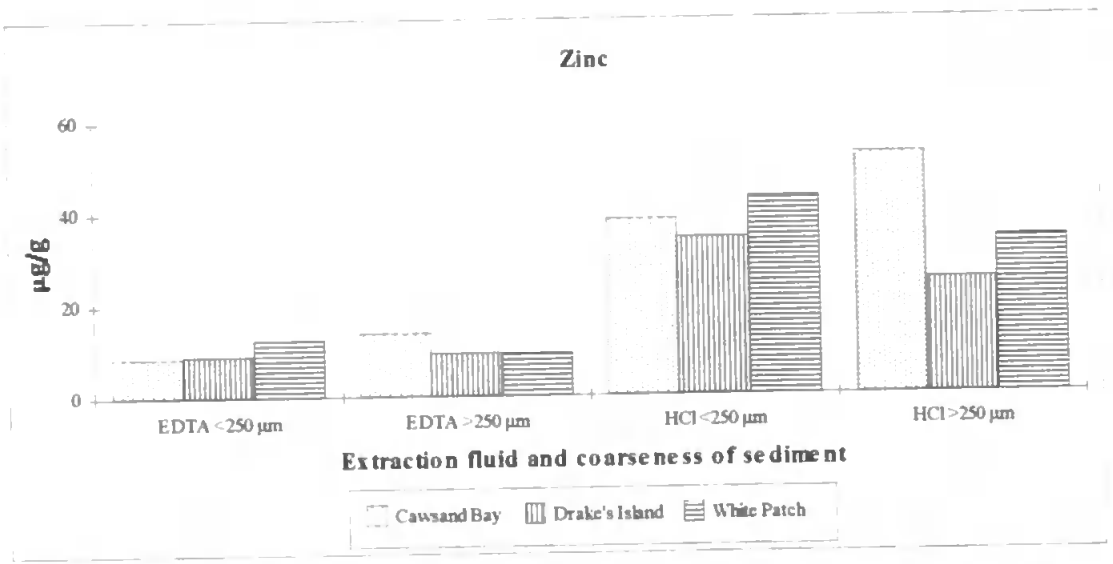

Figure 10.9: Comparison of mean total and bioavailable zinc content of coarse and fine sediments from the three sampling sites April to July, 1994.

From Table 10.5 and Figure 10.9 it can be seen that all sites have similar concentrations of zinc in both fine and coarse fractions extracted with EDTA, although in the fine fraction of sediment, values decrease from White Patch to Drake's Island to Cawsand Bay, and decrease in coarse fractions from Cawsand Bay to Drake's Island and White Patch sediments. Hydrochloric acid extraction of the total amount of zinc in sediments show that Drake's Island and White Patch sediments contain more zinc in the fine fraction of sediment than in the coarse fractions and Cawsand Bay contains more zinc in the coarse fraction than in the fine fraction. White Patch fine sediments contain more zinc than Cawsand Bay and Drake's Island fine sediments respectively and in the coarse fractions Cawsand Bay sediments contain more zinc than White Patch and Drake's Island sediments respectively.

Table 10.6: Comparison of mean values of cadmium in fine and coarse sediment samples from the three sites extracted by EDTA and hydrochloric acid in µg per g dry sediment (n = 4).

Site	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm
Cawsand Bay	1.696	1.286	2.232	3.580
Drake's Island	0.504	0.418	3.018	3.672
White Patch	0.375	0.991	4.911	4.365

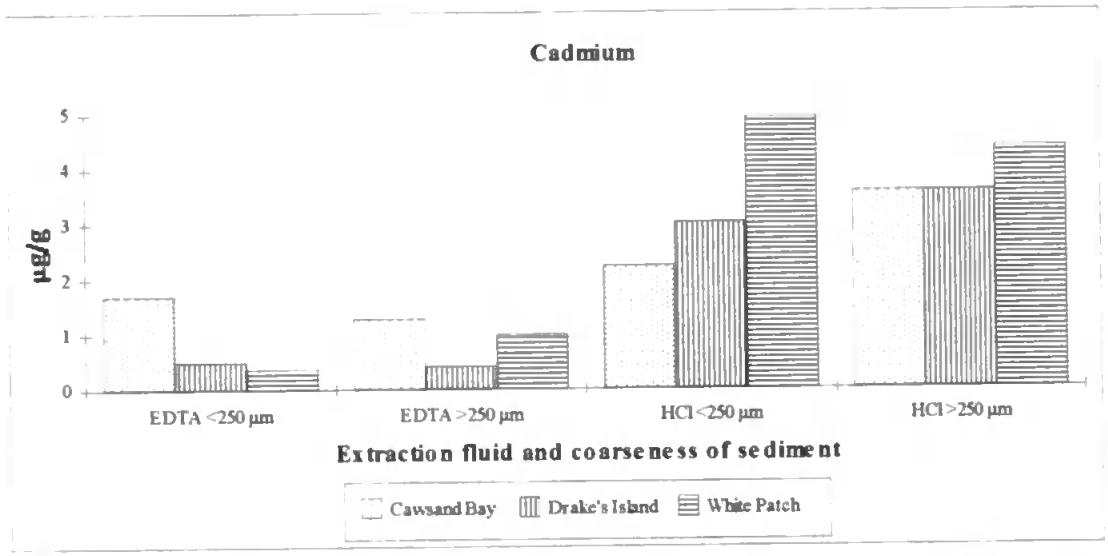

Figure 10.10: Comparison of mean total and bioavailable cadmium content of coarse and fine sediments from the three sampling sites April to July, 1994.

From Table 10.6 and Figure 10.10 it can be seen that EDTA extraction of cadmium from sediments that in Cawsand Bay and Drake's Island sediments there is more bioavailable cadmium in the fine fraction of sediment than the coarse, whereas for sediments from White Patch there is more bioavailable cadmium in the coarse fraction of the sediment than the fine fraction. In fine sediments the bioavailable cadmium is highest at Cawsand Bay with fine sediments from Drake's Island and White Patch containing less respectively. In the coarse fraction of the sediment, sediments from Cawsand Bay contain more cadmium than White Patch and Drake's Island respectively. At all sites the total amount of cadmium (extracted by hydrochloric acid) exceeds the bioavailable concentration and in both fine and coarse fractions of the sediment; the concentration of cadmium is highest at White Patch than at Drake's Island and Cawsand Bay respectively. Cadmium content extracted with hydrochloric acid reveals that more cadmium is present in the coarse fraction of the sediment than the fine fraction at Cawsand Bay and Drake's Island, whereas at White Patch more total cadmium is present in the fine fraction than the coarse fraction.

Table 10.7: Comparison of mean values of lead in fine and coarse sediment samples from the three sites extracted by EDTA and hydrochloric acid in µg per g dry sediment (n = 4).

Site	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm
Cawsand Bay	11.935	18.232	42.040	49.117
Drake's Island	10.814	10.462	38.939	39.601
White Patch	13.318	14.432	41.596	45.536

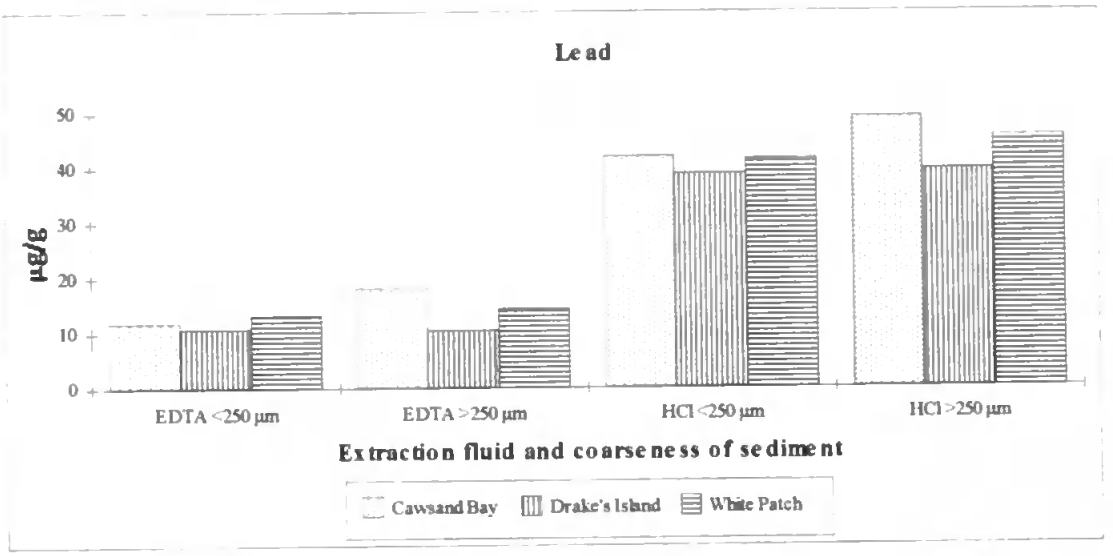

Figure 10.11: Comparison of mean total and bioavailable lead content of coarse and fine sediments from the three sampling sites April to July, 1994.

From Table 10.7 and Figure 10.11 it can be seen that extraction of bioavailable lead by EDTA is greater in the coarse fraction of sediment than the fine for the sites of Cawsand Bay and White Patch, whereas Drake's Island fine sediments contain slightly more lead than the coarse fraction. The fine fraction of sediment contains more lead at White Patch than Cawsand Bay and Drake's Island respectively and the coarse fraction contains more lead at Cawsand Bay than White Patch and Drake's Island respectively. All sites contain more lead in the sediment extracted by hydrochloric acid than EDTA and, at all sites, the total amount of lead is higher in the coarse fraction of sediment than the fine. Hydrochloric acid extraction of fine and coarse fractions of sediment reveal that all sites contain very similar amounts with Cawsand Bay sediments containing more total lead than White Patch and Drake's Island respectively.

Table 10.8: Comparison of mean values of iron in fine and coarse sediment samples from the three sites extracted by EDTA and hydrochloric acid in µg per g dry sediment (n = 4).

Site	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm
Cawsand Bay	22.128	31.806	10059.20	4768.36
Drake's Island	16.362	15.067	2646.97	2239.31
White Patch	30.378	23.986	3825.11	1558.172

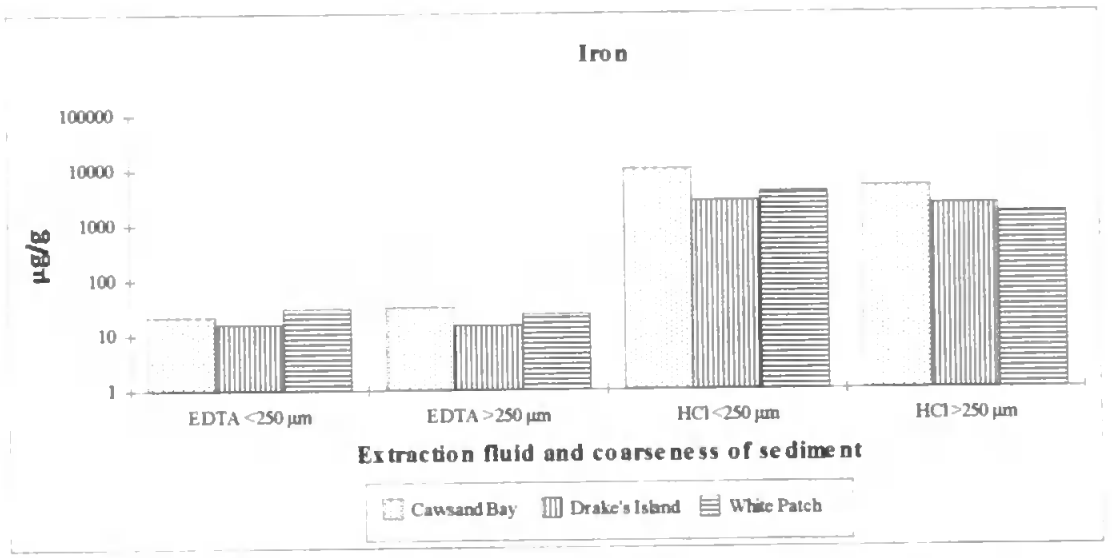

Figure 10.12: Comparison of mean total and bioavailable iron content of coarse and fine sediments from the three sampling sites April to July, 1994.

From Table 10.8 and the logarithmic plot of Figure 10.12 it can be seen that for both EDTA and hydrochloric acid extraction of iron from sediments that for Drake's Island and White Patch sediments there is a higher iron content in the fine fraction of sediments than in the coarse, whereas for Cawsand Bay sediments there is more iron in the coarse fractions than in the fine. Fine fractions of sediment have higher concentrations of bioavailable iron at White Patch and Cawsand Bay and Drake's Island respectively, whereas the coarse fractions have higher concentrations of bioavailable iron in Cawsand Bay sediments than sediments from White Patch and Drake's Island respectively. The total amount of iron in fine fractions of sediment is higher at White Patch than Drake's Island and Cawsand Bay respectively and the total amount of iron in coarse fractions of sediment is higher at Cawsand Bay than Drake's Island and White Patch respectively.

10.2.4. DISCUSSION.

Lead and cadmium are not essential for the life of any known organisms and are therefore more toxic, even at low concentrations, than copper, zinc and iron, which are essential to most marine organisms. However, the heavy metals of copper, zinc and iron can be toxic at relatively high concentrations. The decision to analyse these five heavy metals was made so that the background levels of the most commonly-occurring heavy metals and the most abundant toxic heavy metals in the nearshore environment could be assessed.

The concentration of heavy metals in water samples is thought to be far less important to Foraminiferida than those bioavailable within sediments. With the exception of lead, which was highest at Drake's Island, Cawsand Bay water samples had the highest concentrations of copper, zinc, cadmium and iron. The major input of these metals in sea water to Cawsand Bay must the direct input from the marine environment and is possibly the result of incorporation of these metals into phytoplankton and zooplankton. Iron may be incorporated into the sediment from the de-gaussing point situated off this site. The major sources of heavy metals to both Drake's Island and White Patch would be phyto- and zoo-plankton, sewage, the Rivers Tamar and Plym, industrial effluent, the Dockyard, marinas and Sutton Harbour. The limited sampling period of four months should represent the maximal input of metals to the sites from phyto-and zooplankton blooms, sewage levels boosted by tourism, less dilution by rainwater of metals carried from the catchment areas into the rivers, and the increased activity of marinas.

The distinction made between bioavailable (EDTA extracted) and total concentrations (HCl extracted) of heavy metals in sediments is very important: although some authors continue only to measure the total concentration of metals in sediment, the possible effects upon organisms may only result from the bioavailable content. With the exception of copper at Cawsand Bay, the concentration of total metals in the sediment samples was always higher than the bioavailable content (especially so in the case of iron). The examination of fine (<250 μm) and coarse (>250 μm) fractions of the sediment would be expected to reveal

that higher concentrations of bioavailable heavy metals are available on fine sediments as there is a greater surface-area-to-volume ratio, although this was not found to be always the case.

The separation of deformation type into those with probable natural causes and those producing aberrant tests in response to unknown factors is arbitrary. The production of short, buckled or bent chambers or irregular coiling may equally be the product of hydrodynamic activity during the delicate process of chamber secretion or a change in temperature, salinity or heavy metal content of the sediment. It is also possible, however, that other heavy metals not measured (such as mercury or tin) have caused deformation of foraminiferid tests.

From the heavy metal concentrations measured it can be seen that within sediments Drake's Island samples contained the lowest concentrations of the five heavy metals analysed. The percentage of aberrant tests sampled from this site (not counting those which might be attributable to natural causes) was the highest of the three sites sampled (0.43%). It therefore seems unlikely that test deformation at this site is attributable to bioavailable heavy metal concentration of the sediments. All species showing test deformities at this site were of the genus *Quinqueloculina* and it is probably more likely that the variable input of fresh water to this site from the River Tamar would affect test formation in this stenohaline genus. In addition, although the concentrations of bioavailable heavy metals sampled at Cawsand Bay and White Patch are very similar for copper, zinc and iron those of Cawsand Bay sediments exceed those of White Patch for concentrations of cadmium and lead. Aberrant forms (discounting-counting those with possible natural causes) sampled at Cawsand Bay were only 0.167% of the fauna compared to 0.41% of the White Patch foraminiferid fauna. Of the total number of deformed tests, Cawsand Bay produced 0.29% deformities: the lowest percentage of the three sites.

These results suggest that although the sites sampled have various sources for the heavy metals sampled, deformation of the test are not caused by the presence of these heavy metals.

10.3. EXPERIMENTS UPON *ROTALIELLA ELATIANA* PAWLOWSKI & LEE.

10.3.1. INTRODUCTION.

Despite the relatively large number of authors who have maintained Foraminiferida in laboratories, the investigations carried out have been mainly upon the nutritional needs, reproductive strategies, the process of chamber formation and the effects of antibiotics (see Section 8.1.). The effects of salinity regimes upon Foraminiferida have included the reduction of feeding frequency of *Elphidium crispum* (Murray, 1963), effects of salinity upon growth and reproduction of *Ammonia beccarii tepida* (Bradshaw, 1961), the effect of temperature upon *Ammonia beccarii* (Schnitker, 1974), the behavioural effects of reduced salinity upon *Quinqueloculina seminulum* by Murray (1968 {b}) and morphological changes in *Rotaliella elatiana* (Tintori-Angelli, 1995). Studies of the effect of heavy metals upon Foraminiferida have been carried out by Bryan (1963) on the uptake of radioactive metals, and by Sharifi *et al.* (1991) who studied the deformations of *Ammonia beccarii* caused by copper in the range of 10-20 parts per billion. Sharifi *et al.* (1991) are the only authors to discuss deformation of the test in laboratory-maintained Foraminiferida with reference to heavy metals. Foraminiferida are known to form aberrant tests when maintained in laboratories with temperature, salinity and nutrition standardised, especially the species *Ammonia beccarii*.

Due to the failure to culture *Elphidium crispum* in the laboratory (see Chapter 8) the exposure of offspring of one parental Foraminiferida to metals was not possible. It was hoped to eliminate genetic variability of the phenotype in this way, so that morphological changes in response to the effects of the metals and salinity regimes under investigation could be assessed. *Rotaliella elatiana* Pawlowski & Lee is one of a very few species of

Foraminiferida successfully cultured in the laboratory and is very morphologically stable in culture. *Rotaliella elatiana* was originally collected by Dr. Jan Pawlowski (University of Geneva) from the Gulf of Elat in the Red Sea, and he had maintained this species in culture in the laboratory for approximately four years, prior to kindly providing an inoculate for this study. The inoculate was brought to England from Switzerland by Dr. Pawlowski's colleague, Sylvie Tintori Angelli, on the 6th of December, 1993, together with *Enteromorpha intestinalis* (the food of the Foraminiferida) and full instructions and methods for the successful culture of this species. This species has a classic heterophasic life cycle (Pawlowski, 1990; Pawlowski & Lee, 1992), with a regular alternance of a diploid agamontic phase and a haploid gamontic phase, although sometimes the agamontic phase is repeated many times (Pawlowski, 1991). This species is found in sea water of high salt content (40.9‰) and in association with the macrophytic alga *Enteromorpha* (Pawlowski, 1989).

Rotaliella elatiana is a relatively small species of Foraminiferida, and completes its life cycle very quickly in comparison to other species of Foraminiferida (usually completing its cycle in a week). The number of offspring produced by sexual reproduction of one pair of gamonts can number 4, 6 or 8 embryos and depends upon the number of gametes and mitotic divisions. There is a relationship between the number of embryos and their volume (Pawlowski, 1991). The number of gamontic embryos produced *via* asexual reproduction of an agamontic individual affects the size of the proloculi of the offspring. Either 4, 8 or 12 embryos may be produced asexually; the fewer in number of offspring, the larger the proloculus. Because offspring move away from the parental test to browse, and because the number of embryos produced by asexual and sexual reproduction have the number of 4 and 8 embryos in common, it is not always possible to ascertain if the embryos have been produced by sexual or asexual reproduction. The total number of offspring can be measured, however, and therefore the fecundity of *Rotaliella elatiana* under various metal and salinity regimes can be measured. The relatively quick reproductive potential, small size, and lack of morphological variation whilst in culture makes this species invaluable to the study of the effect of environmental variables and pollutants upon Foraminiferida.

Sub-lethal toxicity experiments are usually carried out in clean glassware devoid of substratum to prevent chelation of heavy metals which would lower the bioavailable forms. In this case, the base of chemically-clean glassware was covered in young *Enteromorpha intestinalis* to provide food and oxygen for the *Rotaliella elatiana*. It was felt that the uptake of metals from the *Enteromorpha* and from the surrounding sea water was a more natural means of uptake of toxin, and the juvenile fronds of the alga would uptake less metal from solution than older fronds. As starvation and salinity increase the effects of metal toxicity (Bryan, *pers. comm.*), the provision of *Enteromorpha intestinalis* as food and monitoring of salinity for these experiments mean that only the effects upon morphology and fecundity would be expressed.

The heavy metals of copper, zinc and cadmium are tested for their toxicity, as the metals of nickel and lead have been found to have little effect in toxicity experiments with invertebrates (Bryan, *pers. comm.*). The chemical form of the heavy metal under investigation is an important consideration because, although the compound will ionise in sea water, the anionic element may well cause some effects; *e.g.* if using a nitrate compound, the nitrate component may cause toxicity effects in itself. For this series of experiments only the chlorides and sulphate compounds of the metals are used, because chlorides and sulphates are abundant in sea water (Bryan; *pers. comm.*). In conducting sub-lethal metal experiments upon invertebrates it is often difficult and time-consuming to gauge the correct concentration of a metal which produces discernible effects; these experiments involved using logarithmic series of concentration of metals so that the effects of different concentrations of metal could be evaluated. The salinity regimes to be used are also quite different in concentration, so that clear responses to reduced or elevated levels can be assessed. The aim of this part of the study is to establish if test deformation is induced by salinity or heavy metal regimes and whether deformation is variable specific, and specific to each metal.

10.3.2. MATERIALS & METHODS.

Taxonomy.

Order FORAMINIFERIDA Eichwald, 1830
Suborder ROTALIINA Delage & Hérouard, 1896
Superfamily GLABRATELLACEA Loeblich & Tappan, 1964
Family ROTALIELLIDAE Loeblich & Tappan, 1964
Genus ***Rotaliella*** Grell, 1954
Species ***Rotaliella elatiana*** **Pawlowski & Lee**, 1992

Diagnosis

A species of *Rotaliella* with a lobate test, broadly open umbilicus, and slightly undulate spiral sutures. This species has numerous denticles surrounding the umbilicus.

Remarks

In contrast to other rotaliellids the embryonic pseudochamber is not perforate and the radial grooves and denticles are more numerous.

Culture methods

The specimens of *Rotaliella elatiana* were maintained in sterile, lidded glass finger bowls and perspex Petri dishes (90 mm diameter) within a Fison's Fi-totron 600 H Environmental Chamber at a temperature of 20°C. *Enteromorpha intestinalis*, the food of *Rotaliella elatiana*, was maintained in a large, sterile crystallising dish of 25 cm diameter covered with a sterile plate of glass. Light was provided by four fluorescent lights, each of 40 Watts, on a 12 hour light/dark cycle. The macrophytic *Enteromorpha intestinalis* was maintained and grown in Brackish Water Medium (Appendix VIII). Because *Rotaliella elatiana* is sensitive to high levels of ammonia (J. Pawlowski, *pers. comm.*), sea water was obtained (from Plymouth Marine Laboratory) which had been collected from twelve miles off the coast of Plymouth. This was evaporated until a salinity of approximately 40.9‰ (corresponding to the salinity at the sample site of the Gulf of Elat) was obtained and checked with a refractometer. The pH of the solution was adjusted to 8.0-8.1, using dilute hydrochloric acid and dissolved pearls of sodium hydroxide and it was then Millipore-filtered using 0.2 μm cellulose-nitrate filters and autoclaved at 121°C at 15 pounds per

square inch for 15 minutes. The sea water medium was changed approximately every week in the foraminiferal culture vessels, and the Brackish Water Medium was changed approximately every fortnight in the *Enteromorpha intestinalis* culture vessels. Fresh *Enteromorpha intestinalis* was added to the foraminiferal vessels using sterile techniques when the *Enteromorpha* in them became less strongly-coloured due to ingestion of the chloroplasts by *Rotaliella elatiana* or due to senescence of the algae. Due to difficulties in counting *Rotaliella elatiana* when attached to the tubular *Enteromorpha intestinalis*, Pawlowski and Tintori Angelli devised a system of inducing asexual reproduction of the algae (sporulation) in Erdshreiber Medium (Appendix VIII), so that it formed a "lawn" of germlings on the base of a Petri dish, which could then be inoculated with the Foraminiferida (Pawlowski & Tintori Angelli, *pers. comm.*).

The culture was bacteria-free as sterilised media and containers were used. The specimens of *Rotaliella elatiana* were examined at every change of media, and there appeared to be no variation of the morphology of the test induced by culture conditions. This small species reproduced very regularly, completing its full life cycle within a week.

Experimental procedures

New glassware was bathed in concentrated nitric acid and twice rinsed in de-ionised distilled water and air-dried. The Petri dishes were sterilised in a hot-air oven overnight. The method to form a lawn of germlings devised by Pawlowski and Tintori-Angelli was used: to each base of several Petri dishes two pieces of *Enteromorpha intestinalis* each of 1 cm length were added to each Petri dish and covered with Erdshreiber Medium to induce sporulation. The Petri dishes were then placed into the same Environmental Chamber as the culture until germlings of *Enteromorpha intestinalis* formed an even coating on the base of the Petri dish (approximately 2 weeks).

Stock solutions of the heavy metals of copper, zinc and cadmium were prepared using autoclaved de-ionised distilled water. Stock solution of copper was prepared by dissolving 2.6824g of $CuCl_2$ $2H_2O$ into 1 litre of water in a chemically-clean volumetric flask to

provide a solution containing 1000 parts per million copper. Stock solution of zinc was prepared by dissolving 4.399 g of $ZnSO_4$ $7H_2O$ into 1 litre of water in a chemically-clean volumetric flask to provide a solution containing 1000 parts per million zinc. Stock solution of cadmium was prepared by dissolving 2.032 g of $CdCl_2$ $2½H_2O$ into 1 litre of water in a chemically-clean volumetric flask to provide a solution containing 1000 parts per million (ppm) cadmium. These stock solutions were stored at 10°C until use. From the metal stock solutions, (using sea water prepared for the culture of *Rotaliella elatiana*), solutions containing metals at different concentrations were made in chemically-clean volumetric flasks. Solutions were of sea water (Control) and added 0.01 ppm, 0.1 ppm, 1.0 ppm, 10.0 ppm and 100.0 ppm of metal. For the experiments to assess the effects of salinity regimens upon *Rotaliella elatiana*, sea water prepared for cultures was evaporated or diluted to provide solutions of 25.9‰, 30.9‰, 40.9‰ (Control), 50.9‰ and 55.9‰ and the pH adjusted to 8.0 to 8.1.

Petri dishes containing an even coverage of *Enteromorpha intestinalis* germlings were used in experiments. Prior to inoculation with 15 agamonts with 6 or 7 chambers, the Erdshreiber medium was rinsed from the *Enteromorpha intestinalis* with sea water. *Rotaliella elatiana* for cadmium experiments were inoculated into Petri dishes of 90 mm diameter, whilst all other experiments were carried out in Petri dishes of 50 mm. 20 ml of each solution was added to each Petri dish and the sterile glass Petri lid replaced. All containers were placed into the environmental chamber with the culture, and each Petri dish examined every other day. The experimental solutions remained in the containers for the duration of the experiment, although the salinity was checked every other day. Salinity did not need adjustment as evaporation from the lidded Petri dishes did not occur. The decision to leave the experimental solutions in the containers was taken rather than replace them so that chelation of metals to the glassware and to *Enteromorpha intestinalis* would not be accumulatory. The Control solutions were not tested for heavy metal content, and therefore the response of the *Rotaliella elatiana* in the experiments was to both the background levels of metals and the concentrations used in the experimental media.

At the end of the experimental time (ten days) the solution was rinsed from the *Enteromorpha* with distilled de-ionised water and representatives of agamonts randomly

removed and mounted upon SEM stubs. These individuals were coated with gold prior to examination in a JEOL JSM-5200 Scanning Electron Microscope. The number of individuals living at the end of the experimental procedure varied greatly and so by randomly selecting living individuals in this way the type of deformation produced by each type of solution is assessed, although not quantitatively.

10.3.3. RESULTS.

Table 10.9: Comparison of number of living *Rotaliella elatiana* exposed to each concentration of cadmium.

Number of days exposed	Control	0.1 ppm	1.0 ppm	10.0 ppm
0	15	15	15	15
2	158	59	62	61
4	342	171	279	58
6	556	171	307	58
8	1906	274	337	58
10	3616	696	1098	8

From Table 10.9 and Figure 10.13 it can be seen that *Rotaliella elatiana* in the Control containers produced the highest number of living Foraminiferida showing that any amount of cadmium was detrimental to the health of offspring. The specimens exposed to 1.0 ppm cadmium produced more living Foraminiferida than those exposed to 0.1 ppm, however, perhaps suggesting that the weaker solution of cadmium is more detrimental to Foraminiferida than the stronger one. Those *Rotaliella elatiana* exposed to 10.0 ppm cadmium increased in number by day 2, but then decreased in number suggesting that exposure time is as important as concentration for lethal effects of cadmium. *Rotaliella elatiana* under all regimes of cadmium exposure except for 10.0 ppm all increased in number from the first day of the experiment until the final day of exposure. On the final day of the experiment the Control group had produced more living specimens than the specimens exposed to 1.0 ppm, 0.1 ppm and 10.0 ppm respectively indicating the effects of cadmium upon fecundity.

Table 10.10: Comparison of percentage of *Rotaliella elatiana* exposed to each concentration of cadmium which reproduced.

Number of days exposed	Control	0.1 ppm	1.0 ppm	10.0 ppm
0	0.00	0.00	0.00	0.00
2	18.35	10.17	12.90	16.39
4	2.34	5.26	5.73	1.72
6	5.94	0.00	1.63	0.00
8	5.88	6.57	1.78	0.00
10	2.10	6.75	4.37	0.00

With reference to Table 10.10 and Figure 10.14 it can be seen that percentage reproduction of all groups was highest on the second day of examination. The cadmium Control group had the highest percentage reproduction level on the second day of experimentation followed by the 10.0 ppm, 1.0 ppm and the 0.1 ppm groups respectively. The 10.0 ppm group then declined from this point in the percentage of individuals reproducing, as did the 1.0 ppm group, although this group had a slightly higher percentage of individuals reproducing on the final day of the experiment. 1.0 ppm cadmium group declined in percentage reproducing until day 6 and reached a plateau of reproduction for days 8 and 10. The Control cadmium group had approximately 5% reproduction in days 6 and 8 before declining in the reproduction rate again.

From Plate 4 it can be seen that cadmium affected the appearance of tests. In some cases cadmium made the surface of the test rough, affected coiling of the test, caused under-inflation of some tests, infilling of sutures and the umbilicus, and few denticles.

Table 10.11: Comparison of number of living *Rotaliella elatiana* exposed to each concentration of copper.

Number of days exposed	Control	0.1 ppm	1.0 ppm	10.0 ppm
0	15	15	15	15
2	59	68	21	0
4	181	231	33	0
6	213	231	18	0
8	308	460	22	0
10	1220	1273	4	0

From Table 10.11 and Figure 10.13 it can be seen that specimens exposed to 0.1 ppm copper produced slightly more living specimens than the Control group. Specimens exposed

to 1.0 ppm slightly increased in number until day 4, fluctuated in number and then decreased to only 4 specimens left alive on day 10. The group of *Rotaliella elatiana* exposed to 10.0 ppm of copper failed to reproduce and died soon after inoculation into the solution. On the final day of the experiment the 0.1 ppm group had produced more living specimens than the Control group and specimens exposed to 1.0 ppm and 10.0 ppm respectively indicating the effects of copper upon fecundity.

Table 10.12: Comparison of percentage of *Rotaliella elatiana* exposed to each concentration of copper which reproduced.

Number of days exposed	Control	0.1 ppm	1.0 ppm	10.0 ppm
0	0.00	0.00	0.00	0.00
2	15.25	16.18	4.76	0.00
4	8.29	11.26	6.06	0.00
6	3.29	0.00	0.00	0.00
8	6.17	5.00	4.55	0.00
10	3.77	3.53	0.00	0.00

From Table 10.12 and Figure 10.14 it can be seen that the group exposed to 0.1 ppm copper initially had a higher proportion which reproduced than the Control group, but was slightly less in days 6 to 10. The 1.0 ppm copper group had a relatively low reproductive rate which fluctuated. The 10.0 ppm copper group failed to reproduce throughout the experimental period.

From Plate 5 it can be seen that copper affected the appearance of tests. In some cases additional copper made the surface of the test rough, affected coiling of the test, caused over-inflation of some chambers, infilling of sutures and the umbilicus, few denticles, shallowing of the radial grooves, and pores smaller than in the control specimens. The solution of 10.0 ppm copper caused death of all specimens and so the effects of copper at this concentration are only apparent on the final chambers of the test formed in response to the copper: they appear to involve irregular coiling, and irregular inflation and length of chambers, as well as infilling of sutures and umbilici.

Table 10.13: Comparison of number of living *Rotaliella elatiana* exposed to each concentration of sea water.

Number of days exposed	25.9‰	30.9‰	40.9‰	50.9‰	55.9‰
0	15	15	15	15	15
2	15	15	22	15	11
4	15	39	65	7	9
6	0	110	239	7	7
8	0	175	239	0	4
10	0	115	255	0	4

From Table 10.13 and Figure 10.13 it can be seen that those maintained under Control conditions, *i.e.* 40.9‰, produced the most live specimens. Those kept at 30.9‰ were the next most productive group, whilst those maintained at 25.9‰, 50.9‰ and 55.9‰ all failed to reproduce, and died. Fecundity of *Rotaliella elatiana* is therefore greatly affected by salinity different from that used to keep this species in culture.

Table 10.14: Comparison of percentage of *Rotaliella elatiana* exposed to each concentration of sea water which reproduced.

Number of days exposed	25.9‰	30.9‰	40.9‰	50.9‰	55.9‰
0	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	4.55	0.00	0.00
4	0.00	10.26	12.31	0.00	0.00
6	0.00	10.91	10.88	0.00	0.00
8	0.00	4.00	0.00	0.00	0.00
10	0.00	0.87	1.18	0.00	0.00

From Table 10.14 and Figure 10.14 it can be seen that deviation from the "normal" salinity needed for this species severely affected the ability to reproduce. Only specimens kept in 40.9‰ sea water (Control) and 30.9‰ sea water reproduced, whilst those in 25.9‰, 50.9‰ and 55.9‰ sea water failed to reproduce. Percentage reproduction of Control specimens was generally higher than those held in 30.9‰ sea water, except for day 8.

From Plate 6 it can be seen that different sea water concentrations affected the appearance of tests. In some cases sea water concentrations made the sutures shallow, gave fewer denticles, irregular coiling and caused infilling of the umbilici. Only specimens subjected to concentrations of 40.9‰ and 30.9‰ lived and reproduced in the experimental period, and so the effects of other sea water concentrations upon tests will only be apparent on the final

chambers, although infilling of umbilici may occur on surviving Foraminiferida which failed to reproduce.

Table 10.15: Comparison of number of living *Rotaliella elatiana* exposed to each concentration of zinc.

Number of days exposed	Control	0.01 ppm	0.1 ppm	1.0 ppm	10.0 ppm
0	15	15	15	15	15
2	27	25	17	25	15
4	57	79	41	45	12
6	78	83	41	45	6
8	84	89	81	50	3
10	84	89	81	50	0

From Table 10.15 and Figure 10.13 it can be seen that *Rotaliella elatiana* produced more specimens under the 0.01 ppm zinc regime than the Control group, indicating that this small additional amount of zinc was probably beneficial to the fecundity of this species of Foraminiferida. Groups exposed to 0.1 ppm, 1.0 ppm and 10.0 ppm zinc respectively appeared to suffer deleterious effects from zinc. There was no reproduction in specimens maintained under 10.0 ppm zinc and these Foraminiferida gradually died.

Table 10.16: Comparison of percentage of *Rotaliella elatiana* exposed to each concentration of zinc which reproduced.

Number of days exposed	Control	0.01 ppm	0.1 ppm	1.0 ppm	10.0 ppm
0	0.00	0.00	0.00	0.00	0.00
2	7.41	8.00	5.88	8.00	0.00
4	17.54	15.19	7.32	11.11	0.00
6	3.85	1.20	0.00	0.00	0.00
8	1.19	1.12	11.11	2.00	0.00
10	0.00	0.00	0.00	0.00	0.00

From Table 10.15 and Figure 10.14 it can be seen that the greatest percentages of *Rotaliella elatiana* exposed to zinc mainly occurred on day 4, although the greatest percentage of reproducing individuals exposed to 0.1 ppm zinc occurred on day 8. Control specimens had the highest percentage reproduction, followed by 0.01 ppm, 0.1 ppm and 1.0 ppm zinc, although those in 10.0 ppm zinc failed to reproduce.

From Plate 7 it can be seen that different zinc concentrations affected the appearance of tests. In some cases zinc affected coiling, inflation, made the sutures and radial grooves shallow, caused fewer denticles, and caused infilling of the umbilici. Specimens subjected to 10.0 ppm failed to reproduce and so the effects of zinc upon tests at this concentration will only be apparent on the final chambers, although infilling of umbilici may occur on surviving Foraminiferida which failed to reproduce.

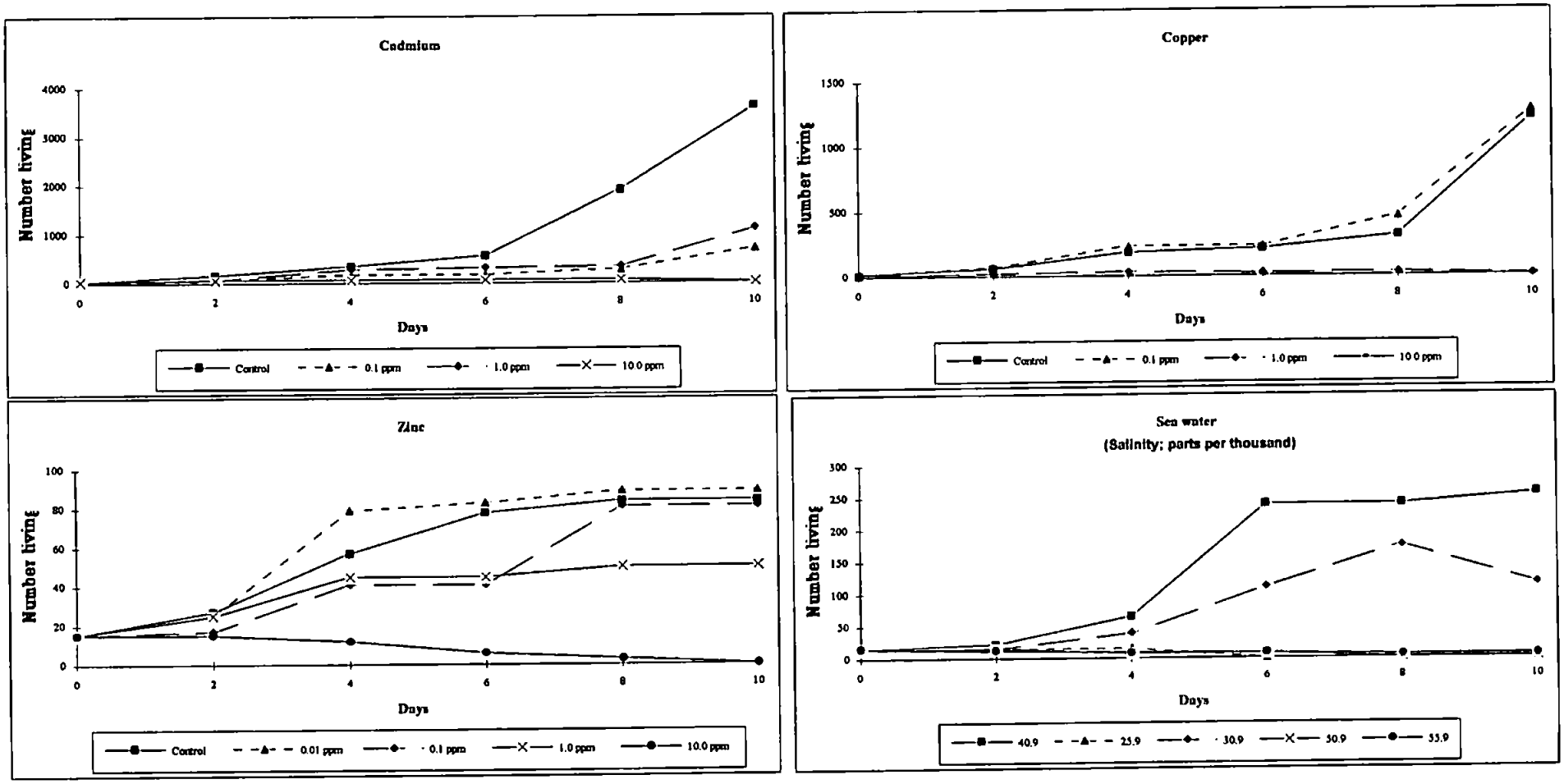

Figure 10.13: Temporal variation of number of *Rotaliella elatiana* living under each experimental regime.

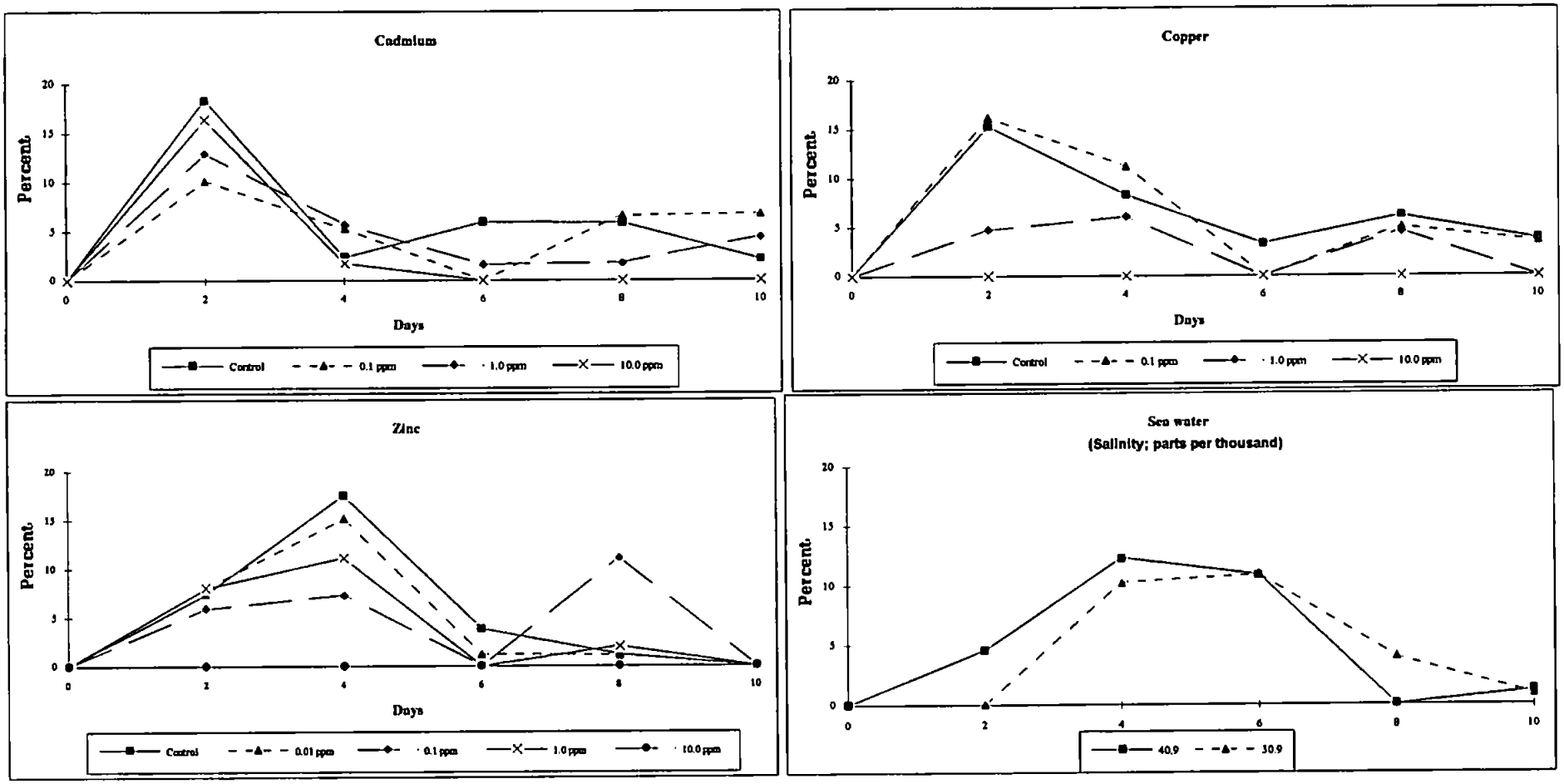

Figure 10.14: Temporal variation of percentage of *Rotaliella elatiana* which reproduced under each experimental regime.

PLATE 4.

Deformations of *Rotaliella elatiana* subjected to concentrations of cadmium

Figure 1: Control specimen

Figure 2: Control specimen

Figure 3: 0.1 ppm; irregular coiling of proloculus and deuteroconch.

Figure 4: 0.1 ppm; rough surface, umbilicus and sutures infilled, few denticles.

Figure 5: 1.0 ppm; surface rough and sutures infilled.

Figure 6: 1.0 ppm; surface rough, sutures infilled, and denticles almost absent.

Figure 7: 10.0 ppm; rough surface and coarser pores than in Controls.

Figure 8: 10.0 ppm; calcite plate covering umbilicus, and sutures infilled.

PLATE 4

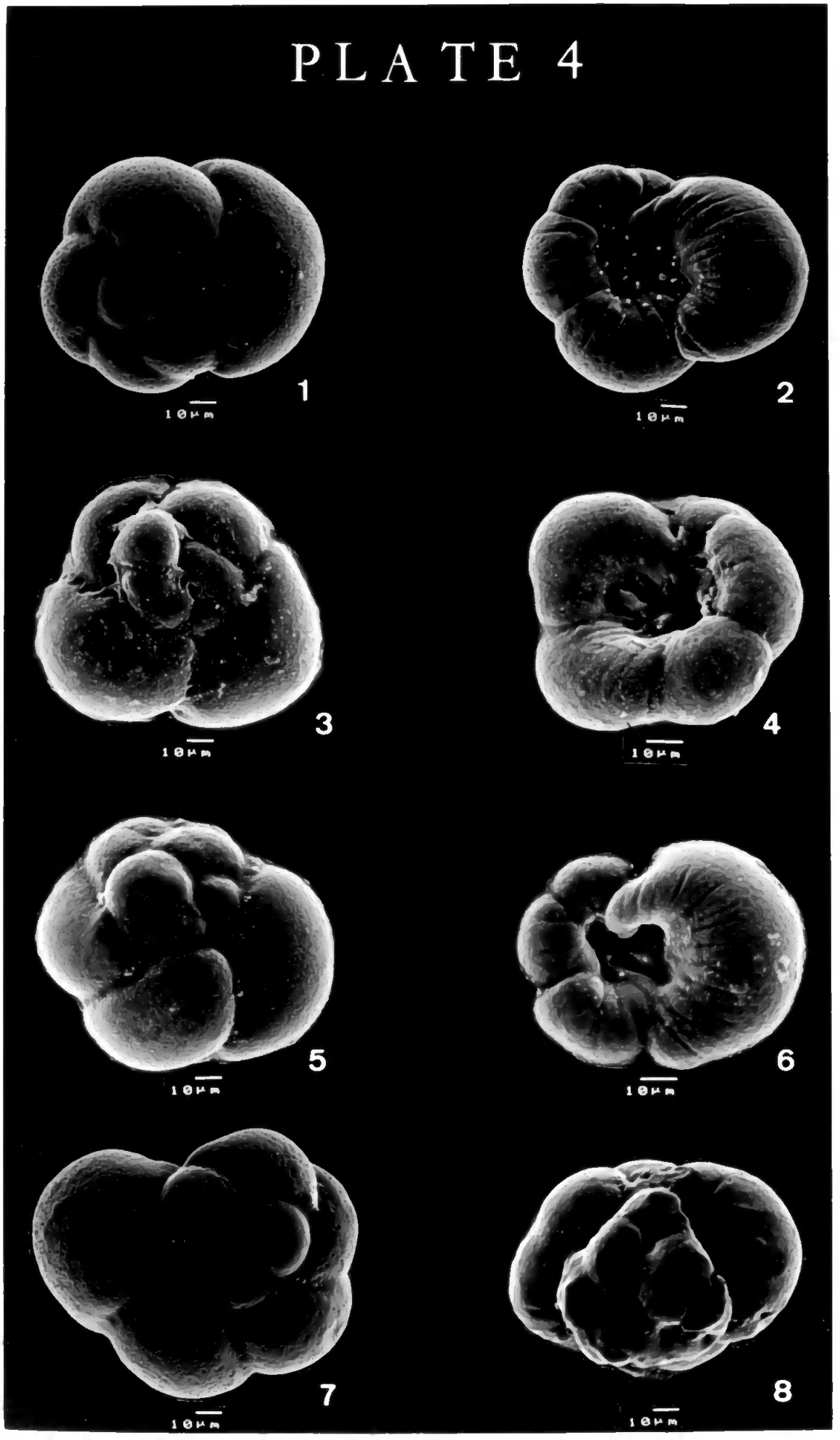

PLATE 5.

Deformations of *Rotaliella elatiana* subjected to concentrations of copper

Figure 1: Control

Figure 2: Control

Figure 3: 0.1 ppm; terminal chamber is over-inflated and pores are small.

Figure 4: 0.1 ppm; surface rough, sutures infilled and terminal chamber has few small pores.

Figure 5: 1.0 ppm; coiling irregular, infilled umbilicus and sutures, radial grooves and denticles absent.

Figure 6: 1.0 ppm; umbilicus and sutures infilled, and few denticles.

Figure 7: 10.0 ppm; surface rough, sutures infilled and the terminal chamber is over-inflated with few small pores.

Figure 8: 10.0 ppm; umbilicus and sutures infilled, radial grooves poorly-defined on final three chambers, and terminal chamber has small pores.

PLATE 5

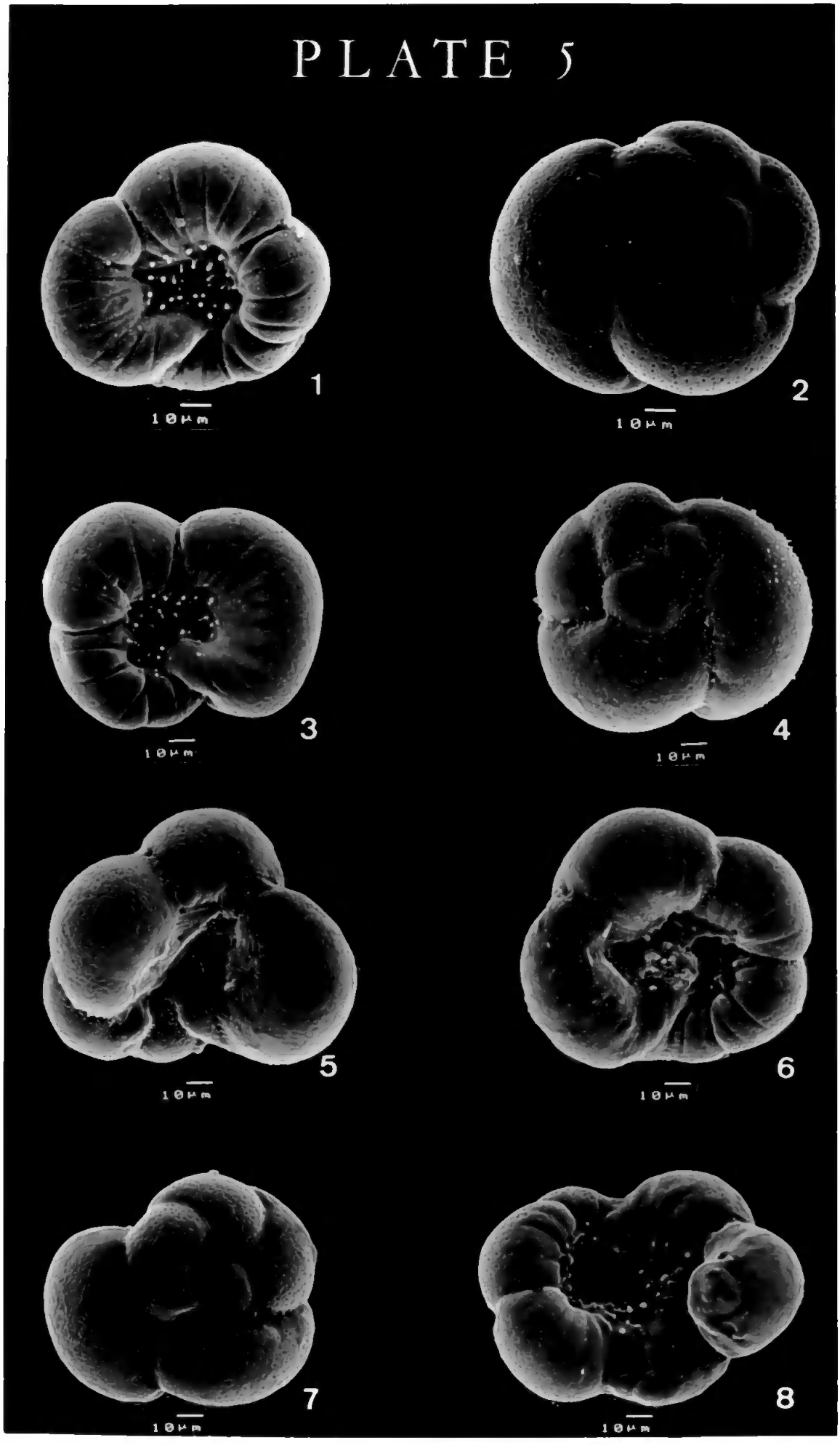

PLATE 6.

Deformations of *Rotaliella elatiana* subjected to concentrations of salinity

Figure 1: 25.9‰; irrregular coiling.

Figure 2: 25.9‰; umbilicus infilled and few denticles present.

Figure 3: 30.9‰; proloculus has additional chamberlets.

Figure 4: 30.9‰; umbilicus infilled.

Figure 5: 40.9‰; Control (contaminated with salt residue).

Figure 6: 40.9‰; Control (contaminated with salt residue).

Figure 7: 50.9‰; surface rough and pores coarse.

Figure 8: 50.9‰; umbilicus and sutures infilled, few denticles and coarse radial grooves.

Figure 9: 55.9‰; sutures infilled.

Figure 10: 55.9‰; sutures infilled.

PLATE 6

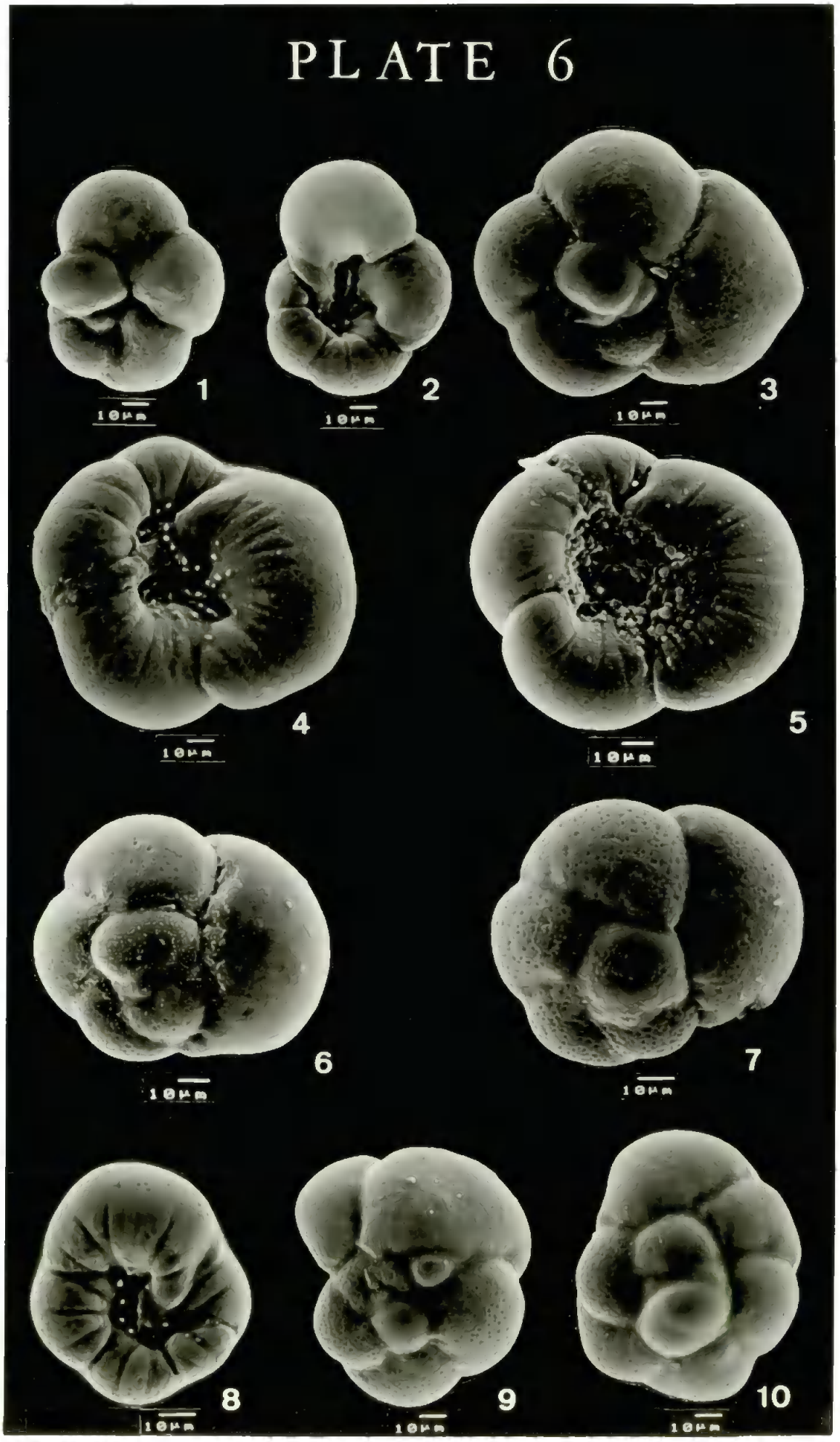
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PLATE 7.

Deformations of *Rotaliella elatiana* subjected to concentrations of zinc

Figure 1: Control

Figure 2: Control

Figure 3: 0.01 ppm; few denticles and infilling of one suture and part of umbilicus.

Figure 4: 0.01 ppm; under-inflation of chambers.

Figure 5: 0.1 ppm; coiling irregular and under-inflation of terminal chamber.

Figure 6: 0.1 ppm; few denticles, sutures shallow and radial grooves not well-defined.

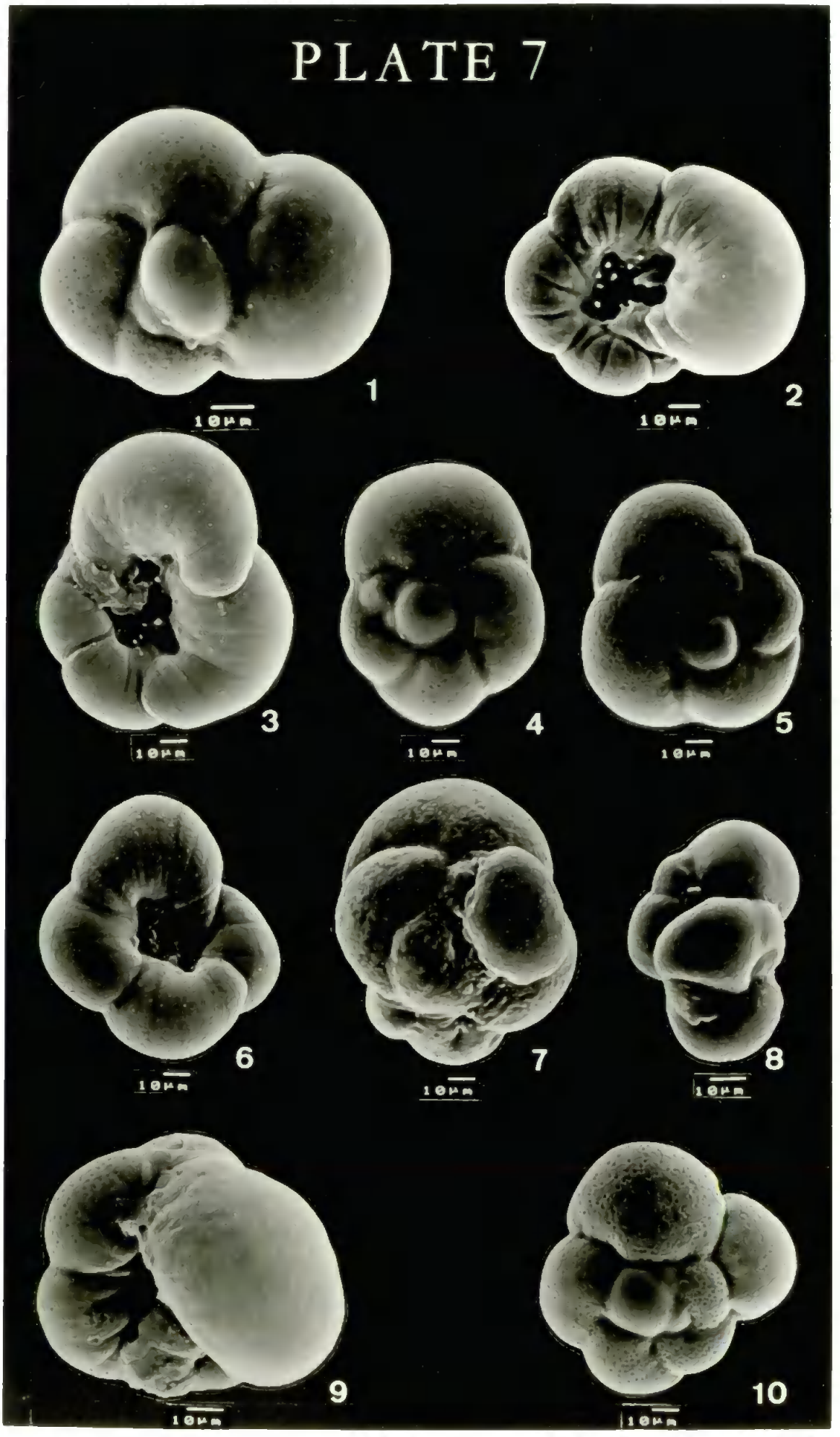
Figure 7: 1.0 ppm; surface rough and coiling irregular.

Figure 8: 1.0 ppm; coiling irregular, under-inflation of chambers, shallow sutures and no pores present.

Figure 9: 10.0 ppm; umbilicus and sutures infilled, few shallow radial grooves, no denticles and over-inflated terminal chamber.

Figure 10: 10.0 ppm; terminal chamber under-inflated.

PLATE 7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10.3.4. DISCUSSION.

The importance of the presence of bacteria in foraminiferal cultures has been detailed by Muller & Lee (1969). That the culture of *Rotaliella elatiana* was bacteria-free and healthy indicates that it has adapted so as not to need the presence of bacteria. The relationship between bacteria and Foraminiferida is unclear; the bacteria may provide vitamins unobtainable in the environment. *Enteromorpha intestinalis* is rich in vitamin B_{12} (Provasoli, 1960), and polysaccharides (Dodson & Aronson, 1978), and provides a good source of a variety of amino acids (Sauze, 1981); so it may be that the nutrients that bacteria may normally provide to other species are provided by the alga. *Enteromorpha intestinalis* is also known to produce anti-bacterial substances (Parekh *et al.*, 1985) as well as antibiotic producing bacteria (Lemos *et al.*, 1985) and, as *Rotaliella elatiana* lives in close association with this alga, it may gain all it needs nutritionally from it and benefit by not being in contact with potentially pathogenic bacteria. In addition, *Enteromorpha intestinalis* provided the *Rotaliella elatiana* with an abundance of dissolved oxygen for growth and reproduction, as it photosynthesised in the foraminiferid containers until consumption. Limited oxygen would be potentially damaging to Foraminiferida and possibly may harm the immune system.

The *Enteromorpha intestinalis* probably suffered from the addition of heavy metals to the media and, at high concentrations, may have died. This alga, as well as supplying oxygen for the Foraminiferida, is also high in carbohydrate and protein content (Fontaine & Bonilla-Ruiz, 1978) and Vinogradov (1953) states that the majority of chlorophyceans tend to concentrate calcium. The *Enteromorpha* thalli are one to two cell layers thick resulting in a large surface-area-to-volume ratio, which enhances their bioaccumulation efficiency (Levine, 1984).

The number of living *Rotaliella elatiana* produced by Control groups for each experiment varied greatly. The number produced by the cadmium Control group totalled more than 3600 on the final day of exposure compared to approximately 1200, 250 and 80 by Control

groups of copper, sea water and zinc respectively. This may reflect that the Petri dishes used for cadmium experiments were larger in size than those used for the other experiments, but does not explain the variability between sea water, copper and zinc Control groups.

The Control groups for cadmium and sea water both produced more living Foraminiferida than other dilutions of the toxin reflecting that cadmium and solutions of salt deviating from the normal content in sea water are very deleterious to this species. For copper and zinc, the experimental solutions of 0.1 ppm and 0.01 ppm respectively produced more living specimens than the Control groups, perhaps suggesting that there is a beneficial effect of dilute inputs of these metals for this species. The death of specimens exposed to 10.0 ppm of copper and zinc and their inability to reproduce may reflect that, although dilute inputs may be beneficial, these metals become toxins at this level. The death and lack of reproduction of specimens exposed to 25.9‰, 50.9‰ and 55.9‰ indicate that salinity is extremely important to this species. Only two salinity regimes, the Control 40.9‰ and 30.9‰, allowed any survivors, indicating that slight hyposalinity can be tolerated, but hypersalinity and extreme hyposalinity cannot be tolerated by this species.

Deformation of the test of *Rotaliella elatiana* was caused by cadmium, copper, zinc and by different salinities. Control specimens did not show test aberrances, and so deformation of this species was caused by the heavy metals or salinity extremes. Fecundity varied greatly amongst experimental groups, but within groups fecundity was greatly affected by concentration of the agent. The test deformations produced are very similar for all the metals and the sea water concentrations. Infilling of sutures between chambers and the umbilici was a common feature of deformation, and coiling mode and inflation of chambers were affected by the experiments conducted. It is not possible to differentiate between tests for the causative agent, which casts doubt upon some previous author's correlation of test deformity with heavy metals in field studies, and particularly upon the correlation of specific deformity with a particular cause.

10.4. THE EFFECT OF ZINC UPON *AMMONIA BATAVUS.*

10.4.1. INTRODUCTION.

Test aberrances of Foraminiferida kept in the laboratory are known to occur in the absence of metals (Hedley & Wakefield, 1967) and, although the genus *Ammonia* is euryhaline and known to be extremely variable in culture, the experimentation of the action of zinc upon *Ammonia batavus* is to complement Sharifi *et al.*'s work (1991) upon the action of copper on this genus. Sharifi *et al.* (1991) tested a maximum of six specimens to each concentration of copper and, therefore, the results are not statistically viable. In an attempt to clarify whether heavy metals do cause deformation of the test, it is important to subject a larger number of specimens to varying concentrations of a heavy metal to ascertain their response, and also to run control groups as a check upon the level of natural variability.

Sharifi *et al.* (1991) find that the distribution of some Foraminiferida in cores are altered by some heavy metals, whilst some species are able to tolerate this type of pollution, others construct deformed tests. Examination of core material reveals that prior to higher levels of copper and zinc there are no foraminiferid deformities, but that deformations are apparent after these higher occurrences of these heavy metals. Since their paper, other authors have also attempted to correlate deformations of the tests of Foraminiferida in field collections with the concentrations of heavy metals in the substrata at the time of collection. To substantiate the hypothesis that heavy metals were causing the observed deformities, Sharifi *et al.* (1991) maintained living *Ammonia beccarii* and exposed them to levels of copper between 10 and 20 parts per billion: specimens formed deformations after 12 weeks. Deformations observed from this trial included production of a high spiral side, additional chamber development, twisting and twinning. Unlike other authors, Sharifi *et al.* (1991), by carrying out laboratory experiments under controlled conditions, attempted to prove that heavy metals were capable of causing the observed deformations.

Ammonia batavus is indigenous to the Plymouth sampling area. This genus is the major species in Section 10.2.3 to have aberrations of the test in the natural communities sampled within Plymouth Sound. Deformations of the test may be specific to each metal, but the testing of the action of zinc upon this species may clarify which type of deformation, if any, occurs in response to zinc contamination. *Ammonia batavus* is slow-growing in comparison to *Rotaliella elatiana* and reproduction is unlikely to occur. Fecundity cannot be tested as a possible response to zinc contamination, although the activity and numbers becoming deformed can be studied.

10.4.2. MATERIALS & METHODS.

Sediment samples were collected from Dartmouth on the 13th April, 1994 at low tide from mudflats bordering the estuary. The sediment was placed into containers in the ratio of approximately 20% sediment, 60% sea water and 20% air (Lee, 1974; Anderson *et al.*, 1991) and placed into a cool box. Within four hours of collection the sediment was emptied into a shallow polypropylene trough containing aerated sea water at room temperature and covered in a glass sheet to prevent evaporation. The specimens of *Ammonia batavus* were extracted from the sediment by direct removal with a pipette and examined for aberrances of the test. Those which had already produced aberrances of the test were discarded and only those with symmetrical tests used in the experiment. Suitable specimens were placed into sterilised glass lidded Petri dishes of 90 mm diameter. Aerated sea water (from 12 miles off the coast of Plymouth) was Millipore filtered (0.45 μm) and the salinity corrected to 35‰ and pH of 8.1 before autoclaving for 20 minutes. This solution was used to make dilutions of zinc in the concentrations of Control, 0.01 ppm, 0.1 ppm, 1.0 ppm, 10.0 ppm and 100 ppm. Thirty specimens were placed into each dilution on the 20th of April, 1994 and the experiment was conducted for 10 days. The *Ammonia batavus* were fed a mixture of *Phaeodactylum tricornatum*, *Dunaliella praemolecta* and *Isochrysis galbana* in the concentration of 10^3 to 10^6 which had been centrifuged to remove the metal-rich growing medium and resuspended in fresh sea water. The zinc media and food items were replaced every day and the activity levels of *Ammonia batavus* recorded.

10.4.3. RESULTS.

Activity

Table 10.17: Activity levels of *Ammonia batavus* maintained under different concentrations of zinc; measured by the number of active specimens.

Day	Control	0.01 ppm	0.1 ppm	1.0 ppm	10.0 ppm	100.0 ppm
1	26	20	19	18	9	0
2	23	19	20	19	13	0
3	29	22	23	22	11	0
4	28	19	19	15	5	1
5	21	16	18	18	4	1
6	23	15	18	14	4	1
7	20	16	14	19	0	0
8	20	13	13	17	0	2
9	18	13	13	11	0	0
10	16	11	7	14	0	0

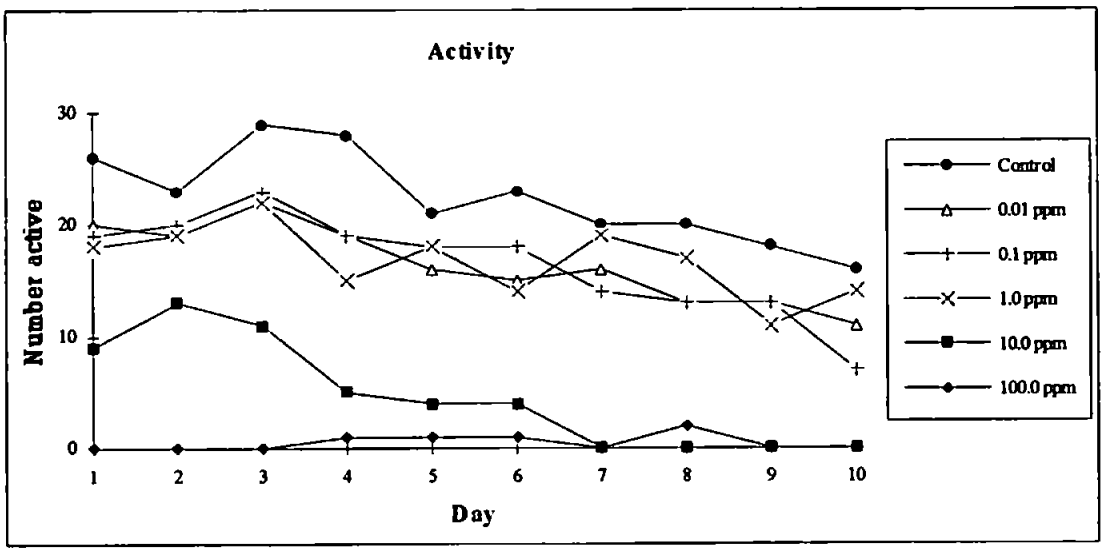

Figure 10.15: Comparison of activity levels of *Ammonia batavus* maintained under varying concentrations of zinc.

From Table 10.16 and Figure 10.15 it can be seen that activity of *Ammonia batavus* was consistently highest in the Control groups, although activity of specimens declined from day 3 onwards. Zinc concentrations of 0.01 ppm, 0.1 ppm and 1.0 ppm produced similar activity levels although those specimens subjected to 1.0 ppm often had higher activity levels than within the other two. Approximately a third of the specimens subjected to 10.0 ppm zinc were active initially and rapidly declined from this level to be totally inactive from day 7 onwards. Activity levels of *Ammonia batavus* subjected to 100.0 ppm fluctuated, with no

activity present in day 1 to day 3, one specimen active from day 4 to day 6 and two specimens active on day 8.

Deformations

Table 10.18: Number of deformations of *Ammonia batavus* maintained under different concentrations of zinc.

Concentration	Control	0.01 ppm	0.1 ppm	1.0 ppm	10.0 ppm	100.0 ppm
Number deformed	2	3	6	3	4	3

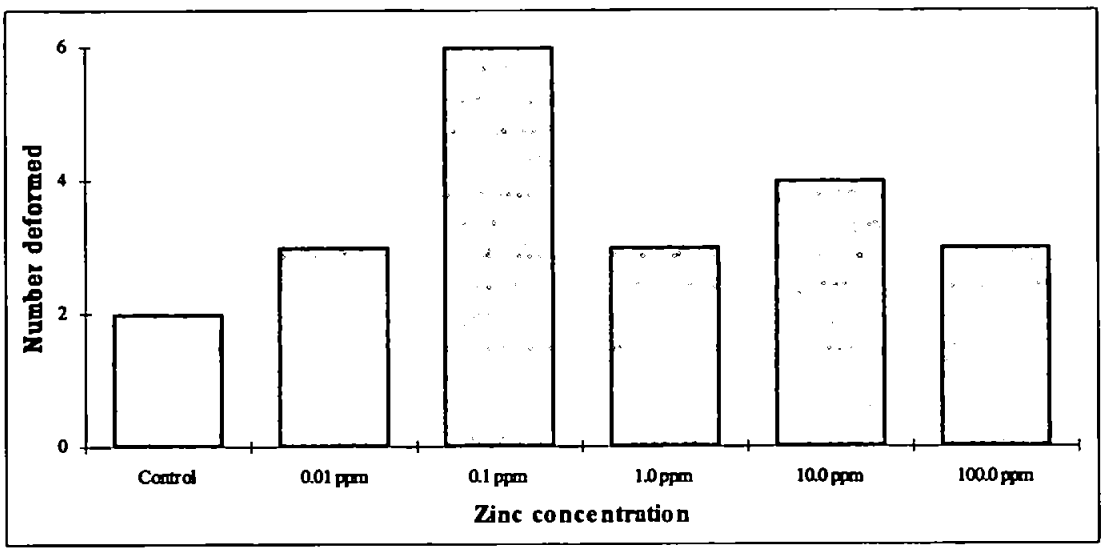

Figure 10.16: Comparison of number of deformations of *Ammonia batavus* maintained under varying concentrations of zinc.

From Table 10.18 and Figure 10.16 it can be seen that the number of deformed specimens is highest in the group of *Ammonia batavus* subjected to 0.1 ppm zinc. The occurrence of deformation is lowest in the Control group, although 2 specimens did produce abnormal chambers. Six specimens produced abnormal chambers in the solution containing 0.1 ppm zinc and the number of deformations decreased with increasing concentration of zinc from this concentration.

Plates 8 and 9 show the types of deformation produced by the different concentrations of zinc. Deformed chambers consisted of buckled, inflated, deflated or additional chamberlets, with no common pattern linking deformation type with concentration. The terminal chambers produced were also often brittle and broke with gentle manipulation of a sable brush.

PLATE 8.

Deformations of *Ammonia batavus* subjected to concentrations of zinc

Figure 1: Control; terminal chamber "buckled".

Figure 2: Control; terminal chamber "buckled".

Figure 3: 0.01 ppm; terminal chamber under-inflated and preceding two chambers malformed.

Figure 4: 0.01 ppm; terminal chamber broken-off and preceding chamber over-inflated.

Figure 5: 0.01 ppm; under-inflation of final three chambers.

Figure 6: 0.1 ppm; irregular coiling and the terminal chamber was secreted from the centre of the umbilicus.

Figure 7: 0.1 ppm; terminal chamber under-inflated and additional calcite secreted into the suture.

Figure 8: 0.1 ppm; terminal chamber appears to be split into two sections.

Figure 9: 0.1 ppm; final three chambers under-inflated and secreted close to previous whorl. One chamber broken.

Figure 10: 0.1 ppm; five final chambers over-inflated and the terminal chamber is "buckled" and irregular.

Figure 11: 0.1 ppm; terminal chamber under-inflated.

PLATE 8

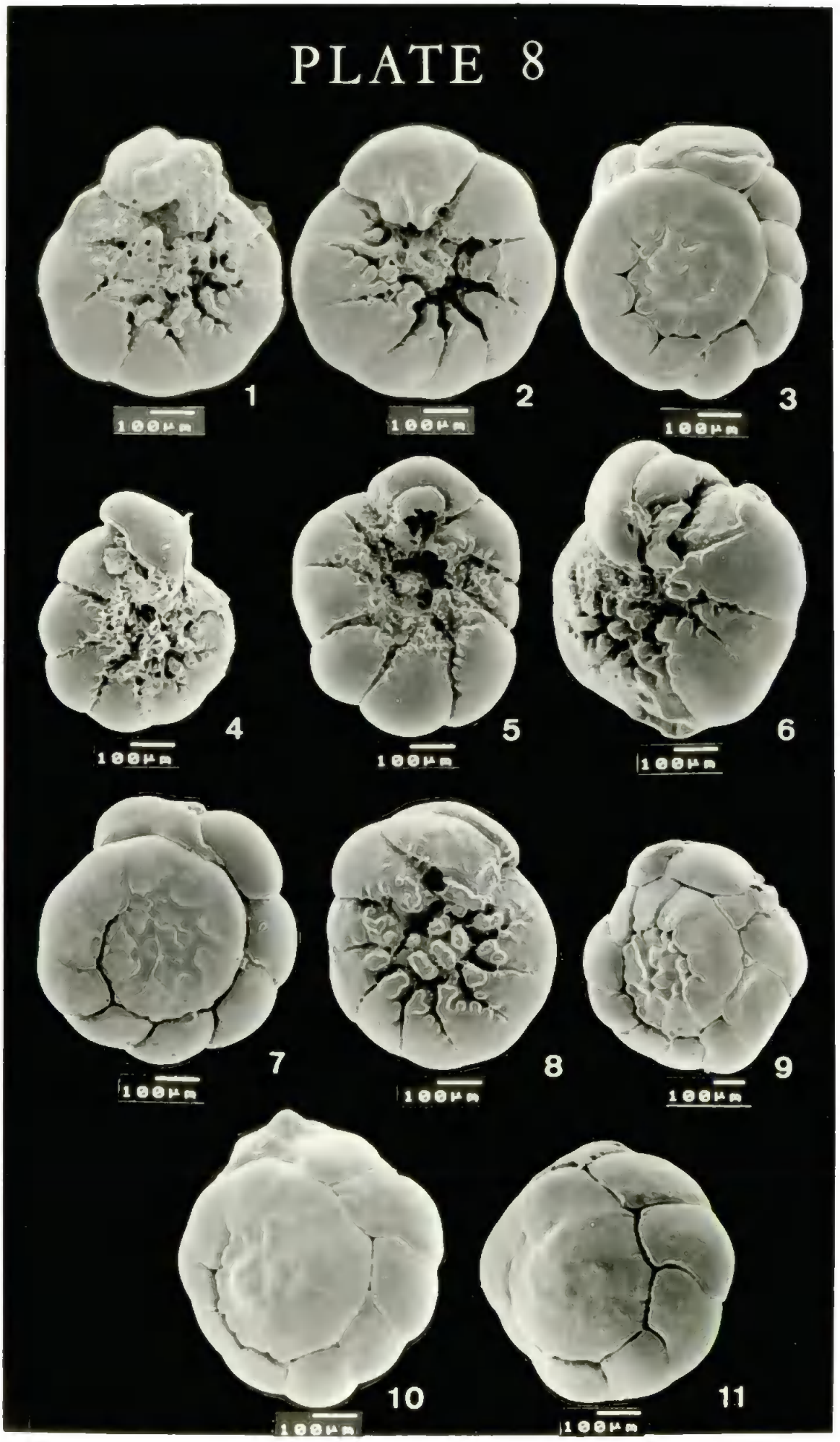
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PLATE 9.

Deformations of *Ammonia batavus* subjected to concentrations of zinc

Figure 1: 1.0 ppm; terminal chamber "buckled" and broken.

Figure 2: 1.0 ppm; terminal chamber "buckled", broken and under-inflated.

Figure 3: 1.0 ppm; terminal chamber under-inflated and additional chamberlet formed.

Figure 4: 10.0 ppm; terminal chamber slightly over-inflated.

Figure 5: 10.0 ppm; terminal chamber "buckled" and under-inflated.

Figure 6: 10.0 ppm; chamber preceding terminal chamber is under-inflated.

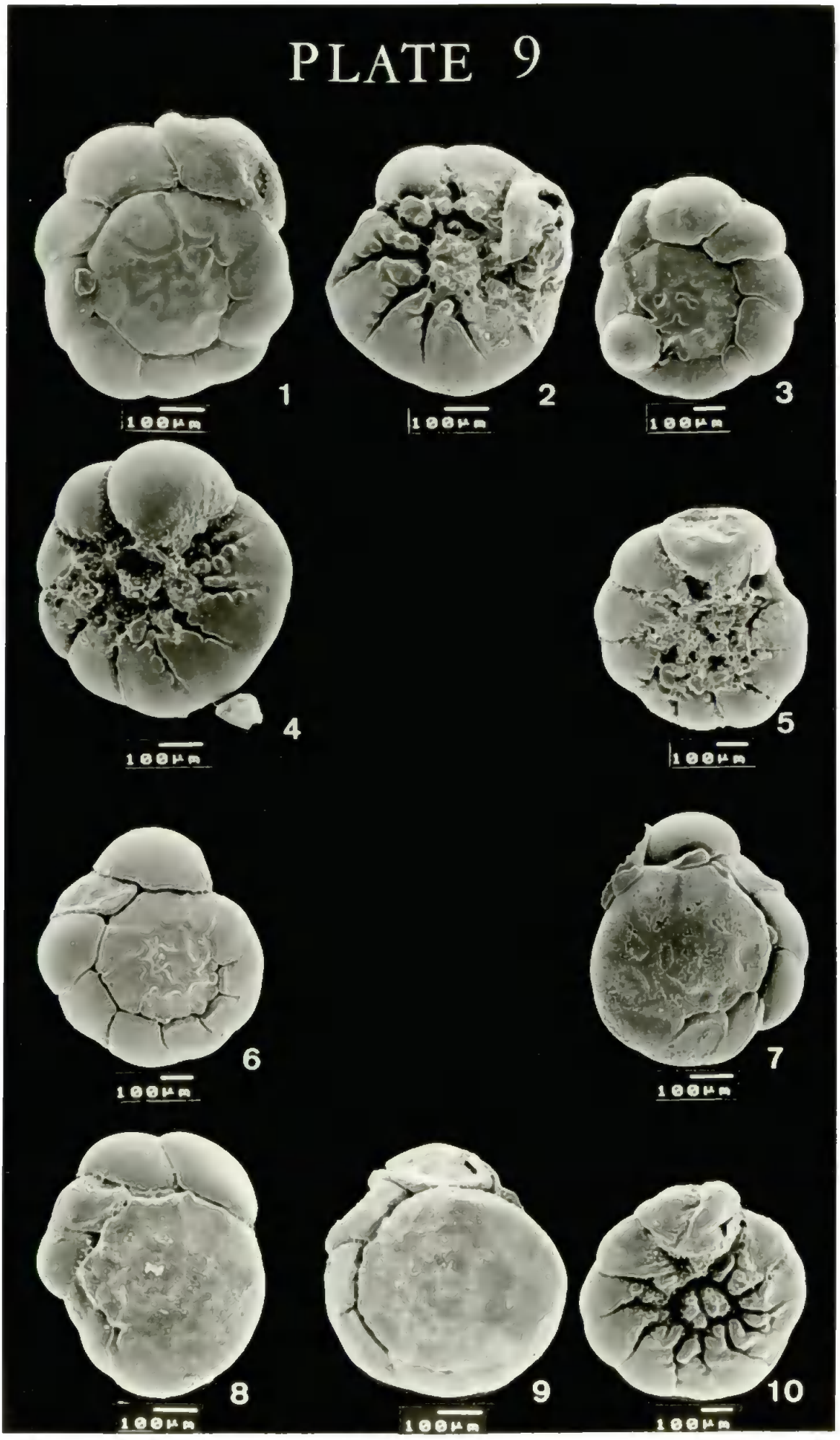
Figure 7: 10.0 ppm; terminal chamber broken-off and last three chambers formed are under-inflated.

Figure 8: 100.0 ppm; final four chambers are over-inflated.

Figure 9: 100.0 ppm; terminal chamber broken-off and preceding two chambers are "buckled" and broken.

Figure 10: 100.0 ppm; terminal chamber "buckled"

PLATE 9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10.4.4. DISCUSSION.

Ammonia batavus formed deformations of the test at all tested concentrations. The Control group also produced deformed chambers on two specimens, indicating that some aberrances of the test were caused by simply being under laboratory conditions. The relatively large number of aberrant tests produced by six specimens maintained at 0.1 ppm is probably due, at least in part, to the zinc contamination.

Additional zinc in the media at all concentrations appears to be detrimental to *Ammonia batavus*, producing aberrant specimens. The decline in number of deformed individuals at concentrations of additional zinc above 1.0 ppm probably reflects the detrimental affects of zinc upon the food and/or the direct death or inactivity of the Foraminiferida thus preventing them from forming any further chambers. The brittleness of terminal chambers may indicate that the calcification process was affected.

The type of deformation produced by the different concentrations of zinc were not concentration-specific, with common aberrances being produced by all concentrations produced. The production of additional chamberlets and twisting of the coiling of the tests are as resulted from Sharifi *et al.*'s experiments (1991) with copper, indicating that these deformations are not metal-specific.

10.5. SUMMARY.

The natural foraminiferid assemblages sampled have a very low abundance of deformed specimens from all three sites, despite having an abundance of the five heavy metals tested in the sediments. The levels of heavy metals at the three sites were not mirrored by the numbers of deformed specimens at the sites sampled. It therefore appears that the most common heavy metals in the environment do not cause foraminiferid deformations of the test.

Experiments upon *Rotaliella elatiana* reveal that any amount of additional cadmium or changes in salinity are detrimental to the health and fecundity of this species, although copper and zinc appear to be beneficial at low concentrations. Control groups produced no deformed specimens, and so the deformations produced were ascribable to the solutions tested. *Rotaliella elatiana* has shown that, for this species at least, Foraminiferida cannot be used as indicators of pollution, for deformation type could not be correlated to specific metals or salinity regimes. This is in agreement with the finding of Boltovskoy *et al.* (1991) who find that almost no variable acts independently upon test morphology.

Experiments upon *Ammonia batavus* with various regimes of zinc reveal that similar types of deformations occurred in the control groups and in the experimental groups, and the type of deformation bore no specific relationship to the concentration of metal used. When compared to the results of Sharifi *et al.* (1991), some of the deformation types exhibited when exposed to concentrations of zinc were produced by their experiments with copper.

The infilling of umbilici and sutures in *Rotaliella elatiana* and the brittleness of terminal chambers of *Ammonia batavus* indicate that the calcification process of experimental individuals was affected. The infilling of areas of the *Rotaliella elatiana* test open to the environment may reflect a protective mechanism of this species to unfavourable conditions in the external environment and the *Enteromorpha intestinalis* provides an abundance of calcium which the Foraminiferida can use. The brittleness of *Ammonia batavus* chambers reflects the inability of this species to form well-calcified chambers when under environmental stress. Although deformed agglutinated Foraminiferida have been recovered from samples by other authors (see Heron-Allen & Earland, 1930; Petrucci *et al.*, 1983), in the examination of samples from Plymouth Sound no agglutinated specimens were found to be deformed, further indicating that perhaps the calcification process is affected. The Golgi Body is the major organelle of secretion of calcite and is perhaps affected by environmental factors.

CHAPTER 11.

CONCLUSIONS.

The benefit of carrying out this varied study of Foraminiferida is that many conclusions can be drawn from the data. Culturing techniques, changes in assemblage composition of sampled sites, temporal changes in abiotic and biotic factors and their relative importance to the Foraminiferida were all studied. Also, the possible mechanisms of test deformation, and the mechanism by which *Elphidium crispum* remains epifaunal have all been investigated. The main conclusions are listed below.

(i) Only the living benthonic Foraminiferida were analysed from 36 sediment samples. These consisted of 85 species from 47 genera in 5 sub-orders.

(ii) The Murray Grab recovered the maximum numbers of live Foraminiferida by sampling the upper surface layer of sediment (without losing the fines), and so allowed absolute abundance to be calculated.

(iii) From core data, hyaline species were found living at depth (13 cm to 28 cm) within the sediment in the Withyhedge Beacon area in consecutive years, especially the species *Elphidium crispum*.

(iv) Absolute abundance of living Foraminiferida was generally highest at White Patch, dropping in Cawsand Bay, and lowest at Drake's Island. Although the Fisher measure of diversity and Margalef's richness of species were not very different between sites, the Shannon diversity and Pielou's evenness of species were.

(v) Analysis of test size revealed that Drake's Island sediments contained more 63-125 µm specimens, Cawsand Bay more 125-250 µm, and White Patch more 250-500 µm and 500-1000 µm tests, than the other two sites.

(vi) Cawsand Bay sediments were dominated by hyaline taxa, with an almost even distribution of quinqueloculine, trochospiral and planispiral forms, and corresponding distributions of specimens with arch, slit and pore apertures.

(vii) Drake's Island sediments were dominated by porcellaneous taxa, with a corresponding dominance of quinqueloculine forms and arch-apertured forms.

(viii) Trochospiral and planispiral taxa predominated in White Patch sediments, with corresponding distributions of arch- and pore-apertured specimens.

(ix) Foraminiferida from the three sampled sites were dominated by herbivorous taxa, followed by detritivorous taxa and then suspension-feeders.

(x) Multi-variate analysis of the assemblages reveals that, although the sampled sites contained similar foraminiferid assemblages in some months, the assemblages generally formed discrete groupings in terms of site.

(xi) Analysis of abiotic variables revealed that the sites do not greatly differ for temperature or salinity, although the substrata of the sites differ markedly. Cawsand Bay sediments consisted of fine, well-sorted, symmetrically-skewed sand. Drake's Island sediments consisted of medium, well-sorted, slightly negatively-skewed sand. White Patch sediments consisted of medium, poorly-sorted, negatively-skewed and polymodal sand.

(xii) Organic content of the sediments was highest at Drake's Island, followed by White Patch, and then Cawsand Bay.

(xiii) Neither the abundance of bacteria nor the number of colony forming units showed a great difference between sites, although the bacterial assemblages did differ for the shapes and types of bacteria present. Rod-shaped bacteria dominated all bacterial assemblages, but whereas Cawsand Bay and Drake's Island assemblages had a fairly even distribution of Gram positive and Gram negative bacteria, White Patch bacteria were predominantly Gram positive.

(xiv) Other meiofauna at the sites were generally more abundant in sediments from Drake's Island than at White Patch, with Cawsand Bay being poorest.

(xv) Seasonal diatom assemblages were very different between sites. White Patch assemblages had a more even distribution of shapes of diatoms than Cawsand Bay; and Drake's Island assemblages were dominated by elliptical and lanceolate forms.

(xvi) Correlations of Foraminiferida and abiotic variables reveal that temperature is important to the timing of reproduction of most groups, whilst salinity is not important. Mean phi size of the sediment is an important variable to groups at Cawsand Bay, and sorting and skewness of the sediment is important to some groups at Cawsand Bay and Drake's Island. Kurtosis of the sediment does not appear to affect Foraminiferida. The proportion of the sediment finer than 63 μm appears to be more important to Drake's Island Foraminiferida than to those at White Patch, and least so at Cawsand Bay.

(xvii) Correlations of Foraminiferida and biotic variables reveal that organic content at Drake's Island is linked to the reproduction of several groups. Although not many foraminiferid groups are correlated with abundance of bacteria or abundance of colony forming units, foraminiferid groups at Cawsand Bay appear to reproduce when the proportion of rod-shaped bacteria rises, and Foraminiferida at Drake's Island and White Patch appear to prefer the presence of Gram positive bacteria. Other meiofauna appear to reproduce at the same time as the Foraminiferida at the sites and do not appear to compete with them, with the exception of Acariformes. From multi-variate analysis it is clear that the diatom assemblages do not dictate the foraminiferal assemblages, although Textulariina are positively correlated with sigmoidal diatoms; Rotaliina with centric, panduriform and sigmoid diatoms; and Miliolina with lanceolate, semi-lanceolate and elliptical diatoms. Apertural shape of Foraminiferida is not correlated with shape of diatoms.

(xviii) Geotaxis and phototaxis experiments with *Elphidium crispum* have shown that both positive phototaxis and negative geotaxis are utilised by this species to remain epifaunal. A combination of both positive geotaxis and positive phototaxis may enable this species to avoid storms, by depending upon the turbidity of the water. A very strong phototaxic response was observed in large specimens in summer months, perhaps to facilitate reproduction. Whether geotaxis is positive or negative appears to be seasonally driven. It is possible that a photoreceptor is located on the dorsal side of this species.

(xix) In attempting to culture, or maintain Foraminiferida, in the laboratory, it is beneficial to avoid anti-biotics, and to use a recirculating system which is well-aerated.

(xx) The natural assemblages of Foraminiferida sampled at the three sites displayed only rare occurrences of deformed tests, which were not correlated with the abundance of five common heavy metals (analysed once a month for four months) and were not, therefore, likely to have been induced by these heavy metals. In toxicology experiments upon *Rotaliella elatiana*, both additional cadmium and concentrations of salinity other than that used to culture this species had detrimental effects upon health and fecundity of this species. Zinc and copper may have been beneficial at low additional concentrations. It was not possible to discriminate between the deformation of tests in response to the metals or to salinity or between metals. The lack of deformation specificity means that test deformation of Foraminiferida cannot be used as an indicator of any specific stressor. Toxicology studies upon *Ammonia batavus* show that similar test deformations

occurred in both control and experimental groups, and are common to deformation types observed by Sharifi *et al.* (1991) in response to copper concentrations.

As with most research, more questions are raised than answered. The occurrence of *Elphidium crispum* living between 13 cm and 28 cm depth in sediments at White Patch in two consecutive years needs further investigation, in order to attempt to find out what benefits, if any, are to gained for this normally epifaunal species from living at this depth. The correlations of Foraminiferida with biotic factors should be further investigated. Limiting monthly sampling to one site, and recording monthly the changes in diatom assemblage composition would clarify the relationships between Foraminiferida and diatoms, which appears to be an important variable for the sub-orders of Foraminiferida. As the vertical distribution of Foraminiferida is ecologically important, a year-long experiment upon *Elphidium crispum*, together with an infaunal species, investigating geotaxis and phototaxis should be undertaken. Ecotoxicology experiments, to complement those already carried out, should be undertaken with an agglutinated species to help understand the mechanism of test deformation.

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APPENDIX I: PHI SIZE DOWN THE CORES.

JUNE CORES, 1994.

	WB 1	WB 2	WB 5A	WB 5B	WB 5C	WB 10A	WB 10B	
MEAN	2.54	2.42	2.4	2.33	2.23	2.14	2.23	
MEDIAN	2.54	2.49	2.46	2.41	2.34	2.22	2.32	
	DI 1	DI 2	DI 5A	DI 5B	DI 5C	DI 10A	DI 10B	
MEAN	2.47	2.49	2.37	2.16	2.14	2.31	2.27	
MEDIAN	2.49	2.49	2.43	2.3	2.25	2.4	2.37	
	BP 1	BP 2	BP 5A	BP 5B	BP 5C	BP 10A		
MEAN	0.41	0.6	0.59	0.63	0.46	0.46		
MEDIAN	-0.28	-0.12	-0.2	-0.13	-0.27	-0.26		
	QG 1	QG 2	QG 5A	QG 5B	QG 5C			
MEAN	0.36	0.22	0.14	0.31	0.32			
MEDIAN	0.33	0.18	0.12	0.32	0.32			

APRIL CORES, 1995.

	WP 1	WP 2	WP 5A	WP 5B	WP 5C	WP 10A	WP 10B	
MEAN	2.31	2.11	1.74	2.19	2.1	1.85	1.94	
MEDIAN	2.43	2.27	2.08	2.34	2.24	1.78	1.93	
	BP 1	BP 2	BP 5A	BP 5B	BP 5C	BP 10A		
MEAN	2.08	2.42	2.52	2.36	2.42	2.32		
MEDIAN	2.42	2.64	2.64	2.5	2.62	2.46		
	MB 1	MB 2	MB 5A	MB 5B	MB 5C	MB 10A		
MEAN	1.75	1.61	1.18	1.72	1.63	1.58		
MEDIAN	2.31	2.16	1.25	2.23	2.15	2.1		
	BW 1	BW 2	BW 5A	BW 5B	BW 5C	BW 10A	BW 10B	BW 10C
MEAN	2.97	2.15	3	2.83	2.9	3.05	3.05	3.11
MEDIAN	3.13	2.43	3.17	3.04	3.11	3.2	3.18	3.25
	DI 1	DI 2	DI 5A	DI 5B	DI 5C	DI 10A		
MEAN	2.44	2.45	2.35	2.42	2.49	2.32		
MEDIAN	2.47	2.46	2.42	2.46	2.49	2.4		

APPENDIX I: LIVE SPECIES AT DEPTH; QUEEN'S GROUND, JUNE, 1994.

Queen's Ground: 300694	QG 1cm	QG 2cm	QG 5a	QG 5b	QG 5c		
AGGLUTINATED	Live	Live	Live	Live	Live		
Cribrostomoides jeffreysii	3	2	4	0	0		
Textularia truncata	12	9	1	1	0		
Trochammina rotaliformis	0	0	0	1	0		
	15	11	5	2	0		
PORCELLANEOUS							
Miliolina alberiana	0	1	0	0	0		
Miliolinella circularis	0	8	3	0	0		
Miliolinella subrotunda	5	6	0	0	0		
Quinqueloculina sp.	1	5	3	1	1		
Quinqueloculina oblonga	0	1	0	0	0		
Quinqueloculina seminulum	0	1	0	1	1		
Quinqueloculina cf. lata seminulum	3	2	0	0	0		
	9	24	6	2	2		
HYALINE							
Ammonia beccari batavus	1	0	0	0	0		
Asterigerinata mamilla	0	0	1	0	0		
Bolivina pseudolicata	0	1	0	0	0		
Brizalina pseudopunctata	0	0	0	1	0		
Bulimina gibba	0	0	1	0	0		
Cibicides pseudoungerianus	0	0	0	1	0		
Elphidium articulatum	0	0	1	0	0		
Elphidium gerthi	1	2	1	0	0		
Fissurina lucida	0	0	0	1	0		
Fissurina marginata	0	0	0	1	0		
Glabratella miletti	3	2	6	2	1		
Gravelinopsis praegeri	0	0	2	0	0		
Nonionella turgida	1	0	0	1	0		
Patellina corrugata	0	0	1	0	0		
Planorbulina mediterranensis	4	11	12	0	0		
	10	16	25	7	1		
Adjusted for volume							
Depth	**1 cm**	**3 cm**	**8 cm**	**13 cm**	**18 cm**	**Total**	**%**
Agglutinated	15	5.5	1	0.4	0	21.9	31.5
Porcellaneous	9	12	1.2	0.4	0.4	23	33.1
Hyaline	10	8	5	1.4	0.2	24.6	35.4
Total Number	34	25.5	7.2	2.2	0.6	69.5	100
%	48.92	36.69	10.36	3.17	0.86	100.00	

APPENDIX I: LIVE SPECIES AT DEPTH; BARN POOL, JUNE, 1994.

Barn Pool: 300694	BP 1cm	BP 2cm	BP 5a	BP 5b	BP 5c	BP 10a		
AGGLUTINATED								
Eggerelloides scaburum	2	4	2	0	0	0		
Psammosphaera bowmani	0	1	0	0	0	0		
Reophax scottii	6	1	0	0	0	0		
Textularia earlandi	1	0	0	0	0	0		
	9	6	2	0	0	0		
PORCELLANEOUS								
Quinqueloculina aspera 1	0	0	1	0	0	0		
Quinqueloculina seminulum	0	0	0	1	0	0		
	0	0	1	1	0	0		
HYALINE								
Ammonia beccari batavus	11	3	0	0	0	1		
Ammonia beccarii limnetes	0	1	0	0	0	0		
Bolivina pseudoplicata	1	0	0	0	0	0		
Brizalina pseudopunctata	4	0	0	0	0	0		
Bulimina elongata	1	0	0	0	0	0		
Fissurina lucida	0	0	0	0	1	0		
Fissurina marginata	1	0	0	0	0	0		
Fissurina orbignyana	0	0	0	0	0	1		
	18	4	0	0	1	2		
Adjusted for volume								
Depth	**1 cm**	**3 cm**	**8 cm**	**13 cm**	**18 cm**	**28 cm**	**Total**	**%**
Agglutinated	9	3	0.4	0	0	0	12.4	37.5
Porcellaneous	0	0	0.2	0.2	0	0	0.4	1.21
Hyaline	18	2	0	0	0.2	0.2	20.4	61.6
Total number	27	5	0.6	0.2	0.1	0.2	33.1	100
	54	10	1.2	0.4	0.3	0.4		

APPENDIX I: LIVE SPECIES AT DEPTH; WITHYHEDGE, JUNE, 1994.

Withyhedge: 300694	WB 1	WB 2	WB 5a	WB 5b	WB 5c	WB 10a	WB 10b		
AGGLUTINATED									
Clavulina obscura	1	0	0	0	0	0	0		
Eggerelloides scabrum	1	0	0	0	1	0	0		
Psammosphaera bowmani	0	0	0	1	0	0	0		
Textularia truncata	0	1	0	0	0	0	0		
Textularia earlandi	1	0	0	0	0	0	0		
	3	**1**	**0**	**1**	**1**	**0**	**0**		
PORCELLANEOUS									
Miliolina alberiana	3	0	0	0	0	0	0		
Miliolinella circularis	0	0	0	2	0	0	0		
Quinqueloculina lata	1	0	0	0	0	0	0		
Quinqueloculina oblonga	2	0	0	0	0	1	0		
	6	**0**	**0**	**2**	**0**	**1**	**0**		
HYALINE									
Ammonia beccari batavus	8	0	0	0	5	0	0		
Ammonia beccari limnetes	1	0	0	1	0	0	0		
Brizalina pseudopunctata	1	0	0	0	1	0	0		
Brizalina spathulata	2	0	0	0	3	0	0		
Bulimina elegantissima	0	0	0	0	3	0	0		
Globulina gibba	1	0	0	0	4	0	0		
Globulina marginata	2	0	0	0	0	0	0		
Elphidium articulatum	1	1	0	0	2	0	0		
Elphidium crispum	96	7	2	3	23	26	1		
Elphidium gerthi	1	0	0	0	1	0	0		
Fissurina lucida	0	0	0	1	0	0	0		
Fursenkoina fusiformis	0	0	0	0	1	0	0		
Lagena laevis	0	0	0	0	1	0	0		
Lagena semistriata	0	0	0	0	1	0	0		
Nonion depressulus	11	0	1	1	7	1	0		
	124	**8**	**3**	**6**	**52**	**27**	**1**		
Adjusted for volume									
Depth	**1 cm**	**3 cm**	**8 cm**	**13 cm**	**18 cm**	**28 cm**	**38 cm**	**Total**	**%**
Agglutinated	3	0.5	0	0.2	0.2	0	0	3.9	2.54
Porcellaneous	6	0	0	0.4	0	0.1	0.1	6.6	4.3
Hyaline	124	4	0.6	1.2	10.4	2.7	0.1	143	93.2
Total number	133	4.5	0.6	1.8	10.6	2.8	0.2	154	
	86.6	2.93	0.391	1.173	6.906	1.8241	0.1303	100	

APPENDIX I: LIVE SPECIES AT DEPTH; DRAKE'S ISLAND, JUNE, 1994.

Drake's Island: 300694	1cm	2cm	5a	5b	5c	10a	10b			
AGGLUTINATED										
Textularia truncata	2	0	0	0	0	0	0			
	2	0	0	0	0	0	0			
HYALINE										
Ammonia beccarii batavus	1	0	0	0	0	0	0			
Globulina gibba	0	1	0	0	0	0	0			
	1	1	0	0	0	0	0			
Adjusted for volume										
Depth	1cm	2cm	8cm	13cm	18cm	28cm	38cm	Total	%	
Agglutinated	2	0	0	0	0	0	0	2	50	
Porcellaneous	0	0	0	0	0	0	0	0	0	
Hyaline	1	1	0	0	0	0	0	2	50	
Total number	3	1	0	0	0	0	0	4	100	
Percentage	75	25	0	0	0	0	0			

APPENDIX I: LIVE SPECIES AT DEPTH; BREAKWATER, APRIL, 1995.

Breakwater: 060495	BW 1cm	BW 2cm	BW 5a	BW 5b	BW 5c	BW 10a		
PORCELLANEOUS								
Quinqueloculina cf. *lata seminulum*	0	0	1	0	0	0		
Spiroloculina excavata	0	0	1	0	0	0		
	0	0	2	0	0	0		
HYALINE								
Fissurina lucida	0	0	0	0	0	1		
Grigelis cf. *guttifera*	0	0	0	0	0	1		
	0	0	0	0	0	2		
Adjusted for volume								
Depth	1cm	2cm	8cm	13cm	18cm	28cm	Total	%
Agglutinated	0	0	0	0	0	0	0	0
Porcellaneous	0	0	0.4	0	0	0	0.4	66.67
Hyaline	0	0	0	0	0	0.2	0.2	33.33
Total number	0	0	0.4	0	0	0.2	0.6	
Percentage	0	0	66.66	0	0	33.33		

APPENDIX I: LIVE SPECIES AT DEPTH; MELAMPUS BEACON, APRIL, 1995.

Melampus Beacon: 060495	M1cm	M2cm	M5a	M5b	M5c	M10a		
AGGLUTINATED								
Eggerelloides scabrum	1	0	1	0	0	1		
	1	0	1	0	0	1		
PORCELLANEOUS								
Quinqueloculina sp.	0	0	0	0	1	0		
	0	0	0	0	1	0		
HYALINE								
Ammonia beccarii batavus	2	0	0	0	0	0		
Fissurina lucida	0	0	0	0	1	0		
Trifarina angulosa	0	0	0	0	1	0		
	2	0	0	0	2	0		
Adjusted for volume								
Melampus Beacon	1cm	3cm	8cm	13cm	18cm	28cm	Total	%
Agglutinated	1.00	0.00	0.13	0.00	0.00	0.04	1.16	34.9
Porcellaneous	0.00	0.00	0.00	0.00	0.06	0.00	0.06	1.67
Hyaline	2.00	0.00	0.00	0.00	0.11	0.00	2.11	63.4
Total	3.00	0.00	0.13	0.00	0.17	0.04	3.33	
Percentage	90.16	0.00	3.76	0.00	5.01	1.07		

APPENDIX I: LIVE SPECIES AT DEPTH; BARN POOL, APRIL, 1995.

Barn Pool: 060495	BP 1cm	BP 2cm	BP 5a	BP 5b	BP 5c	BP 10a		
AGGLUTINATED								
Psammosphaera bowmani	1	0	0	0	0	0		
PORCELLANEOUS								
Pyrgo sp.	0	0	0	0	0	1		
Quinqueloculina oblonga	4	0	0	1	0	0		
HYALINE								
Ammonia beccarii batavus	9	0	4	1	0	0		
Bolivina pseudoplicata	1	0	0	0	0	0		
Brizalina pseudopunctata	2	0	0	0	0	0		
Cyclogyra involvens	0	0	1	0	0	0		
Fissurina lucida	0	0	2	0	1	0		
Haynesina germanica	1	0	0	0	0	0		
Nonion depressulus	2	0	0	0	0	0		
Uvigerina sp.	2	0	0	0	0	0		
Adjusted for volume								
Depth	1 cm	3cm	8cm	13 cm	18cm	28cm	Total	%
Agglutinated	1	0	0	0	0	0	1	4.065
Porcellaneous	4	0	0	0.2	0	0.1	4.3	17.48
Hyaline	17	0	1.4	0.2	0.2	0	18.8	76.42
Total number	22	0.5	1.4	0.4	0.2	0.1	24.6	
Percentage	89.431	2.03252	5.691057	1.626	0.813008	0.407		

APPENDIX I: LIVE SPECIES AT DEPTH; DRAKE'S ISLAND, APRIL, 1995.

Drake's Island: 060495	DI 1cm	DI 2cm	DI 5a	DI 5b	DI 5c	DI 10a		
AGGLUTINATED	Live	Live	Live	Live	Live	Live		
Psammosphaera bowmani	2	2	4	2	0	2		
PORCELLANEOUS								
Miliolinella circularis	0	2	0	0	0	0		
Quinqueloculina oblonga	0	2	0	0	1	0		
Quinqueloculina seminulum	1	0	0	0	0	0		
HYALINE								
Ammonia beccarii batavus	4	0	0	1	0	0		
Globulina gibba	0	1	0	0	0	0		
Globulina marginata	0	1	0	0	0	0		
Cibicides lobatulus	1	0	0	0	0	0		
Elphidium margaritaceum	0	1	0	0	0	0		
Lagena substriata	0	0	0	1	0	0		
Nonion depressulus	0	1	0	0	0	0		
Rosalina globularis	0	1	0	0	0	0		
Stainforthia cf. *concava*	1	0	0	0	0	0		
Adjusted for volume								
Depth	1cm	3cm	8cm	13cm	18cm	28cm	Total	%
Agglutinated	2	1	0.8	0.4	0	0.2	4.4	26.7
Porcellaneous	1	2	0	0	0.2	0	3.2	19.4
Hyaline	6	2.5	0	0.4	0	0	8.9	53.9
Total number	9	5.5	0.8	0.8	0.2	0.2	16.5	100
Percentage	54.55	33.33	4.85	4.85	1.21	1.21		

APPENDIX I: LIVE SPECIES AT DEPTH; WITHYHEDGE, APRIL, 1995.

Withyhedge: 060495	WB1cm	WB 2cm	WB 5a	WB 5b	WB 5c	WB 10a	WB 10b		
AGGLUTINATED									
Eggerelloides scabrum	1	0	1	0	0	2	0		
Psammosphaera bowmani	1	0	0	0	0	0	0		
	2	0	1	0	0	2	0		
PORCELLANEOUS									
Miliolinella circularis	0	0	0	0	3	0	0		
Quinqueloculina aspera I	0	0	1	0	0	0	0		
Quinqueloculina oblonga	0	0	0	0	0	1	0		
	0	0	1	0	3	1	0		
HYALINE									
Ammonia beccarii batavus	1	0	13	1	8	44	3		
Asterigerinata mamilla	0	0	0	1	0	0	0		
Bolivina pseudoplicata	1	0	0	0	0	0	0		
Bulimina elegantissima	0	0	0	0	0	1	0		
Elphidium crispum	0	1	3	3	4	23	1		
Fissurina lucida	0	0	2	3	0	2	0		
Fissurina marginata	2	1	0	0	0	0	0		
Globulina gibba	0	0	2	0	0	0	0		
Lagena clavata	0	0	0	0	0	1	0		
Nonion depressulus	2	0	0	0	6	25	0		
Stainforthia cf. *concava*	1	0	0	0	0	0	0		
	7	2	20	8	18	96	4		
Adjusted for volume									
Depth	1 cm	3 cm	8 cm	13 cm	18 cm	28 cm	38 cm	Total	%
Agglutinated	2	0	0.2	0	0	0.2	0	2.4	7.868
Porcellaneous	0	0	0.2	0	0.6	0.1	0	0.9	2.950
Hyaline	7	1	4	1.6	3.6	9.6	0.4	27.2	89.18
Total number	9	1	4.4	1.6	4.2	9.9	0.4	30.5	100
	29.5082	3.2787	14.42	5.2459	13.77	32.459	1.3115		

APPENDIX I: LIVE *ELPHIDIUM CRISPUM* AT DEPTH; WITHYHEDGE, JUNE, 1994.

Withyhedge: 300694			
Size	1cm	5c	10a
150-300μm	1	3	0
301-450μm	3	1	1
451-600μm	11	1	3
601-750μm	39	7	12
751-900μm	27	8	9
901-1050μm	10	2	2
1051-1200μm	2	0	0
1201-1350μm	1	0	0

APPENDIX I: LIVE *ELPHIDIUM CRISPUM* AT DEPTH; WITHYHEDGE, APRIL, 1995.

Withyhedge: 060495	060495		
Size	1 cm	5c	10a
150-300μm	0	0	0
301-450μm	0	0	1
451-600μm	0	0	0
601-750μm	0	0	3
751-900μm	1	1	8
901-1050μm	1	2	4
1051-1200μm	1	1	7

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: August	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	40	24	0	0	0	64
E. scabrum	0	16	28	0	0	44
T. earlandi	0	8	0	0	0	8
C. involvens	20	48	8	0	0	76
Q. aspera	8	0	16	0	0	24
Q. cliarensis	0	12	0	0	0	12
Q. dimidiata	84	24	0	0	0	108
Q. lata	32	40	68	0	0	140
Q. oblonga	184	128	0	0	0	312
M. subrotunda	12	12	0	0	0	24
F. lucida	32	0	0	0	0	32
F. marginata	12	0	0	0	0	12
B. pseudoplicata	12	0	0	0	0	12
B. spathulata	4	0	0	0	0	4
B. variabilis	44	0	0	0	0	44
B. elongata	20	20	0	0	0	40
B. marginata	0	4	0	0	0	4
B. elegantissima	12	0	0	0	0	12
Uvigerina sp.	12	0	0	0	0	12
F. fusiformis	20	0	0	0	0	20
R. williamsoni	8	0	0	0	0	8
C. lobatulus	0	4	0	0	0	4
C. pseudoungerianus	4	0	0	0	0	4
H. germanica	88	72	0	0	0	160
N. depressulus	220	380	0	0	0	600
Nonionella sp.	0	12	0	0	0	12
A. batavus	104	432	224	0	0	760
E. crispum	108	68	56	60	0	292
E. gerthi	20	4	0	0	0	24
E. magellanicum	0	4	0	0	0	4
						2872

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: September	63-125 μm	125-250 μm	250-500 μm	500-1000 μm	>1000 μm	Total
R. scottii	12	0	0	0	0	12
A. pseudospiralis	4	0	0	0	0	4
C. obscura	4	0	0	0	0	4
P. corrugata	4	4	0	0	0	8
C. involvens	68	120	8	0	0	196
Adelosina sp. 1	12	0	0	0	0	12
Q. aspera	8	4	12	0	0	24
Q. dimidiata	80	0	0	0	0	80
Q. lata	12	28	56	0	0	96
Q. oblonga	128	140	0	0	0	268
Q. seminulum	0	0	12	0	0	12
M. subrotunda	12	4	0	0	0	16
L. orbiculatis	0	4	0	0	0	4
L. clavata	4	0	0	0	0	4
L. interrupta	0	4	0	0	0	4
O. squamosa	0	4	0	0	0	4
F. lucida	72	12	0	0	0	84
F. marginata	4	0	0	0	0	4
F. orbignyana	8	0	0	0	0	8
B. pseudoplicata	8	0	0	0	0	8
Bolivina sp.	12	0	0	0	0	12
B. spathulata	8	0	0	0	0	8
B. variabilis	52	0	0	0	0	52
S. concava var. *loeblichi*	4	0	0	0	0	4
B. elongata	108	44	0	0	0	152
B. marginata	4	0	0	0	0	4
B. elegantissima	36	0	0	0	0	36
F. fusiformis	24	0	0	0	0	24
R. williamsoni	44	0	0	0	0	44
C. lobatulus	0	4	0	4	0	8
C. pseudoungerianus	4	12	0	0	0	16
P. mediterranensis	0	4	4	0	0	8
H. germanica	136	32	0	0	0	168
N. depressulus	276	260	0	0	0	536
Nonionella sp.	4	8	0	0	0	12
A. batavus	292	264	260	0	0	816
E. crispum	0	76	80	68	0	224
E. gerthi	100	16	0	0	0	116
						3092

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: October	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
C. involvens	4	20	8	0	0	32
Adelosina sp. 1	0	12	0	0	0	12
Q. aspera	0	0	20	0	0	20
Q. aspera var. 1	0	8	0	0	0	8
Q. cliarensis	0	8	16	0	0	24
Q. dimidiata	8	24	0	0	0	32
Q. lata	16	28	36	0	0	80
Q. mediterranensis	0	0	0	4	0	4
Q. oblonga	80	768	0	0	0	848
Q. seminulum	0	0	4	4	0	8
L. clavata	4	0	0	0	0	4
O. melo	8	0	0	0	0	8
F. lucida	8	0	0	0	0	8
F. marginata	16	0	0	0	0	16
F. orbignyana	8	0	0	0	0	8
B. variabilis	8	0	0	0	0	8
B. elongata	16	0	0	0	0	16
F. fusiformis	48	0	0	0	0	48
N. depressulus	84	4	0	0	0	88
A. batavus	0	56	104	0	0	160
E. crispum	0	8	0	4	0	12
E. gerthi	8	8	0	0	0	16
						1460

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: November	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	2	0	0	0	0	2
E. scabrum	2	0	2	0	0	4
C. obscura	2	0	0	0	0	2
P. corrugata	2	0	0	0	0	2
C. involvens	2	4	0	0	0	6
Q. aspera	0	0	2	0	0	2
Q. lata	34	8	2	0	0	44
Q. oblonga	60	54	0	0	0	114
Q. seminulum	0	2	6	0	0	8
F. lucida	18	0	0	0	0	18
F. marginata	2	0	0	0	0	2
F. orbignyana	2	0	0	0	0	2
B. spathulata	10	0	0	0	0	10
B. variabilis	8	0	0	0	0	8
B. elongata	18	8	0	0	0	26
B. elegantissima	2	0	0	0	0	2
Uvigerina sp.	2	0	0	0	0	2
F. fusiformis	2	0	0	0	0	2
R. globularis	0	2	0	0	0	2
R. williamsoni	6	0	0	0	0	6
P. mediterranensis	0	4	0	0	0	4
H. germanica	4	6	0	0	0	10
N. depressulus	108	28	0	0	0	136
A. batavus	20	48	48	0	0	116
E. crispum	0	2	6	14	0	22
E. gerthi	0	2	0	0	0	2
E. macellum	0	2	0	0	0	2
E. margaritaceum	0	2	0	0	0	2
						558

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: December	63-125µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
E. scabrum	0	1	0	0	0	1
C. involvens	0	2	1	0	0	3
Q. aspera	0	0	1	0	0	1
Q. cliarensis	0	1	0	0	0	1
Q. dimidiata	2	1	0	0	0	3
Q. lata	4	1	4	17	0	26
Q. oblonga	13	31	0	0	0	44
Q. seminulum	0	1	0	0	0	1
M. circularis var. *elongata*	0	0	1	0	0	1
M. subrotunda	1	0	0	0	0	1
L. orbiculatis	0	0	1	0	0	1
L. clavata	0	1	0	0	0	1
F. lucida	2	0	0	0	0	2
B. variabilis	2	0	0	0	0	2
B. elongata	1	1	0	0	0	2
N. depressulus	7	0	0	0	0	7
A. batavus	0	5	26	0	0	31
E. crispum	0	0	1	2	0	3
E. gerthi	1	0	0	0	0	1
						132

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: January	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
H. bradyi	0	2	0	0	0	2
D. rotaliformis	4	0	0	0	0	4
E. scabrum	0	6	0	0	0	6
C. obscura	2	0	0	0	0	2
S. vivipara	2	0	0	0	0	2
C. involvens	0	2	0	0	0	2
Adelosina sp. 1	0	4	0	0	0	4
Q. aspera	0	4	6	0	0	10
Q. dimidiata	4	0	0	0	0	4
Q. lata	6	0	10	0	0	16
Q. oblonga	34	28	6	0	0	68
M. circularis var. *elongata*	2	2	0	0	0	4
M. subrotunda	0	0	4	0	0	4
L. perlucida	0	2	0	0	0	2
F. lucida	0	2	0	0	0	2
F. marginata	4	0	0	0	0	4
F. orbignyana	6	0	0	0	0	6
Fissurina sp. 1	2	0	0	0	0	2
Fissurina sp. 2	2	0	0	0	0	2
B. pseudoplicata	6	0	0	0	0	6
B. spathulata	8	2	0	0	0	10
B. variabilis	8	0	0	0	0	8
B. elongata	4	6	0	0	0	10
Uvigerina sp.	2	0	0	0	0	2
T. angulosa	8	0	0	0	0	8
F. fusiformis	12	0	0	0	0	12
R. globularis	0	2	0	0	0	2
C. lobatulus	0	0	2	0	0	2
C. pseudoungerianus	2	4	0	0	0	6
A. mamilla	0	2	0	0	0	2
N. depressulus	24	4	0	0	0	28
A. batavus	20	44	96	0	0	160
E. crispum	0	0	6	8	0	14
E. gerthi	2	0	0	0	0	2
						418

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: February	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	2	0	0	0	0	2
D. ochracea sinuosa	2	0	0	0	0	2
D. rotaliformis	2	0	0	0	0	2
E. scabrum	0	4	2	0	0	6
C. involvens	2	4	0	0	0	6
Q. aspera	0	0	2	0	0	2
Q. dimidiata	4	0	0	0	0	4
Q. lata	14	30	22	0	0	66
Q. mediterranensis	0	0	2	0	0	2
Q. oblonga	32	148	0	0	0	180
Q. seminulum	0	0	4	0	0	4
M. circularis var. *elongata*	0	2	0	0	0	2
M. subrotunda	2	0	0	0	0	2
L. orbiculatis	2	0	0	0	0	2
L. substriata	0	2	0	0	0	2
F. lucida	6	12	0	0	0	18
B. pseudoplicata	6	0	0	0	0	6
B. spathulata	6	10	0	0	0	16
B. variabilis	20	0	0	0	0	20
B. elongata	14	12	2	0	0	28
B. marginata	2	0	0	0	0	2
B. elegantissima	6	4	0	0	0	10
T. angulosa	2	2	0	0	0	4
F. fusiformis	18	22	0	0	0	40
G. praegeri	0	2	0	0	0	2
R. williamsoni	2	4	0	0	0	6
C. lobatulus	0	4	2	0	0	6
C. pseudoungerianus	0	4	0	0	0	4
N. depressulus	54	6	0	0	0	60
A. batavus	20	128	254	4	0	406
E. crispum	0	0	14	52	0	66
E. gerthi	2	2	0	0	0	4
E. macellum	0	2	0	0	0	2
						984

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: March	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
C. jeffreysii	0	4	0	0	0	4
D. rotaliformis	0	4	0	0	0	4
E. scabrum	0	32	20	0	0	52
C. obscura	4	0	0	0	0	4
S. vivipara	4	0	0	0	0	4
C. involvens	8	8	0	0	0	16
Adelosina sp. 1	4	0	0	0	0	4
Q. dimidiata	20	0	0	0	0	20
Q. lata	16	20	24	0	0	60
Q. oblonga	112	352	0	0	0	464
Q. seminulum	4	8	0	0	0	12
A. sp. cf. *A. scalaris*	4	0	0	0	0	4
F. lucida	16	0	0	0	0	16
F. marginata	8	0	0	0	0	8
F. orbignyana	4	0	0	0	0	4
B. pseudoplicata	16	4	0	0	0	20
B. spathulata	24	0	0	0	0	24
B. variabilis	32	0	0	0	0	32
S. concava var. *loeblichi*	0	0	4	0	0	4
B. elongata	24	8	0	0	0	32
Uvigerina sp.	4	0	0	0	0	4
F. fusiformis	24	0	0	0	0	24
R. williamsoni	12	0	0	0	0	12
C. lobatulus	0	4	0	0	0	4
N. depressulus	200	72	0	0	0	272
A. batavus	32	96	240	0	0	368
E. crispum	0	4	20	32	0	56
E. gerthi	12	0	0	0	0	12
						1540

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: April	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
H. bradyi	2	0	0	0	0	2
E. scabrum	0	2	0	0	0	2
C. involvens	2	0	0	0	0	2
Q. cliarensis	0	2	0	0	0	2
Q. dimidiata	18	0	0	0	0	18
Q. lata	2	4	2	2	0	10
Q. oblonga	46	38	0	0	0	84
Q. seminulum	0	0	4	0	0	4
F. lucida	2	0	0	0	0	2
Fissurina sp. 1	2	0	0	0	0	2
B. spathulata	2	0	0	0	0	2
B. variabilis	4	0	0	0	0	4
B. elongata	0	2	0	0	0	2
B. elegantissima	4	0	0	0	0	4
F. fusiformis	10	0	0	0	0	10
G. praegeri	6	0	0	0	0	6
R. williamsoni	2	0	0	0	0	2
N. depressulus	92	48	0	0	0	140
A. batavus	24	60	110	2	0	196
E. crispum	0	0	10	4	0	14
E. gerthi	4	2	0	0	0	6
						514

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: May	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
L. arenulata	0	0	1.33	0	0	1.33
H. bradyi	0	1.33	0	0	0	1.33
D. rotaliformis	1.33	0	0	0	0	1.33
E. scabrum	0	1.33	0	0	0	1.33
C. obscura	1.33	0	0	0	0	1.33
C. involvens	0	2.67	0	0	0	2.67
Q. aspera	0	0	5.33	0	0	5.33
Q. cliarensis	0	1.33	1.33	0	0	2.67
Q. dimidiata	6.67	1.33	0	0	0	8
Q. lata	9.33	14.67	1.33	0	0	25.33
Q. oblonga	8	20	0	0	0	28
Q. seminulum	0	4	1.33	0	0	5.33
M. circularis var. *elongata*	0	1.33	0	0	0	1.33
M. subrotunda	0	1.33	0	0	0	1.33
L. clavata	1.33	1.33	0	0	0	2.67
F. lucida	12	0	0	0	0	12
F. orbignyana	1.33	0	0	0	0	1.33
B. pseudoplicata	2.67	0	0	0	0	2.67
B. variabilis	10.67	1.33	0	0	0	12
S. concava var. *loeblichi*	0	1.33	0	0	0	1.33
B. elongata	8	13.33	0	0	0	21.33
B. elegantissima	1.33	0	0	0	0	1.33
Uvigerina sp.	1.33	0	0	0	0	1.33
T. angulosa	1.33	0	0	0	0	1.33
F. fusiformis	5.33	0	0	0	0	5.33
G. praegeri	1.33	0	0	0	0	1.33
R. williamsoni	4	2.67	0	0	0	6.67
C. lobatulus	0	1.33	2.67	0	0	4
C. pseudoungerianus	1.33	1.33	0	0	0	2.67
A. manilla	1.33	0	0	0	0	1.33
N. depressulus	46.67	80	0	0	0	126.67
A. batavus	9.33	42.67	29.33	2.67	0	84
E. crispum	0	8	4	0	0	12
E. gerthi	0	2.67	0	0	0	2.67
E. macellum	1.33	0	0	0	0	1.33
						392

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: June	63-125 μm	125-250 μm	250-500 μm	500-1000 μm	>1000 μm	Total
E. scabrum	0	0	1	0	0	1
C. diffusa	0	0	2	0	0	2
M. secans	0	0	0	1	0	1
Q. aspera	0	0	3	2	0	5
Q. cliarensis	1	0	0	0	0	1
Q. lata	7	16	0	0	0	23
Q. oblonga	1	8	0	0	0	9
Q. seminulum	0	1	2	0	0	3
M. circularis var. *elongata*	1	0	0	0	0	1
M. subrotunda	0	1	0	0	0	1
L. clavata	1	0	0	0	0	1
O. melo	1	0	0	0	0	1
F. lucida	2	0	0	0	0	2
B. spathulata	1	0	0	0	0	1
B. variabilis	1	0	0	0	0	1
B. elongata	3	1	0	0	0	4
B. elegantissima	2	0	0	0	0	2
Uvigerina sp.	2	0	0	0	0	2
F. fusiformis	1	0	0	0	0	1
G. praegeri	0	1	0	0	0	1
R. williamsoni	2	0	0	0	0	2
N. depressulus	2	3	0	0	0	5
A. batavus	3	14	14	0	0	31
E. crispum	0	17	18	0	0	35
						136

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Cawsand Bay: July	63-125 μm	125-250 μm	250-500 μm	500-1000μm	>1000 μm	Total
P. bowmani	0	1	0	0	0	1
H. bradyi	0	4	0	0	0	4
R. scottii	12	0	0	0	0	12
T. earlandi	2	7	0	0	0	9
C. obscura	6	0	0	0	0	6
C. diffusa	0	0	1	0	0	1
Q. aspera	0	1	1	1	0	3
Q. dimidiata	16	1	0	0	0	17
Q. lata	1	4	4	0	0	9
Q. oblonga	3	47	0	0	0	50
Q. seminulum	0	4	1	0	0	5
M. subrotunda	0	1	0	0	0	1
L. perlucida	0	1	0	0	0	1
O. laevigata	0	1	0	0	0	1
F. lucida	3	0	0	0	0	3
B. spathulata	2	0	0	0	0	2
B. variabilis	2	0	0	0	0	2
B. elongata	0	1	4	0	0	5
Uvigerina sp.	1	0	0	0	0	1
F. fusiformis	6	0	0	0	0	6
G. praegeri	1	1	0	0	0	2
C. lobatulus	0	0	1	0	0	1
C. pseudoungerianus	0	0	1	0	0	1
H. germanica	2	3	0	0	0	5
N. depressulus	15	38	0	0	0	53
Nonionella sp.	0	2	0	0	0	2
A. batavus	3	7	9	0	0	19
E. crispum	1	6	17	6	0	30
						252

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: August	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	2	0	0	0	2
R. scottii	2	0	0	0	0	2
S. wrightii	0	2	0	0	0	2
D. ochracea sinuosa	2	0	0	0	0	2
D. rotaliformis	2	0	0	0	0	2
E. scabrum	0	2	0	0	0	2
T. sagittula	4	2	12	0	0	18
S. vivipara	2	0	0	0	0	2
C. involvens	4	0	0	0	0	4
M. secans	0	0	0	0	2	2
Q. aspera	0	0	4	0	0	4
Q. dimidiata	44	0	0	0	0	44
Q. lata	136	4	0	0	0	140
Q. oblonga	2	4	0	0	0	6
Q. seminulum	4	0	16	4	0	24
M. circularis var. *elongata*	20	20	0	0	0	40
M. subrotunda	8	10	0	0	0	18
L. clavata	0	2	0	0	0	2
G. gibba	0	0	6	0	0	6
G. gibba var. *myristiformis*	0	0	2	0	0	2
F. lucida	4	0	0	0	0	4
F. marginata	2	0	0	0	0	2
F. orbignyana	2	0	0	0	0	2
B. pseudoplicata	2	0	0	0	0	2
B. spathulata	6	0	0	0	0	6
B. variabilis	44	0	0	0	0	44
S. concava var. *loeblichi*	0	2	0	0	0	2
B. elongata	12	0	0	0	0	12
B. marginata	2	0	0	0	0	2
B. elegantissima	8	0	0	0	0	8
Uvigerina sp.	2	0	0	0	0	2
F. fusiformis	2	0	0	0	0	2
G. praegeri	4	0	0	0	0	4
R. williamsoni	6	2	0	0	0	8
C. lobatulus	0	2	6	2	0	10
C. pseudoungerianus	2	0	0	0	0	2
P. mediterranensis	0	0	6	0	0	6
A. mamilla	4	0	2	0	0	6
H. germanica	6	8	0	0	0	14
N. depressulus	16	4	0	0	0	20
Nonionella sp.	0	0	2	0	0	2
A. batavus	4	18	4	0	0	26
E. crispum	0	6	6	0	0	12
E. gerthi	20	4	0	0	0	24
	378	94	66	6	2	546

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: September	63-125 µm	125-250 µm	250-500 µm	500 -1000µm	>1000 µm	Total
P. bowmani	0	6	0	0	0	6
H. bradyi	0	2	0	0	0	2
C. jeffreysii	0	0	2	0	0	2
D. rotaliformis	0	2	0	0	0	2
T. sagittula	8	4	8	0	0	20
S. vivipara	6	0	0	0	0	6
S. vivipara var. *runiana*	2	0	0	0	0	2
P. corrugata	4	0	0	0	0	4
C. involvens	2	0	0	0	0	2
Q. aspera	0	0	10	4	0	14
Q. cliarensis	0	2	0	0	0	2
Q. dimidiata	54	0	0	0	0	54
Q. lata	106	2	0	0	0	108
Q. oblonga	2	0	0	0	0	2
Q. seminulum	2	10	8	2	0	22
M. circularis var. *elongata*	18	2	0	0	0	20
M. subrotunda	12	6	0	0	0	18
G. gibba	0	0	2	2	0	4
F. marginata	0	4	0	0	0	4
F. orbignyana	4	0	0	0	0	4
B. pseudoplicata	2	0	0	0	0	2
B. variabilis	26	0	0	0	0	26
B. elongata	4	4	0	0	0	8
F. fusiformis	2	0	0	0	0	2
G. praegeri	4	2	0	0	0	6
R. anomala	4	0	0	0	0	4
R. globularis	0	2	0	0	0	2
R. williamsoni	4	0	0	0	0	4
C. lobatulus	0	0	6	4	0	10
C. pseudoungerianus	0	2	2	0	0	4
P. mediterranensis	0	2	0	0	0	2
A. mamilla	0	2	0	0	0	2
H. germanica	4	0	0	0	0	4
N. depressulus	8	6	0	0	0	14
A. batavus	2	4	6	0	0	12
E. crispum	6	8	20	2	0	36
E. gerthi	18	0	0	0	0	18
	304	72	64	14	0	454

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: October	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	3	0	0	0	3
T. teivyense	0	1	0	0	0	1
H. bradyi	0	1	0	0	0	1
D. ochracea sinuosa	3	0	0	0	0	3
T. sagittula	0	2	1	0	0	3
S. vivipara	1	0	0	0	0	1
S. vivipara var. *runiana*	1	0	0	0	0	1
C. involvens	0	1	0	0	0	1
Adelosina sp. 1	0	1	0	0	0	1
Q. aspera	0	0	3	3	0	6
Q. cliarensis	0	1	0	0	0	1
Q. dimidiata	17	0	0	0	0	17
Q. lata	64	7	0	0	0	71
Q. mediterranensis	0	0	1	0	0	1
Q. oblonga	3	4	0	0	0	7
Q. seminulum	0	3	3	0	0	6
M. circularis var. *elongata*	1	1	0	0	0	2
M. subrotunda	1	4	0	0	0	5
L. clavata	0	1	0	0	0	1
F. marginata	1	0	0	0	0	1
F. orbignyana	2	0	0	0	0	2
Fissurina sp. 1	1	0	0	0	0	1
B. spathulata	1	0	0	0	0	1
B. variabilis	11	0	0	0	0	11
B. elongata	1	1	0	0	0	2
B. marginata	1	0	0	0	0	1
B. elegantissima	5	0	0	0	0	5
T. angulosa	1	0	0	0	0	1
F. fusiformis	4	0	0	0	0	4
R. globularis	0	1	0	0	0	1
R. williamsoni	5	0	0	0	0	5
C. lobatulus	0	0	1	0	0	1
C. pseudoungerianus	1	0	0	0	0	1
H. germanica	6	2	0	0	0	8
N. depressulus	3	0	0	0	0	3
A. batavus	0	6	11	0	0	17
E. crispum	1	0	2	1	0	4
E. gerthi	7	0	0	0	0	7
	142	40	22	4	0	208

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: November	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	2	0	0	0	2
H. bradyi	0	2	0	0	0	2
D. ochracea sinuosa	2	0	0	0	0	2
S. vivipara	2	0	0	0	0	2
Adelosina sp. 1	0	2	0	0	0	2
Q. aspera	0	2	6	2	0	10
Q. cliarensis	0	4	2	0	0	6
Q. dimidiata	8	0	2	0	0	10
Q. lata	24	4	6	0	0	34
Q. mediterranensis	0	0	2	0	0	2
Q. oblonga	2	8	0	0	0	10
Q. seminulum	4	8	6	0	0	18
M. circularis var. *elongata*	2	6	0	0	0	8
M. subrotunda	6	0	6	0	0	12
F. marginata	2	0	0	0	0	2
B. pseudoplicata	2	0	0	0	0	2
B. variabilis	12	0	0	0	0	12
B. elongata	0	6	0	0	0	6
B. elegantissima	6	0	0	0	0	6
R. williamsoni	2	0	0	0	0	2
C. lobatulus	0	0	6	0	0	6
C. pseudoungerianus	0	4	0	0	0	4
P. mediterranensis	0	0	2	0	0	2
A. mamilla	0	2	0	0	0	2
H. germanica	2	2	0	0	0	4
N. depressulus	30	0	0	0	0	30
B. frigida	0	2	0	0	0	2
A. batavus	6	8	0	0	0	14
E. crispum	0	4	2	0	0	6
E. gerthi	2	0	0	0	0	2
	114	66	40	2	0	222

Drake's Island: December	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
T. sagittula	0	2	0	0	0	2
Q. dimidiata	1	0	0	0	0	1
Q. lata	1	0	0	0	0	1
Q. oblonga	2	0	0	0	0	2
Q. seminulum	0	0	1	0	0	1
M. circularis var. *elongata*	2	1	0	0	0	3
M. subrotunda	3	1	0	0	0	4
B. variabilis	3	0	0	0	0	3
C. lobatulus	0	0	1	0	0	1
A. batavus	0	0	2	0	0	2
E. crispum	0	0	1	0	0	1
E. gerthi	1	0	0	0	0	1
	13	4	5	0	0	22

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: January	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	8	0	0	0	8
H. bradyi	0	6	0	0	0	6
D. rotaliformis	3	0	0	0	0	3
E. scabrum	0	3	0	0	0	3
Adelosina sp. 1	0	1	0	0	0	1
Q. aspera	0	1	0	0	0	1
Q. cliarensis	0	2	0	0	0	2
Q. dimidiata	3	0	0	0	0	3
Q. lata	14	4	0	0	0	18
Q. oblonga	3	3	0	0	0	6
Q. seminulum	4	0	0	0	0	4
M. circularis var. *elongata*	5	1	0	0	0	6
M. subrotunda	7	0	0	0	0	7
G. gibba	0	0	0	1	0	1
B. variabilis	12	0	0	0	0	12
S. concava var. *loeblichi*	0	0	1	0	0	1
B. elongata	5	4	0	0	0	9
B. elegantissima	3	0	0	0	0	3
F. fusiformis	1	0	0	0	0	1
R. williamsoni	3	0	0	0	0	3
C. lobatulus	0	1	4	0	0	5
C. pseudoungerianus	0	2	0	0	0	2
H. germanica	0	2	0	0	0	2
N. depressulus	17	2	0	0	0	19
A. batavus	1	14	3	0	0	18
E. gerthi	5	0	0	0	0	5
	86	54	8	1	0	149

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: February	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	2	0	0	0	2
H. bradyi	0	1	0	0	0	1
E. scabrum	0	1	0	0	0	1
T. sagittula	0	2	0	0	0	2
Q. aspera	0	0	2	0	0	2
Q. cliarensis	0	1	1	0	0	2
Q. dimidiata	2	0	0	0	0	2
Q. lata	5	0	0	0	0	5
Q. oblonga	1	1	0	0	0	2
Q. seminulum	0	1	3	0	0	4
M. circularis var. *elongata*	2	0	0	0	0	2
M. subrotunda	1	0	0	0	0	1
G. gibba	0	0	1	0	0	1
B. variabilis	1	0	0	0	0	1
B. elongata	1	1	0	0	0	2
C. lobatulus	0	0	4	0	0	4
C. pseudoungerianus	0	1	0	0	0	1
H. germanica	1	0	0	0	0	1
N. depressulus	9	0	0	0	0	9
A. batavus	0	5	3	0	0	8
E. gerthi	1	2	0	0	0	3
	24	18	14	0	0	56

Drake's Island: March	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	1	0	0	0	1
T. earlandi	2	0	0	0	0	2
S. vivipara	0	1	0	0	0	1
C. involvens	1	0	0	0	0	1
M. secans	0	0	0	1	0	1
Q. aspera	0	0	4	0	0	4
Q. cliarensis	0	1	0	0	0	1
Q. dimidiata	1	0	0	0	0	1
Q. lata	29	1	1	0	0	31
Q. seminulum	3	0	1	0	0	4
M. subrotunda	3	0	0	0	0	3
G. gibba	0	0	1	0	0	1
B. spathulata	1	0	0	0	0	1
B. variabilis	3	0	0	0	0	3
B. elongata	1	0	0	0	0	1
B. elegantissima	2	0	0	0	0	2
C. lobatulus	0	0	5	0	0	5
C. pseudoungerianus	0	0	2	0	0	2
H. germanica	0	0	1	0	0	1
N. depressulus	19	0	0	0	0	19
A. batavus	1	1	3	0	0	5
E. gerthi	3	0	0	0	0	3
	69	5	18	1	0	93

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: April	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	1	0	0	0	0	1
Q. aspera	0	0	0	1	0	1
Q. lata	7	1	0	0	0	8
Q. seminulum	1	0	0	0	0	1
M. circularis var. *elongata*	1	0	0	0	0	1
C. lobatulus	0	0	1	0	0	1
A. mamilla	0	0	1	0	0	1
N. depressulus	3	0	0	0	0	3
B. frigida	1	0	0	0	0	1
	14	1	2	1	0	18

Drake's Island: May	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	6	0	0	0	6
H. bradyi	4	10	0	0	0	14
D. ochracea sinuosa	1	0	0	0	0	1
E. scabrum	0	12	1	0	0	13
C. obscura	2	0	0	0	0	2
Adelosina sp. 1	0	1	0	0	0	1
Q. aspera	0	1	2	0	0	3
Q. aspera var. 1	0	2	0	0	0	2
Q. cliarensis	0	2	0	0	0	2
Q. dimidiata	3	0	0	0	0	3
Q. lata	21	17	0	0	0	38
Q. oblonga	0	4	0	0	0	4
Q. seminulum	0	4	0	0	0	4
M. circularis var. *elongata*	2	1	0	0	0	3
M. subrotunda	1	2	1	0	0	4
P. depressa	0	1	1	0	0	2
O. melo	0	1	0	0	0	1
F. orbignyana	0	1	0	0	0	1
Fissurina sp. 1	1	0	0	0	0	1
B. pseudoplicata	1	0	0	0	0	1
B. variabilis	6	0	0	0	0	6
S. concava var. *loeblichi*	1	0	0	0	0	1
B. elongata	5	5	0	0	0	10
B. marginata	1	0	0	0	0	1
B. elegantissima	4	0	0	0	0	4
F. fusiformis	1	0	0	0	0	1
R. anomala	0	1	0	0	0	1
R. williamsoni	2	0	0	0	0	2
C. lobatulus	0	3	4	0	0	7
P. mediterranensis	0	1	0	0	0	1
A. mamilla	0	1	0	0	0	1
H. germanica	4	11	0	0	0	15
N. depressulus	37	5	0	0	0	42
B. frigida	1	1	0	0	0	2
A. batavus	0	3	1	0	0	4
E. gerthi	9	3	0	0	0	12
	107	99	10	0	0	216

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

Drake's Island: June	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	3	0	0	0	3
S. wrightii	0	0	1	0	0	1
M. secans	0	0	0	1	0	1
Q. aspera	0	1	0	1	0	2
Q. cliarensis	2	0	0	0	0	2
Q. dimidiata	6	1	0	0	0	7
Q. lata	24	4	0	0	0	28
Q. oblonga	2	9	0	0	0	11
Q. seminulum	1	2	2	0	0	5
M. circularis var. *elongata*	2	9	0	0	0	11
M. subrotunda	3	3	1	0	0	7
B. variabilis	1	0	0	0	0	1
B. elongata	0	1	0	0	0	1
R. williamsoni	1	0	0	0	0	1
C. lobatulus	0	0	1	0	0	1
P. mediterranensis	0	0	1	0	0	1
N. depressulus	9	5	0	0	0	14
A. batavus	0	2	0	0	0	2
E. crispum	0	0	0	2	0	2
E. gerthi	0	1	0	0	0	1
	51	41	6	4	0	102

Drake's Island: July	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	4	0	0	0	4
H. bradyi	3	6	0	0	0	9
Q. cliarensis	0	1	0	0	0	1
Q. dimidiata	16	1	0	0	0	17
Q. lata	17	0	0	0	0	17
Q. oblonga	1	21	0	0	0	22
Q. seminulum	2	1	0	0	0	3
M. circularis var. *elongata*	2	1	2	0	0	5
M. subrotunda	0	1	3	0	0	4
P. depressa	0	0	2	0	0	2
G. gibba	0	0	1	0	0	1
B. spathulata	2	0	0	0	0	2
B. variabilis	6	0	0	0	0	6
B. elongata	1	0	0	0	0	1
B. elegantissima	7	0	0	0	0	7
F. fusiformis	3	0	0	0	0	3
G. praegeri	0	1	0	0	0	1
C. lobatulus	0	3	2	0	0	5
P. mediterranensis	0	0	1	0	0	1
H. germanica	7	7	0	0	0	14
N. depressulus	17	5	0	0	0	22
A. batavus	1	1	0	0	0	2
E. crispum	0	1	0	0	0	1
E. gerthi	4	3	0	0	0	7
	89	57	11	0	0	157

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: August	63-125 µm	125-250 µm	250-500µm	500-1000 µm	>1000 µm	Total
D. ochracea sinuosa	4	0	0	0	0	4
E. scabrum	0	20	0	0	0	20
T. earlandi	12	4	0	0	0	16
T. sagittula	4	16	56	4	0	80
C. involvens	36	28	0	0	0	64
Adelosina sp. 1	8	20	0	0	0	28
Q. aspera	4	4	4	0	0	12
Q. cliarensis	4	8	4	0	0	16
Q. dimidiata	340	20	0	0	0	360
Q. lata	108	0	16	0	0	124
Q. mediterranensis	0	0	4	4	0	8
Q. oblonga	180	112	0	0	0	292
Q. seminulum	4	36	0	0	0	40
M. circularis var. *elongata*	8	12	0	0	0	20
M. subrotunda	80	56	0	0	0	136
L. orbiculatis	8	4	0	0	0	12
L. clavata	48	0	0	0	0	48
L. perlucida	4	0	0	0	0	4
F. lucida	20	8	0	0	0	28
F. orbignyana	12	0	0	0	0	12
Fissurina sp. 2	0	8	0	0	0	8
B. pseudoplicata	56	4	0	0	0	60
B. striatula	4	0	0	0	0	4
B. pseudopunctata	8	0	0	0	0	8
B. spathulata	64	0	0	0	0	64
B. variabilis	144	4	0	0	0	148
B. elongata	108	64	0	0	0	172
B. marginata	28	0	0	0	0	28
B. elegantissima	56	0	0	0	0	56
Uvigerina sp.	72	0	0	0	0	72
F. fusiformis	96	0	0	0	0	96
G. praegeri	12	0	0	0	0	12
R. globularis	0	4	0	0	0	4
R. williamsoni	16	0	0	0	0	16
H. germanica	4	0	0	0	0	4
N. depressulus	64	64	0	0	0	128
N. turgida	4	0	0	0	0	4
Nonionella sp.	20	4	0	0	0	24
A. batavus	180	224	324	0	0	728
E. crispum	4	48	372	380	0	804
E. gerthi	92	68	0	0	0	160
						3924

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: September	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	4	0	0	0	0	4
C. jeffreysii	4	0	0	0	0	4
A. pseudospiralis	0	0	16	4	0	20
S. wrightii	0	0	4	0	0	4
D. ochracea sinuosa	4	0	0	0	0	4
D. rotaliformis	8	0	0	0	0	8
E. scabrum	0	24	0	0	0	24
T. earlandi	12	0	0	0	0	12
T. sagittula	8	0	8	0	0	16
C. obscura	8	0	0	0	0	8
C. involvens	40	4	0	0	0	44
C. diffusa	0	0	8	0	0	8
Adelosina sp. 1	32	16	0	0	0	48
Adelosina sp. 2	0	4	0	0	0	4
Q. aspera	4	12	4	4	0	24
Q. cliarensis	0	12	8	4	0	24
Q. cf. cliarensis	0	32	0	0	0	32
Q. dimidiata	116	16	0	0	0	132
Q. lata	48	8	0	0	0	56
Q. oblonga	200	276	4	0	0	480
Q. seminulum	40	24	12	0	0	76
M. circularis var. *elongata*	20	8	0	0	0	28
M. subrotunda	76	40	0	0	0	116
L. orbiculatis	8	0	0	0	0	8
A. sp. cf. *A. scalaris*	4	0	0	0	0	4
L. clavata	28	0	0	0	0	28
L. perlucida	16	0	0	0	0	16
F. lucida	40	12	0	0	0	52
F. marginata	48	8	0	0	0	56
F. orbignyana	4	0	0	0	0	4
Fissurina sp. 2	0	4	0	0	0	4
B. striatula	4	0	0	0	0	4
B. spathulata	172	4	0	0	0	176
B. variabilis	248	0	0	0	0	248
S. concava var. *loeblichi*	20	8	0	0	0	28
B. elongata	188	36	0	0	0	224
B. marginata	28	0	0	0	0	28
B. elegantissima	48	0	0	0	0	48
Uvigerina sp.	24	0	0	0	0	24
F. fusiformis	280	0	0	0	0	280
G. praegeri	16	0	0	0	0	16
R. globularis	0	4	0	0	0	4
R. williamsoni	52	0	0	0	0	52
C. lobatulus	0	8	0	0	0	8
C. pseudoungerianus	4	0	0	0	0	4
N. depressulus	100	116	0	0	0	216
N. turgida	4	0	0	0	0	4
Nonionella sp.	12	0	0	0	0	12
A. batavus	256	364	644	0	0	1264

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: September	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
E. crispum	12	8	104	348	0	472
E. gerthi	112	4	0	0	0	116
E. margaritaceum	4	0	0	0	0	4
						4580

White Patch: October	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
D. ochracea sinuosa	4	0	0	0	0	4
D. rotaliformis	4	0	0	0	0	4
T. sagittula	0	0	4	0	0	4
C. involvens	4	0	0	0	0	4
C. diffusa	0	4	0	0	0	4
M. secans	0	0	4	0	0	4
Q. aspera	0	0	4	0	0	4
Q. cliarensis	4	8	8	0	0	20
Q. dimidiata	24	0	0	0	0	24
Q. lata	0	0	36	0	0	36
Q. oblonga	32	68	0	0	0	100
Q. seminulum	0	4	8	0	0	12
M. circularis var. *elongata*	4	0	0	0	0	4
M. subrotunda	4	0	8	0	0	12
P. depressa	0	0	4	0	0	4
L. clavata	12	0	0	0	0	12
O. squamosa	4	0	0	0	0	4
F. lucida	20	12	0	0	0	32
F. marginata	8	0	0	0	0	8
F. orbignyana	4	4	0	0	0	8
B. variabilis	28	0	0	0	0	28
B. elongata	20	8	0	0	0	28
F. fusiformis	64	0	0	0	0	64
G. praegeri	4	0	0	0	0	4
R. williamsoni	4	0	0	0	0	4
C. pseudoungerianus	4	4	0	0	0	8
P. mediterranensis	0	4	0	0	0	4
N. depressulus	4	12	0	0	0	16
Nonionella sp.	0	4	0	0	0	4
A. batavus	56	228	236	0	0	520
E. crispum	0	8	8	0	0	16
E. gerthi	12	0	0	0	0	12
						1012

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: November	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
R. scottii	4	0	0	0	0	4
D. ochracea sinuosa	4	0	0	0	0	4
E. scabrum	0	4	0	0	0	4
T. sagittula	0	0	12	0	0	12
C. involvens	16	8	0	0	0	24
Adelosina sp. 1	8	0	0	0	0	8
Adelosina sp. 2	0	0	4	0	0	4
Q. aspera	0	0	12	0	0	12
Q. cliarensis	8	12	12	0	0	32
Q. cf. *cliarensis*	0	12	8	0	0	20
Q. dimidiata	40	8	0	0	0	48
Q. lata	40	8	12	0	0	60
Q. mediterranensis	0	0	4	0	0	4
Q. oblonga	48	76	4	0	0	128
Q. seminulum	8	0	28	0	0	36
M. circularis var. *elongata*	0	0	4	0	0	4
M. subrotunda	20	0	4	0	0	24
L. orbiculatis	8	0	0	0	0	8
A. sp. cf. *A. scalaris*	4	0	0	0	0	4
L. gracilis	4	0	0	0	0	4
L. sulcata	4	0	0	0	0	4
G. gibba	4	4	0	0	0	8
F. lucida	8	24	0	0	0	32
F. marginata	4	0	0	0	0	4
F. orbignyana	8	0	0	0	0	8
B. pseudoplicata	4	0	0	0	0	4
B. pseudopunctata	4	0	0	0	0	4
B. spathulata	64	4	0	0	0	68
B. variabilis	168	0	0	0	0	168
S. concava var. *loeblichi*	8	4	4	0	0	16
B. elongata	40	12	0	0	0	52
B. marginata	0	12	0	0	0	12
T. angulosa	8	0	0	0	0	8
F. fusiformis	20	0	0	0	0	20
R. williamsoni	8	0	0	0	0	8
C. lobatulus	0	0	4	0	0	4
N. depressulus	20	0	0	0	0	20
Nonionella sp.	8	0	0	0	0	8
A. batavus	88	176	396	0	0	660
E. crispum	0	0	0	92	0	92
						1644

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: December	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
C. involvens	12	24	2	0	0	38
Adelosina sp. 1	2	6	0	0	0	8
Q. cliarensis	0	4	0	0	0	4
Q. cf. *cliarensis*	0	0	2	0	0	2
Q. dimidiata	12	8	0	0	0	20
Q. lata	26	2	0	0	0	28
Q. oblonga	48	60	0	0	0	108
Q. seminulum	0	2	4	0	0	6
M. subrotunda	4	2	0	0	0	6
L. orbiculatis	4	0	0	0	0	4
A. sp. cf. *A. scalaris*	2	0	0	0	0	2
F. lucida	10	2	0	0	0	12
B. pseudoplicata	4	0	0	0	0	4
B. pseudopunctata	2	0	0	0	0	2
B. spathulata	26	0	0	0	0	26
B. variabilis	54	0	0	0	0	54
S. concava var. *loeblichi*	0	4	0	0	0	4
B. elongata	10	0	0	0	0	10
B. marginata	2	0	0	0	0	2
B. elegantissima	8	0	0	0	0	8
T. angulosa	2	4	0	0	0	6
F. fusiformis	14	0	0	0	0	14
R. williamsoni	2	0	0	0	0	2
A. mamilla	0	2	0	0	0	2
N. depressulus	0	4	0	0	0	4
Nonionella sp.	6	0	0	0	0	6
A. batavus	16	28	138	4	0	186
E. crispum	0	0	6	24	0	30
E. gerthi	4	0	0	0	0	4
						602

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: January	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	12	0	0	0	12
R. scottii	12	0	0	0	0	12
A. pseudospiralis	0	0	4	0	0	4
E. scabrum	0	4	0	0	0	4
T. sagittula	0	8	4	0	0	12
C. involvens	0	8	0	0	0	8
C. diffusa	0	4	4	0	0	8
Adelosina sp. 1	4	8	0	0	0	12
Q. aspera	0	8	16	0	0	24
Q. cliarensis	12	12	0	0	0	24
Q. cf. *cliarensis*	0	0	8	4	0	12
Q. dimidiata	4	32	0	0	0	36
Q. lata	4	4	16	0	0	24
Q. oblonga	40	104	0	0	0	144
Q. seminulum	4	0	0	8	0	12
M. circularis var. *elongata*	0	8	0	0	0	8
M. subrotunda	0	4	0	0	0	4
L. clavata	8	0	0	0	0	8
G. gibba	0	4	0	0	0	4
F. lucida	4	16	0	0	0	20
B. spathulata	56	0	0	0	0	56
B. variabilis	72	0	0	0	0	72
S. concava var. *loeblichi*	0	8	0	0	0	8
B. elongata	20	4	0	0	0	24
B. elegantissima	4	0	0	0	0	4
T. angulosa	0	4	0	0	0	4
F. fusiformis	16	0	0	0	0	16
C. lobatulus	0	0	0	4	0	4
Nonionella sp.	4	0	0	0	0	4
A. batavus	32	220	608	28	0	888
E. crispum	0	0	0	364	0	364
						1836

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: February	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
A. pseudospiralis	0	4	12	4	0	20
S. wrightii	0	0	4	0	0	4
E. scabrum	0	120	56	0	0	176
T. earlandi	0	8	0	0	0	8
T. sagittula	0	12	16	0	0	28
C. involvens	8	16	0	0	0	24
Adelosina sp. 1	0	4	0	0	0	4
Adelosina sp. 2	0	4	0	0	0	4
Q. aspera	0	0	16	0	0	16
Q. cliarensis	4	20	0	0	0	24
Q. cf. *cliarensis*	0	0	4	0	0	4
Q. lata	12	128	36	0	0	176
Q. oblonga	20	0	0	0	0	20
Q. seminulum	0	24	4	0	0	28
M. circularis var. *elongata*	4	0	0	0	0	4
M. subrotunda	12	0	0	0	0	12
L. orbiculatis	4	4	0	0	0	8
A. sp. cf. *A. scalaris*	0	4	0	0	0	4
G. gibba	0	20	0	0	0	20
F. lucida	4	44	0	0	0	48
B. pseudopunctata	0	8	0	0	0	8
B. spathulata	8	24	0	0	0	32
B. variabilis	24	36	0	0	0	60
S. concava var. *loeblichi*	0	12	0	0	0	12
B. elongata	12	24	0	0	0	36
B. marginata	0	4	0	0	0	4
T. angulosa	0	16	0	0	0	16
R. williamsoni	8	0	0	0	0	8
C. lobatulus	0	4	16	0	0	20
P. mediterranensis	0	0	4	0	0	4
H. germanica	0	8	0	0	0	8
N. depressulus	4	0	0	0	0	4
Nonionella sp.	4	0	0	0	0	4
A. batavus	8	312	868	32	0	1220
E. crispum	0	0	28	488	4	520
E. gerthi	4	8	0	0	0	12
						2600

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: March	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
A. pseudospiralis	0	2	0	0	0	2
E. scabrum	0	28	20	0	0	48
C. obscura	2	0	0	0	0	2
S. vivipara	8	0	0	0	0	8
M. secans	0	0	0	0	4	4
Q. aspera	0	0	14	4	0	18
Q. bicornis	0	0	0	2	0	2
Q. cliarensis	0	6	2	0	0	8
Q. dimidiata	10	0	0	0	0	10
Q. lata	4	0	0	2	0	6
Q. oblonga	12	6	2	0	0	20
Q. seminulum	0	6	12	0	0	18
M. subrotunda	4	6	2	0	0	12
L. interrupta	0	2	0	0	0	2
F. lucida	16	2	0	0	0	18
Fissurina sp. 2	0	2	0	0	0	2
B. pseudopunctata	8	0	0	0	0	8
B. spathulata	6	2	0	0	0	8
B. variabilis	8	0	0	0	0	8
S. concava var. *loeblichi*	2	2	2	0	0	6
B. elongata	6	10	0	0	0	16
F. fusiformis	8	0	0	0	0	8
G. praegeri	2	2	0	0	0	4
R. globularis	0	2	0	0	0	2
R. williamsoni	2	2	0	0	0	4
C. lobatulus	0	0	4	0	0	4
A. mamilla	2	0	0	0	0	2
N. depressulus	4	6	0	0	0	10
Nonionella sp.	0	2	0	0	0	2
A. batavus	10	72	308	20	0	410
E. crispum	0	6	4	188	0	198
						870

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: April	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
C. involvens	0	1	0	0	0	1
Q. aspera	1	0	2	1	0	4
Q. cliarensis	0	0	1	0	0	1
Q. dimidiata	6	0	0	0	0	6
Q. lata	2	0	0	0	0	2
Q. oblonga	6	7	0	0	0	13
Q. seminulum	1	1	3	0	0	5
M. subrotunda	1	0	0	0	0	1
F. marginata	1	0	0	0	0	1
F. orbignyana	1	0	0	0	0	1
B. striatula	1	0	0	0	0	1
B. spathulata	2	0	0	0	0	2
B. variabilis	11	0	0	0	0	11
S. concava var. *loeblichi*	1	1	0	0	0	2
B. elongata	4	0	0	0	0	4
B. elegantissima	2	0	0	0	0	2
Uvigerina sp.	1	0	0	0	0	1
F. fusiformis	4	0	0	0	0	4
N. depressulus	2	1	0	0	0	3
A. batavus	4	5	23	0	0	32
E. crispum	0	0	0	4	0	4
						101

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: May	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	6	0	0	0	6
H. bradyi	6	0	0	0	0	6
C. jeffreysii	0	4	0	0	0	4
S. wrightii	0	0	6	0	0	6
D. ochracea sinuosa	2	0	0	0	0	2
E. scabrum	0	0	8	0	0	8
T. sagittula	2	0	2	0	0	4
C. involvens	2	0	0	0	0	2
Adelosina sp. 1	2	4	0	0	0	6
Q. aspera	0	0	2	0	0	2
Q. cliarensis	0	2	2	0	0	4
Q. cf. *cliarensis*	0	2	0	2	0	4
Q. dimidiata	32	6	0	0	0	38
Q. lata	38	10	0	0	0	48
Q. oblonga	22	88	0	0	0	110
Q. seminulum	4	4	0	0	0	8
M. circularis var. *elongata*	8	12	0	0	0	20
M. subrotunda	2	12	0	0	0	14
A. sp. cf. *A. scalaris*	2	0	0	0	0	2
G. gibba	2	10	0	0	0	12
F. lucida	10	6	0	0	0	16
F. orbignyana	0	2	0	0	0	2
Fissurina sp. 2	0	2	0	0	0	2
B. pseudoplicata	2	0	0	0	0	2
B. pseudopunctata	10	0	0	0	0	10
B. spathulata	18	0	0	0	0	18
B. variabilis	34	6	0	0	0	40
S. concava var. *loeblichi*	6	2	0	0	0	8
B. elongata	20	24	0	0	0	44
B. marginata	6	6	0	0	0	12
B. elegantissima	12	0	0	0	0	12
Uvigerina sp.	24	0	0	0	0	24
T. angulosa	2	4	0	0	0	6
F. fusiformis	16	0	0	0	0	16
G. praegeri	0	10	0	0	0	10
R. anomala	0	2	0	0	0	2
R. williamsoni	4	2	0	0	0	6
C. lobatulus	0	8	6	0	0	14
C. pseudoungerianus	0	2	0	0	0	2
P. mediterranensis	0	2	0	0	0	2
A. mamilla	0	2	0	0	0	2
H. germanica	8	0	0	0	0	8
N. depressulus	8	26	0	0	0	34
Nonionella sp.	4	6	0	0	0	10
A. batavus	20	52	88	4	0	164
E. crispum	10	42	12	84	0	148
E. gerthi	40	28	0	0	0	68
						988

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: June	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
H. bradyi	2	0	0	0	0	2
A. pseudospiralis	0	0	2	0	0	2
S. wrightii	0	0	4	0	0	4
C. involvens	0	2	0	0	0	2
C. diffusa	0	2	0	0	0	2
Adelosina sp. 1	0	2	0	0	0	2
Adelosina sp. 2	0	2	0	2	0	4
Q. aspera	0	0	0	4	0	4
Q. cliarensis	0	0	4	0	0	4
Q. dimidiata	14	0	0	0	0	14
Q. lata	4	6	0	0	0	10
Q. oblonga	18	40	0	0	0	58
Q. seminulum	8	16	10	0	0	34
M. circularis var. *elongata*	20	60	4	0	0	84
M. subrotunda	6	0	2	0	0	8
L. clavata	2	2	0	0	0	4
L. sulcata	0	4	0	0	0	4
F. lucida	0	2	0	0	0	2
Fissurina sp. 1	2	0	0	0	0	2
B. pseudopunctata	6	0	0	0	0	6
B. spathulata	10	0	0	0	0	10
B. variabilis	22	0	0	0	0	22
S. concava var. *loeblichi*	2	4	0	0	0	6
B. elongata	0	6	0	0	0	6
B. elegantissima	4	0	0	0	0	4
F. fusiformis	8	0	0	0	0	8
A. mamilla	0	2	0	0	0	2
N. depressulus	0	16	0	0	0	16
Nonionella sp.	2	2	4	0	0	8
B. frigida	2	0	0	0	0	2
A. batavus	44	96	10	4	0	154
E. crispum	0	86	90	32	0	208
E. gerthi	4	8	0	0	0	12
						710

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: July	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
P. bowmani	0	4	0	0	0	4
T. teivyense	0	8	0	0	0	8
H. bradyi	12	0	0	0	0	12
R. scottii	12	8	0	0	0	20
A. pseudospiralis	0	16	40	20	0	76
S. wrightii	0	0	4	0	0	4
D. ochracea sinuosa	8	0	0	0	0	8
D. rotaliformis	4	0	0	0	0	4
E. scabrum	0	20	4	0	0	24
T. earlandi	16	48	0	0	0	64
T. sagittula	0	4	20	4	0	28
C. obscura	8	0	0	0	0	8
S. vivipara	4	0	0	0	0	4
C. involvens	0	8	8	0	0	16
C. diffusa	0	0	4	4	0	8
Adelosina sp. 1	0	12	4	0	0	16
Adelosina sp. 2	0	4	0	0	0	4
S. excavata	0	0	4	0	0	4
Q. aspera	16	8	4	4	0	32
Q. cliarensis	0	4	12	0	0	16
Q. cf. *cliarensis*	0	0	24	0	0	24
Q. dimidiata	88	0	0	0	0	88
Q. lata	36	24	0	0	0	60
Q. mediterranensis	0	16	20	0	0	36
Q. oblonga	24	104	4	0	0	132
Q. seminulum	16	152	68	0	0	236
M. circularis var. *elongata*	52	76	24	0	0	152
M. subrotunda	244	80	0	0	0	324
L. clavata	12	16	0	0	0	28
L. gracilis	0	4	0	0	0	4
L. perlucida	8	0	0	0	0	8
G. gibba	0	12	0	0	0	12
F. lucida	24	32	0	0	0	56
B. pseudoplicata	20	0	0	0	0	20
B. spathulata	36	4	0	0	0	40
B. variabilis	40	4	0	0	0	44
S. concava var. *loeblichi*	8	4	0	0	0	12
B. elongata	16	32	0	0	0	48
B. elegantissima	4	0	0	0	0	4
Uvigerina sp.	32	0	0	0	0	32
T. angulosa	12	4	0	0	0	16
F. fusiformis	12	0	0	0	0	12
R. williamsoni	8	4	0	0	0	12
P. mediterranensis	0	4	0	0	0	4
H. germanica	20	0	0	0	0	20
N. depressulus	24	116	0	0	0	140
Nonionella sp.	0	0	8	0	0	8

APPENDIX II: NUMBER OF SPECIMENS PER GRAB.

White Patch: July	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Total
B. frigida	4	0	0	0	0	4
A. batavus	40	156	220	0	0	416
E. crispum	4	12	336	412	8	772
E. gerthi	28	32	0	0	0	60
						3184

APPENDIX III: CAWSAND BAY; ABSOLUTE ABUNDANCE OF FORAMINIFERID GROUPS.

	no. per grab	no. per 100g	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial
Aug	2872	2513	1100	1312	400	60	0	116	0	696	44	2004	2060	44	64
Sep	3092	1106	1544	1044	432	72	0	20	8	704	112	2248	2368	108	20
Oct	1460	995	316	944	188	12	0	0	0	1068	44	348	392	44	0
Nov	558	333	306	172	66	14	0	8	2	174	22	352	376	22	4
Dec	132	158	33	45	35	19	0	1	0	81	4	46	50	3	0
Jan	418	379	164	116	130	8	0	14	2	112	18	272	292	20	2
Feb	984	696	220	404	304	56	0	12	0	268	22	682	704	20	2
Mar	1540	716	584	616	308	32	0	64	4	576	32	864	900	28	8
Apr	514	454	222	158	126	8	0	4	0	120	4	386	390	6	0
May	392	233	137	205	47	2.67	0	6.67	0	80	16	289	305	18.7	1.3
Jun	136	93	31	62	40	3	0	1	0	46	4	85	89	4	0
Jul	252	182	76	130	39	7	0	32	0	86	5	129	134	9	18

	biserial	triserial	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	other aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	88	100	1156	800	620	0	188	1584	44	1056	0	1788	964	2468	276	8
Sep	108	156	1244	948	508	0	276	1780	104	928	4	1848	924	2408	332	32
Oct	56	16	148	160	1036	0	144	1184	32	100	0	320	1052	1300	72	0
Nov	20	6	180	158	168	0	36	326	22	172	2	318	208	468	54	4
Dec	2	3	15	31	78	0	5	114	3	10	0	43	83	120	6	0
Jan	36	26	48	176	110	0	50	306	16	44	2	250	136	314	62	8
Feb	82	40	140	438	262	0	92	742	22	128	0	600	354	806	136	12
Mar	104	88	364	388	560	0	72	1096	28	340	4	832	644	1276	196	4
Apr	16	8	162	204	118	0	18	324	10	162	0	360	148	478	24	6
May	21	27	145	101	77	0	42.7	192	14.7	141	1.33	260	110.7	313	49.3	8
Jun	3	7	40	36	43	3	18	73	3	40	2	48	82	117	12	1
Jul	19	6	88	25	86	1	30	118	5	92	7	107	132	196	39	4

APPENDIX III: CAWSAND BAY; RELATIVE ABUNDANCE OF FORAMINIFERID GROUPS.

	no. per grab	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial	biserial
Aug	2872	38.30	45.68	13.93	2.09	0.00	4.04	0.00	24.23	1.53	69.78	71.73	1.53	2.23	3.06
Sep	3092	49.94	33.76	13.97	2.33	0.00	0.65	0.26	22.77	3.62	72.70	76.58	3.49	0.65	3.49
Oct	1460	21.64	64.66	12.88	0.82	0.00	0.00	0.00	73.15	3.01	23.84	26.85	3.01	0.00	3.84
Nov	558	54.84	30.82	11.83	2.51	0.00	1.43	0.36	31.18	3.94	63.08	67.38	3.94	0.72	3.58
Dec	132	25.00	34.09	26.52	14.39	0.00	0.76	0.00	61.36	3.03	34.85	37.88	2.27	0.00	1.52
Jan	418	39.23	27.75	31.10	1.91	0.00	3.35	0.48	26.79	4.31	65.07	69.86	4.78	0.48	8.61
Feb	984	22.36	41.06	30.89	5.69	0.00	1.22	0.00	27.24	2.24	69.31	71.54	2.03	0.20	8.33
Mar	1540	37.92	40.00	20.00	2.08	0.00	4.16	0.26	37.40	2.08	56.10	58.44	1.82	0.52	6.75
Apr	514	43.19	30.74	24.51	1.56	0.00	0.78	0.00	23.35	0.78	75.10	75.88	1.17	0.00	3.11
May	392	34.95	52.30	11.99	0.68	0.00	1.70	0.00	20.41	4.08	73.72	77.81	4.77	0.33	5.36
Jun	136	22.79	45.59	29.41	2.21	0.00	0.74	0.00	33.82	2.94	62.50	65.44	2.94	0.00	2.21
Jul	252	30.16	51.59	15.48	2.78	0.00	12.70	0.00	34.13	1.98	51.19	53.17	3.57	7.14	7.54

	triserial	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	oth aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	3.48	40.25	27.86	21.59	0.00	6.55	55.15	1.53	36.77	0.00	62.26	33.57	85.93	9.61	0.28
Sep	5.05	40.23	30.66	16.43	0.00	8.93	57.57	3.36	30.01	0.13	59.77	29.88	77.88	10.74	1.03
Oct	1.10	10.14	10.96	70.96	0.00	9.86	81.10	2.19	6.85	0.00	21.92	72.05	89.04	4.93	0.00
Nov	1.08	32.26	28.32	30.11	0.00	6.45	58.42	3.94	30.82	0.36	56.99	37.28	83.87	9.68	0.72
Dec	2.27	11.36	23.48	59.09	0.00	3.79	86.36	2.27	7.58	0.00	32.58	62.88	90.91	4.55	0.00
Jan	6.22	11.48	42.11	26.32	0.00	11.96	73.21	3.83	10.53	0.48	59.81	32.54	75.12	14.83	1.91
Feb	4.07	14.23	44.51	26.63	0.00	9.35	75.41	2.24	13.01	0.00	60.98	35.98	81.91	13.82	1.22
Mar	5.71	23.64	25.19	36.36	0.00	4.68	71.17	1.82	22.08	0.26	54.03	41.82	82.86	12.73	0.26
Apr	1.56	31.52	39.69	22.96	0.00	3.50	63.04	1.95	31.52	0.00	70.04	28.79	93.00	4.67	1.17
May	6.89	36.99	25.77	19.64	0.00	10.89	48.98	3.75	35.97	0.34	66.33	28.24	79.85	12.58	2.04
Jun	5.15	29.41	26.47	31.62	2.21	13.24	53.68	2.21	29.41	1.47	35.29	60.29	86.03	8.82	0.74
Jul	2.38	34.92	9.92	34.13	0.40	11.90	46.83	1.98	36.51	2.78	42.46	52.38	77.78	15.48	1.59

APPENDIX III: DRAKE'S ISLAND; ABSOLUTE ABUNDANCE OF FORAMINIFERID GROUPS.

	no. per grab	no. per 100g	63-125 µm	125-250 µm	250-500 µm	500-1000µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial
Aug	546	374	378	94	66	6	2	30	2	282	18	214	234	12	2
Sep	454	295	304	72	64	14	0	32	12	242	12	156	180	16	0
Oct	208	122	142	40	22	4	0	11	2	118	5	72	79	10	0
Nov	222	150	114	66	40	2	0	6	2	112	2	100	104	6	0
Dec	22	34	13	4	5	0	0	2	0	12	0	8	8	0	0
Jan	149	118	86	54	8	1	0	20	0	48	1	80	81	14	0
Feb	56	116	24	18	14	0	0	6	0	20	1	29	30	3	0
Mar	93	95	69	5	18	1	0	3	1	46	1	42	44	1	0
Apr	18	26	14	1	2	1	0	1	0	11	0	6	6	0	1
May	216	236	107	99	10	0	0	36	0	66	3	111	114	20	5
Jun	102	172	51	41	6	4	0	4	0	74	0	24	24	3	0
Jul	157	141	89	57	11	0	0	13	0	71	1	72	73	13	0

	biserial	triserial	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	other aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	58	44	76	68	276	10	40	440	18	48	0	146	370	380	104	22
Sep	50	8	84	52	240	4	38	342	18	56	0	68	364	342	60	22
Oct	19	9	25	28	117	0	27	161	4	16	0	53	141	162	28	2
Nov	14	12	44	34	112	0	36	142	2	42	0	76	138	172	28	12
Dec	5	0	2	3	12	0	0	21	0	1	0	5	17	16	5	1
Jan	14	15	26	31	48	1	12	104	1	32	0	68	69	101	29	7
Feb	3	3	13	13	20	1	8	36	1	11	0	25	28	42	6	5
Mar	6	3	25	12	45	1	11	61	1	20	0	32	58	73	9	7
Apr	0	0	3	3	11	0	2	12	1	3	0	5	13	15	2	1
May	9	28	69	19	64	2	31	96	4	83	2	100	101	154	39	8
Jun	2	1	17	5	73	1	9	76	0	17	0	18	80	94	2	2
Jul	11	8	44	9	69	3	16	91	4	46	0	57	93	124	19	7

APPENDIX III: DRAKE'S ISLAND; RELATIVE ABUNDANCE OF FORAMINIFERID GROUPS.

	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial	biserial	triserial
Aug	69.23	17.22	12.09	1.10	0.37	5.49	0.37	51.65	3.30	39.19	42.86	2.20	0.37	10.62	8.06
Sep	66.96	15.86	14.10	3.08	0.00	7.05	2.64	53.30	2.64	34.36	39.65	3.52	0.00	11.01	1.76
Oct	68.27	19.23	10.58	1.92	0.00	5.29	0.96	56.73	2.40	34.62	37.98	4.81	0.00	9.13	4.33
Nov	51.35	29.73	18.02	0.90	0.00	2.70	0.90	50.45	0.90	45.05	46.85	2.70	0.00	6.31	5.41
Dec	59.09	18.18	22.73	0.00	0.00	9.09	0.00	54.55	0.00	36.36	36.36	0.00	0.00	22.73	0.00
Jan	57.72	36.24	5.37	0.67	0.00	13.42	0.00	32.21	0.67	53.69	54.36	9.40	0.00	9.40	10.07
Feb	42.86	32.14	25.00	0.00	0.00	10.71	0.00	35.71	1.79	51.79	53.57	5.36	0.00	5.36	5.36
Mar	74.19	5.38	19.35	1.08	0.00	3.23	1.08	49.46	1.08	45.16	47.31	1.08	0.00	6.45	3.23
Apr	77.78	5.56	11.11	5.56	0.00	5.56	0.00	61.11	0.00	33.33	33.33	0.00	5.56	0.00	0.00
May	49.54	45.83	4.63	0.00	0.00	16.67	0.00	30.56	1.39	51.39	52.78	9.26	2.31	4.17	12.96
Jun	50.00	40.20	5.88	3.92	0.00	3.92	0.00	72.55	0.00	23.53	23.53	2.94	0.00	1.96	0.98
Jul	56.69	36.31	7.01	0.00	0.00	8.28	0.00	45.22	0.64	45.86	46.50	8.28	0.00	7.01	5.10

	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	other aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	13.92	12.45	50.55	1.83	7.33	80.59	3.30	8.79	0.00	26.74	67.77	69.60	19.05	4.03
Sep	18.50	11.45	52.86	0.88	8.37	75.33	3.96	12.33	0.00	14.98	80.18	75.33	13.22	4.85
Oct	12.02	13.46	56.25	0.00	12.98	77.40	1.92	7.69	0.00	25.48	67.79	77.88	13.46	0.96
Nov	19.82	15.32	50.45	0.00	16.22	63.96	0.90	18.92	0.00	34.23	62.16	77.48	12.61	5.41
Dec	9.09	13.64	54.55	0.00	0.00	95.45	0.00	4.55	0.00	22.73	77.27	72.73	22.73	4.55
Jan	17.45	20.81	32.21	0.67	8.05	69.80	0.67	21.48	0.00	45.64	46.31	67.79	19.46	4.70
Feb	23.21	23.21	35.71	1.79	14.29	64.29	1.79	19.64	0.00	44.64	50.00	75.00	10.71	8.93
Mar	26.88	12.90	48.39	1.08	11.83	65.59	1.08	21.51	0.00	34.41	62.37	78.49	9.68	7.53
Apr	16.67	16.67	61.11	0.00	11.11	66.67	5.56	16.67	0.00	27.78	72.22	83.33	11.11	5.56
May	31.94	8.80	29.63	0.93	14.35	44.44	1.85	38.43	0.93	46.30	46.76	71.30	18.06	3.70
Jun	16.67	4.90	71.57	0.98	8.82	74.51	0.00	16.67	0.00	17.65	78.43	92.16	1.96	1.96
Jul	28.03	5.73	43.95	1.91	10.19	57.96	2.55	29.30	0.00	36.31	59.24	78.98	12.10	4.46

APPENDIX III: WHITE PATCH; ABSOLUTE ABUNDANCE OF FORAMINIFERID GROUPS.

	no. per grab	no. per 100g	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial
Aug	3924	2473	1916	840	780	388	0	120	0	1100	112	2592	2704	100	0
Sep	4580	2169	2356	1052	812	360	0	104	0	1072	172	3232	3404	160	44
Oct	1012	562	324	368	320	0	0	12	0	228	64	708	772	64	4
Nov	1644	1093	680	364	508	92	0	24	0	404	72	1144	1216	60	8
Dec	602	700	270	152	152	28	0	0	0	220	18	364	382	12	2
Jan	1836	1074	296	472	660	408	0	44	0	316	32	1444	1476	40	24
Feb	2600	1561	140	868	1064	524	4	236	0	316	80	1968	2048	48	24
Mar	870	916	114	166	370	216	4	52	8	98	22	690	720	22	4
Apr	101	80	51	16	29	5	0	0	0	33	2	66	68	2	0
May	988	244	378	394	126	90	0	36	0	256	34	662	696	32	2
Jun	710	727	180	358	130	42	0	8	0	226	12	464	476	14	4
Jul	3184	1926	892	1032	808	444	8	260	4	1148	108	1664	1776	120	112

	biserial	triserial	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	other aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	476	348	1172	792	1036	0	540	2376	72	936	0	1616	2112	2852	864	12
Sep	768	348	864	1376	1020	0	788	2924	160	692	16	2604	1684	3096	1164	28
Oct	96	28	48	552	212	8	136	784	56	32	4	660	268	784	128	16
Nov	292	76	144	684	380	0	188	1284	60	112	0	1048	492	1148	388	4
Dec	104	26	76	200	182	0	56	496	16	34	0	326	216	402	140	0
Jan	164	36	372	896	300	4	152	1284	28	364	8	1096	668	1540	220	4
Feb	152	232	576	1256	292	20	112	1860	96	532	0	1600	892	2056	412	24
Mar	38	64	216	428	94	4	66	568	26	208	2	526	312	724	106	8
Apr	20	7	8	32	32	0	16	76	2	7	0	62	36	71	27	0
May	104	106	264	214	254	12	138	612	42	196	0	416	516	686	218	28
Jun	56	10	238	166	222	0	40	424	6	238	2	244	440	594	90	0
Jul	224	124	1012	456	1124	12	320	1760	144	944	16	936	2056	2532	452	4

APPENDIX III: WHITE PATCH; RELATIVE ABUNDANCE OF FORAMINIFERID GROUPS.

	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	>1000 µm	Textulariina	Spirillinina	Miliolina	Lagenina	Rotaliina	Hyaline	unilocular	uniserial
Aug	48.83	21.41	19.88	9.89	0.00	3.06	0.00	28.03	2.85	66.06	68.91	2.55	0.00
Sep	51.44	22.97	17.73	7.86	0.00	2.27	0.00	23.41	3.76	70.57	74.32	3.49	0.96
Oct	32.02	36.36	31.62	0.00	0.00	1.19	0.00	22.53	6.32	69.96	76.28	6.32	0.40
Nov	41.36	22.14	30.90	5.60	0.00	1.46	0.00	24.57	4.38	69.59	73.97	3.65	0.49
Dec	44.85	25.25	25.25	4.65	0.00	0.00	0.00	36.54	2.99	60.47	63.46	1.99	0.33
Jan	16.12	25.71	35.95	22.22	0.00	2.40	0.00	17.21	1.74	78.65	80.39	2.18	1.31
Feb	5.38	33.38	40.92	20.15	0.15	9.08	0.00	12.15	3.08	75.69	78.77	1.85	0.92
Mar	13.10	19.08	42.53	24.83	0.46	5.98	0.92	11.26	2.53	79.31	82.76	2.53	0.46
Apr	50.50	15.84	28.71	4.95	0.00	0.00	0.00	32.67	1.98	65.35	67.33	1.98	0.00
May	38.26	39.88	12.75	9.11	0.00	3.64	0.00	25.91	3.44	67.00	70.45	3.24	0.20
Jun	25.35	50.42	18.31	5.92	0.00	1.13	0.00	31.83	1.69	65.35	67.04	1.97	0.56
Jul	28.02	32.41	25.38	13.94	0.25	8.17	0.13	36.06	3.39	52.26	55.78	3.77	3.52

	biserial	triserial	planispiral	trochospiral	quinqueloculine	other coiling	round	arch	slit	pore	other aperture	infaunal	epifaunal	herbivores	detritivores	suspension-feeders
Aug	12.13	8.87	29.87	20.18	26.40	0.00	13.76	60.55	1.83	23.85	0.00	41.18	53.82	72.68	22.02	0.31
Sep	16.77	7.60	18.86	30.04	22.27	0.00	17.21	63.84	3.49	15.11	0.35	56.86	36.77	67.60	25.41	0.61
Oct	9.49	2.77	4.74	54.55	20.95	0.79	13.44	77.47	5.53	3.16	0.40	65.22	26.48	77.47	12.65	1.58
Nov	17.76	4.62	8.76	41.61	23.11	0.00	11.44	78.10	3.65	6.81	0.00	63.75	29.93	69.83	23.60	0.24
Dec	17.28	4.32	12.62	33.22	30.23	0.00	9.30	82.39	2.66	5.65	0.00	54.15	35.88	66.78	23.26	0.00
Jan	8.93	1.96	20.26	48.80	16.34	0.22	8.28	69.93	1.53	19.83	0.44	59.69	36.38	83.88	11.98	0.22
Feb	5.85	8.92	22.15	48.31	11.23	0.77	4.31	71.54	3.69	20.46	0.00	61.54	34.31	79.08	15.85	0.92
Mar	4.37	7.36	24.83	49.20	10.80	0.46	7.59	65.29	2.99	23.91	0.23	60.46	35.86	83.22	12.18	0.92
Apr	19.80	6.93	7.92	31.68	31.68	0.00	15.84	75.25	1.98	6.93	0.00	61.39	35.64	70.30	26.73	0.00
May	10.53	10.73	26.72	21.66	25.71	1.21	13.97	61.94	4.25	19.84	0.00	42.11	52.23	69.43	22.06	2.83
Jun	7.89	1.41	33.52	23.38	31.27	0.00	5.63	59.72	0.85	33.52	0.28	34.37	61.97	83.66	12.68	0.00
Jul	7.04	3.89	31.78	14.32	35.30	0.38	10.05	55.28	4.52	29.65	0.50	29.40	64.57	79.52	14.20	0.13

APPENDIX III: DIVERSITY MEASURES.

	CAWSAND BAY				DRAKE'S ISLAND				WHITE PATCH			
	Alpha	Shannon	Richness	Evenness	Alpha	Shannon	Richness	Evenness	Alpha	Shannon	Richness	Evenness
Aug	4	2.37	3.64	0.698	10	2.9	6.51	0.776	6	2.78	4.83	0.749
Sep	6	2.55	4.6	0.701	10	2.89	5.88	0.802	8	2.8	6.05	0.709
Oct	3	1.72	2.88	0.557	14	2.71	6.93	0.744	6	2.1	4.48	0.606
Nov	6	2.27	4.27	0.682	10	2.97	5.37	0.874	7	2.48	5.39	0.667
Dec	6	1.96	3.69	0.667	3	2.35	3.56	0.946	6	2.45	4.37	0.727
Jan	8	2.45	5.3	0.7	9	2.89	5	0.888	5	1.93	4.12	0.556
Feb	6	2.13	4.64	0.608	7	2.78	4.97	0.912	6	1.98	4.45	0.551
Mar	5	2.16	3.68	0.65	8	2.34	4.63	0.758	6	1.95	4.43	0.568
Apr	4	1.79	3.04	0.598	2	1.78	2.77	0.812	7	2.43	4.33	0.799
May	9	2.4	5.69	0.676	12	2.87	6.51	0.801	10	3.03	6.67	0.788
Jun	8	2.3	4.68	0.725	7	2.4	4.11	0.801	7	2.38	4.88	0.682
Jul	8	2.57	4.88	0.772	8	2.73	4.55	0.859	8	2.88	5.96	0.74

APPENDIX IV: WEIGHT OF SEDIMENT RETAINED UPON SIEVES (g); CAWSAND BAY.

Phi	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*
-1.00	0.31	0.49	0.01	0.07	0.10	0.17	0.06	0.05	0.53	0.16	0.41	0.18
0.00	0.44	0.41	0.01	0.01	0.04	0.01	0.01	0.01	0.06	0.02	0.13	0.01
0.50	0.34	0.31	0.18	0.06	0.27	0.30	0.35	0.11	0.36	0.21	1.11	0.19
1.00	0.45	0.57	0.13	0.07	0.36	0.29	0.43	0.06	0.21	0.20	0.46	0.16
1.50	0.54	0.69	0.19	0.18	0.44	0.36	0.65	0.19	0.36	0.23	0.62	0.35
2.00	0.96	0.82	0.23	0.52	0.76	1.34	0.79	0.31	1.88	1.61	1.13	1.08
2.50	2.86	2.13	1.95	16.30	9.15	26.17	4.23	3.28	23.99	12.90	26.23	17.96
3.00	19.34	23.57	10.63	52.03	62.54	139.30	28.39	28.55	85.61	44.79	51.20	39.40
3.50	36.20	51.87	9.47	22.69	27.11	30.02	22.99	31.41	42.01	23.04	16.12	13.93
4.00	19.84	29.28	7.44	6.63	15.77	22.33	10.75	22.27	16.28	13.54	8.31	8.10
Total	81	110	30	99	117	220	69	86	171	97	106	81

APPENDIX IV: WEIGHT OF SEDIMENT RETAINED UPON SIEVES ,(g); DRAKE'S ISLAND.

Phi	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*
-1.00	0.44	5.33	0.5	0.36	1.62	0.08	0.77	0.68	1.47	0.53	0.34	0.7
0.00	1	10.12	0.64	0.1	0.34	0.05	0.36	0.41	0.56	0.01	0.09	0.12
0.50	1.84	4.59	4	2.72	4.71	3.6	7.62	12.34	20.6	1.14	1.96	3.93
1.00	7.12	8.46	6.27	5.12	16.46	5.23	17.61	27.01	17.29	1.93	4.55	9.36
1.50	17.61	18.74	6.95	10.25	26.04	6.54	16.2	31.89	17.95	6.15	7.97	16.03
2.00	41.88	29.26	7.37	17.7	55.7	9.73	25.01	38.17	24.98	20.11	27.39	37.86
2.50	47.87	24.08	5.74	19.58	29.93	6.94	16.53	22.95	16.76	19.63	20.6	22.97
3.00	63.08	19.32	0.5	10.97	17.28	2.99	7.21	9.75	7.49	12.5	13.74	13.77
3.50	17.54	5.21	0.02	1.31	2	0.43	0.82	1.25	1.16	3.35	3.25	2.74
4.00	2.29	1.53	0.16	0.27	0.25	0.1	0.16	0.24	0.18	0.68	0.46	0.7
Total	200.67	126.64	32.15	68.38	154.33	35.69	92.29	144.69	108.44	66.03	80.35	108.18

APPENDIX IV: WEIGHT OF SEDIMENT RETAINED UPON SIEVES (g); WHITE PATCH.

Phi	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*
-1.00	20.46	4.13	4.02	8.42	37.84	30.33	5.68	15.88	14.07	31.78	15.59	15.85
0.00	5.17	0.77	0.12	0.37	0.8	3.15	0.54	0.41	0.62	1.95	0.43	0.31
0.50	5.33	0.98	1.51	4.92	8.12	22.31	7.55	6.54	10.4	19.34	10.32	6.53
1.00	9.87	2.47	1.78	9.69	9.85	12.99	9.1	11.43	14.01	15.23	19.73	10.69
1.50	14.99	5.14	2.35	20.64	12.08	9.23	13.09	16.83	14.38	13.36	17.82	12.73
2.00	16.39	8.6	4.67	28.07	16.63	7.57	23.31	19.76	16.97	17.32	25.53	19.67
2.50	10.02	7.25	9.29	36.82	16.37	6.02	20.06	15.97	11.05	20.27	19.29	13.91
3.00	12.4	8.9	6.66	33.06	28.94	10.39	18.45	11.36	11.88	17.09	17.93	9.96
3.50	9.51	6.57	4.11	9.18	7.32	8.25	11.55	5.92	6.66	12.91	7.98	6.78
4.00	5.34	4.23	1.8	6.78	4.65	3.51	6.64	3.03	3.39	6.64	3.19	3.24
Total	109.48	49.04	36.31	157.95	142.6	113.75	115.97	107.13	103.43	155.89	137.81	99.67

APPENDIX IV: PROPORTION OF SEDIMENT <63 µm.

Month	Total sed	> 63 µm	< 63 µm	% < 63 µm	Month	Total sed	> 63 µm	< 63 µm	% < 63 µm	Month	Total sed	> 63 µm	< 63 µm	% < 63 µm
Aug	93.08	84.70	8.38	9.00	Aug	211.20	198.67	12.53	5.93	Aug	130.26	113.48	16.78	12.88
Sep	133.05	120.24	12.81	9.63	Sep	50.05	46.15	3.90	7.79	Sep	61.05	53.66	7.39	12.10
Oct	82.07	75.73	6.34	7.73	Oct	114.00	110.20	3.80	3.33	Oct	173.17	148.45	24.72	14.27
Nov	108.24	100.26	7.98	7.37	Nov	73.68	69.68	4.00	5.43	Nov	205.32	164.54	40.78	19.86
Dec	241.24	237.14	4.10	1.70	Dec	36.53	36.23	0.30	0.82	Dec	117.49	115.29	2.20	1.87
Jan	137.19	121.75	15.44	11.25	Jan	162.54	154.81	7.73	4.76	Jan	156.06	147.29	8.77	5.62
Feb	80.90	70.90	10.00	12.36	Feb	96.10	93.50	2.60	2.71	Feb	138.70	118.50	20.20	14.56
Mar	109.00	90.30	18.70	17.16	Mar	152.40	146.10	6.30	4.13	Mar	128.10	109.00	19.10	14.91
Apr	199.55	180.68	18.87	9.46	Apr	115.12	110.18	4.94	4.29	Apr	118.40	104.88	13.52	11.42
May	116.14	100.80	15.34	13.21	May	70.18	66.88	3.30	4.70	May	188.56	156.99	31.57	16.74
Jun	127.49	107.61	19.88	15.59	Jun	83.83	82.31	1.52	1.81	Jun	162.92	139.38	23.54	14.45
Jul	98.68	83.16	15.52	15.73	Jul	115.68	109.49	6.19	5.35	Jul	120.63	100.87	19.76	16.38

APPENDIX IV: PERCENTAGE OF SEDIMENTS <63 µm.

Cawsand Bay			Drake's Island			White Patch		
Size (microns)	% below	%	Size (microns)	% below	%	Size (microns)	% below	%
0.59	0.827	0.76	0.59	0	0	0.59	1.045	0.99
0.71	1.8933	1.066	0.71	0	0	0.71	2.4068	1.3618
0.86	3.1555	1.262	0.86	0.2961	0.2961	0.86	4.0324	1.6256
1.04	4.4394	1.284	1.04	1.0486	0.7525	1.04	5.7002	1.6678
1.26	5.6581	1.219	1.26	2.0356	0.987	1.26	7.2942	1.594
1.52	6.8659	1.208	1.52	3.0472	1.0116	1.52	8.8882	1.594
1.84	8.2152	1.349	1.84	4.0712	1.024	1.84	10.7038	1.8156
2.23	9.8799	1.665	2.23	5.3419	1.2707	2.23	12.9522	2.2484
2.7	11.9256	2.046	2.7	7.0444	1.7025	2.7	15.7179	2.7657
3.27	14.2541	2.329	3.27	8.9937	1.9493	3.27	18.9058	3.1879
3.95	16.8002	2.546	3.95	11.35	2.3563	3.95	22.3998	3.494
4.79	19.5205	2.72	4.79	14.0025	2.6525	4.79	26.1155	3.7157
5.79	22.3605	2.84	5.79	16.914	2.9115	5.79	29.9579	3.8424
7.01	25.2766	2.916	7.01	20.0723	3.1583	7.01	33.9059	3.948
8.48	28.2362	2.96	8.48	23.4773	3.405	8.48	37.9594	4.0535
10.27	31.2394	3.003	10.27	27.2771	3.7998	10.27	42.2029	4.2435
12.43	34.3404	3.101	12.43	31.6074	4.3303	12.43	46.7525	4.5496
15.05	37.6918	3.351	15.05	36.6162	5.0088	15.05	51.7138	4.9613
18.21	41.6525	3.961	18.21	42.3653	5.7491	18.21	57.1291	5.4153
22.04	46.6577	5.005	22.04	48.8052	6.4399	22.04	62.9877	5.8586
26.68	53.2081	6.55	26.68	55.8003	6.9951	26.68	69.279	6.2913
32.29	61.6082	8.4	32.29	63.3011	7.5008	32.29	75.9821	6.7031
39.08	71.6187	10.01	39.08	71.1598	7.8587	39.08	82.9068	6.9247
47.3	82.1298	10.51	47.3	79.1172	7.9574	47.3	89.5149	6.6081
57.25	91.6833	9.554	57.25	86.9388	7.8216	57.25	95.2257	5.7108
69.3	99.2238	7.54	69.3	94.5384	7.5996	69.3	99.6909	4.4652

APPENDIX V: CALCULATION OF ORGANIC CONTENT.

Calculation of organic content

Weight of salt

$$\text{Weight of salt} = \left\{\frac{\text{wet sediment weight - dry sediment weight}}{24.61}\right\}$$

Percentage loss

$$\text{Percentage loss} = \left\{\frac{\text{dry weight of sediment - ashed weight of sediment}}{\text{dry weight of sediment}}\right\}$$

Correction for salt content

$$\text{Correction for salt content} = \left\{\frac{\text{weight of salt}}{0.0405}\right\}$$

Percentage organic content

Percentage organic content = percentage loss - correction for salt content

APPENDIX V: CALCULATION OF ORGANIC CONTENT.

CAWSAND BAY

Month	Wet weight (g)	Dry weight (g)	Ashed weight (g)
August	1.03022	0.72602	0.70922
September	1.00084	0.70704	0.68366
October	1.03888	0.69123	0.66526
November	1.00624	0.71389	0.69723
December	1.06273	0.80527	0.78562
January	0.98817	0.64603	0.62515
February	1.02862	0.71127	0.68637
March	1.04753	0.72695	0.70852
April	0.98740	0.71088	0.69447
May	1.01099	0.69969	0.68259
June	1.45859	0.97652	0.94812
July	1.09420	0.70484	0.68784

DRAKE'S ISLAND

Month	Wet weight (g)	Dry weight (g)	Ashed weight (g)
August	1.01892	0.62851	0.57566
September	1.01886	0.69970	0.67909
October	1.05178	0.67685	0.63627
November	1.02369	0.60112	0.53977
December	1.07904	0.59165	0.47068
January	0.97928	0.53115	0.49350
February	0.97554	0.49453	0.45242
March	0.97698	0.59218	0.56061
April	1.05046	0.53759	0.49821
May	1.07528	0.70758	0.68778
June	1.26768	0.73148	0.71143
July	0.99673	0.57863	0.54767

APPENDIX V: CALCULATION OF ORGANIC CONTENT.

WHITE PATCH

Month	Wet weight (g)	Dry weight (g)	Ashed weight (g)
August	0.95946	0.57777	0.54355
September	1.02737	0.64669	0.61146
October	0.97495	0.64665	0.60894
November	1.05224	0.62090	0.58338
December	1.14353	0.67988	0.64211
January	1.03277	0.61758	0.58571
February	1.03291	0.63892	0.60768
March	0.93717	0.59513	0.56459
April	0.99759	0.66499	0.64439
May	0.90246	0.46496	0.43616
June	1.03470	0.65392	0.62486
July	1.09628	0.78936	0.75902

APPENDIX V: ABSOLUTE ABUNDANCE OF OTHER MEIOFAUNA.

	Copepoda			Amphipoda			Ostracoda			Polychaeta			Bivalvia			Gastropoda			Scaphopoda			Acariformes		
	CB	DI	WP	CB	DI	WP	CB	DI	WP	CB	DI	WP	CB	DI	WP	CB	DI	WP	CB	DI	WP	CB	DI	WP
Aug	568	56	408	24	8	0	84	768	64	0	0	0	0	70	0	0	8	0	0	6	0	0	36	0
Sep	728	68	616	12	0	16	144	638	224	0	0	20	0	84	8	4	10	0	0	44	4	0	26	0
Oct	632	195	160	16	2	0	56	152	12	4	0	0	0	38	0	0	5	0	0	2	0	0	37	0
Nov	222	118	516	0	10	16	42	132	48	4	0	0	6	100	4	0	12	0	0	12	0	0	2	0
Dec	64	34	366	1	0	2	10	25	10	0	0	0	0	19	2	0	4	0	0	5	0	0	2	0
Jan	230	10	448	4	0	4	30	71	36	2	0	4	2	78	8	0	7	4	0	16	0	0	0	0
Feb	490	5	220	0	3	0	46	29	52	2	1	0	2	17	8	0	0	0	0	4	0	0	0	0
Mar	620	9	62	0	0	0	84	39	34	0	0	0	0	32	4	0	14	0	0	19	0	0	0	0
Apr	178	17	144	6	1	1	18	29	5	0	0	0	2	15	0	0	2	0	0	1	0	0	3	0
May	172	29	158	1.33	3	2	50.7	178	38	5.33	0	0	2.67	56	8	0	6	2	0	8	0	0	11	0
Jun	92	83	52	3	2	0	36	199	38	0	0	0	1	56	2	1	0	0	0	7	0	0	49	0
Jul	362	67	472	3	0	4	66	130	112	0	0	0	3	51	4	0	0	4	0	7	0	0	2	0

APPENDIX V: ABUNDANCE OF CENTRIC DIATOMS.

Centric	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Actinocyclus octonarius	1	0	2	0	0	0	0	0	0	1	0	0
Actinoptychus senarius	2	0	11	12	1	0	0	0	4	4	7	6
Actinoptychus splendens	0	0	1	0	0	0	0	0	0	0	0	0
Asteromphalus heptactis	1	0	1	0	0	0	0	0	0	0	0	0
Aulacodiscus kittonii	0	0	1	0	0	0	0	0	0	0	0	0
Coscinodiscus marginatus	0	0	0	0	1	0	0	1	0	0	13	19
Coscinodiscus nodulifer	0	0	0	0	0	0	0	1	7	18	37	36
Coscinodiscus radiatus	3	0	17	16	0	0	0	0	5	13	27	8
Podosira stelliger	0	0	2	0	0	0	0	0	0	0	20	1
Roperia tessellata	0	0	0	0	0	0	0	0	0	0	4	0

APPENDIX V: ABUNDANCE OF PANDURIFORM DIATOMS.

Pandurlform	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Amphiprora angustata	1	0	0	1	27	0	0	2	8	0	2	0
Amphiprora surirelloides	3	0	1	3	2	0	1	2	0	2	26	4
Diploneis bombus	4	1	0	12	0	0	0	0	0	18	3	4
Diploneis chersonensis	10	7	22	20	0	0	3	3	9	31	29	61
Diploneis crabro	8	8	25	37	0	6	9	1	9	59	133	20
Diploneis didyma	0	0	1	0	0	0	3	2	79	9	0	0
Diploneis fusca	2	1	1	0	0	0	0	0	0	0	0	0
Diploneis sp.	0	2	4	5	0	0	0	0	1	1	0	0
Nitzschia bilobata	1	0	0	0	0	0	0	0	0	0	1	0
Oestrupia musca	1	0	1	0	0	0	0	0	0	0	0	0

APPENDIX V: ABUNDANCE OF SEMI-LANCEOLATE DIATOMS.

Semi lanceolate	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Amphora graeffi var. *minor*	6	1	0	0	0	0	0	0	0	0	0	0
Amphora grevilleana	0	1	0	0	0	0	0	0	0	0	0	0
Amphora hyalina	4	1	0	0	0	0	0	0	0	0	4	0
Amphora ocellata	0	0	0	0	0	0	0	0	0	0	0	1
Amphora ostrearia	0	0	0	0	0	1	0	0	0	0	0	1
Amphora ostrearia var. *vitrea*	1	1	1	0	0	2	9	7	0	0	0	0
Amphora robusta	1	12	1	0	0	0	0	0	0	0	0	0
Amphora spectabilis	0	2	4	0	2	1	5	3	1	1	0	0
Amphora ventricosa	3	16	1	8	7	0	0	2	15	1	1	4
Amphora sp.	0	2	0	3	0	0	0	0	0	1	1	0
Hantzschia marina	0	1	0	0	0	0	0	0	0	1	0	0
Hantzschia virgata	0	1	0	0	0	0	0	0	0	0	0	0
Hantzschia virgata var. *gracilis*	0	1	0	0	0	0	0	0	0	0	0	0

APPENDIX V: ABUNDANCE OF OTHER SHAPES OF DIATOMS.

Other	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Grammatophora serpentina	0	0	1	0	2	0	0	1	0	2	1	2
Licmophora flabellata	3	0	0	0	0	0	0	0	4	0	1	0
Navicula cancellata	1	16	0	4	1	4	0	0	0	1	9	5
Pinnularia rectangulata	1	0	0	0	0	4	0	1	0	0	0	4
Pinnularia trevelyana	0	0	1	0	0	0	0	4	0	0	3	0
Rhabdonema arcuatum	0	0	0	0	0	1	0	0	0	0	0	0

APPENDIX V: ABUNDANCE OF LANCEOLATE DIATOMS.

Lanceolate	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Brebissonia boeckii	0	0	0	0	0	1	0	3	0	0	0	0
Caloneis bravis	1	0	0	0	0	0	0	0	0	0	0	0
Caloneis liber	4	1	0	0	0	0	0	0	1	1	0	0
Caloneis westii	19	6	0	0	1	7	1	0	0	0	4	2
Navicula meniscus	3	1	0	0	8	1	0	13	0	0	0	0
Navicula palpebralis	2	3	0	0	0	17	6	10	1	0	2	0
Navicula peregrina	1	1	0	2	15	20	2	5	5	5	0	3
Navicula phyllepta	0	1	0	0	0	0	0	0	0	0	0	0
Navicula pseudocomoides	1	0	0	0	7	7	0	0	0	0	0	0
Navicula sp.	8	7	1	8	18	0	0	0	4	0	0	0
Nitzschia angularis	0	12	0	10	1	3	1	0	0	2	0	1
Scoliopleura tumida	0	0	0	0	0	0	16	11	5	0	0	0
Stauroneis amphioxys	1	0	0	0	0	0	1	1	7	0	0	0
Tropioneis lepidoptera	0	0	0	0	0	0	1	0	0	0	0	0

APPENDIX V: ABUNDANCE OF SIGMOID DIATOMS.

Sigmoid	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Donkinia recta	0	1	0	0	0	0	0	1	18	0	0	0
Gyrosigma balticum	87	4	5	0	0	2	0	0	7	0	0	0
Gyrosigma hippocampus	9	0	0	0	0	0	0	0	0	0	0	0
Gyrosigma littorale	1	0	0	0	0	0	0	0	0	0	0	0
Gyrosigma wansbeckii	1	0	0	2	0	0	0	0	1	0	0	0
Pleurosigma aestuarii	1	0	0	0	1	1	2	2	1	1	11	13
Pleurosigma marinum	26	9	15	11	0	0	0	0	9	3	0	1
Pleurosigma strigosum	20	10	37	10	0	3	2	3	45	2	4	15

APPENDIX V: ABUNDANCE OF ELLIPTICAL DIATOMS.

Elliptical	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Achnanthes brevipes	0	0	0	0	0	0	1	1	0	0	0	0
Achnanthes longipes	3	3	2	1	0	0	0	0	1	2	1	4
Achnanthes pseudogroenlandica	0	1	0	0	0	0	0	0	0	0	0	0
Amphora ovalis	0	0	0	56	0	2	1	4	5	4	27	21
Campylodiscus echeneis	0	0	1	0	0	0	0	0	0	0	0	0
Cocconeis disculoides	5	4	5	1	0	2	3	2	0	0	0	0
Cocconeis scutellum	1	0	0	0	5	1	5	4	0	2	0	2
Cocconeis speciosa	1	0	1	0	0	0	0	0	6	1	0	0
Cocconeis sublittoralis	3	4	6	22	153	16	5	19	5	4	6	10
Diploneis lineata	5	24	3	1	5	95	0	0	3	2	0	4
Diploneis littoralis	6	23	4	46	0	9	123	57	33	11	1	8
Diploneis notabilis	7	7	0	0	0	0	0	0	0	0	0	0
Diploneis smithii	5	10	14	3	0	1	25	31	8	0	0	0
Mastogloia splendida	1	0	0	0	0	0	0	0	1	0	0	0
Navicula abrupta	9	8	1	10	0	0	0	0	0	0	0	0
Navicula atlantica	0	0	0	0	0	5	0	0	0	0	0	0
Navicula britannica	1	0	0	0	0	0	0	0	0	0	0	0
Navicula clavata	0	8	9	4	12	10	1	2	21	4	1	2
Navicula clementis	2	1	0	0	0	0	0	0	0	0	0	0
Navicula cruciculoides	0	0	0	0	0	0	0	1	0	0	0	0
Navicula crucifera	2	3	0	0	0	0	0	0	0	0	0	0
Navicula directa var. *ramota*	0	0	0	0	11	12	7	0	16	5	5	5
Navicula distans	33	1	0	0	1	0	5	11	0	0	0	1
Navicula elegans	6	1	0	1	2	0	0	0	0	0	2	1
Navicula florinae	2	0	0	0	0	0	0	0	0	0	0	0
Navicula forcipata	19	120	2	71	9	78	76	72	76	26	7	14
Navicula hennedyii	1	0	28	18	2	6	0	6	3	10	13	5

APPENDIX V: ABUNDANCE OF ELLIPTICAL DIATOMS.

Elliptical	CB Aug	CB Oct	CB Jan	CB Apr	DI Aug	DI Oct	DI Jan	DI Apr	WP Aug	WP Oct	WP Jan	WP Apr
Navicula hyalina	1	10	0	8	0	0	6	5	1	0	1	0
Navicula inclementis	1	0	0	1	0	0	1	0	0	0	0	0
Navicula latissima	1	0	2	0	0	0	0	0	0	0	0	0
Navicula lyra	1	0	0	1	0	1	0	0	1	3	0	0
Navicula lyroides	8	6	0	2	0	1	0	0	14	1	1	0
Navicula maculosa	3	2	0	14	11	2	0	0	3	0	0	0
Navicula marina	0	0	0	0	1	0	0	0	0	0	1	0
Navicula pennata	2	1	1	0	1	0	0	1	0	1	0	0
Navicula pseudopalpebralis	1	0	0	0	0	0	0	0	0	0	0	0
Navicula tuscula	2	0	0	0	0	0	0	0	5	0	1	0
Nitzschia navicularis	0	0	1	2	1	2	5	5	0	3	1	1
Pinnularia ambigua	0	0	1	0	5	0	0	0	4	6	0	0
Rhaphoneis surirella	4	0	0	10	0	1	1	4	3	1	4	5
Scoliotropis latestriata	0	0	0	0	0	0	1	0	0	0	0	0
Surirella comis	3	0	6	1	0	0	0	0	1	6	3	3
Surirella fatuosa	0	0	1	0	0	0	0	0	0	0	1	3
Surirella ovata	0	0	0	0	0	0	0	0	0	0	1	1
Surirella smithii	1	1	1	11	0	0	0	1	2	2	2	0
Surirella sp.	0	0	0	0	0	0	0	0	1	5	0	0

APPENDIX VI

'K' MEDIUM

Stock solutions

Compound	Amount	Amount of sterile, distilled water
$NaNO_3$	7.5 g	100 ml
Na_2GlyPO_4	0.315 g	100 ml
TRIS	12.1 g	100 ml
NH_4Cl	0.054 g	100 ml
H_2SeO_3	0.013 g	100 ml

Trace Stock

$Na_2MoO_4.2H_20$	0.07 g
$CoSO_4.7H_2O$	0.14 g
$ZnSO_4.7H_2O$	0.23 g
$MnCl_2.4H_2O$	1.8 g
$CuSO_4.7H_2O$	0.025 g
FeNaEDTA	0.429 g
$Na_2EDTA.2H_2O$	3.72 g

Method for Stock Solutions

Dissolve the amounts of the above compounds into separate sterile bottles of 100 ml sterile, distilled water.

Method for Trace Stock

Dissolve the first five compounds into 100 ml of sterile, distilled water. Remove 1 ml of this solution with a sterile syringe and add to a sterile bottle containing 100 ml of sterile, distilled water. Add the remaining two ingredients to this solution.

Vitamin Stock

Biotin	1.0 mg
Cyanocobalamin	1.0 mg
Thiamin HCl	0.010 g

Method for Vitamin Stock solution

Dissolve the Biotin and the Cyanocobalamin into 200 ml of sterile, distilled water. Remove 0.1 ml of this solution with a sterile syringe and add to a bottle containing 100 ml of sterile, distilled water. Add the Thiamin HCl to this bottle and shake to dissolve.

Method for 'K' Medium

Using aseptic techniques Millipore filter 1 l of sea water (which has not been collected close to shore and has no ammonia in it) over cellulose nitrate filters of 0.45 μm pore diameter, into a sterile bottle. To the sea water add 1 ml of each of the Stock soulutions and the Trace stock solution. Heat the mixture in a microwave to 85°C. Cool to below 40°C and add 1 ml of the vitamin stock solution.

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group1 Foraminiferida from Cawsand Bay.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	18	37	3	31.03	63.79	5.17
6	26	25	0	50.98	49.02	0
9	25	24	1	50.0	48.0	2.0
12	3	12	1	18.75	75.0	6.25
15	7	23	0	23.33	76.67	0.0
18	7	23	0	23.33	76.67	0.0
21	3	12	0	20.0	80.0	0.0
24	13	17	0	43.33	56.67	0.0
27	3	11	1	20.0	73.33	6.67
30	3	11	0	21.43	78.57	0.0
33	0	14	0	0.00	100.0	0.0
36	6	22	0	21.43	78.57	0.0
39	3	11	0	21.43	78.57	0.0
42	4	10	0	28.57	71.43	0.0
45	5	23	0	17.86	82.14	0.0
48	5	8	1	35.71	57.14	7.14
51	3	10	0	23.08	76.92	0.0
54	5	16	9	16.67	53.33	30.0

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 2 Foraminiferida from Cawsand Bay.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	52	52	7	46.85	46.85	6.31
6	31	52	6	34.83	58.43	6.74
9	36	41	1	46.15	52.56	1.28
12	2	22	1	8.00	88.00	4.00
15	12	36	0	25.00	75.00	0.00
18	10	36	1	21.28	76.60	2.13
21	7	16	0	30.43	69.57	0.00
24	13	32	1	28.26	69.57	2.17
27	5	17	0	22.73	77.27	0.00
30	5	17	0	22.73	77.27	0.00
33	3	19	0	13.64	86.36	0.00
36	7	37	0	15.91	84.09	0.00
39	4	18	0	18.18	81.82	0.00
42	2	20	0	9.09	90.91	0.00
45	15	28	1	34.09	63.64	2.27
48	2	19	0	9.52	90.48	0.00
51	5	16	0	23.81	76.19	0.00
54	18	15	9	42.86	35.71	21.43

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 3 Foraminiferida from Cawsand Bay.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	39	63	17	32.77	52.94	14.29
6	39	47	4	43.33	52.22	4.44
9	19	56	9	22.62	66.67	10.71
12	0	20	0	0.00	100.00	0.00
15	9	30	1	22.50	75.00	2.50
18	10	28	0	26.32	73.68	0.00
21	9	10	0	47.37	52.63	0.00
24	11	27	0	28.95	71.05	0.00
27	3	16	0	15.79	84.21	0.00
30	7	12	0	36.84	63.16	0.00
33	1	18	0	5.26	94.74	0.00
36	8	30	0	21.05	78.95	0.00
39	2	17	0	10.53	89.47	0.00
42	9	10	0	47.37	52.63	0.00
45	10	28	0	26.32	73.68	0.00
48	3	16	0	15.79	84.21	0.00
51	7	12	0	36.84	63.16	0.00
54	10	26	2	26.32	68.42	5.26

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 4 Foraminiferida from Cawsand Bay.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	20	31	13	31.25	48.44	20.31
6	17	17	5	43.59	43.59	12.82
9	10	13	6	34.48	44.83	20.69
12	3	4	0	42.86	57.14	0.00
15	3	11	0	21.43	78.57	0.00
18	5	9	0	35.71	64.29	0.00
21	2	5	0	28.57	71.43	0.00
24	3	9	1	23.08	69.23	7.69
27	3	3	0	50.00	50.00	0.00
30	2	4	0	33.33	66.67	0.00
33	0	6	0	0.00	100.00	0.00
36	5	7	0	41.67	58.33	0.00
39	0	6	0	0.00	100.00	0.00
42	1	5	0	16.67	83.33	0.00
45	6	6	0	50.00	50.00	0.00
48	1	5	0	16.67	83.33	0.00
51	2	4	0	33.33	66.67	0.00
54	4	8	0	33.33	66.67	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 1 Foraminiferida from Drake's Island.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	3	3	0	50.00	50.00	0.00
6	1	5	0	16.67	83.33	0.00
9	0	6	0	0.00	100.00	0.00
12	0	2	0	0.00	100.00	0.00
15	0	4	0	0.00	100.00	0.00
18	0	4	0	0.00	100.00	0.00
21	0	2	0	0.00	100.00	0.00
24	1	2	1	25.00	50.00	25.00
27	0	3	0	0.00	100.00	0.00
30	0	3	0	0.00	100.00	0.00
33	0	3	0	0.00	100.00	0.00
36	2	1	0	66.67	33.33	0.00
39	0	3	0	0.00	100.00	0.00
42	0	2	1	0.00	66.67	33.33
45	0	2	0	0.00	100.00	0.00
48	0	2	0	0.00	100.00	0.00
51	0	2	0	0.00	100.00	0.00
54	1	1	0	50.00	50.00	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 2 Foraminiferida from Drake's Island.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	3	3	1	42.86	42.86	14.29
6	2	4	0	33.33	66.67	0.00
9	3	3	0	50.00	50.00	0.00
12	0	2	0	0.00	100.00	0.00
15	1	3	0	25.00	75.00	0.00
18	3	1	0	75.00	25.00	0.00
21	1	1	0	50.00	50.00	0.00
24	2	2	0	50.00	50.00	0.00
27	1	1	0	50.00	50.00	0.00
30	0	2	0	0.00	100.00	0.00
33	0	2	0	0.00	100.00	0.00
36	0	4	0	0.00	100.00	0.00
39	0	2	0	0.00	100.00	0.00
42	0	2	0	0.00	100.00	0.00
45	1	2	1	25.00	50.00	25.00
48	1	0	0	100.00	0.00	0.00
51	1	0	0	100.00	0.00	0.00
54	1	1	0	50.00	50.00	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 3 Foraminiferida from Drake's Island.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	0	3	12	0.00	0.00	100.00
6	0	0	0	0.00	0.00	100.00
9	0	0	0	0.00	0.00	100.00
12	0	0	0	0.00	0.00	100.00
15	0	0	0	0.00	0.00	100.00
18	0	0	0	0.00	0.00	100.00
21	0	0	0	0.00	0.00	100.00
24	0	0	0	0.00	0.00	100.00
27	0	0	0	0.00	0.00	100.00
30	0	0	0	0.00	0.00	100.00
33	0	0	0	0.00	0.00	100.00
36	0	0	0	0.00	0.00	100.00
39	0	0	0	0.00	0.00	100.00
42	0	0	0	0.00	0.00	100.00
45	0	0	0	0.00	0.00	100.00
48	0	0	0	0.00	0.00	100.00
51	0	0	0	0.00	0.00	100.00
54	0	0	0	0.00	0.00	100.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 4 Foraminiferida from Drake's Island.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	20	31	13	31.25	48.44	20.31
6	17	17	5	43.59	43.59	12.82
9	10	13	6	34.48	44.83	20.69
12	3	4	0	42.86	57.14	0.00
15	3	11	0	21.43	78.57	0.00
18	5	9	0	35.71	64.29	0.00
21	2	5	0	28.57	71.43	0.00
24	3	9	1	23.08	69.23	7.69
27	3	3	0	50.00	50.00	0.00
30	2	4	0	33.33	66.67	0.00
33	0	6	0	0.00	100.00	0.00
36	5	7	0	41.67	58.33	0.00
39	0	6	0	0.00	100.00	0.00
42	1	5	0	16.67	83.33	0.00
45	6	6	0	50.00	50.00	0.00
48	1	5	0	16.67	83.33	0.00
51	2	4	0	33.33	66.67	0.00
54	4	8	0	33.33	66.67	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 1 Foraminiferida from White Patch.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	23	51	5	29.11	64.56	0.06
6	26	34	4	40.63	53.13	0.06
9	29	28	0	50.88	49.12	0.00
12	2	17	0	10.53	89.47	0.00
15	12	24	1	32.43	64.86	0.03
18	10	26	0	27.78	72.22	0.00
21	14	20	2	38.89	55.56	0.06
24	10	24	0	29.41	70.59	0.00
27	4	10	3	23.53	58.82	0.18
30	6	8	0	42.86	57.14	0.00
33	3	10	1	21.43	71.43	0.07
36	7	19	0	26.92	73.08	0.00
39	3	10	0	23.08	76.92	0.00
42	3	10	0	23.08	76.92	0.00
45	5	15	6	19.23	57.69	0.23
48	2	5	0	28.57	71.43	0.00
51	3	4	0	42.86	57.14	0.00
54	3	4	0	42.86	57.14	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 2 Foraminiferida from White Patch.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	24	49	30	23.30	47.57	29.13
6	17	33	5	30.91	60.00	9.09
9	16	25	2	37.21	58.14	4.65
12	2	11	0	15.38	84.62	0.00
15	7	19	0	26.92	73.08	0.00
18	7	15	2	29.17	62.50	8.33
21	4	7	0	36.36	63.64	0.00
24	11	11	0	50.00	50.00	0.00
27	1	10	0	9.09	90.91	0.00
30	5	5	1	45.45	45.45	9.09
33	0	10	0	0.00	100.00	0.00
36	1	17	2	5.00	85.00	10.00
39	2	6	0	25.00	75.00	0.00
42	2	6	0	25.00	75.00	0.00
45	5	11	0	31.25	68.75	0.00
48	3	5	0	37.50	62.50	0.00
51	4	4	0	50.00	50.00	0.00
54	9	4	3	56.25	25.00	18.75

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 3 Foraminiferida from White Patch.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	20	25	15	33.33	41.67	25.00
6	9	34	2	20.00	75.56	4.44
9	8	17	5	26.67	56.67	16.67
12	0	4	0	0.00	100.00	0.00
15	3	3	1	42.86	42.86	14.29
18	1	5	0	16.67	83.33	0.00
21	2	1	0	66.67	33.33	0.00
24	2	3	1	33.33	50.00	16.67
27	2	1	0	66.67	33.33	0.00
30	1	2	0	33.33	66.67	0.00
33	2	1	0	66.67	33.33	0.00
36	2	4	0	33.33	66.67	0.00
39	0	3	0	0.00	100.00	0.00
42	1	2	0	33.33	66.67	0.00
45	2	4	0	33.33	66.67	0.00
48	1	2	0	33.33	66.67	0.00
51	3	0	0	100.00	0.00	0.00
54	6	0	0	100.00	0.00	0.00

APPENDIX VI: 10°C CULTURE.

Records of activity and contamination of Group 4 Foraminiferida from White Patch.

Number of days	Number active	Number inactive	Number contaminated	Percentage active	Percentage inactive	Percentage contaminated
3	43	53	10	40.57	50.00	9.43
6	35	46	5	40.70	53.49	5.81
9	41	26	3	58.57	37.14	4.29
12	2	20	0	9.09	90.91	0.00
15	13	28	1	29.55	63.64	2.27
18	12	29	1	28.57	69.05	2.38
21	5	15	0	25.00	75.00	0.00
24	17	23	0	42.50	57.50	0.00
27	7	12	1	35.00	60.00	5.00
30	11	8	0	57.89	42.11	0.00
33	9	10	0	47.37	52.63	0.00
36	6	32	0	15.79	84.21	0.00
39	3	16	0	15.79	84.21	0.00
42	5	16	0	26.32	84.21	0.00
45	11	27	0	28.95	71.05	0.00
48	3	15	1	15.79	78.95	5.26
51	12	6	0	66.67	33.33	0.00
54	16	18	2	44.44	50.00	5.56

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS PRELIMIARY EXPERIMENTAL SPECIMENS: RAW DATA

July, 1993: Geotaxis.

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
250-500	13	7	16	4
500-1000	30	30	35	25
Day 2				
250-500	10	10	8	12
500-1000	29	31	32	28
Day 3				
250-500	6	14	8	12
500-1000	30	30	26	34
Day 4				
250-500	8	12	9	11
500-1000	27	33	26	34
Day 5				
250-500	8	12	9	11
500-1000	28	32	22	38
Totals				
250-500	**45**	**55**	**50**	**50**
500-1000	**144**	**156**	**141**	**159**

July, 1993:Phototaxis (Light below).

Day & size (µm)	Control		Experimental	
Day 1	**Light**	**Dark**	**Light**	**Dark**
250-500	12	8	12	8
500-1000	23	37	34	26
Day 2				
250-500	10	10	12	8
500-1000	27	33	24	36
Day 3				
250-500	13	7	17	3
500-1000	34	26	41	19
Day 4				
250-500	11	9	14	6
500-1000	32	28	32	28
Day 5				
250-500	13	7	14	6
500-1000	29	31	42	18
Totals				
250-500	**59**	**41**	**69**	**31**
500-1000	**145**	**155**	**173**	**127**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS PRELIMIARY EXPERIMENTAL SPECIMENS: RAW DATA

July, 1993: Phototaxis (Light above).

Day & size (µm)	Control		Experimental	
Day 1	**Light**	**Dark**	**Light**	**Dark**
250-500	13	7	12	8
500-1000	22	38	48	12
Day 2				
250-500	12	8	16	4
500-1000	31	29	54	6
Day 3				
250-500	14	6	14	6
500-1000	28	32	49	11
Day 4				
250-500	9	11	15	5
500-1000	27	33	55	5
Day 5				
250-500	9	11	17	3
500-1000	24	36	49	11
Totals				
250-500	**57**	**43**	**74**	**26**
500-1000	**132**	**168**	**255**	**45**

October, 1993: Geotaxis.

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
250-500	3	3	4	2
500-1000	36	14	39	11
>1000	4	2	2	4
Day 2				
250-500	1	5	1	5
500-1000	18	32	24	26
>1000	4	2	3	3
Day 3				
250-500	2	4	1	5
500-1000	26	24	29	21
>1000	3	3	3	3
Day 4				
250-500	5	1	0	6
500-1000	23	27	28	22
>1000	5	1	1	5
Day 5				
250-500	3	3	0	6
500-1000	31	19	33	17
>1000	4	2	5	1
Totals				
250-500	**14**	**16**	**6**	**24**
500-1000	**134**	**116**	**153**	**97**
>1000	**20**	**10**	**14**	**16**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS PRELIMIARY EXPERIMENTAL SPECIMENS: RAW DATA

October, 1993: Phototaxis (Light below).

Day & size (µm)	Control		Experimental	
Day 1	**Dark**	**Light**	**Dark**	**Light**
250-500	3	3	4	2
500-1000	26	24	30	20
>1000	2	4	4	2
Day 2				
250-500	0	6	2	4
500-1000	22	28	18	32
>1000	0	6	1	5
Day 3				
250-500	3	3	4	2
500-1000	19	31	22	28
>1000	2	4	1	5
Day 4				
250-500	4	2	3	3
500-1000	27	23	22	28
>1000	2	4	1	5
Day 5				
250-500	4	2	6	0
500-1000	30	20	31	19
>1000	0	6	4	2
Totals				
250-500	**14**	**16**	**19**	**11**
500-1000	**124**	**126**	**123**	**127**
>1000	**6**	**24**	**11**	**19**

November, 1993: Geotaxis.

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
500-710	10	20	22	8
710-1000	17	13	24	6
>1000	10	5	12	3
Day 2				
500-710	16	14	23	7
710-1000	17	13	24	6
>1000	8	7	12	3
Day 3				
500-710	18	12	26	4
710-1000	19	11	23	7
>1000	8	7	12	3
Day 4				
500-710	16	14	15	15
710-1000	14	16	22	8
>1000	10	5	8	7
Day 5				
500-710	13	17	16	14
710-1000	19	11	19	11
>1000	9	6	6	9
Totals				
500-710	**73**	**77**	**102**	**48**
710-1000	**86**	**64**	**1120**	**38**
>1000	**45**	**30**	**50**	**25**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS PRELIMIARY EXPERIMENTAL SPECIMENS: RAW DATA

November, 1993: Phototaxis (Light below)

Day & size (µm)	Control		Experimental	
Day 1	**Light**	**Dark**	**Light**	**Dark**
500-710	17	13	20	10
710-1000	17	13	21	9
>1000	9	6	8	7
Day 2				
500-710	14	16	27	3
710-1000	16	14	18	12
>1000	11	4	9	6
Day 3				
500-710	11	19	20	10
710-1000	9	21	11	19
>1000	5	10	4	11
Day 4				
500-710	13	17	21	9
710-1000	16	14	7	23
>1000	5	10	3	12
Day 5				
500-710	15	15	16	14
710-1000	18	12	12	18
>1000	8	7	6	9
Totals				
500-710	**70**	**80**	**104**	**46**
710-1000	**76**	**74**	**69**	**81**
>1000	**38**	**37**	**30**	**45**

November, 1993: Phototaxis (Light above).

Day & size (µm)	Control		Experimental	
Day 1	**Light**	**Dark**	**Light**	**Dark**
500-710	16	14	23	7
710-1000	14	16	20	10
>1000	10	5	8	7
Day 2				
500-710	14	16	20	10
710-1000	16	14	24	6
>1000	4	11	13	2
Day 3				
500-710	20	10	18	12
710-1000	19	11	22	8
>1000	8	7	11	4
Day 4				
500-710	18	12	23	7
710-1000	15	15	22	8
>1000	10	5	12	3
Day 5				
500-710	12	18	24	6
710-1000	19	11	17	13
>1000	6	9	14	1
Totals				
500-710	**80**	**70**	**108**	**42**
710-1000	**83**	**67**	**105**	**45**
>1000	**38**	**37**	**58**	**17**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA

March, 1994: Geotaxis

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
250-355	6	2	0	8
355-500	22	18	20	20
Day 2				
250-355	5	3	2	6
355-500	22	18	22	18
Day 3				
250-355	5	3	0	8
355-500	17	23	14	26
Day 4				
250-355	7	1	5	3
355-500	24	16	17	23
Day 5				
250-355	2	6	2	6
355-500	18	22	19	21
Totals				
250-355	**25**	**15**	**9**	**31**
355-500	**103**	**97**	**92**	**108**

March, 1994: Phototaxis (Light above)

Day & size (µm)	Control		Experimental	
Day 1	**Dark**	**Light**	**Dark**	**Light**
250-355	6	2	3	5
355-500	24	16	8	32
Day 2				
250-355	3	5	3	5
355-500	24	16	13	27
Day 3				
250-355	7	1	1	7
355-500	22	18	12	28
Day 4				
250-355	4	4	1	7
355-500	19	21	12	28
Day 5				
250-355	2	6	3	5
355-500	19	21	12	28
Totals				
250-355	**22**	**18**	**11**	**29**
355-500	**108**	**92**	**57**	**143**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA

April, 1994: Geotaxis (25°)

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
355-500	22	18	13	27
500-1000	4	2	2	4
Day 2				
355-500	15	25	17	23
500-1000	3	3	4	2
Day 3				
355-500	13	27	20	20
500-1000	4	2	3	3
Day 4				
355-500	19	21	17	23
500-1000	3	3	5	1
Day 5				
355-500	16	24	15	25
500-1000	3	3	0	6
Totals				
355-500	**85**	**115**	**82**	**118**
500-1000	**17**	**13**	**14**	**16**

April, 1994: Phototaxis (Light above)

Day & size (µm)	Control		Experimental	
Day 1	**Dark**	**Light**	**Dark**	**Light**
355-500	20	20	14	26
500-1000	2	4	2	4
Day 2				
355-500	23	17	14	26
500-1000	3	3	3	3
Day 3				
355-500	21	19	12	28
500-1000	3	3	0	6
Day 4				
355-500	17	23	15	25
500-1000	4	2	0	6
Day 5				
355-500	24	16	12	28
500-1000	3	3	4	2
Totals				
355-500	**105**	**95**	**67**	**133**
500-1000	**15**	**15**	**9**	**21**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA

June, 1994: Geotaxis

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
250-355	8	2	7	3
355-500	13	7	5	15
500-1000	25	25	31	19
>1000	6	14	13	7
Day 2				
250-355	6	4	5	5
355-500	3	17	16	4
500-1000	20	30	27	23
>1000	6	14	10	10
Day 3				
250-355	5	5	4	6
355-500	12	8	13	7
500-1000	21	29	28	22
>1000	10	10	11	9
Day 4				
250-355	3	7	3	7
355-500	7	13	13	7
500-1000	31	19	27	23
>1000	9	11	10	10
Day 5				
250-355	5	5	5	5
355-500	9	11	16	4
500-1000	21	29	25	25
>1000	9	11	7	13
Totals				
250-355	**27**	**23**	**24**	**26**
355-500	**44**	**56**	**63**	**37**
500-1000	**118**	**132**	**138**	**112**
>1000	**40**	**60**	**51**	**49**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA
June, 1994: Phototaxis (Light above)

Day & size (µm)	Control		Experimental	
Day 1	**Dark**	**Light**	**Dark**	**Light**
250-355	5	5	5	5
355-500	10	10	9	11
500-1000	20	30	24	26
>1000	11	9	4	16
Day 2				
250-355	7	3	1	9
355-500	11	9	5	15
500-1000	27	23	3	47
>1000	9	11	4	16
Day 3				
250-355	6	4	1	9
355-500	10	10	3	17
500-1000	28	22	7	43
>1000	10	10	2	18
Day 4				
250-355	6	4	2	8
355-500	8	12	3	17
500-1000	26	24	8	42
>1000	10	10	0	20
Day 5				
250-355	7	3	1	9
355-500	11	9	3	17
500-1000	25	25	0	50
>1000	13	7	3	17
Totals				
250-355	**31**	**19**	**10**	**40**
355-500	**50**	**50**	**23**	**77**
500-1000	**126**	**124**	**42**	**208**
>1000	**53**	**47**	**13**	**87**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA

July, 1994: Geotaxis

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
355-500	3	3	4	2
500-1000	36	14	29	21
>1000	1	3	2	2
Day 2				
355-500	4	2	5	1
500-1000	30	20	28	22
>1000	0	4	3	1
Day 3				
355-500	5	1	2	4
500-1000	22	28	26	24
>1000	2	2	0	4
Day 4				
355-500	1	5	3	3
500-1000	33	17	22	28
>1000	0	4	2	2
Day 5				
355-500	3	3	2	4
500-1000	20	30	25	25
>1000	3	1	1	3
Totals				
355-500	**16**	**14**	**16**	**14**
500-1000	**141**	**109**	**130**	**120**
>1000	**6**	**14**	**8**	**12**

July, 1994: Phototaxis

Day & size (µm)	Control		Experimental	
Day 1	**Dark**	**Light**	**Dark**	**Light**
355-500	3	3	2	4
500-1000	27	23	2	48
>1000	2	2	0	4
Day 2				
355-500	5	1	1	5
500-1000	28	22	7	43
>1000	2	2	0	4
Day 3				
355-500	3	3	0	6
500-1000	27	23	3	47
>1000	3	1	0	4
Day 4				
355-500	4	2	1	5
500-1000	21	29	6	44
>1000	3	1	0	4
Day 5				
355-500	2	4	2	4
500-1000	25	25	0	50
>1000	3	1	0	4
Totals				
355-500	**17**	**13**	**6**	**24**
500-1000	**128**	**122**	**18**	**232**
>1000	**13**	**7**	**0**	**20**

APPENDIX VII.

GEOTAXIS AND PHOTOTAXIS SECONDARY EXPERIMENTAL SPECIMENS: RAW DATA
September, 1994: Geotaxis

Day & size (µm)	Control		Experimental	
Day 1	**High**	**Low**	**High**	**Low**
355-500	1	3	2	2
500-1000	14	26	26	14
Day 2				
355-500	0	4	4	0
500-1000	20	20	33	7
Day 3				
355-500	4	0	2	2
500-1000	22	18	23	17
Day 4				
355-500	2	2	4	0
500-1000	17	23	20	20
Day 5				
355-500	0	4	2	2
500-1000	18	22	22	18
Totals				
355-500	**7**	**13**	**14**	**6**
500-1000	**91**	**109**	**124**	**76**

APPENDIX VIII.

Variation in concentration of copper in µg per gram of dry sediment and in sea water in parts per million at Cawsand Bay April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	34.739	0.999	4.499	3.998	6.04
May	3.975	8.005	9.909	10.628	0.07
June	11.847	42.263	26.486	76.288	0.15
July	4.917	10.610	12.935	7.560	0.12

Variation in concentration of zinc in µg per gram of dry sediment and in sea water in parts per million at Cawsand Bay April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	5.748	8.992	12.498	19.988	0.94
May	9.936	11.474	39.166	60.817	0.08
June	7.814	17.068	64.253	98.726	0.14
July	10.817	17.658	37.313	30.242	0.18

Variation in concentration of cadmium in µg per gram of dry sediment and in sea water in parts per million at Cawsand Bay April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	0.499	1.499	2.999	3.498	0.03
May	0.248	0.000	0.000	0.000	0.17
June	5.545	2.438	2.943	6.283	0.29
July	0.492	1.209	2.985	4.536	0.30

Variation in concentration of lead in µg per gram of dry sediment and in sea water in parts per million at Cawsand Bay April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	9.747	18.2334	29.996	33.979	0.85
May	10.682	15.477	39.166	38.38	0.42
June	10.839	13.817	35.315	72.698	0.74
July	16.472	25.399	63.682	51.411	1.7

Variation in concentration of iron in µg per gram of dry sediment and in sea water in parts per million at Cawsand Bay April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	13.496	23.978	17717.34	2918.22	0.66
May	20.866	17.344	7248.02	1399.39	0.25
June	22.434	44.295	10221.7	14584.46	1.71
July	31.714	41.606	5049.75	171.37	0.64

Variation in concentration of copper in µg per gram of dry sediment and in sea water in parts per million at Drake's Island April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	5.493	1.747	16.472	9.477	3.07
May	3.708	3.873	0.454	0.935	0.07
June	5.492	4.786	20.686	22.398	0.13
July	5.361	5.985	0.505	2.411	0.14

APPENDIX VIII.

Variation in concentration of zinc in µg per gram of dry sediment and in sea water in parts per million at Drake's Island April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	6.492	7.486	21.464	16.996	0.87
May	9.393	8.957	14.982	4.673	0.07
June	7.989	8.06	85.267	73.035	0.14
July	11.743	12.891	15.153	4.823	0.18

Variation in concentration of cadmium in µg per gram of dry sediment and in sea water in parts per million at Drake's Island April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	0.749	0.499	3.993	4.489	0.07
May	0.000	0.000	0.000	0.000	0.06
June	0.499	0.252	4.541	7.304	0.29
July	0.766	0.921	3.536	2.894	0.28

Variation in concentration of lead in µg per gram of dry sediment and in sea water in parts per million at Drake's Island April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	10.987	9.233	27.454	27.433	0.92
May	7.415	8.715	17.252	15.422	0.48
June	7.240	7.557	64.581	80.339	0.78
July	17.615	16.344	46.470	35.208	1.61

Variation in concentration of iron in µg per gram of dry sediment and in sea water in parts per million at Drake's Island April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	14.982	9.732	17.471	16.460	0.59
May	17.303	13.315	2.724	3.271	0.21
June	12.483	17.884	10514.63	8929.789	0.62
July	20.678	19.337	53.036	7.717	0.5

Variation in concentration of copper in µg per gram of dry sediment and in sea water in parts per million at White Patch April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	16.741	0.499	339.423	199.862	1.81
May	8.726	4.597	7.285	1.958	0.07
June	29.081	20.161	111.208	43.167	0.14
July	7.252	7.171	16.168	8.719	0.16

Variation in concentration of zinc in µg per gram of dry sediment and in sea water in parts per million at White Patch April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	6.497	8.498	24.458	16.489	0.05
May	12.97	10.344	24.769	7.342	0.06
June	14.168	8.605	80.286	68.021	0.13
July	16.255	9.397	42.441	44.107	0.15

APPENDIX VIII.

Variation in concentration of cadmium in µg per gram of dry sediment and in sea water in parts per million at White Patch April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	0.750	0.750	5.990	4.497	0.07
May	0.000	0.000	1.943	1.958	0.00
June	0.249	0.246	8.680	7.413	0.27
July	0.500	2.967	3.032	3.590	0.26

Variation in concentration of lead in µg per gram of dry sediment and in sea water in parts per million at White Patch April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	15.242	12.247	27.953	29.480	0.82
May	10.848	9.424	11.656	13.705	0.54
June	12.428	8.114	65.64	93.311	0.81
July	14.754	27.943	61.136	45.646	0.79

Variation in concentration of iron in µg per gram of dry sediment and in sea water in parts per million at White Patch April to July, 1994.

Month	EDTA <250 µm	EDTA >250 µm	HCl <250 µm	HCl >250 µm	Water ppm
April	17.491	17.246	18.469	18.487	0.70
May	26.413	20.458	227.780	0.489	0.21
June	28.833	20.407	11305.200	6078.312	0.50
July	48.765	37.834	3748.990	135.399	0.46

APPENDIX VIII.

MICRONUTRIENT SOLUTION

$ZnSO_4 7H_2O$	1 ml	(solution	0.1%)
$MnSO_4 4H_2O$	2 ml	(solution	0.1%)
H_3BO_3	5 ml	(solution	0.2%)
$Co(NO_3)6H_2O$	5 ml	(solution	0.02%)
Na_2MoO_4	5 ml	(solution	0.02%)
$CuSO_4 5H_2O$	1 ml	(solution	0.0005%)
Distilled water	981 ml		
$FeSO_4 7H_2O$	0.7 g		
EDTA	0.8 g		

Soil extract

The soil used should be good quality garden or leaf soil: not too high in clay content, and containing no fertilisers or herbicides or pesticides.

Sieve the soil over a 1mm aperture sieve. Place 600g of soil into 2 litres of distilled water and shake to mix. Autoclave the medium for 60 minutes at 120°C. Filter with a fine gauze the next day. Separate the decanted extract from soil particles by centrifugation (10 minutes at 8,000 r.p.m.). Filter the extract through Whatman No. 1 paper, and place into small (100ml) conical flasks, and form lids out of doubled aluminium foil. Autoclave for 60 minutes at 120°C. After 24 hours, autoclave again for 30 minutes at 120°C. Store in the refrigerator until use.

APPENDIX VIII.

BRACKISH WATER MEDIUM

KNO_3	20 ml	(solution 1.0%)
K_2HPO_4	20 ml	(solution 0.1%)
$MgSO_4 7H_2O$	20 ml	(solution 0.1%)
soil extract	30 ml	
micronutrient solution	5 ml	
distilled water	450 ml	
0.2 µm Millipore-filtered sea water	455 ml	

Method

Add all ingredients together, and adjust pH to 8.0 using sodium hydroxide and hydrochloric acid. Filter the solution over Whatman No. 1 paper, and autoclave the medium for 20 minutes at 120°C. If the medium shows precipitation, re-filter with Whatman No. 1 paper. Add 5µg of vitamin B_{12} when the medium has cooled.

APPENDIX VIII.

ERDSHREIBER MEDIUM

$NaNO_3$	100 mg
$Na_2HPO_4 7H_2O$	20 mg
soil extract	50 ml
sea water	950 ml

Method

Add all ingredients together, adjust pH to 8.0 by the addition of sodium hydroxide or hydrochloric acid. Filter the medium through Whatman No. 1 paper and autoclave for 20 minutes at 120°C. If precipitation occurs, re-filter through filter paper.

SEA WATER MEDIUM

Sea water for the culture of *Rotaliella elatiana* was prepared by evaporating the sea water to a salinity of 40.9‰, and the pH was adjusted to 8.0-8.1 by the addition of sodium hydroxide or hydrochloric acid. The resultant medium was Millipore-filtered (0.2 µm) and autoclaved at 120°C for 20 minutes.